POSITIVE ENERGY HOMES

Creating Passive Houses for Better Living

ROBIN BRIMBLECOMBE AND KARA ROSEMEIER

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Foreword

There are over 40 000 Passive House houses and buildings in Europe, and a smattering of them in other parts of the world. For many green builders, Passive House is a destination. However, it is fundamentally an energy standard that happens to have a degree of comfort as a side-effect.

With Positive Energy Homes, Passive House is not a destination but a step, albeit a big one, in a larger journey. It's a trip that builds on comfort and includes beauty, light and connection to the environment.

But perhaps most importantly, it is positive. In much of the world, the target is net-zero, a point where a building generates as much energy as it uses. This is irrespective of quality or comfort; you can get to zero with lots of solar panels and wind turbines on an uncomfortable, draughty home.

And what is zero? Nothing. But positive energy is an attitude about actually contributing, where we 'give back more energy to the common pool than we take out'.

It's hard to get people excited about saving money on energy these days, but everyone understands comfort, the idea of a home where they are never too cold or too hot, too humid, too draughty. People also care about health; Architect Elrond Burrell notes that: 'Asthma rates, for example, in some affluent countries such as the UK and New Zealand are, quite frankly, ridiculously high. If our buildings were more comfortable and healthy this would be much less likely to be the case.'

Finally, in these turbulent times one cannot lose sight of resilience, the ability of our homes to protect us when the power goes out, when the storms hit. A Positive Energy Home will keep its occupants safe and comfortable for days or even weeks.

It is important that we have building standards that reduce energy consumption, as the Passive House standard does. But the role of a building is to keep us healthy, happy, safe and comfortable; energy consumption is secondary to that. The Positive Energy Homes concept builds on Passive House in a way that focuses on people, not buildings. If there was a metric for happiness per square metre, homes designed to the Positive Energy Homes standard would come out on top.

Lloyd Alter
Adjunct Professor, School of Interior Design, Ryerson University

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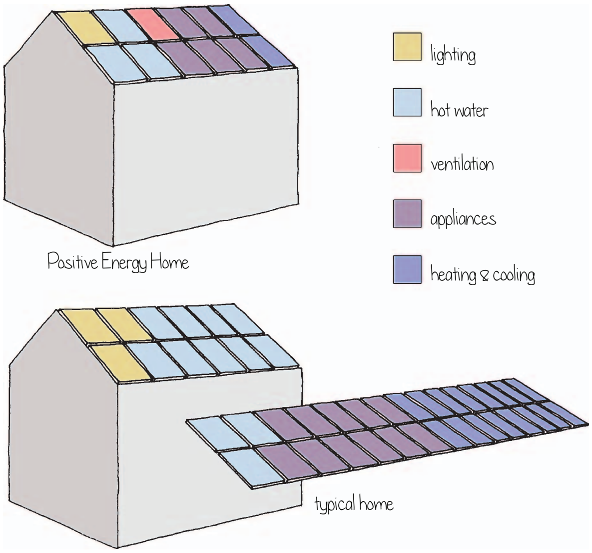
Introduction

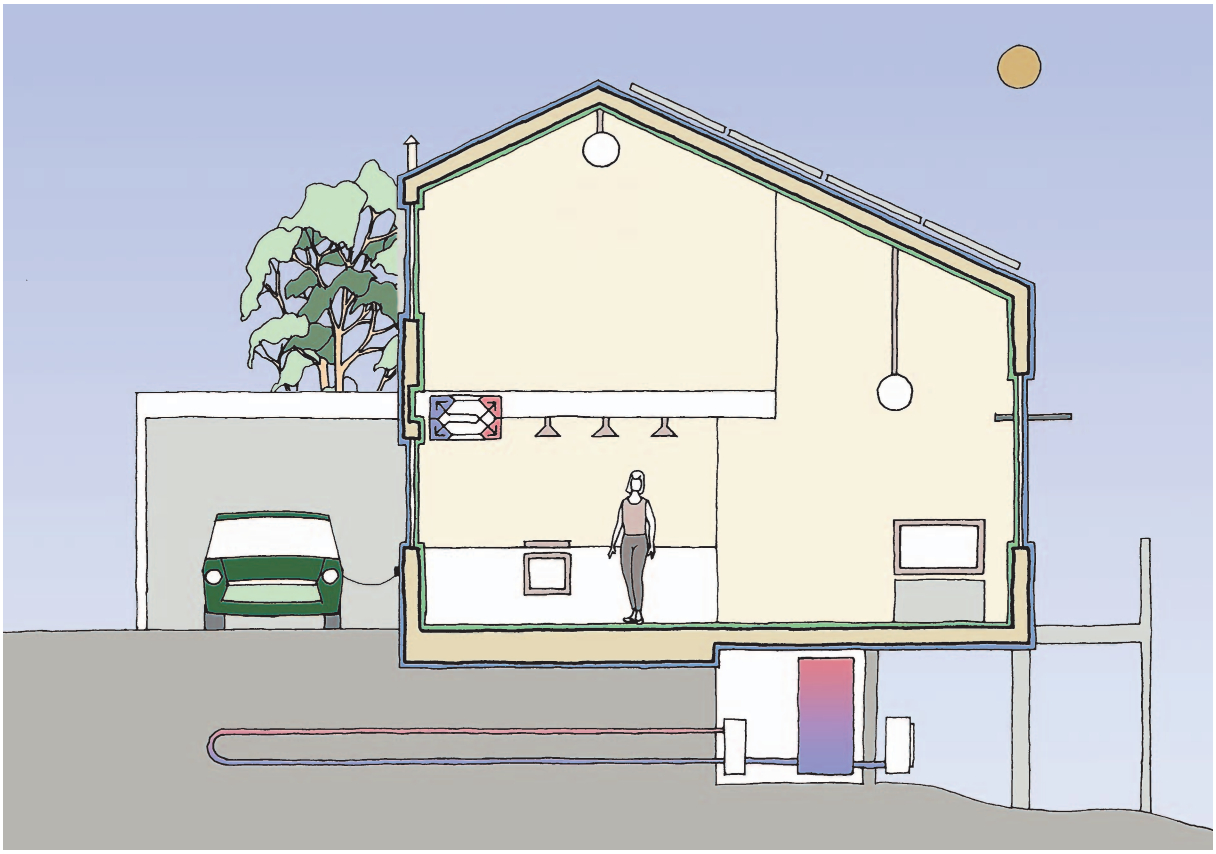
Humanity is at a crossroads. Intuitively, and backed by science, we know that we need to use resources a lot smarter for a chance at continuing to enjoy the standard of living we have become accustomed to. We also know in our hearts of hearts that we need to share them far more equitably to avoid further conflicts, forced migration and suffering. Access to energy is one of the reasons for many of our current global challenges and without feeling that we have enough for our families and ourselves, then the thought of sharing can be daunting. The good news is that we can all do something about this in our own homes. Positive Energy Homes are houses that provide superior comfort and health for their occupants while generating more energy than they need through onsite renewables. They empower people to live healthy and comfortable lives, providing clean energy to power transport, work and play, with enough left over to share.

To achieve this we need to curb the consumption in our homes. This does not necessarily require us to change the way we go about our lives, but to make far better use of the energy we consume. LEDs are a good example: they deliver the light we need, with only a tenth of the power of an incandescent light bulb. However, this book is not about creating homes that provide the same service using less energy: this book is about creating homes that provide superior comfort, air quality and engagement year round, while harvesting more energy than they devour.

A home you love living in that produces enough clean energy to share with your community is surprisingly simple to create with a thorough understanding of how buildings work and careful attention to detail in construction. We aim to provide our readers with a recipe for building a Positive Energy Home. Starting with a discussion on delivering home comfort and health, the book moves on to explain the role of the building fabric in the creation of great places to live. From there, effective strategies for providing fresh air and smart options for heating and cooling are explored. Add to this daylight harvesting and efficient lighting, and engaging and relaxing



Number of solar panels required to power a typical home compared with a Positive Energy Home, showing indicative breakdown of energy use.



Components of a Positive Energy Home including: airtight thermal bridge free thermal envelope; solar heat gain control; heat recovery ventilation; high-efficiency appliances and lighting; all-electric cooking, heating/cooling and hot water; and onsite energy generation.

spaces to live are within reach. We then take a look at the selection of efficient appliances and their sensible use to make our lives easier while eliminating waste. With these measures in place, achieving a positive energy balance for your comfortable, healthy home is as simple as putting a solar array on the roof (see figure on p. ix).

Creating homes that are positive for the people and planet starts with optimising the fabric of houses, reducing the need for active intervention (heating and cooling) to keep our homes comfortable and healthy. Although not the only way to create a home that produces more energy than it consumes, the Passive House standard is a fabric-first approach to the design and construction of energy efficient buildings. Deeply rooted in building science and with a well-proven track record, we are basing our concept of Positive Energy Homes on the Passive House standard. We believe that in addition to serving as the foundation for Positive Energy Homes, an introduction to the Passive House standard will also allow our readers to draw on the many tested and proven Passive House examples, experienced professionals, online resources and literature that will be invaluable in the creation of a wonderful home.

The Passive House Institute, a central European research facility, has spent the better part of three decades developing an intimate understanding of the science of buildings, which we explore throughout this book. Unlike building codes that are based on current industry trends, Passive House has been developed around the fundamental laws of physics and the principles of biology. It is therefore fair to assume that the Passive House standard will be as relevant in the future as it is today. Passive Houses are healthy and comfortable buildings that require very little energy to deliver blissful places to live.

What differentiates Positive Energy Homes from Passive Houses? Not much. All the essentials of Positive Energy Homes are already in place when you design and build a certified Passive House. Positive Energy Homes are Passive Houses able to generate a surplus of renewable energy. The new Passive House certification classes Plus and Premium (see Chapter 10 for details) have an identical goal. In contrast to net-zero energy strategies, the emphasis of Positive Energy Homes is not on simply generating enough energy to cover the annual demand. It is on increasing our quality of living while radically reducing our energy demand to near zero, thereby putting the renewable energy produced on site to much better use.

Our motivation for writing this book is the belief that everyone deserves a good home – a private sphere that shelters us, and allows us to unfold. The science to get there is clear, but not all the concepts are intuitive or accessible. Plus, there are many myths that shroud the path. With this book, we aim to give you a guide and inspiration for how positive energy living can be achieved. We will tell you what to look for in the design of your home to prevent energy leaks, and then discuss ways to over-compensate for the energy that is inevitably used in the process of providing you with appropriate warming or cooling, fresh air, hot water, light and appliances that make life easier. Obviously this book cannot replace the training and experience of the many qualified professionals required to create a home. However, it aims to provide the reader with the technical knowledge and performance targets needed to work with a project team to deliver a home that powers itself from clean energy.

This book is written by authors in the South Pacific. Our examples are homes in our neighbourhood, and some details have to be considered in this context. The principles we explain are universally valid, because they are firmly grounded in physics. Just as gravity works the same way throughout the world, so does the physics of building. Positive Energy Homes are concerned with outcomes: healthy and comfortable homes that have energy left to share. How these homes will look will need to adapt to the local climate, the occupants preferences and other local conditions. Each of the opportunities we discuss offer significant benefits on their own, but, when implemented together, the results are far greater than the sum of the parts.

We focus on detached residential buildings in this book, not because we believe that everyone should live in one – far from it – but simply because multi-unit buildings add a layer of complexity to housing design that is beyond the scope of this book. And while there are some hints at retrofitting existing houses where the same principles apply, the focus is on the design of new homes. This is because there are simply too many ways in which an existing home may have been constructed, all of which require thorough analysis and custom fixes. Therefore, we do not dwell on how to retrofit building fabric, purely because it would add layer upon layer of intricacy. We fully acknowledge that most of the built environment has already been constructed, and that the most efficiency gains are to be had from retrofitting existing homes. But doing so is the black belt of positive energy housing. The maxim for retrofitting a house is similar to the Hippocratic Oath: ‘first do no harm’. As with medicine, for buildings this requires a robust assessment of the ‘patient’, which is beyond the scope of this book.

Furthermore, we acknowledge that the construction and use of homes has broader environmental impacts than just operational energy. Tackling all of these opportunities is bigger than just one book. As such, we have attempted to lay out practical and accessible solutions to creating Positive Energy Homes, and leave the many great complementary opportunities to source water, materials and products in a sustainable manner to specialists on these topics.

This book is for people who make decisions about the future. Designers, builders and future homeowners all need to think very carefully about the world 50 years from now, because the houses they design and build now will still be standing then. Will the home feel like a mobile phone from the 1980s: clunky, out of place and of limited use? Or will it be a testament to a new way of thinking: a world where everyone has a fair share of resources, and the right to a good home?

CHAPTER 1

Creating healthy homes

The prime purpose of houses is to shelter us from harm. Positive energy living is about creating a home in a friendly environment, well protected from the elements and filled with fresh air. Our houses should be a safe haven, allowing us to thrive.

Are our houses fit for this purpose? When talking to immigrants to New Zealand from Europe or North America, the conversation will often turn to a lament about how cold our houses are. A friend from Canada recently exclaimed that the coldest she has ever been was in her house in Auckland. This is remarkable, because the mercury frequently drops to minus 20°C where she spent most of her life, whereas frost is so rare in Auckland that it is newsworthy. Many houses in Australia and New Zealand are cold and draughty in winter, and warm and stuffy in summer. Given that people in the developed world spend most of their time indoors, making our homes more liveable makes a lot of sense, and offers environmental and financial benefits.

So what are the hallmarks of a truly liveable home? This chapter explores what makes a home a comfortable and healthy place.

We love to be in touch with the outdoors but also crave the comfort of indoors. Consequently, we tend to be attracted to houses that offer indoor–outdoor living. But typically, this porosity is only then a delight when ambient conditions are pleasant. A Positive Energy Home in contrast allows us to enjoy the light and air we love, while sheltering us year round.

To achieve this, the indoor–outdoor flow needs to be controllable. Leaky homes are not able to exclude elements of the outdoors when they are not wanted. Just as a tap is a much better way to manage water use in the kitchen sink than a constant leak, homes that have ways to control the entrance and exit of the weather, pollutants, allergens, noise, smells and creatures are much more pleasant to live in! A clear boundary, called the thermal envelope, around the spaces where we live is necessary to control indoor comfort and air quality. To be effective, this boundary must not be interrupted.

With our lives predominantly spent indoors, we ought to be impelled to create wholesome indoor environments, especially for vulnerable subgroups of society, such as the very young, very old or otherwise fragile, who are likely to spend even larger portions of their time in the home.

The quality of the indoor environment is predominantly determined by the level of indoor air pollution, thermal comfort, noise and the quality of light. How the building fabric performs and how houses are ventilated and illuminated will impact markedly on the degree of refuge the

Certified Passive House in Wanaka, New Zealand (Photo: Simon Devitt).

indoor environment can afford. An intact envelope makes the indoor environment controllable, but we need to open up selectively for fresh air from the outdoors. The way we ventilate our homes is particularly crucial for thermal comfort and indoor air quality, and also impacts on the noise level of indoor spaces. As much as the building fabric and ventilation both have a key role in the provision of good indoor environmental quality, they are simultaneously tied to the energy consumption of houses. For example, a higher rate of fresh air supply will better dilute airborne pollutants, but without effective heat recovery; it will also result in excessive energy needs for the conditioning of indoor spaces and have implications for thermal comfort and noise levels. Likewise, larger windows will permit more solar gains – but also leak significantly more energy than opaque walls when the sun is not shining. How do we unite these conflicting goals? Design solutions to meet these challenges are covered in upcoming chapters, but first let's talk about the key concepts that underpin the creation of comfortable, healthy and efficient homes.

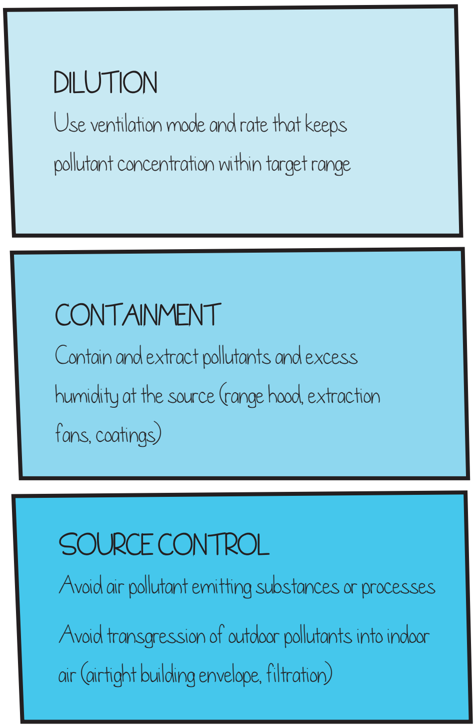
1.1 AIR CONTROL

Healthy homes need good quality air for us to breathe.

Indoor air quality is affected by contaminants that cause harm or irritation, have a bad smell or reduce our ability to see clearly (e.g. smoke). These contaminants can come from outside the home or are emitted indoors (e.g. from furniture, household products, stoves, pets and people). Depending on how strong or how toxic they are, these contaminants affect us to different degrees.

In the year 2000, the World Health Organization (WHO) identified healthy indoor air as a human right (WHO Regional Office for Europe 2000). However, despite this declaration and the importance of air quality in our homes, there are few legal guidelines that describe safe levels of indoor pollutants in residential buildings. Most regulations either apply to workplaces or outdoor air. The impact on our wellbeing from air pollutant concentrations, however, will be the same, regardless of where we are exposed. Reasons for the absence of binding thresholds for residential environments may be the vast variety of potential contaminants and analytical equipment to measure them that can be quite intrusive, which is usually less problematic for outdoor or workplace air monitoring. Without turning our home into a laboratory: what options do we have for air control?

Ideally, a strategy for good indoor air quality in houses should start with avoiding the use of pollutant-emitting materials and substances, as well as filtering any harmful contents from outdoor air before it is let in. However, this is extremely difficult, because most building material manufacturers are not required to declare ingredients, and we often do not know the exact composition of other substances used in the household either. Do you know which pollutants lurk in your bathroom cleaning spray? In addition, breathing emits carbon dioxide (CO_2), and odours and particles are a by-product of the typical usage of houses. With people actually living in their homes, controlling the source of contaminants can therefore never be complete. Filtering pollutants from outdoor air before it enters the home is only practically feasible when mechanical forces for ventilation are used, because the pressure generated by natural forces is insufficient for outdoor air to pass reliably through a filter.



Building blocks for good indoor air quality.

The next step up in the strategy for controlling indoor air quality in the home is containment of pollutants and excess humidity, for example, by using range hoods or extractor fans in kitchens and bathrooms to extract pollutants and humidity at their point of origin before they can spread. Pollutants can also be contained using coatings to prevent contaminants in suspicious materials, such as fibreboards, from becoming airborne.

Dilution of pollutant concentration levels by ventilating with fresh air is the last resort in this strategy – yet it can be the most reliable step of the way, because it is fully in our hands.

It's only natural

Some schools of thought aspire to homes that are one with nature. As an example, a review of Mies van der Rohe's Farnsworth House – a masterpiece of the International Style of architecture that emerged in the first half of the 20th century – positively remarked that:

> *'[...] the house is very much a balance with nature, and an extension of nature. A change in the season or an alteration of the landscape creates a marked change in the mood inside the house.[...] the man-made environment and the natural environment are here permitted to respond to, and to interact with, each other.'* (Palumbo 2003)

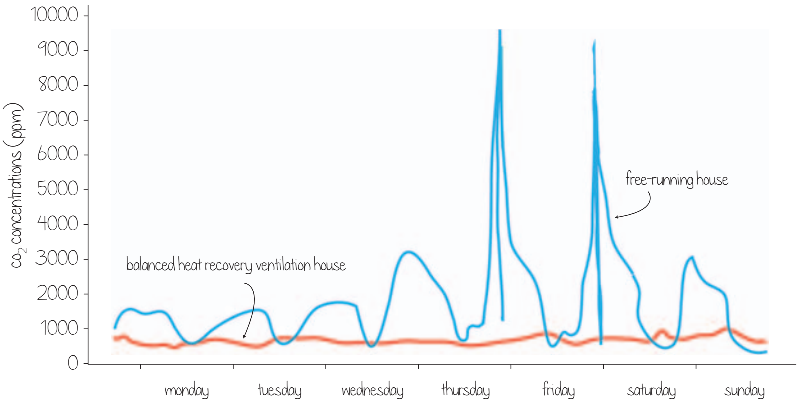
The first owner, Dr Edith Farnsworth, agrees that there is hardly any separation, writing in her memoirs that she frequently found the house awash with several inches of water, and that inside, one burns in summer and freezes in winter. Being one with nature may not always be desirable!

Farnsworth House (Photo: Library of Congress, Prints & Photographs Division, ILL, 47-PLAN.V, 1–10).

Separating between ‘natural’ and ‘man-made’ is, in our view, not helpful for good decision making about houses. So-called natural building materials, such as rammed earth, may contain substances harmful to us, such as radon-emitting isotopes. Timber dust is another known carcinogen. Using only ‘natural’ materials is not a conclusive short cut to building a healthy home. We need to carefully examine all materials with regard to their potential to harm or help us. Positive Energy Homes can be built with materials that have undergone minimal processing, such as straw bales. The S-House in Austria, for example, did not use any plastic or metal for the construction of the building envelope, and several straw bale houses have been certified as Passive Houses.

Approximately 30 m^3 of fresh air per person per hour are required to keep contaminant concentrations at bay. In addition, ensuring this fresh air is distributed effectively throughout the indoor environment also matters. For example, a very well-ventilated bathroom will not automatically lead to good indoor air quality in the other rooms of the house. There needs to be a driver to consistently deliver a sufficient amount of fresh air per person every hour. Even more fresh air is needed for spaces with higher pollutant source strength. For example, with someone smoking, a marked increase of the fresh airflow rate is needed to dilute harmful substances sufficiently. What drivers for this air exchange are available will be discussed in Chapter 3.

Monitoring of CO_2 concentrations in the home is a recommended check to see whether the ventilation delivers the expected outcomes. CO_2 levels are comparatively unobtrusive and inexpensive to monitor, and are indicative of other gaseous indoor air pollutant concentrations. Standards for mechanical ventilation quite often contain a CO_2 threshold for this reason: 1000 ppm (ppm) is commonly used as a static value. Acute toxicity is only likely at concentrations exceeding this value 20-fold, but observed effects of CO_2 concentrations above 1000 ppm include drowsiness, lack of concentration, headaches and increased heart rate. For example, the ventilation strategy in the free-running (no forced ventilation) house in the figure below is clearly not working. But even with a good ventilation system, it pays to check whether the volume



Monitoring of CO_2 levels in two new three-bedroom houses in Auckland over a week in winter. Both houses were inhabited by four persons and a pet. Only the house with a balanced ventilation maintains levels below the 1000 ppm threshold, and shows a fairly consistent indoor air quality. This is in stark contrast to the free-running house, which relies on natural forces and someone opening the windows. CO_2 readings here are strongly fluctuating, and far exceeding the recommended threshold at peaks.

flow that the system designer specified is actually getting to the spaces as planned, and meeting requirements there. Chapter 3 will explore these tests in more detail.

Build-up of air contaminants can have a wide range of negative health effects, and dilution with fresh air is the most reliable way to prevent this. The provision of fresh air should not be an afterthought in the design of a house – it needs a clear concept, including a quality assurance process. It needs to be checked, though, whether the air provided is actually fresh. Outdoor air may not be unpolluted, and air leaking in through the building envelope may be impacted by fibres and other substances on its passage. Some standards allow for a maximum difference to outdoor concentration levels, rather than prescribing a static value. For a house in a forest, with lower CO_2 outdoor concentrations, the threshold is lower than for a home next to the motorway, following this approach. Independently from the location of the building, intensities above 1500 ppm are viewed as concerning.

With a closed window, or an awning window kept ajar, CO_2 levels are likely to build up in bedrooms overnight. On a winter night, the choices in such a bedroom are: keep the windows closed and achieve warm stuffy conditions, or open the windows and achieve cold fresh conditions. In other words, waking up with a headache or a stiff neck. Only when heat from the outgoing stale air is transferred to the incoming air can we be perfectly warm and fresh in our bedrooms overnight – we will explore this concept further in Chapter 3.

Cold or fresh?

If it is possible to provide air that is both warm and fresh, most people will agree that warmer bedroom temperatures are actually quite pleasing. However, you may think that you need it cold in your bedroom for a good night’s sleep. What leads to this perception? We associate cold with fresh air, and are therefore concerned that warm air is not fresh. In summer, when we can open windows wide, we can experience fresh and warm air together, and unless it is very hot, we sleep well. The same situation is possible in winter with the right ventilation strategy.

1.2 THE COMFORTS OF HOME

Thermal comfort is a state where there are no prompts to correct the environment by behaviour. If you are thermally comfortable, you can kick back and relax. This relaxation is important for our wellbeing: in the absence of thermal comfort, stress symptoms surface, with associated negative health effects.

Factors that influence thermal comfort are activity and clothing levels, air and radiant temperature, as well as air speed and humidity. All but the first two factors are largely determined by the building design and are explored in detail in this book. Clothing and activity levels are quite easily controlled by the residents, and we have made the assumption that most people will be conducting regular activities in typical clothing, rather than wearing a wetsuit or practising competitive wrestling just to be warm!

The human body core temperature needs to be stable within a narrow range of 37°C ±0.8°C. For thermal regulation, our body can resort to perspiration, respiration and dry heat transfer through convection, radiation and conduction. Because our bodies are always generating heat internally, we need to constantly reject excess heat to the surroundings to prevent overheating. When the temperature around our body is close to or above 37°C, we feel hot as our body struggles to reject the excess heat. Should there be high humidity in addition, most of the skin will already be wet, making it impossible to sweat for more cooling. This is a highly stressful and perilous state! Conversely, when too much heat is being lost to the surroundings, we feel cold and our bodies actively convert chemical energy to heat to maintain internal temperatures. Peripheral blood vessels constrict, breathing gets shallower and shivering sets in to increase heat generation. If the cool temperatures prevail, the body core temperature falls to life-threatening levels. For our body core temperature, a few degrees can make the difference between life and death. The ideal temperature for the body is when the air can readily remove the excess heat generated without over cooling. The balancing act of heat generation, heat absorption and dissipation requires energy, and is physically exhausting. Generally, we are thermally comfortable if the regulation requirements are kept to a minimum, and no effort is needed to balance our temperature with the environment.

Do we need to feel the cold?

Occasionally, it is claimed that we are better off feeling the cold in our homes. You hear people explaining that if we miss out on seasonal variation in temperature, our bodies become less resilient, and are easier attacked by pathogens. There is little support in science for this claim. Its validity is furthermore in question if we consider that our species successfully inhabits, and possibly even originates from, places with little seasonal variation in temperature. Yet, undoubtedly, feeling the cold at times can be refreshing. If you live in a place where it gets cold outside, opening a window in winter will let you experience the delight of frosty air. If you remember to close the window again after this episode, and you live in a Positive Energy Home, there will be no lasting impact on the temperature of your home or your power bill, so go for it, whenever you need your head cleared!

The challenge for designing a thermally comfortable home is that everyone has a different opinion of comfort at any given time. Constantly changing variables including mood, clothing, metabolic rate and activity level (just to name a few) require environmental responses for us to stay comfortable. Nevertheless, it is possible to create a baseline that allows for easy adjustments to accommodate individual preferences in our homes. Following is a closer look at the major constituents of thermal comfort.

1.2.1 Radiant temperature

The most common form of radiant energy is sunshine, but any object that is warmer than its surroundings will emit radiant energy. The radiant temperature is one component of thermal comfort that is greatly influenced by a building's design.

Radiant energy, including sunlight, that we perceive is commonly divided into the ultraviolet (UV), visible and infrared (IR) parts of the electromagnetic spectrum. UV is the highest energy of these three and, in large enough doses, can damage eyes, skin and organic building elements such

Infrared photo showing radiant heat emitted from occupants and appliances, and heat loss through the uninsulated wall.

as plastics and fabrics. Visible light is crucial for sight, and can play an important role in maintaining the heat balance of a home. Chapter 4 explains this in more detail.

The radiation we most commonly associate with heat is infrared, which is just beyond the red end of the visible spectrum. Infrared energy is what we feel when we walk past a brick wall that has been exposed to the sun all day. The bricks have heated after absorbing the sun's energy and re-emit this energy as infrared radiation. Whether from our body or building structures, this radiant energy can be readily detected using an infrared camera.

Whether an object emits visible or infrared radiation is determined by the temperature of the object. Objects we perceive as warm by and large emit non-visible infrared, whereas very hot objects may reach a temperature where the emitted radiation approaches the red end of the visible spectrum. An example is an electric stove element, which emits primarily infrared with a small amount of visible red radiation.

Being warm objects, our bodies exude heat as infrared radiation to their surroundings. When we wear clothing, this radiant energy is partially absorbed, trapping the warmth close to our bodies. Yet, when our skin is directly exposed to our surroundings body warmth is readily emitted, and absorbed and reflected by the objects around us. Our perception of warmth is influenced by how warm, how big and how far away objects are from us. For example, we can feel the radiant energy from the sun from a very large distance away, but need to be quite close to a candle to feel the warming effect.

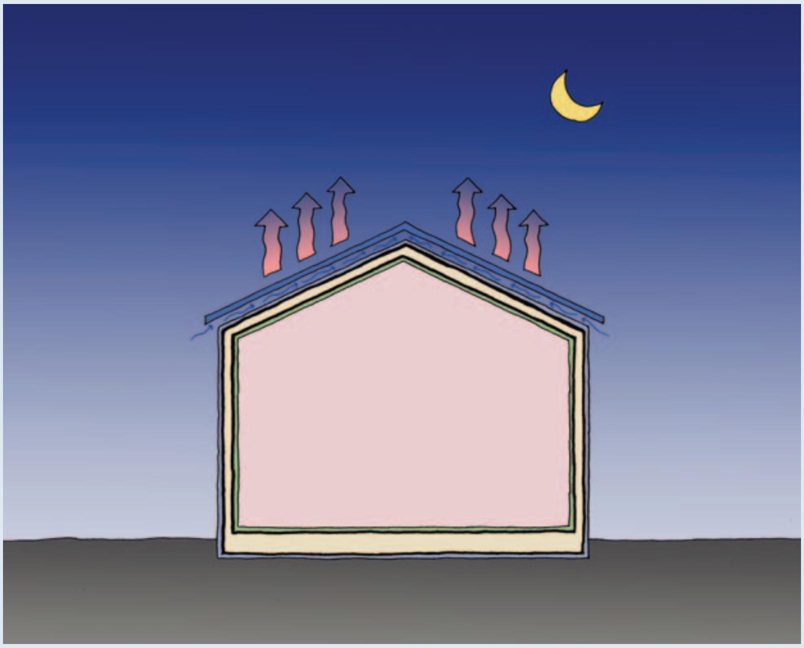
Conversely, if we are adjacent to a cold surface such as a concrete wall, then we act as the heater, and our body heat will be absorbed by the cold surface, which we will perceive as draught – even if there is no air movement. When we are not surrounded by surfaces, the energy radiated from our bodies is literally lost in space. A clear night sky, for example, absorbs all heat from all objects directed towards it.

Does ventilating roofs help with keeping them dry?

It depends. When the ventilation happens between the roofing material and a breathable roofing underlay, then yes. However, if the ventilation also occurs between the roofing underlay and the insulation layer, then no. Here is why: on a clear sky winter night – when no clouds impede the radiation exchange with the black sky – surfaces tilted towards the sky can cool below air temperature. If comparatively warmer outdoor air passes by the much colder underlay, the moisture in air can condense on the underlay. The situation is similar to a familiar occurrence of warm moist air condensing on a cold bathroom mirror. Droplets may form on the underside of the membrane, and drip onto the insulation. Rather than the ventilation keeping the roof insulation dry, it may be the cause of it getting wet. Ventilating a roof should therefore only happen in the layer between the roofing and underlay. Naturally, the underlay needs to be able to drain moisture away – but that is its main purpose anyway.

The same phenomenon can be also be observed with cars in winter: windscreens are more likely to have ice on them than the vertical windows, because they are tilted towards the sky.

Similar problems occur with ventilating under the house. Here, the radiative heat exchange may be between a sheathing of the floor and the ground. In this case, the problem is not confined to clear nights, but particularly prevalent during summer, when the air will be warm – but the ground and subfloor construction will still be dark and cool.



The roofing material gets colder than outdoor air on a clear night due to radiation towards the sky. Moisture in outdoor air may condense on the underside of the roofing material.

Highly reflective surfaces, such as polished steel or aluminium foil, resist the absorption of radiant energy, so the radiant heat from our body will be reflected back at us increasing our perception of warmth. This is why foil blankets can be effective at warming people up – the foil reflects the radiant heat from the body back inwards. Shiny surfaces also emit very little heat. For example, if a shiny surface and a black surface are the same temperature, the black surface will radiate more heat than the shiny surface. Some insulation products use aluminium foil surfaces to reduce heat transfer, but it is difficult to maintain the effect, because the aluminium will not stay shiny in use, and reflection requires a direct 'line of sight' to be most effective.

Within the home, the properties and temperature of internal surfaces determine the amount of radiant energy present, and therefore have a significant influence on our comfort. For example, even if the internal air temperature is quite warm, if we are sitting next to a cold surface such as a window in winter, then the radiant heat being lost from our body and absorbed by the window will cause us to feel uncomfortable. If, on the other hand, a poorly insulated wall or window absorbs the sun in summer, causing it to heat up, the radiant heat can be unpleasant, even if the air temperature is quite cool. The mean radiant temperature people are exposed to indoors can be computed from measurements with a globe thermometer, or approximated from known heat transmission values of all elements of the building enclosure. To achieve comfortable internal surface temperatures, we need to isolate the internal surface from the external conditions.

Insulation is the not-so secret weapon to achieve the decoupling of internal surface temperatures from whatever is going on outside. Surface temperatures are then determined primarily by indoor conditions, and therefore more easily controlled. Because it is much easier to insulate walls, floors and roofs, windows are the usual suspects for low surface temperatures in a home. Significantly improving the performance of windows not only helps to reduce the energy bills – it also greatly improve comfort. In fact, a better quality of window may even markedly increase the usable floor area of a room during extreme weather events.

For Passive House certification, maximum heat transmission values specific to the climate and building element are required to keep surface temperatures sufficiently high, thereby preventing comfort and mould issues.

1.2.2 Air temperature

In the aftermath of the oil shocks in the 1970s, a WHO working group investigated how low air temperatures may drop before occupant health is negatively impacted. Their report concluded that there is no risk at a minimum air temperature of 18°C for healthy, appropriately dressed, sedentary adults, yet saw 20°C as the minimum for sick, handicapped, the very young and very old (WHO Regional Office for Europe 1987). Note that thermal comfort was not considered in this conclusion – the report focussed on acceptable minimums to save fossil fuels that had just quadrupled in price.

Air temperature is perhaps the most obvious factor associated with thermal comfort, and most widely discussed. The temperature perceived by humans is actually a mixture of the temperature of surrounding surfaces or mean radiant temperature and air temperature. Together they form what is called the operative temperature. In an enclosure with sufficiently warm air, we are still not comfortable if the surfaces are cold. In fact, the resulting temperature asymmetry may feel particularly uncomfortable. While air temperature in a range of 20–24°C is typically perceived as homely, this is only true if the gradient between air and surface temperatures is not large.

If the building fabric performs as an effective insulator, it is easy to control the air temperature with heating and cooling. In fact, with a high-performance fabric, we only need to actively heat or cool on extreme days, because the building is thermally self-sufficient otherwise. The magnitude of heating or cooling required to keep temperatures in a comfortable range needs to be based on a thorough calculation of losses and gains of the house. Doing this calculation month-by-month is precise enough for buildings with high thermal inertia, such as Passive Houses.

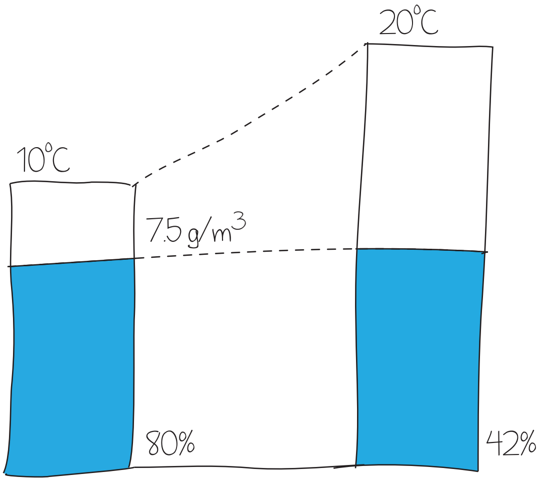
The Passive House standard aims to deliver not just acceptable conditions, but consistent comfort year round. In winter, the minimum indoor air temperature for Passive Houses is 20°C. This temperature is mostly maintained without adding heat from a heater. In summer, indoor air temperatures may only exceed 25°C at a maximum of 10% of the occupied time. For residential usage, this limits warmer indoor air temperatures to 876 h per year. If lower temperatures cannot be achieved by passive means (such as shading or night-time ventilation), active cooling is required. Chapter 3 provides further information on heating and cooling.

1.2.3 Humidity

Humidity in dwellings is determined by the ambient humidity, air change rate, storage effects of building materials and furniture, and human activities such as breathing, sweating, cooking, cleaning and personal hygiene. Some hobbies, such as keeping aquaria or growing indoor plants, contribute further to indoor moisture. Indoor temperatures also have a role, because warmer air can keep more moisture suspended. As the activities households engage in vary, so will the amount of moisture released into air. To give an indication of this, the Passive House calculation method uses an assumption of an average of 2.4 L water vapour released per person per day. In buildings where *in situ* concrete casting, wet plastering or masonry was used during construction, the evaporation of the water from these materials can dominate the humidity balance for years after the building's completion.

Outdoor humidity, in congruence with the air change rate, is another crucial determinant of indoor humidity levels. The most commonly used measure of humidity levels, 'relative humidity', is a poor indicator for a comparison of humidity levels, because the capacity of air to absorb water vapour increases linearly with its temperature. Colder air has a lower storage capacity for water vapour and, once it is exceeded, excess vapour becomes liquid water. For example, the absolute water vapour content in air at 10°C with 80% relative humidity amounts to 7.5 g/m^3 and is therefore smaller than that of air at 20°C with only 50% relative humidity (8.6 g/m^3). This means that warming of air reduces the relative humidity and cooling of air increase the relative humidity, both of which have implications for comfort.

Increasing the rate of air change will usually have a drying effect when outdoor temperatures are markedly below indoor temperatures, even if outdoor levels for relative humidity are higher,



The capacity of air to keep water vapour suspended depends on its temperature; if, for example, outdoor air at 10°C and 80% relative humidity is warmed to 20°C, the relative humidity drops to 42%.

as can be assumed in winter. The magnitude of this drying effect depends on the temperature gradient, relative humidity gradient, and amount of intentional (ventilation) and unintentional (in- and exfiltration) exchange of air between indoors and outdoors. If, for example, outdoor air at 10°C with 80% relative humidity is warmed up to 20°C, its relative humidity will nearly halve. When it is very cold outside and nicely warm on the inside, continuous ventilation can lead to the interior becoming so dry that countermeasures are needed, such as drying your clothes inside to increase indoor humidity. Yet in a poorly heated indoor situation, ventilation will have little or no drying effect in winter, because unwarmed outdoor air will retain its relative humidity.

People are unable to judge humidity levels or dampness with any accuracy in moderately warm environments. Hence, in a comfortable temperature range, humidity *per se* is unlikely to be picked as a comfort issue by occupants. Yet humidity influences the perception of temperature, and a 10% higher relative humidity is perceived as equally warm as a 0.3°C increase in operative temperature in moderate environments. Warm temperatures that would in a drier environment still be acceptable can already be intolerable when the air is more humid.

It is difficult to pinpoint an optimal range for indoor humidity. An upper limit of comfortable relative humidity cannot be determined without the context of other comfort parameters, most prominently temperature. Skin wettedness (the fraction of the skin that is covered with water) is a good indicator for warm discomfort and thermal stress. In a dry environment, sweat can evaporate quickly instead of spreading over the skin, and thereby induce cooling. If, in contrast, the skin is already completely wet, no additional cooling through regulatory sweating is possible, which fast becomes intolerable.

Mainly for summer comfort reasons, in a certified Passive House, excess humidity – defined as exceeding 12 g of water per kg of dry air – has to be limited to 20% of the occupied time without active cooling, and 10% of the occupied time with active cooling. For example, air at 25.5°C and 60% relative humidity just exceeds 12 g/kg, as does air at 24°C and 66% relative humidity. These, and other combinations that lead to more than 12 g water being suspended in 1 kg of dry air, are only tolerable for 1752 h per year without active cooling. If active cooling is needed anyway, the system must also be capable to curb these oppressive conditions further.

Apart from comfort, there are other reasons to be wary of high relative humidity. In the literature and simulation programs, water vapour is often treated as an indoor air pollutant. Although this classification is not strictly correct, because no contamination occurs and no toxicity exists, damp conditions indoors can nevertheless be damaging. High relative humidity may lead to material degradation. Moreover, clear causalities exist between high relative humidity rates and the prevalence of contaminants, such as fungi, dust mites and formaldehyde. If this was not enough, high indoor relative humidity will likely be buffered in enveloping surface materials, which alters their thermal conductivity, and water vapour transport mechanisms. Excessive evaporation processes at the building envelope can occur, which have an impact on the room temperature. Loss of energy and comfort is a likely consequence in this case.

Of particular concern is that high humidity levels at interior surfaces may lead to mould formation. Temperature and acidity ranges that mould needs for growth are aplenty in residential buildings. Growth substrates are likewise abundant: dust, paper and most other organic matter can be consumed. The determining factor for mould growth in indoor environments is therefore humidity.

Most fungi relevant for the residential environment need an activity of water at surfaces of ≥0.7 to thrive. Liquid water as a result of condensation is not required. Water activity at surfaces is approximately equal to the relative humidity at surfaces. A couple of hours or weeks of humidity can be enough to trigger mould growth, depending on the specimen and magnitude of water activity. When mould spores are present in large quantities, they can affect allergies and respiratory problems. The toxins emitted by some forms of mould fungi can furthermore be responsible for neurological diseases and even fatalities. Although indoor air humidity is an indicator for mould growth conditions, the concern is particularly for high humidity at surfaces. Insulation and airtightness help to keep the surface temperature of external building elements sufficiently high, to avoid not only liquid water, but also a high degree of water activity. Elements in the thermal envelope that readily transfer heat, such as a steel beam, need particular attention. In a Positive Energy Home, thermal bridging of this kind needs to be minimised to keep internal surface temperatures well above the danger zone at every surface. While a universal upper limit for relative humidity in a house is not easily found, a lower limit is likewise difficult to establish. Very low (<15%) relative humidity has reported negative health impacts such as irritation of mucous membranes and increased susceptibility to respiratory diseases. But dust in indoor air plays a role in the perception of low relative humidity, and a lower dust content increases the tolerance of dry air, and vice versa. On a mountain top, and in a house ventilated with fine-filtered air, the dust content in air is very low, and dry air is therefore not easily perceived as objectionable.

In summary, exact thresholds for humidity do not exist, but too much and too little humidity in air may both have health implications. It is therefore wise to manage water vapour content in indoor air for the provision of good indoor environmental quality: 30–60% relative humidity is a good range to aim for most of the time.

1.2.4 Air velocity

The air speeds we find acceptable depend on how warm we generally are. In winter, we do not want to be exposed to air speeds of more than 0.15 m/s. At velocities up to 0.15 m/s, smoke rises vertically, and the sea is mirror smooth. All is calm. Yet in summer, fast moving air can be a welcome cooling mechanism. But whether higher air velocity is acceptable is not only tied to temperature, but also the degree of personal control. If I can switch a fan on and off at will, I am more inclined to like the effect. Which body parts the air touches is likewise of importance. The head and neck are particularly sensitive to draught. Whether the air is moved by wind or by a fan is in contrast inconsequential. If fan driven air causes discomfort, the air velocity is simply too high for the temperature of the enclosure or the temperature of the air that is being moved.

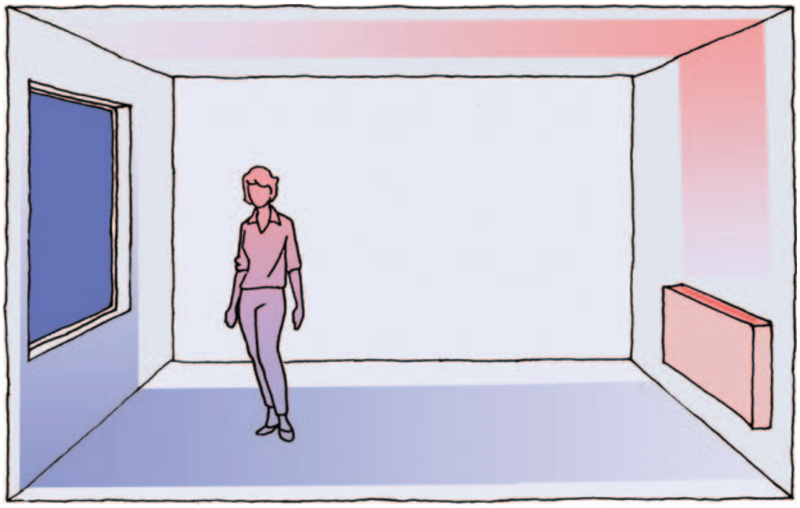
1.2.5 Localised discomfort

While a general assessment for a room may result in a high acceptance rate of its conditions, localised discomfort, due to cooling or warming of parts of the body, is still not ruled out.

Draught is the primary cause for localised cooling, and poorly designed ventilation or air conditioning systems are notorious for causing draught-related discomfort. Draught is particularly annoying when the air is already cold.

Although draught may occur as a result of intended air movement, it can also be the outcome of an air roller process induced by downdraught at cold surfaces. Downdraught occurs when air next to a cold surface rapidly sinks. It increases with the height of the cold surface above floor level, it is therefore a particular concern with floor-to-ceiling windows. The height above the floor, and the surface temperature determine the magnitude of draught effects at floor level. To counter negative downdraught effects, heating appliances are often placed under a window.

With better insulating windows, the effect generally ceases, but this needs to be carefully assessed, taking into account design, outdoor and indoor air temperatures, performance of



Warm air rises, drops down on opposite wall; the cold surface creates downdraught, leading to a sea of cold air at floor level. The longer the air is in contact with the cold surface – in other words, the higher up in the wall the cold surface begins, the more severe the resulting draught.

window components, height of the window above floor, and distance of places of interest (e.g. seating areas) from the window. For this purpose, not only the thermal quality of the glazing matters, but the thermal quality of the frame is often the determining factor.

Even if there is no air movement at all, a marked divergence of radiant temperatures impacting on our bodies is perceived as a localised cooling, which feels like draught. At cool to moderate air temperatures, this is unpleasant. This temperature imbalance may furthermore amplify actual air movement. Dissatisfaction with the lopsidedness of temperature is particularly pronounced with a warm ceiling/cold floor configuration, or with cold (usually exterior) walls opposite to warmer interior surfaces. Windows are again the typical culprits for this type of discomfort. For certification of windows suitable for Passive Houses, the interior surface of the window must not be colder than 17.8°C, assessed at 22°C operative temperature for the room. Comfort considerations guide the performance requirements of windows, as discussed in Chapter 2.

Discomfort may also result from stratified air temperatures in an enclosure. This stratification may be vertical, due to stack effects, or horizontal (e.g. due to the air roller processes described earlier). Cold feet with a hot head are extremely uncomfortable. In rooms with an operative temperature around 20°C, 21°C at head height, combined with 18°C at the feet, is just acceptable. A wider spread is only tolerated in significantly warmer rooms.

1.2.6 Some numbers for thermal comfort

Are these comfortable conditions? This is a winter day. I am wearing two layers of clothing. I am in a Positive Energy Home, where the mean radiant temperature of the surfaces is 20.3°C, which is close to the air temperature of 21°C. There is no draught. I am typing this, which puts my metabolic rate at 1.1 met. I am slightly cooler than I would like to be, but still in the comfort zone. On a scale from –3 to +3, where 0 represent no reason to complain, my vote would be about half a point in the negative. Research suggests 90% of people exposed to the same conditions will agree with me.

My neighbour's air temperature is also 21°C, and the relative humidity in her house is the same. She is wearing two layers of clothing while writing a novel. However, her house is not so well

Thermal conditions in my living room.

insulated, and the mean radiant temperature of the surfaces is only 16.7°C. There is also a bit of a draught induced by the cold surface of a large window. Only 74% of people will still find these acceptable conditions, and everyone else will be too cold (far colder than I am, with a full point in the negative). Maybe I should invite my neighbour over for a cup of tea to warm her up? International standard 7730 (ISO 2005) categorises indoor environments regarding their predicted thermal comfort outcomes based on calculated values for the percentage of dissatisfaction (PPD), and the predicted mean vote (PMV) – a digression from an ideal, neutral state.

Clothing, activity, mean radiant temperature, air temperature, relative humidity and air speed all influence how far we agree with the conditions of the environment. When we have data for these parameters, it is possible to predict how people will value the resulting conditions in an enclosure quite accurately. For our purposes, what we need to know is that with sufficiently warm surface temperatures due to the good level of insulation throughout the home and no draughts in winter, winter comfort is easily achieved in a Passive House. For summer comfort, keeping the sun out is paramount – see Chapter 2 for details.

1.3 THE ART OF NOISE PROTECTION

A quality indoor environment is peaceful and serene. In fact, one of the most striking experiences that people who visited as Passive House report is how quiet it was. Houses can of course not keep out all kinds of environmental noise. A Passive House next to a runway will not be completely quiet. But some measures to improve the energy-efficiency of houses have noise-cancelling side effects. On the other hand, a ventilation system as a feature of an energy-efficient house may also introduce new sources of noise, which needs to be managed.

Decibels (dB) are a unit to describe loudness (if an A is added to the unit, the effects have been adjusted for human perception). While dose-related noise impacts on health below the threshold of pain (140 dB) are not clearly established, evidence of the generally negative effects of environmental noise is mounting. Managing exposure to noise can help to reduce hearing impairment, heart diseases, poor school performance, sleep disturbance and general annoyance and likely also a range of other complaints, such as psychiatric disorders and immune defects. Noise that impacts on the indoor environment may originate from outdoor or indoor sources. Ventilation will have a role in both, because it is a gatekeeper for outdoor noise, but may also be responsible for generating or transmitting sound within a building.

At night-time, noise levels outside at the façade should ideally be below 40 dB, as negative health effects can be expected when this value is exceeded. Urban environments are often noisier than this. But what matters most is the way we perceive noise on the inside of buildings. The building envelope is therefore tasked with filtering ambient noise sufficiently to achieve the desired indoor noise levels.

Airborne noise travels through leakage paths and intentional openings. A very air leaky building will not keep noise out. Yet, even if there are no unintentional leaks, if openings such as windows and trickle vents are the only means of purposeful ventilation – outdoor noise will impact on the indoor environment with every ventilation event. Impact noise, such as foot falls on floor boards, is another example of unwanted sound. Effects of both forms of noise are determined by the design, construction and technology of the building, and its uses. Weight, contact areas and layering of building elements are important in this regard.

Acoustic comfort encompasses more than achieving appropriate loudness levels: it should also consider reduced sound propagation, increased speech intelligibility and appropriate reverberation. How we perceive sound further depends on its consistency (irregular and unpredictable sounds are nothing to get used to), frequency (a wide range is less disturbing than the sound of a single frequency), duration, distance from the source and options to mask the effect.

In the following paragraphs we narrow this list down to noise issues specific to energy-efficient homes, which relate to the way we ventilate them.

1.4 VENTILATION AND NOISE

A fully opened window will provide no noise attenuation, and windows left ajar only marginally filter outdoor noise. If windows are the only way to ventilate a house, noise enters the building with every ventilation event. Particularly with regard to night-time ventilation, a conundrum becomes apparent: outdoor noise leads us to close the windows, yet with reluctance. While we cannot sleep well in a noisy bedroom, the air quality is rapidly deteriorating when the windows remain shut. Sound proofing façades without specifying how adequate ventilation may occur is therefore not a satisfactory solution for noisy environments. Mechanical ventilation can offer this solution. It can achieve a large degree of acoustic decoupling from the environment, while still allowing for the exchange of air. We need to make sure, though, that we are not paving the way for novel acoustic nuisances with its use.

For ducted ventilation in a forced air system, the smoothness of airways is one determinant for the noisiness of the system. Noise emissions in the ducting system are furthermore dependent on the velocity of air, which is in turn caused by the volume of air and the profile of ducts. Moreover, flow distortions at bends, constrictions, turn-offs and nozzles all generate noise. And, in addition to generating noise, ducts may also carry noise generated elsewhere. The design of a ducting network needs to mitigate these issues by choosing a smooth ducting material with a large enough profile, minimising flow distortions, and implementing cross talk attenuation where needed, such as when ducts branch into bedrooms.

The mechanical parts of ventilation systems are further sources of noise, which may spread as either airborne or structure borne sound. Acoustic decoupling and appropriate housing of the appliance are needed to keep these sources in check.

Last but not least, transfer or overflow openings that provide a path for air to move through the home in a cascading ventilation system can leak sound if not detailed suitably. Overflow components with tested acoustic performance are, however, readily available.

The noise of ventilation systems in certified Passive Houses is to be reduced to 25 dBA or below for residential rooms, and 30 dBA for utility rooms. For comparison: someone breathing in the room is perceived as 10 dBA, and listening to the TV amounts to ~60 dBA; 20–30 dBA denotes a very quiet room. Ventilation units are not necessarily that quiet, in which case they need to be housed away from living quarters and fitted with noise-attenuating measures to achieve the outcomes for the rooms.

A well-designed and commissioned mechanical ventilation system operates nearly inaudibly. In fact, the complaint most often heard by people who install properly designed systems is that they are apparently not working – because people cannot hear them. A quick check with the anemometer, however, then reveals that all is working as it should – only very quietly.

1.5 LIGHT AND BEAUTY

Another crucial factor for liveable homes is light. Light plays an important role for our wellbeing. It illuminates, creates textures and makes us appreciate our environment. In this book, light has its own chapter (6), where the benefits of natural and electric lighting in our homes are fleshed out, and options to deliver these values energy efficiently explored.

One aspect that we must not forget when designing Positive Energy Homes is that houses need to be visually appealing. Beautiful surroundings improve the quality of our lives. There is no conflict between beauty and the performance requirements of houses. The latter are constraints that good designers willingly accept.

SUMMARY

A liveable home is delightful, thermally comfortable, continuously provides a sufficient amount of fresh air for every occupant and keeps unwanted sound below levels of bother. It is resilient with regard to changing external conditions – including economic – capable of sheltering its occupants from harm, and allowing them to thrive. The quality of the thermal envelope and the mechanics of ventilation are crucial to achieving these outcomes.

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CHAPTER 2

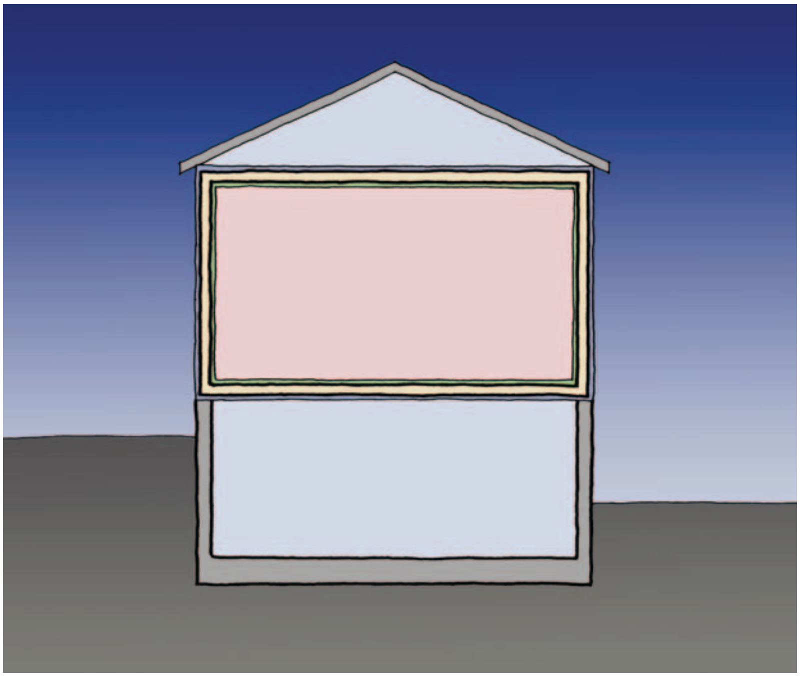
The thermal envelope

Our skin is a membrane that covers us completely. It protects our internal organs from external pathogens, while allowing us to sense and interact with the world around us. A membrane makes an entity. Here am I – there are you, this is inside, that is outside. The membrane allows us to make this distinction. We may philosophise whether this separation is ultimately an illusion, but our senses present us with membranes as the containers for beings and things. In buildings, the outermost surface of conditioned spaces – the boundary where transmission heat flow to either unconditioned annexes or outdoor air occurs – is called the thermal envelope. If clothing is viewed as our 'second skin', the 'third skin' that is protecting our bodies, and holding our lives together, is the thermal envelope of a house. It creates the enclosure that allows us to feel at home. Like clothing, it needs to fit the occasion – but unlike clothing, it is not easy to change, and must therefore be a good fit whatever the season. In this chapter, we will highlight what it takes to design and build a cocoon to unfold in.

Imagine you have returned to your home in wintertime. You are really cold, and in need of some warmth. You turn on the heater, and after a while it gets pleasantly warm. Why is it not staying that way once you switch the heater off? This is because thermal energy is trying to reach an equilibrium. Between two adjacent spaces of the same temperature, nothing will drive the heat to move. Transfer of heat occurs where there is a difference in temperature of abutting regions. The flow is always from the warmer to the colder zone. In winter, the warmth on the inside of a house is impelled to the outside to reach thermal equilibrium, but in summer this flow may be reversed, particularly when the interior is actively cooled. Without a means to control this flow, our indoor conditions are dictated by whatever happens outdoors. The membrane that makes or breaks the performance of a house is the thermal envelope. It is not necessarily identical with the building envelope, because it only encloses conditioned spaces in a house.

The thermal envelope must wrap tightly around the rooms that need to be thermally controlled to allow us to thrive in them. A loosely fitting thermal envelope does not permit optimal protection from the elements. Moreover, the thermal envelope should be as small as possible, because its surface area is directly proportional to transmission heat loss. Passive House is a 'fabric first' approach to energy-efficient buildings. It aims to optimise the integral, long-lasting fabric of a building: elements that are not easily upgraded later. Getting the thermal envelope right is therefore high up on the agenda for achieving Passive House standard as the first step to a Positive Energy Home.

Because heat transfer across the thermal envelope is directly proportional to the surface area of the heated or cooled space, creating a building geometry that encloses the greatest volumes in the

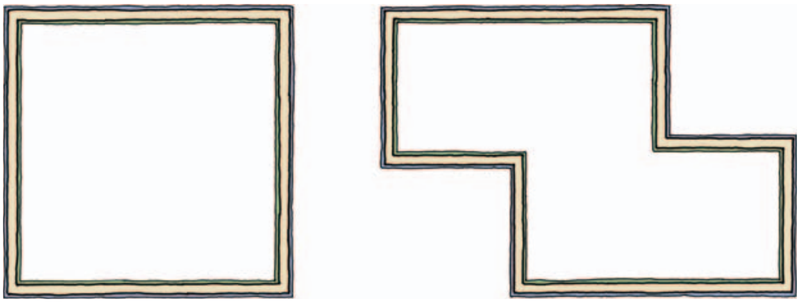


Thermal envelope, blue spaces inside the building envelope are unconditioned.

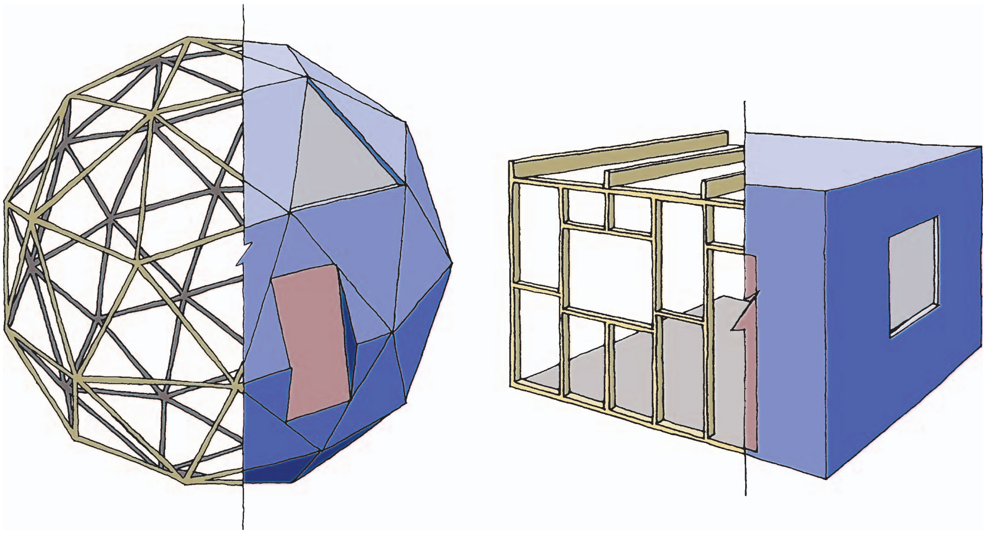
smallest surface area is a top priority. Mathematically, a sphere encloses the greatest volumes in the smallest surface area.

It is clearly not that practical to build sphere-shaped houses, or to put furniture on sphere-shaped floors, and spheres immediately loses the geometrical advantage if you try to stack them. The next best shape is a cube. Cubes are much more versatile as buildings, and far easier to furnish. Do energy-efficient houses have to look like boxes, and is energy-efficiency a good excuse for boring design? A resounding no to both suggestions! Only the surfaces that envelope conditioned spaces need to be kept as small as possible. Unconditioned, adjacent spaces, such as sunrooms, sheds, attics, balconies and garages can be used to break up otherwise monotonous façades without inflating the thermal envelope.

Although the size and geometry of the thermal envelope greatly influence the magnitude of the heat loss transmitted through the fabric, it is useful to consider that what we are actually after in our homes is usable floor area. The ratio of surface to treated (conditioned) floor area is a useful metric for comparing different building shapes and geometries.



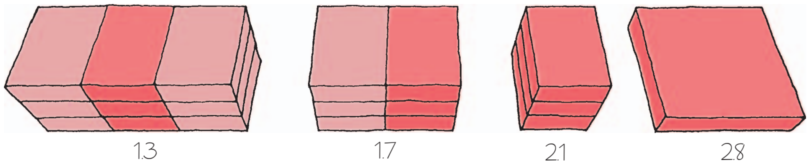
Square floor plan versus Z floor plan – same floor area, but the transmission heat loss through walls is 20% increased with the Z floor plan.



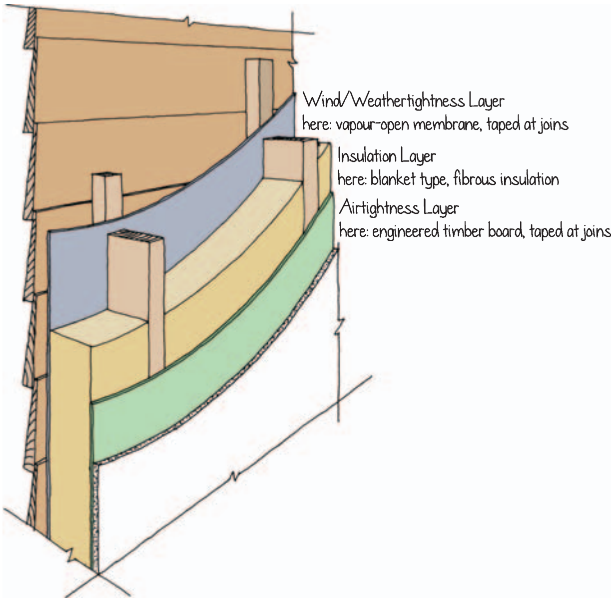
Spheres provide the best volume to surface area ratio, but are more difficult to build, furnish and stack than cubes.

Keeping the shape of the thermal envelope simple has many advantages. Compact buildings lose less heat to the environment. They are also less complex and therefore typically less expensive to build. The reduced complexity makes them also more likely to adapt to changing needs and trends while continuing to perform well over the life of the home. But size matters, too. Micro-houses in particular have a very high ratio of surface to treated floor area, and it takes an enormous effort to curb heat losses through the building fabric sufficiently. Smaller houses cost and consume less, and make sense that way. However, due to their high surface to floor area ratio, they can require impractically thick thermal envelopes to achieve the ideal conditions discussed in Chapter 1. Therefore, when houses get tiny, they should be clustered together and preferably stacked to minimise the surfaces exposed to outside conditions, because otherwise the specific heat loss will be anything but tiny!

At the boundary between thermally controlled and uncontrolled spaces, three functional layers need to materialise. An airtightness layer (green in the top figure on p. 24), which – in a heating climate – needs to be internal of the insulation layer (yellow in the diagram). Furthest to the outside, a wind- and weathertightness layer (blue in the diagram) has to be placed. All three functional layers must be uninterrupted to perform at their optimum, but the effectiveness of the airtightness and wind-/weathertightness layer is particularly sensitive to perforations. The easiest



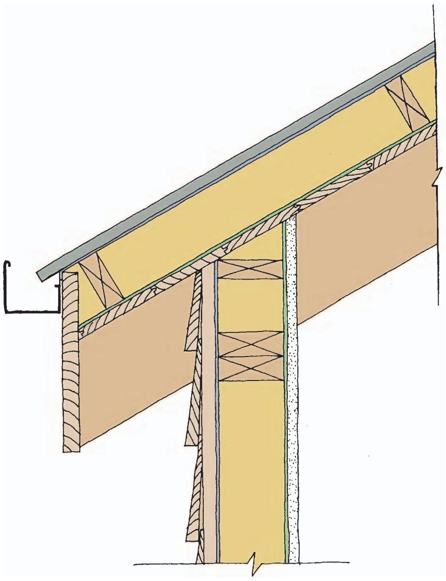
Treated floor area of 144 m^2. The ratio of surface to treated floor area, or form-factor, depends on the compactness of the design. Compared with the middle terrace house with a form-factor of 1.3, the duplex (1.7) loses 32% more heat, the free-standing three-level house (2.1) loses 65% more heat, and the free-standing single floor house (2.8) loses more than double the amount of heat through transmission.



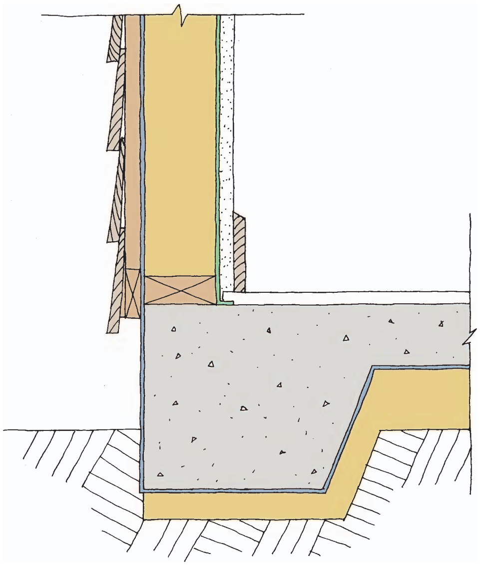
Cut-away of a wall with three layers marked.

way to visualise the effect that even minor leaks in the airtightness layer have is to image a very large balloon blown up inside the home, sealed up against every surface and joint. Even a small leak will deflate the balloon.

At every surface there has to be certainty as to what constitutes each layer of the thermal envelope. In the diagram above, the airtightness layer consists of engineered timber boards taped at the joints, there is a blanket type insulation between the studs, such as mineral wool, and the wind- and weathertightness layer consists of a vapour open membrane with taped joints. It is not an issue for the material of each functional layer to vary from place to place: for example, the



Insulation on top of the sarking to keep rafters visible. Connecting the membranes that form the airtightness layer is difficult, because the straight line is blocked by the sarking. Putting the insulation next to the rafters would make it easier, but is not the same, aesthetically.



Insulation under the slab. How to connect gaplessly with the wall insulation? Even if the insulation under the foundations were extended to the perimeter area, it is impossible to connect to the wall insulation without creating drainage issues. Putting insulation on top of the slab would solve this problem, but still needs careful detailing to avoid creating other problems. Cantilevering the timber frame could be another solution.

airtightness layer of the lowest boundary of the thermal envelope may be a concrete floor, and the airtightness layer of a lightweight wall may (as in the diagram) be a taped, engineered timber board. But when these layers do not line up, detailing for continuity becomes extremely difficult, and connecting joints with misaligned layers requires craftsmanship and patience akin to watchmaking for good results. You are unlikely to find skills and capabilities matched to this challenge on a building site, or want to pay for the time required. With off-site construction, the likelihood of getting tricky details under control increases, but the best option is to design them out.

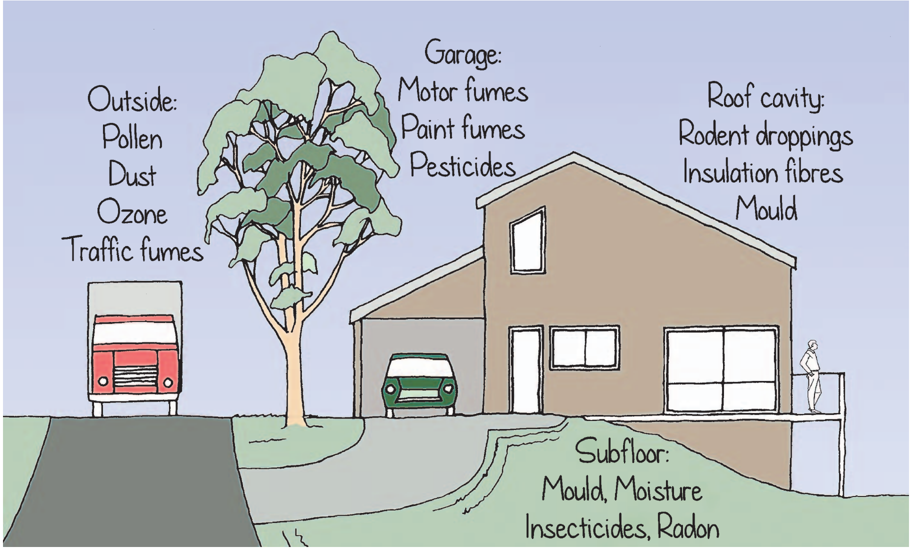
The functional layers need to be clearly marked and labelled in all plans and sections, so that no one looking at a drawing is in any doubt where the layers are, and what they are made of.

You can find similar layers in good outdoor clothing – for the same reason we need them in buildings – to isolate the inside as much as possible from the outside, thereby retaining conditions for our wellbeing independently of outside conditions.

More detail on three layers is revealed in the following sections.

2.1 AIRTIGHTNESS LAYER

An airtightness layer eliminates uncontrolled passage of air through the thermal envelope, and the associated transfer of moisture and sound. Airtight materials, sealing and blower-door testing are important for this performance. But before we explore this further, let us get a frequently asked question out of the way: ‘do leaks in the thermal envelope help with the provision of fresh air?’ In other words: ‘is it detrimental to indoor air quality to make houses more airtight?’



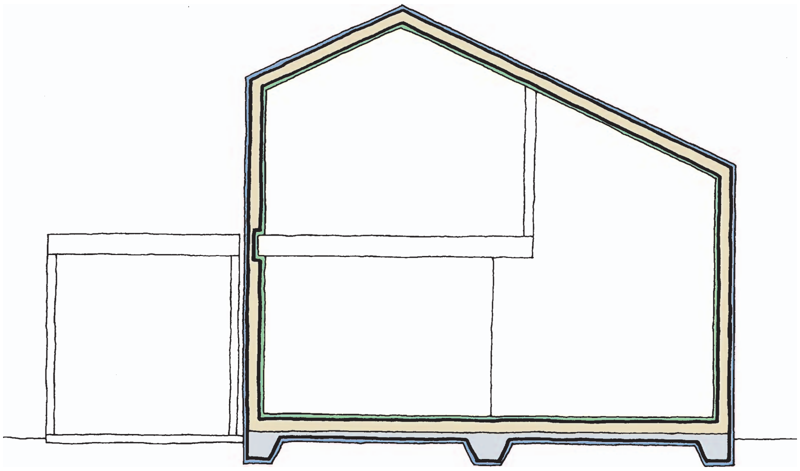
Air pollutants that may get into the house via infiltration.

The answer is an unreserved 'no'. First of all, to be able to provide the required flow rate of fresh air for good indoor air quality (~30 m^3 per person/h) consistently on a calm day, the thermal envelope would need to be so leaky that living in the house on a windy day would be extremely uncomfortable, with double or more of the required amounts of air thrusting in. But is the air that enters through cracks in the building fabric actually fresh?

This is highly debatable. The figure above lists pollutants that may travel with air through leaks in the building envelope. In short: indoor air quality is not improved by leaks, and leaks are not a reliable contributor to fresh air requirements. In fact, as you will discover, the airtightness layer is essential in the provision of breathing space!

The airtightness layer plays an important part in ensuring consistent and comfortable conditions within the building. It needs to be gapless to prevent:

- uncontrolled movement of air between the inside and the outside of the building, which can cause significant heat loss or gain and contribute to discomfort and mould formation on surfaces and in cavities
- air movement through or around insulation materials, which reduces their effectiveness as insulators
- malfunctioning of the ventilation system, which is carefully designed and balanced to deliver the right amount of air (and/or heat cool) throughout the building, which can be significantly disrupted by uncontrolled infiltration or pressure difference throughout the building caused by in- and exfiltration
- airborne noise from entering the indoor environment
- increased risks of fire and smoke propagation and larger forces for rain penetration due to varying pressure zones; with air free to move in building cavities, pump effects can occur.

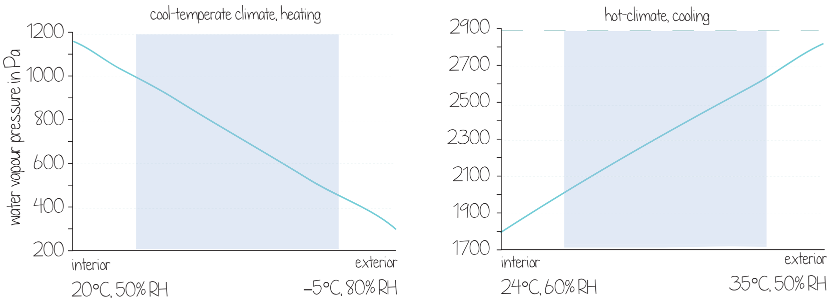


The airtightness layer (green) is an uninterrupted layer at the warm surface of the thermal envelope.

The most important job of the airtightness layers is to protect against moisture build-up in cavities. During winter, the temperature across the thermal envelope of a heated building drops steadily as we move from the warm internal surface outwards. As such, if moist air is allowed to penetrate into the building fabric, it may meet cold surfaces on its way to the outside, and condense there. Damage can ensue, such as fungal growth on timber elements. In the previous chapter, we discussed that the ability of air to hold water vapour suspended is tied to its temperature. The airtightness layer should therefore form an uninterrupted barrier to air movement at the warm side of the thermal envelope – typically the interior of the insulation layer – to keep the moisture where it is readily absorbed in air.

Moisture can also get to a cold surface via diffusion through solid materials, but compared with moisture carried with air this is a minor concern. Nonetheless, in a cool climate, the airtightness layer may be employed to also retain vapour, provided its make-up is apt. For example, engineered timber boards may be a good fit for both purposes. Polymer sheets are another option to combine airtightness and vapour control.

In warm climates, particularly when active cooling is used, the vapour pressure profile may be reversed, and require the same of the layering. The warm air that can absorb high amounts of moisture is on the outside of the building envelope and the cold surface is on the inside.



Vapour pressure gradient across monolithic wall in a heating and cooling situation; the warm air can absorb more water vapour, which increases the vapour pressure. We can experience this pressure with a kettle of boiling water: the steam is so powerful that it can blow a whistle.

For example, if it is 35°C and humid outside and 24°C on the inside: if warm, moisture-laden air is able to penetrate into the building fabric from the outside, it may reach dew point as it approaches the cool internal surface. It is still important to ensure that the airtight layer is on the warm side – only the warm side will be exterior of the insulation in this case.

For many climates there is a prevailing vapour pressure gradient during the heating season with only brief exceptions, which makes the layering easy. For climate with hot summers and cold winters, the water vapour pressure will predominantly fall from inside to outside during winter. In climates with no pronounced seasons, the direction of the vapour pressure gradient may change frequently, which requires a thorough analysis of heat and moisture transfer processes to find a fitting vapour retention strategy. But even in a climate with distinct seasons there are also summer conditions to consider. In summer, it may well be warmer on the outside, but if indoor temperatures are not significantly cooler, there is no concern for water vapour condensing anywhere. Having a vapour retarder rather than a vapour barrier, such as polyethylene or aluminium foil, which block water vapour completely is preferable for summer and in climates with frequently changing conditions. With materials that allow water vapour to pass through when conditions change, the moisture in the cavity can evaporate to the inside as well during summer, which increases the drying potential of the construction.

Not all air leaks are equally problematic

Air leaks that 'shoot' straight through an element in the thermal envelope are less of a worry than diffuse or creeping cracks. While gun shot holes still leak energy and impact on comfort, the warm indoor air is typically out at the other side before it had time to offload moisture in the cavity. Leaks at the bottom of the plasterboard that correspond to air escape routes at the top of the wall externally are far worse: the warm, moist indoor air has plenty of time to be in contact with colder surfaces towards the outside of the wall. Condensation is much more likely as a result.

In- and exfiltration through the building fabric is driven by pressure differentials. These may be caused by temperature or height differences, wind or mechanical forces. For low-rise buildings in a moderate climate, wind is the dominant source of pressure differences around the home. The side of the home facing the wind will be under positive pressure, pushing air through the building fabric, while at the lee side of the home air is sucked out of the building. Of course, which façade is pressurised and depressurised will change with the wind direction, and the smallest increase in wind speed will have a large impact on the pressure exerted on the building envelope, because the energy in wind has a cubic relationship to wind speed. The extent to which the site is sheltered has therefore a marked impact. Homes in exposed windy sites will be far more susceptible to leaking air than those on sheltered and relatively calm sites. A gapless airtightness layer can, however, cancel these locational disadvantages, mitigate the pressure differences across the building fabric, and hence create the precondition for controlled ventilation. To visualise this, if you blow soap bubbles on a windy day there is no predicting where they will end up or stopping them popping in your face, whereas on a perfectly calm day they will float peacefully off in the direction they were blown. Any ventilation strategy needs the airtightness layer to work effectively. A leaky bucket will not get all of the water to where it is needed, and the spills may even cause damage. To do their jobs, both buckets and houses need to be tight.

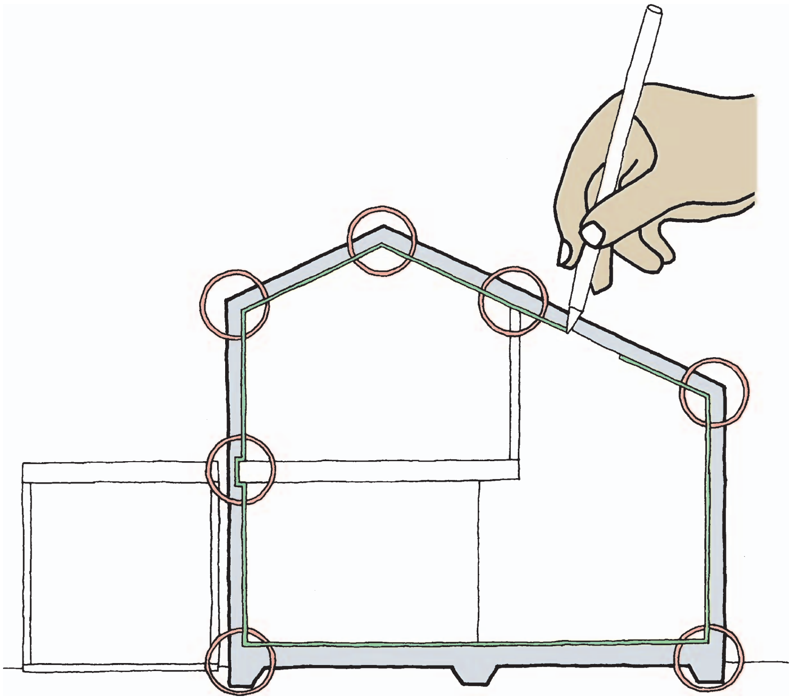
2.1.1 Creating an airtight envelope

A useful exercise for designing the airtight layer is being able to draw a continuous line to represent it on the warm side of the thermal envelope in all floor plans and sections.

Wherever the pen needs to be lifted to give way to structural elements, or the material of the airtightness layer changes, a detail needs to be drawn, carefully outlining how continuity is to be achieved, with all materials and steps necessary for this specified. This is also a good opportunity to think about sequencing of the work.

The first part of creating an airtightness layer is designing out penetrations. For example, if the manifold that distributes air ducts sits interior of the airtightness layer, but the ducts are to run in the insulation layer, all ducts originating from it will need to go through the airtight membrane. Hours of sealing ensues. However, if the ducts are moved to run interior of the airtightness layer as well, only one duct needs to be sealed to the membrane.

Another common strategy to minimise penetrations is to add an installation layer that rebates the airtightness layer into the wall. The airtightness layer is applied to the interior surface of the studs, and another 45–50 mm insulated cavity for services is added. The plasterboard can then be used in the traditional way, because power boxes, light switches, cables and pipes are not penetrating the airtightness layer that sits some centimetres behind. Although materials for the installation layer add cost, the measure may save on labour, because all installations can



Tracing the airtightness layer with a pen in section. Areas circled in red need to be detailed carefully.

Manifold and ducts run interior of the airtightness layer. Only one penetration of the airtightness layer is necessary (Photo: Murray Durbin).

be completed more quickly. It also allows for testing the airtightness layer at a stage where remedying any flaws can be done quite cost-effectively. One caveat is that the airtightness layer still needs to be in a warm enough zone: that is, with plenty of insulation to its exterior.

2.1.2 Airtight materials

Selecting an airtight material to line the warm surface of the home is the next step in the airtightness strategy. Many standard construction materials, such as precast concrete slabs, or wet plaster and renders provide suitable airtightness. But others that you would expect to be airtight – such as blockwork or solid timber – may not be airtight at all.

Materials that can be used for an airtightness layer include:

- concrete: cast concrete is sufficiently airtight, while concrete blocks and other preformed concrete elements need to be wet-plastered to be airtight
- wet plaster: can be used to create an airtight membrane over solid construction, such as blockwork
- most engineered timber boards: if there are no knots or other defects. Some oriented strand boards may be too porous
- plasterboard
- suitable polymer membranes.

The difficulty with using boards to form the airtightness layer is that they need to be taped at the joints. This is particularly challenging with boards that remain visible, such as plasterboard.

Filling the recesses formed by the edges of the sheets with jointing compound will not guarantee lasting airtight performance, because the fill used is not immune to cracking that occurs with movement or settlement of the structure. It is simply too rigid for this task. Micro-cracks that may not yet be an aesthetic issue are, however, in sufficient numbers already an airtightness issue. The other problem is integration of the plasterboards with adjacent construction such as window frames or timber construction, where a gypsum-based filler will not adhere. Add to this problems with penetrations such as power boxes, beams, ducts and pipes, and using plasterboard as the airtightness layer becomes increasingly cumbersome. Furthermore, plasterboard is not effective in preventing water vapour from diffusing through it. Therefore when the climate requires a vapour retarder in addition to an airtightness layer, the abilities of the plasterboard are overextended.

2.1.3 Designing for airtightness

As always, the devil is very much in the detail: connecting the principally airtight materials in a way that will guarantee unimpeded performance over the lifetime of the building requires utmost attention in the design and execution processes. Joints in particular need to be detailed very thoroughly, and solutions that require advanced origami skills will most likely not work on a building site. Careful construction sequencing is furthermore needed to ensure that effective connections are achieved, and not destroyed by subsequent trades.

Silicone sealer is rarely a durable solution, and may require regular maintenance to retain its sealing performance. Expanding foam may detach from surfaces over time, or become brittle with light exposure. Few sealants offer a chance to last the lifetime of the building. You want a material that has good adhesion and cohesion, immediately tacks well, but does not dry out over time. Solid acrylic polymers are successfully used as a lasting adhesive for many connections, either applied on tapes or as a liquid in a cartridge, used with membranes. All sealed joints need to be able to cope with the stresses of building movement. For example, many tapes have a fibre reinforcement to help with this, but occasionally, mechanical fixings are needed in addition.

To design an airtight joint, the following constraints need to be regarded:

- All materials need to be specified, including adhesives, tapes and grommets, as well as any relevant mechanical fasteners, primers and pretreatment.
- Sufficient space for the assembly of parts needs to be available.
- Joints need to be connected without tension on the connectors.
- No forces must pull on adhesives or membranes to avoid creep fatigue.

The airtightness layer of one building element has to meet another airtightness layer. This sounds like matter of course, but requires us to clearly identify the airtightness layer of every part of the thermal envelope. Chimneys are an example of often overlooked elements. If a brick-built chimney is not plastered, air will leak through gaps in the mortar and cracks in the brick. Connecting an airtight membrane to a sieve does not serve any purpose at all!

All trades need to be informed about the level of airtightness that must be achieved: even trades that have seemingly no role in it (such as plumbers, electricians and painters). Airtightness truly is a team effort, and while not everyone on a building site may be tasked with contributing to the airtightness layer, everyone on a building site is capable of destroying it unknowingly.

Every trade needs to be on board with the creation of an airtight building

Electricians are the 'natural enemy' of an airtight building envelope. If they are not sufficiently informed about the purpose and location of the airtightness layer, and specifically instructed to keep it intact, they will pull cables through it, and cut holes in it for power boxes. This is creating what blower-door testers call a 'power box typhoon': very high air velocities can be measured at these places under testing conditions. If there are several these, and the additional heat loss and comfort implications have not been anticipated in the sizing of the heating system, it may become impossible to achieve a thermally comfortable indoor environment as a result.

Cases are also known where plasterers use a trowel to cut through a tape that previously connected the airtightness layer of the wall to a window frame, to get a cleaner edge, and plumbers are known for installing pipes in a way that makes it impossible to connect to an airtightness layer behind them. Think Murphy's law, and instruct everyone on the building site about requirements for airtightness, and require everyone to be present at the blower-door test to fix any leaks!

With solid construction, the most reliable and cost-effective way of creating an airtightness layer is using wet plaster. For this purpose, however, the plaster needs to reach even into regions where it does not have a cosmetic value: to unseen areas including behind kitchen units, bath tubs, floor voids, dropped soffits and staircases.

Specialised tapes are available that enable an airtight connection between plaster and foils, because foils can typically not simply be plastered over. Connector tapes provide an adhesive for the foil on one side, and a mesh for the plaster to key-in on the other.

In all cases, careful consideration of the longevity of the products being used is crucial to ensure an effective seal over the life of the building. The loads that a connector tape has to endure are quite significant:

✻ shearing load from movement in line with the glue layer

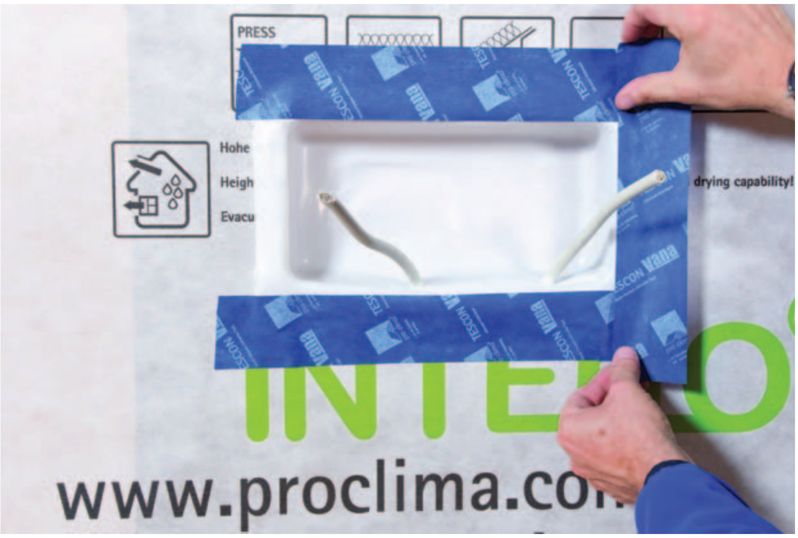
✻ peeling load when, for example, a connected membrane overhead slumps and its load tries to peel the tape off

✻ load at an angle; for example, perpendicular to the glue layer, where two connected elements move differently.

These loads should be minimised as much as possible, because the connector must be capable of bearing the resulting loads indefinitely. Adhesion of the glue to connected surfaces and the tape fabric must be secured, as well as cohesion in the glue layer itself. Failure of cohesion would lead to glue residues on connected surfaces and the tape fabric at a loss of the seal. Moreover, the glue

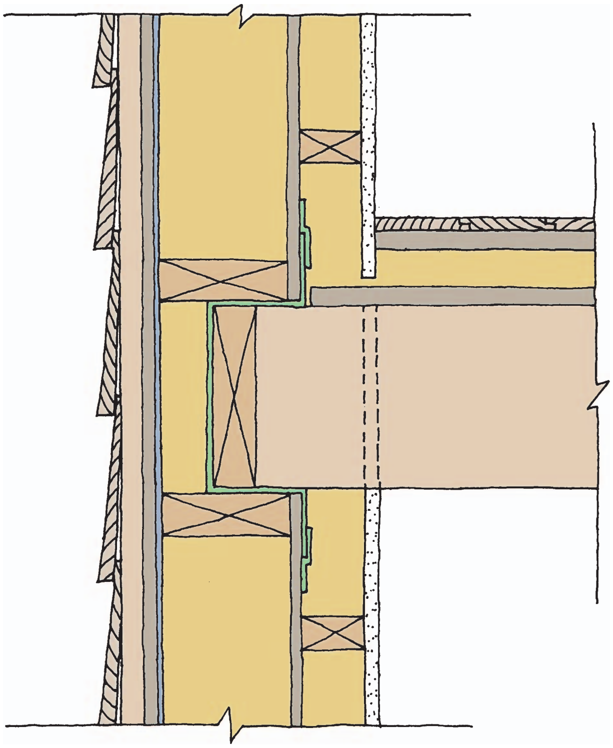

Sealing a foil to plaster using mesh tape (Photos: pro clima Moll bauökologische Produkte GmbH).


Sealing pipes and ducts to the airtightness layer (Photo: pro clima Moll bauökologische Produkte GmbH).



Airtight gaskets, and electrical points (Photo: pro clima Moll bauökologische Produkte GmbH).

must not dry out even when exposed to very high and very low temperatures. It also has to adhere to most substrates. The tape fabric must not shrink, be wide enough to provide sufficient overlap, and allow for some movement without tearing. Speciality airtight tapes are necessary for these tasks. These have undergone artificial ageing and load tests and are designed to cure, creating a very strong, long lasting seal. The tape glues are ideal for the purposes but it can be a challenge if the tape is placed in the wrong location, because, once cured, it can be incredibly difficult to remove without damaging the adhered surface.



Membrane flap already in place to connect to airtightness layer of upper storey; here engineered timber board.

Other crucial details include penetrations made for services that cross the airtightness layer such as plumbing, electrical and ducting. For pipes, cables and ducts, speciality gaskets are available that can be taped or plastered into the airtightness layer and form an airtight seal around the penetrating service.

Sequencing building jobs with airtightness in mind is another important aspect. For example, in a platform timber frame construction, a membrane flap needs to be already in place before the upper storey framing is installed, or it will be impossible to achieve a continuous airtightness layer later.

2.1.4 Pressure testing

After careful design of joints and attention to detail in construction, an effective method to single out remnant leaks within the envelope is through the use of a blower-door test. The blower-door is a frame with a fan and pressure gauge that seals into a standard opening. The entrance door is not always the best place to put it, because doing so eliminates assessing the door itself, and quite often it is air leaky. If possible, a large window is the preferred place to insert the blower-door frame. A nylon tarpaulin or adjustable boards in the frame allow the building to be pressurised or depressurised.

Blower-door, interior is pressurised (the membrane bulges outwards) (Photo: Andy Ong).

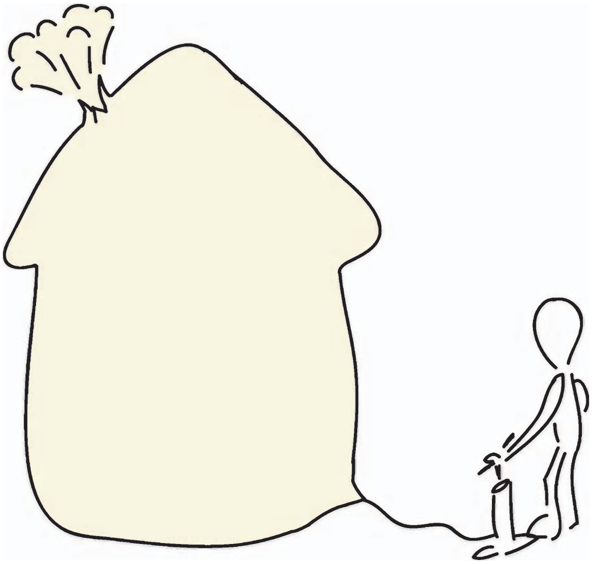
The exchanged volume that is necessary to maintain the pressure difference can be measured. If the building was completely airtight, no air would need to be added or extracted to maintain the pressure difference after a little while. The volume that the fan adds or subtracts from the building volume must therefore be identical to the volume that is leaking through the envelope.

The pressure differential that the leakage rate is most often evaluated at is 50 Pa (Pa). However, measurements are undertaken in a range of pressure differentials, to cover all reasonable possibilities, from which the result at 50 Pa is calculated.

The volume exchanged at 50 Pa pressure differential may then be spread over the area of the thermal envelope (the result is then called q_{50}) to calculate a leakage rate per m² or surface area, the volume in the house (n_{50}) to calculate the number of air changes per hour, or the treated floor area (w_{50}). Building codes may require to comply with q_{50} or w_{50} values, but for Passive Houses, we are after the n_{50} result. As an example: if the interior volume of the house is 500 m³, and 1500 m³/h were exchanged at 50 Pa pressure difference, the n_{50} is 3.0/h. This house would not comply with Passive House requirements, where the n_{50} has to be 0.6/h or below. For the house with 500 m³ interior volume this means that a maximum of 300 m³/h through the building envelope at 50 Pa pressure difference.

Why 50 Pa?

The 50 Pa pressure difference is useful for detecting leaks, but will only match the typical leakage rate of the house on a rather windy day, where this high pressure differential may occur naturally. The average leakage rate will, however, likely be significantly lower. The reason this pressure differential was chosen for testing is that the influence of wind and weather on the test result is minimised at higher pressure. With that said, measuring on a very windy day is still not permitted according to the measurement standard, because high winds would skew the results.



If the balloon skin was completely tight, you would not need to work the balloon pump to keep a certain size of the balloon. With a leak, you need to pump in exactly the same amount of air that escapes through the leak to keep the balloon at the same size. A blower-door works the same way, except that it does not keep the same size, but the same pressure differential.

The air change rate of the envelope under more naturally pressurised conditions varies considerably with the exposure of the site and the prevailing winds. On calm windless days, the pressure difference across the building envelope will be low, resulting in a slow rate of air exchange, compared with a very windy day where the pressure difference between the windward and leeward side of the house will be significant. The extent to which the leaks will contribute to heat loss in use can, however, be approximated from the blower-door test result (e.g. with the Passive House Planning Package, see Chapter 8). Using this approximation to determine whether the air exchange contributes to the fresh air requirements of the home is perilous. The contribution will vary widely depending on the wind profile at the site, which is influenced by many factors, such as contours, other buildings and, of course, the weather. To stay healthy, we need a constant air exchange. Add to this the questionable quality of air that infiltrates, and it is easy to see why this practice is flawed. Something as important as the provision of fresh air should not be left to the vagary of the wind!

The blower-door test delivers a result needed for verification, but the greatest value comes from being able to identify leaks in the construction. The pressures used are equivalent to the pressure of a 5 mm water column, and are therefore low enough for people to comfortably walk around within the building. Leaks can often be detected by simply feeling along the envelope for air movement. More-sensitive leak testing can be achieved using an anemometer to discover airflow, a thermal camera to detect cold air coming into the building or with the help of theatre smoke to visualise the air movement into or out of the building. To maximise the value of the test it is important to have the relevant materials ready, such as rolls of tape or wet plaster, as well as ladders or scaffolds to access difficult to reach areas, and contractors on site to rectify leaks on the spot. In many cases, the initial result can be significantly improved after a couple of hours of checking and fixing leaks.

Given the greatest value of the blower-door test comes from being able to identify and repair leaks, it is important to schedule the test at the appropriate time in the construction process. For example, where the airtightness layer is fixed behind a plasterboard interior liner, the first pressure test should be conducted before the plasterboard is laid, so that the airtightness layer is exposed and any gaps can be easily accessed and sealed. However, majority of windows and doors will already need to have been installed by this time as well. To get the most out of blower-door testing, it is crucial to schedule building jobs with the test in mind.

While interim tests with the aim of easily improving a precarious result are advisable, a mandatory final test after all building work is completed will be the decider whether the house can be certified. Passive House certification requires that the house is tested under positive and negative pressure. Negative pressure, where air is pumped out of the building is effective for finding leaks on the inner surface of the building, whereas under positive pressure the pathways of leaks can be observed from the outside when the interior is filled with theatre smoke. Testing both ways also allows an appraisal of the effectiveness of seals at elements with valve characteristics, such as windows and doors. For example, outward opening windows will seal better under negative pressure, where the pressure aids the compression, but under positive pressure the compression seal may overstretch. In use, the seal needs to work both ways, because the wind may cause a variety of pressure situations for the window, and it is therefore prudent to perform both tests. During testing, it is appropriate to temporarily seal up the ventilation system, because this is designed for the transfer of air across the building envelope, but other temporary seals are not permitted for the final test.

2.2 INSULATION LAYER

Insulation, as the name suggests, insulates us from the outside conditions. It is a comfort blanket for the house. The only limiting factor for the thickness of the insulation layer is your budget. You can otherwise not overdo insulation: increasing the insulation layer will always have a positive effect, if done well. The purpose of the insulation layer is to prevent:

- outdoor climate conditions dictating indoor climate
- unnecessary heat loss or gain
- noise from entering the building.

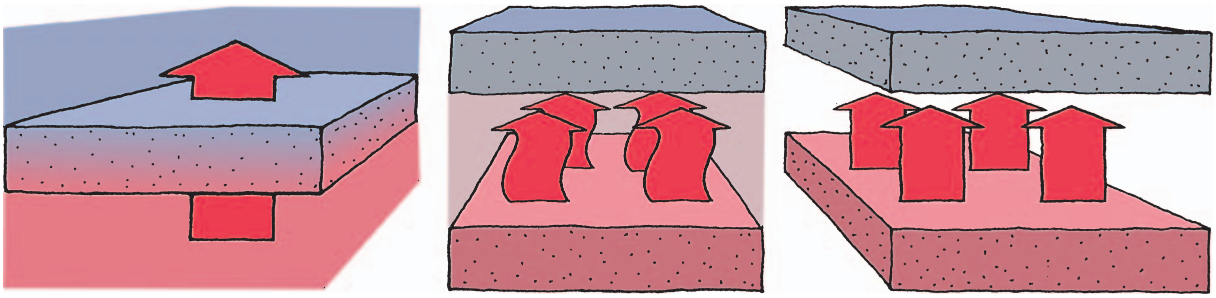
Not all thermal insulation materials are also acoustic insulators, though. Rigid materials in particular do not help with keeping noise out, while more flexible insulation materials can increase the acoustic performance of the thermal envelope. Inorganic insulation materials, such as mineral wool, can also help with resisting the spread of fire.

Insulating materials come in every form and shape, and are derived from a large variety of raw materials. To perform well, they need to have a low thermal conductivity, be continuous, and wrapped in an airtightness and wind- and weathertightness layer. Loose fill insulation is particularly well suited to form a gapless blanket in a cavity, because it moulds itself tightly to any structural elements and liners. Rigid materials are more suited as exterior wall insulation or under slabs, where they do not have to fit between structural elements.

Not every insulation material performs well in all situations: it is very much horses for courses. Additional performance requirements, such as structural, moisture-proof, fire-proof and acoustical, need to be established and checked against material properties to find the best match for the case at hand. Because it is typically difficult and cost-prohibitive to change an unsuitable insulation layer retrospectively, this process of elimination has to be conducted with great care.

Insulation materials are mostly inexpensive compared with other building materials of the same volume. Labour and incidentals (such as scaffolding) constitute generally the largest part of the cost of installing an insulation layer. Saving money by reducing the thickness of the insulation layer is for this reason alone a rather short-sighted strategy: the insulation layer needs to perform well throughout the lifetime of the building, and expanding it after liners have gone in will be very expensive!

Conduction, radiation and convection are the heat transfer mechanisms that insulation needs to curb.



Heat transfer through a building material: conduction (left), convection (middle) and radiation (right).

The conduction of heat occurs by the direct exchange of energy between molecules or atoms within a material. Conduction dominates the heat exchange through dense, highly ordered materials such as metals. Fluffier materials, such as insulation, have an overall lower thermal conductivity, and movement of heat through air becomes the major factor for the heat transfer. Vacuum insulation panels use this fact to advantage: the vacuum cuts out the convective heat transfer in the absence of air. This lowers their thermal conductivity to a fraction of that of generic insulation, where air movement is only reduced, but not eliminated. The heat transfer rates for conduction and convection processes change proportionally to the indoor–outdoor temperature gradient. Radiation, as the third fraction of heat exchange, is the exception to this rule. The radiation heat transfer rate changes with differences in temperature to the power of four. Small changes in the temperature difference make a significant difference in radiative heat exchange. Radiation heat exchange needs neither air to move between surfaces, nor does it require physical contact. A line of sight suffices.

Apart from the temperature difference, the ability of surfaces to emit heat matters. Shiny metals reflect infrared waves better, and absorb less of them. Consequently, the radiative heat loss fraction is reduced. This is, however, partially counteracted by the fact that metals are very good heat conductors. Furthermore, to achieve the desired effect the metals have to stay shiny in use. For example, if metals are enclosed in glass panes, this can be taken for granted. Low-emissivity coating of multi-pane glazing units is an example where this is used to good effect (see below for details). For most other uses, however, we need to assume that dust and dirt will accumulate on the surfaces over time, and with oxidation or rust in the mix metals will lose their shine, in which case they are no longer a good reflector – but still a good conductor of heat.

Thermal conductivity in W/(mK) captures all three processes. It is a material-specific value, which makes it much better suited for comparing the relative merits of materials than the more commonly used (in Australia and New Zealand) R-value. The R-value is the quotient of layer thickness and thermal conductivity, and is therefore layer specific rather than material specific. Looking at two R-values, it is impossible to determine the better performing material – unless the layer thickness is known and computed into an equation. Using thermal conductivity as an indicator, a comparison of the performance of materials becomes a straightforward exercise (Table 2.1).

We can loosely categorise building materials into four categories of thermal performance:

- conductive materials, such as metal frames and concrete that provide little to no thermal insulation benefit and in many cases can compromise the performance of thermal envelopes (e.g. steel beams, metal window frames, concrete slabs)
- non-conductive building materials, such as timber that on their own do not offer high levels of insulation but if used sensibly can cross the thermal envelope without significantly compromising performance (e.g. structural timber studs in a wall)
- bulk insulation materials, such as mineral wool and synthetic materials such as polystyrene, all of which are relatively cheap but require a reasonable thickness to deliver an effective thermal envelope
- speciality insulation materials, such as aerogel and vacuum panels, which are very expensive but are able to achieve high levels of insulation where space is limited.

Building materials in the first category are the cause of problematic thermal bridging – more on this later. Timber is a more benign structural element when thermal bridging is considered, but if used extensively within the insulation layer, it will reduce the overall thermal performance of the building element markedly, and should therefore be used sparingly in insulated cavities.

To be effective, insulation needs to fit tightly to the structure and other elements it borders. For cavity insulation, flexible, blanket type or loose fill materials are best, because it will be difficult to fit rigid insulation gaplessly between structural members such as timber studs that are never entirely straight and smooth. Poorly fitted insulation is, however, like a poorly fitting wetsuit: it will not keep you warm.

The thermal performance of construction elements such as a wall, roof or floor is a product of the thermal resistance of its layers. This is expressed with a total R-value (in m^2 K/W) for the construction, summing up the resistance of all layers and surfaces. Inversely, the heat flux through the building envelope is expressed as a U-value in W/(m^2K). Calculations for R and U-values need to take proper account of the effect of any bridging materials in the insulation layers. Purely area weighting these bridging materials with their increased thermal conductivity ignores the disturbance thermal bridges create for the heat flow of adjacent areas. To illustrate this: if you

Table 2.1. Typical building materials and their thermal conductivity.

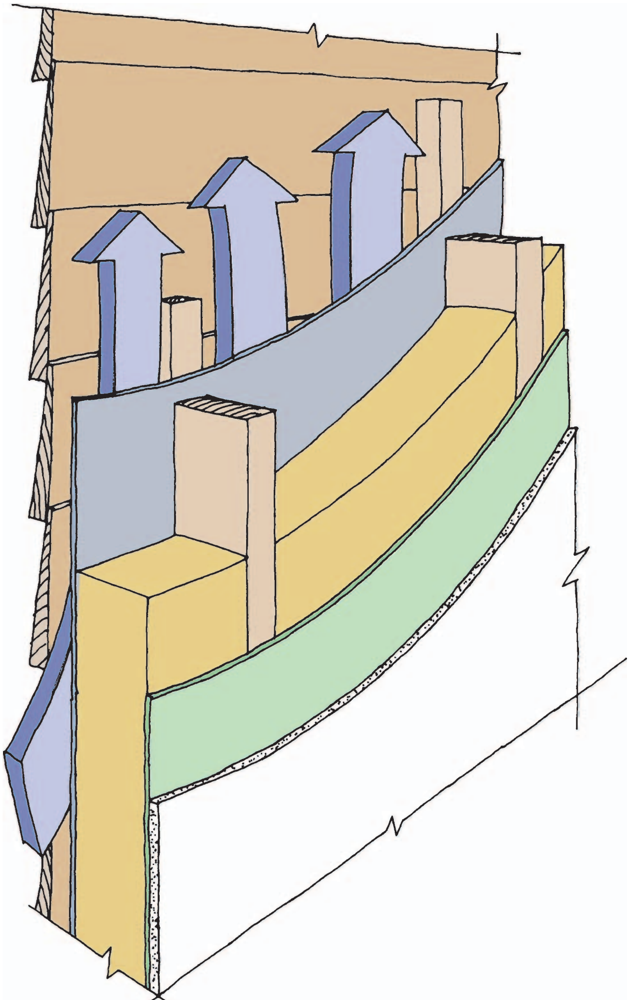
Material	Typical thermal conductivity in W/(mK)
Vacuum insulation panels	0.006
Generic insulation	0.040
Softwood timber	0.120
Reinforced concrete	2.000
Stainless steel	20
Aluminium	200

build a bridge over a river, you will not only create traffic over the bridge, but also in the streets leading up to it. A bridge is a significant short-cut after all! International standard ISO 6946:2007 (ISO 2007) takes these effects into account. Building code tools, however, may not do this.

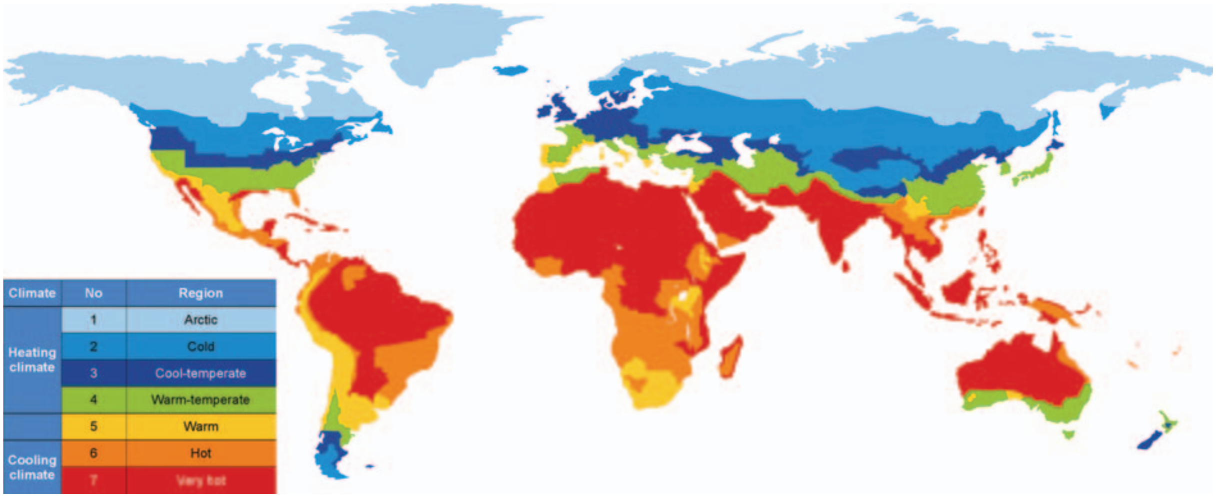
Where a building element borders air, a thin film of air will form at its surface. Depending on the stillness of this layer of air, a resistance to heat flow will be created. The effect is therefore aptly named surface resistance. Because air can be assumed stiller indoors than outdoors, the internal surface resistance is typically larger. The effect of internal and external air films needs to be added to the total resistance of a building element, but of course only if the element actually borders air.

Does a ventilated air layer behind a cladding form part of the thermal resistance of a building element? Looking at the situation closely, it becomes clear that near ambient conditions prevail in a ventilated cavity.

As the heat loss through the thermal envelope is occurring from indoor air to outdoor air, the heat transfer is therefore bound to happen in the ventilated air layer behind the cladding, so this



Outdoor air moving through a ventilated cavity; the air in the cavity will be nearly the same temperature as outdoor air.



Climate zones for component certification (Figure: Passive House Institute).

is where the calculation of an element's resistance to heat flow has to end. The cladding does, however, reduce the wind speed in the cavity, compared with the wind speed exterior of it slightly, which is acknowledged with an increased exterior surface resistance for these cases.

Elements of the thermal envelope, such as walls, floors and ceiling, consist of material layers from which an overall resistance needs to be calculated. To determine how thick an insulation layer has to be, the build up of the wall, roof or slab can be recreated in the U-value calculator of the Passive House Planning Package (PHPP), which permits quick comparisons of the thermal performance of endless variations. The effect on the energy balance of the house is instantaneous, which makes it possible to fine-tune the configuration of building elements.

While PHPP operates with U-values, people in some parts of the world are more familiar with R-values. So, what R-values are we looking at for Passive Houses? It really depends on localised climate and the compactness of the thermal envelope, but as a ballpark figure, for Melbourne, the average construction R-value will have to be ~3.00 m^2 K/W, and for Christchurch ~5.00 m^2 K/W.

Table 2.2. Insulation requirements corresponding to climate zones.

Climate zone	U-value (W/(m^2K)	Total R-value (m^2K/W)	Approximate minimum thickness of typical bulk insulation layer in a timber frame construction (mm)
Arctic	0.09	11.11	435
Cold	0.12	8.33	325
Cool-temperate	0.15	6.67	255
Warm-temperate	0.25	4.00	150
Warm	0.50	2.00	70
Hot	0.50	2.00	70
Very hot	0.25	4.00	150

More generally, the values in Table 2.2 are an indicator of what level of insulation you should achieve depending on the climate your house is in.

Very hot and warm temperate climates have the same minimum requirements. This does not surprise if you keep in mind that insulation also works to keep the heat out.

2.2.1 Retrofitting insulation

When retrofitting insulation, the hygrothermal situation of a building changes. Surfaces that were previously indirectly heated via heat transfer through the fabric, and therefore relatively warm, will be insulated from interior conditions, and become cold surfaces as a result, risking high water activity or even condensation.

Therefore, when insulation is added retrospectively, every effort possible should be taken to create an effective airtightness layer across the entire warm surface. For most buildings, this is quite difficult to achieve without relining the warm surface of the building. Where an effective airtight layer cannot reliably be achieved, another strategy could be employed is to use insulation materials with the capability to wick any moisture that reached the cold side of it back to the warm side again. On the warm side, there is a good chance of keeping the water vapour suspended in air. These materials are called ‘capillary active’. For example, calcium silicate boards and certain wood fibre boards behave this way. Naturally, any render or liner internally of them must not block the moisture transport and, particularly, there must not be any air gap between the interior liner and the insulation material, because it would break the wick. Generally, retrofitting existing homes with insulation when there is no opportunity to also apply a gapless airtightness layer should only be conducted with the support of an experienced professional along with hygroscopic analysis, as discussed in Chapter 8.

2.2.2 Embodied energy of extra insulation

Finally, if you are worried about the embodied energy – the energy needed to manufacture a product – there is little reason to worry about insulation layers. Firstly, the embodied energy of the insulation layer is only a small fraction of the energy embodied in the building. How small exactly depends on the structure and the insulation material used, but, to give an example, the difference in embodied energy between a timber frame structure and a solid structure can easily exceed 250 kWh/m^2 of wall, roof or floor. Secondly, even the most energy-intense insulation materials, polymer foams, contain only about a tenth of this difference as embodied energy. Therefore, if reducing embodied energy is a priority, avoid the use of dense materials as far as possible (e.g. use a timber frame rather than a steel frame construction). Typically, any additional embodied energy from an insulation layer is recouped in the first year from the savings in heating and cooling energy. Furthermore, embodied energy, unlike the energy used for conditioning a building, is not lost. As the term ‘embodied’ suggests, it is retained in the product. If the product is reused after its life as a building component ended, nothing is lost. If it is recycled, then significantly less energy than in the first instance is needed to gain a useful product. That said, there are still significant differences in the amount of embodied energy of insulation layers. Cellulose, straw and timber fibre insulation are on the low end of the scale, and polymer foams such as polystyrene on the high end. But whatever insulation you use, the problems with embodied energy of insulation layers are minuscule compared with the problems of fossil fuels burnt in the operation of houses.

2.3 WIND- AND WEATHERTIGHTNESS LAYER

The third and final control layer of the thermal envelope provides wind- and weathertightness. What is the difference between air- and windtightness? Airtightness is about preventing indoor air from penetrating the thermal envelope, whereas windtightness is about preventing outdoor air from getting into the thermal envelope. The windtightness function is typically combined with the function of keeping out water, but be aware that for keeping water out overlapping membranes may be sufficient, but to keep the wind out, joints will have to be taped.

The purposes of this layer are to prevent:

- water from entering building cavities
- wind from circulating around insulation layers or washing around the edges of insulation (this would greatly reduce insulating properties)
- the creation of varying pressure zones in building cavities (which could amplify pump-effects, as already discussed with airtightness).

The wind- and the weathertightness layer may sometimes not be in the same place. In a roof, for example, the roofing plus underlay may provide the service of weathertightness. However, if the insulation is not directly under the roofing, but rather above the ceiling, a separate windtightness layer may be necessary. If the roof cavity is ventilated, and therefore windy at times, wind-washing of the insulation might otherwise ensue. Typically, however, wind- and weathertightness layer are either the same (external render on an exterior insulation finishing system), or in close proximity (cladding as primary weathertightness layer with breather membrane as a combined wind- and weathertightness layer and second line of defence behind).

To be on the safe side, the wind- and weathertightness layer, while impervious to water, should allow water vapour to pass through, at least in a heating climate where the water vapour pressure gradient during the heating season will dominantly drop from inside to outside. Any moisture that still sneaks into building cavities through imperfections in the airtightness layer or through diffusion processes then has a chance to evaporate to the outside, as opposed to being trapped in the cavity. Foils achieve this either with micro-pores, or through the use of non-porous (monolithic) copolyester products, which are water repellent but permeable to moisture and gases (the same type of membrane used in nappies).

Photo of weathertightness layer. (Photo: Marc Coviello).

The three functional layers are summarised in the Table 2.3.

Table 2.3. The three functional layers of the thermal envelope.

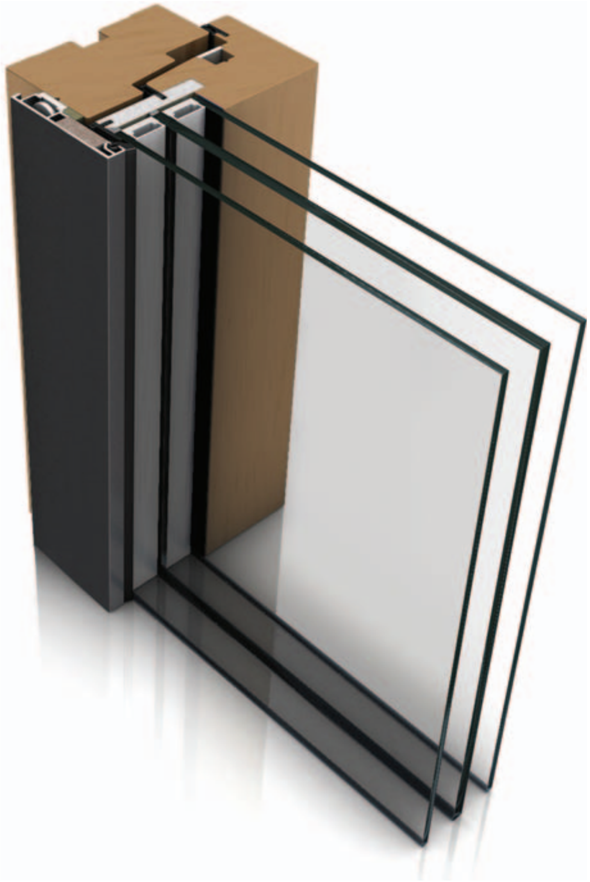
	
Airtightness layer (green)	On the warm side, in heating climates: inside of the insulation layer. Must be permanently airtight, and have moderate vapour retention capacities, to prevent: – condensation of moisture on cold surfaces in building cavities – unnecessary heat losses – draught – dysfunction of ventilation systems – noise from entering the building.
Insulation layer (yellow)	Enveloped by the two other layers, and with minimal interruptions to prevent: – outdoor climate conditions dictating indoor climate – unnecessary heat losses – cold surface temperatures (mould) – noise from entering the building.
Wind-/weathertightness layer (blue)	Exterior of the insulation layer. Must be wind-proof, water repellent and breathable to prevent: – water from entering building cavities – wind from circulating around insulation layers or washing around the edges of insulation (this would greatly reduce insulating properties) – creating varying pressure zones in building cavities (which could amplify moisture transport mechanisms, pump-effect).

2.4 LET THE SUNSHINE IN!

Windows admit the outside world. They let the sunshine into your home, allow you to have a chat with the neighbours and enjoy a breeze on your skin! Even though most Passive Houses use mechanical ventilation for a good reason (see Chapter 3), there needs to be at least one operable window in every bed- and living room, to provide you the delights that come with windows.

For thermal performance, the transparent parts of the building envelope are the most difficult to get right. Windows really are a double-edged sword: they are typically the weakest link in the thermal protection chain. Even triple-glazed windows leak more energy than a run-of-the-mill wall. But they also let the sunshine in and, if done well, can therefore be a net energy gain factor in the thermal envelope, which is useful in a heating climate. But then of course, there is summer too, where large windows can lead to massive overheating!

Whether losses or gains dominate for a specific window depends on the window orientation, size and geometry, as well as its optical and thermal properties, and, last but not least, the amount of shading it receives. The shading may result from external features, or the building itself may shade part of the window (e.g. the window reveal or any overhangs). Obviously, solar gains can only be collected through the glazed portion of a window, and the ratio of frame to glass is therefore a factor that influences the energy balance. Where to locate windows in a wall also



Cut through a triple-glazed window (Photo: Pazen Fenster + Technik GmbH).

requires thoughtful consideration. For example, parts of the window that sit lower than 80 cm above the floor will typically not be useful for solar gains or daylight harvesting. These areas will therefore likely be a net energy sink.

In Australia and New Zealand, the discussion about windows is typically focussed on glass. But glass is only one part of a window. Depending on window size, and whether there are mullions and transoms, the frame can easily be 50% of the window area. But even large casement windows still have a significant portion of their areas made up of the framing material. There really is no point in putting triple-glazing into an aluminium frame that is not completely thermally broken. While the insulated glazing unit blocks heat transfer, the aluminium frame rolls out the red carpet for it to escape.

In an insulated glazing unit, an often overlooked detail that determines its performance is the edge spacer: the element that separates the panes of glass. Aluminium, which is traditionally used as an edge spacer because it is form stable and diffusion tight, is an extremely good heat conductor. Therefore, if you improve the thermal performance of the glazing, but leave a strip of aluminium at the perimeter of the glass, this will be all the encouragement that warmth needs to crossover to the other side. As a result, the perimeter of the glazing unit becomes cold on the inside, which leads to condensation on these surfaces – even when there are multiple layers of glass!

Windows need to be airtight when closed. Proper sealants are needed for this – a second sealant layer is preferred to make sure that at least one seal is catching when windows are slightly misaligned.

Lastly, how the window is integrated with the wall or roof it sits in can make a huge difference for its performance. Airtightness, insulation and wind- and weathertightness are the usual concerns, and windows need to be connected to all three functional layers of the thermal envelope. For insulation, the best results are achieved when the window is installed in line with the middle of the insulation layer, and parts of the frame are covered with insulation in addition. Specialised tapes are a solution for airtightness, or compression seals (careful, though, because the latter are only airtight up to a certain expansion rate). Whatever form the seal between window and surrounds takes, it needs to be connected to the adjacent airtightness layer without unduly stressing the sealing materials, because there will be movement.

What makes glazing energy efficient? Two window panes keep more warmth inside than only one, but the effect is only minor, and certainly not substantial enough to achieve a comfortable and healthy indoors. What else is needed for energy-efficient glazing units? Low emissivity (low-e) coatings are part of the strategy. Although glass is generally quite open to short-wave solar radiation, and less permeable for long-wave radiant heat, uncoated glass still absorbs warmth from the indoors, and conducts it to the outside. An invisibly thin layer of low-emissivity coating, typically silver, changes this: most of the warmth is then reflected back into the room instead of being conducted out of it. Additionally, for high-performance glazing, the gap between the panes is filled with an inert gas that has an even lower thermal conductivity than air. Finally, the aforementioned edge spacer needs to be made from a material that conducts significantly less heat than the aluminium traditionally used for the purpose. This material must still be very stable and diffusion tight (to keep the gas in the cavity and moisture out of it). Polymers, either reinforced with fibreglass or with a thin layer of stainless steel in the core, are the better alternative. Not only do they cut the heat loss at the perimeter to less than a third of the aluminium edge spacer, but equally important, they increase the interior surface temperature, and consequently condensation is unlikely to form.

With these steps combined and optimised, a double glazed window can perform five times better than single glazing. Furthermore, triple and quadruple glazed windows can be 10 or more times better at keeping the warmth inside, but this is bought with reduced solar gains. Windows really have to be well matched to the climate and orientation they are in to get optimal performance year round.

The U-value of a window is determined by the area weighted performance of frame and glazing, and the length and quality of the edge spacer. With the best double-glazing supported in a well-insulated frame, a window U-value of 1.20 W/(m^2K) is achievable. Lower values require triple glazing. The installation of a window unit in a wall or roof can add new pathways for heat to escape. For example, additional structure may be needed, or flashing may get in the way of insulation. The installed U-value is therefore typically higher than the window unit U-value.

For comfort and optimum economic performance, the U-values for windows in Table 2.4 should not be exceeded.

These values also form part of the criteria for the certification of windows, where they apply to a medium-sized window. The U-value will likely change with the size of the window, because the impact of the frame becomes more pronounced with small windows.

Within the logic of this table, Melbourne, Sydney, Canberra and Adelaide are categorised as having a warm-temperate climate, together with the North Island of New Zealand. Cairns is hot, and Alice Springs very hot. Australia does not have land area in the cool-temperate, cool or arctic climate zones according to these certification criteria, but parts of the Australian Alps and Tasmania likely fit into the cool-temperate climate along with the South Island of New Zealand. Obviously, this is all very generalised, with finer detail difficult for a standard that covers the world. The values above should therefore be used for orientation only, and windows be fine-tuned in the context of the building and its environment.

Certified windows

It is not necessary to use certified windows to achieve Passive House certification. It is easier to use them, though, because all the data you need for optimising your design are reliably available with certified windows, and can easily be picked from a drop-down menu in PHPP.

The heat gain side of the window equation is ruled by location, orientation, tilt, size, shading situation and the degree to which solar irradiation passes through the glazing configuration. The latter is expressed as a g-value (the fraction of solar heat that reached the interior), which reduces with the number of panes and coatings used. If no solar gains are blocked, the g-value equals 1; if half the solar gains are blocked then the g-value equals 0.5. The Solar Heat Gain Coefficient (SHGC)

Table 2.4. Window U-values corresponding to climate zones.

Climate zone	Component U-value W/(m²K)	Installed U-value W/(m²K)
Arctic		
Vertical	0.40	0.45
Inclined (45°)	0.50	0.50
Horizontal	0.60	0.60
Cold		
Vertical	0.60	0.65
Inclined (45°)	0.70	0.70
Horizontal	0.80	0.80
Cool-temperate		
Vertical	0.80	0.85
Inclined (45°)	1.00	1.00
Horizontal	1.10	1.10
Warm-temperate		
Vertical	1.00	1.05
Inclined (45°)	1.10	1.10
Horizontal	1.20	1.20
Warm		
Vertical	1.20	1.25
Inclined (45°)	1.30	1.30
Horizontal	1.40	1.40
Hot		
Vertical	1.20	1.25
Inclined (45°)	1.30	1.30
Horizontal	1.40	1.40
Very hot		
Vertical	1.00	1.05
Inclined (45°)	1.10	1.10
Horizontal	1.20	1.20

used in some countries is similar to the g-value, but not identical, because boundary conditions for the assessment vary. Looking at the balance of gains and losses, a triple-glazed window may not be the best choice in a milder location. Although it keeps more heat in, it also keeps more sunshine out, which is undesirable in winter, but, on the other hand, it may be a bonus for the summer situation. A balance has to be struck for each window, trialling various configurations to find the optimum considering the factors outlined above. This is easily achieved in the Passive House Planning Package.

The considerations discussed so far also apply to the situation in summer, but the overriding factor for summer performance is controlled shading. Keeping the sun out is the simple trick for avoiding, or at least reducing, overheating in summer. Insulation works both ways, so an insulated and airtight opaque envelope will help with keeping the heat out, but if solar rays are allowed to cross the envelope via unshaded windows, they are more efficiently trapped than in a poorly insulated house. Therefore keep the sun out as much as possible in summer! Overhangs have to be modelled in four dimensions (including time) to check their suitability for this task. Many fixed shading devices only shade the midday sun at the height of summer and do nothing to keep out morning and afternoon sun, and increasingly less for the midday sun in spring and autumn. Movable, external shading devices, such as shutters, are a far better option for allowing sun in when wanted and keeping it out when overheating is an issue. They can even be automated with a small photovoltaic motor and a photo-sensor. That way, even if the sun comes out while you are at work, you still return to a nicely conditioned home, because the photo-sensor picked up light on the façade in question, and the motor kicked in to close the shutters or roller blinds.

For ventilation purposes, casement or top-tilt opening windows are preferable over awning windows, which perform poorest with regard to an effective air exchange. Also keep in mind that it should be possible to open a window for night-time ventilation in summer without creating security issues.

Finally, doors are surprisingly an often overlooked part of the thermal envelope, even though our experience of houses typically begins with opening one! Doors in the thermal envelope – and please note that this also includes, for example, doors to an internal access garage or other non conditioned parts of the building such as basements or roof spaces – need to be insulated at least as well as the windows of the project. And they need to be very airtight. Unlike with most modern windows, sufficient airtightness is not a given for doors. Doors certified for Passive Houses must not leak more than 2.25 m^3 of air per hour and metre of the perimeter, when the pressure difference on either side of it is 100 Pa (equivalent to a good storm). This is not too hard to achieve with good seals. It is harder, though, when accessibility is also a goal, and thresholds or jams need to be avoided. Nevertheless, it is possible to combine these goals, using magnetic seals, for example, which are pulled up from the floor when the door is closed, and released when it is opened, thereby granting access without barriers. The door must not be locked for this test, but simply kept shut. Sliding and folding doors add a big challenge to creating an airtight building envelope because it is rather difficult to produce a sliding or folding door that is airtight when closed. If they are to be used, it is highly recommended to use Passive House certified products or alternatively require a guarantee of conformity with the Passive House criteria for doors from the manufacturer.

Radio frequency identification (RFID) chips are a solution for tiny doors for four-legged members of the household. Well-insulated and airtight pet doors are available that open automatically if the 'right' pet approaches. A remote control allows more configurations: for example, letting your cat in, but not out again.

2.5 THERMAL BYPASS

We all love a short-cut!

Think of the insulation we put in the thermal envelope as a shark-infested moat around your house to discourage warmth from crossing. If the moat is narrow or only has a couple of sharks, then it is easy to jump across – bridges are not a game changer. This is the case in a poorly insulated home where heat readily transfers through the whole envelope. In a well-insulated home, the moat gets wider and is filled with more and hungrier sharks to really keep the warmth inside. But what use are these defences if we then put a bridge over the moat? Or dug a tunnel under it? Or provided a ferry service? We need to look very closely at the thermal envelope to check if we have not left places where it is just too easy for the heat to arch over to the other side.

The designed path is not always the paths actually taken.

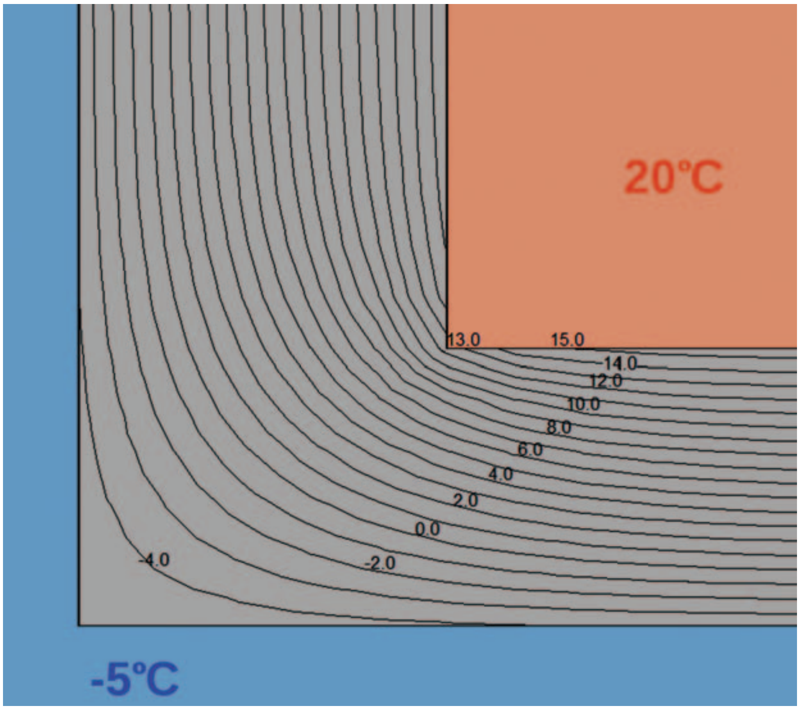
2.5.1 Thermal bridges

Thermal bridges are sometimes called cold bridges, which denotes their effect on interior surfaces. Strictly speaking, though, what crosses them is not cold, but rather heat.

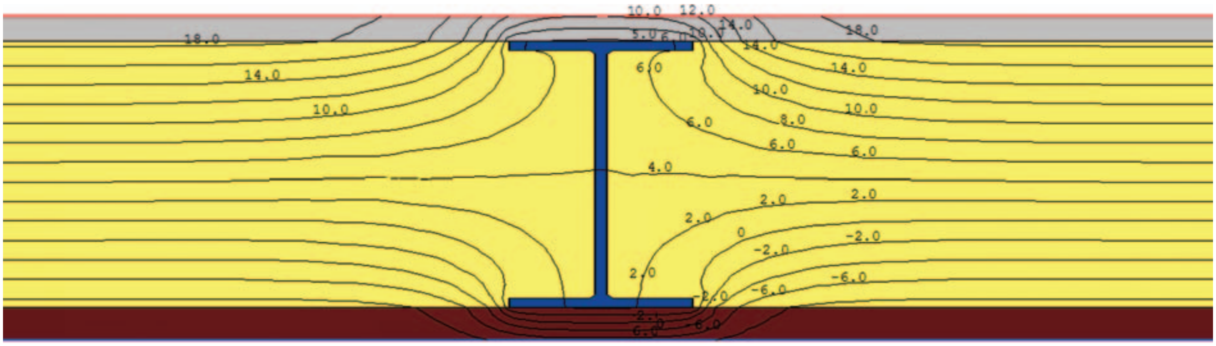
There are two basic categories of thermal bridging: geometrical thermal bridges, which are hard to avoid; and material-related thermal bridges, typically caused by structural elements interrupting the insulation layer.

Geometrical thermal bridging occurs at exterior corners, where the heat-absorbing surface area on the inside is vastly smaller than the heat emitting area on the outside. As a result, the heat transfer is increased, which explains why mould is most common in corners: the surface temperatures are lower there.

There is not much you can do to avoid geometrical thermal bridges other than minimise the number of external corners on your home, and keep in mind that obtuse angles are slightly better in this regard than acute. When external dimensions are used to calculate the heat loss at the thermal envelope – and for a Certified Passive House this is what you need to do – then corners are covered twice, and the additional heat loss is therefore typically covered, if not overestimated. This simplification, however, ceases to be valid when geometrical thermal bridges are coupled with material-related thermal bridges, such as a steel column in an exterior corner. For these cases, and quite regularly for window installation details, more detailed modelling of the construction may be required using programs such as THERM (discussed in Chapter 8) to predict the performance more accurately. Using software to model thermal bridges also allows calculation of whether the temperatures in the corner will be warm enough to prevent high water activity and mould formation.



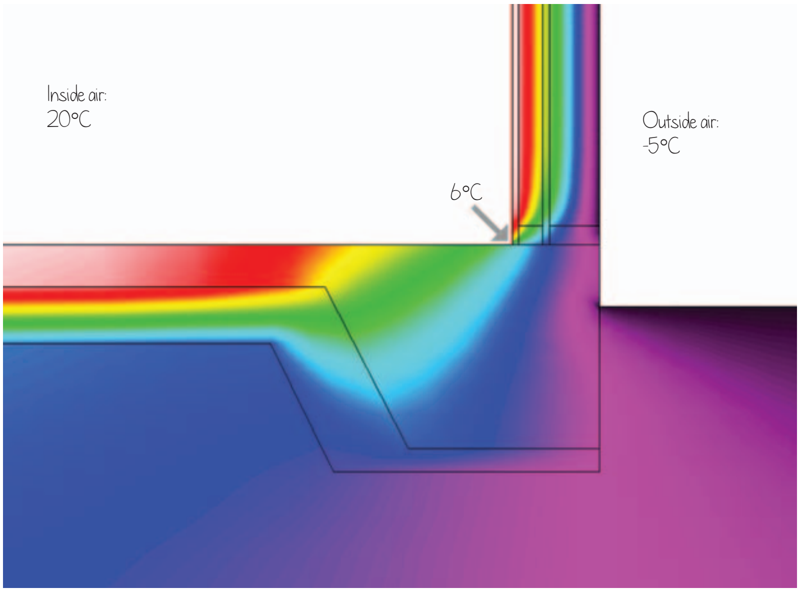
Geometrical thermal bridge at convex corner of a monolithic wall; while the interior surface temperature ~10 cm from the corner is 15°C, it drops to 12.5°C directly in the corner. With 50% relative humidity indoors, mould formation is likely at temperatures below 12.6°C.



The lines of equal temperature (isotherms) are not parallel at the thermal bridge, a steel I-beam, and well beyond. The influence of the thermal bridge extends about three times the width of the bridging element. Internal surface temperatures are also markedly lower in the regions adjacent to the thermal bridge.

Structural elements such as concrete columns or steel beams have a markedly higher thermal conductivity than an adjacent insulation layer. For this reason, the lines of equal temperature are disturbed. The disturbance pertains not only to the area that is bridged, but also to layers in contact with the bridge. Purely area weighting the effect of thermal bridges gives highly inaccurate results.

The international standard to calculate one-dimensional heat loss, ISO 6946:2007, does a good job at estimating the effect of repeating thermal bridges, such as timber studs, in a building element, provided the discrepancies between the thermal conductivity of the bridging material and other materials in the inhomogeneous layer is not too stark. If, for example, steel is the bridging material, then methods with a higher accuracy for these cases have to be used. Better accuracy is also needed for all non-repeating thermal bridges: for example, steel beams over large openings in a wall or other structural elements in the thermal envelope, such as cantilevering concrete slabs or parapets.



Insulation is missing at the front side of the concrete slab, and even though there is insulation under the slab and in the wall, the temperature at the foot of the wall drops to concerning levels.

Another place to look for thermal bridges are wall footings, where they connect to a concrete foundation. It is difficult to get a gapless insulating layer there – but not impossible.

Designing thermal bridges out is the first call in dealing with them. Do balconies really need to be formed by cantilevering concrete slabs, or can they be erected as a separate structure in front of the thermal envelope? It would still be necessary to connect the separate structure with bolts or brackets to the structure of the wall, but these punctiform thermal bridges are far milder in their effect than the linear thermal bridge that would be formed by a cantilevering slab. Therefore, before you think of ways to mediate thermal bridges, think of alternative construction approaches that do not require linearly bridging elements.

If this premise is exhausted or not feasible, any remaining bridging materials need to have the lowest thermal conductivity possible for the job. Consider, for example, aerated concrete or lighter concrete instead of heavy concrete, or steel instead of aluminium. Likely, however, this will only be the first step in preventing negative effects. You may also need to wrap insulation around the bridging material. Modelling in a thermal bridging software will show whether the outcomes for interior surface temperatures and a low additional heat loss are achieved. For a Certified Passive House, you are looking to reduce the additional heat loss at thermal bridges to less than 0.01 W/(mK). A thermal bridge of 50 m length with this thermal bridge coefficient (e.g. around the perimeter of a 150 m^2 house) would add 10 W to the size of a necessary heater if it is 0°C outside. Not much for a typical house, but in a Passive House, 10 W are enough to heat 1 m^2 of the house even if it is very cold. If unavoidable, the 0.01 W/(mK) value may be exceeded at places, but only if the case can be made that there are no negative effects on interior surface temperatures, and if the additional heat loss is compensated for elsewhere in the thermal envelope.

2.5.2 More ways to bypass the insulation layer

On a calm day, a woollen jumper may be enough to keep us warm, but if it gets windier, the wind circles around the fibres, and the jumper loses most of its insulating capacity. Basically the same can happen with houses. If insulation is not thoroughly protected from the outside, parts of its performance can be washed away by fast moving air (wind-washing). Exterior corners are particularly susceptible to wind-washing, but it can also take effect at unexpected places, such as party walls with a gap between them. For heat loss calculations, which are usually performed one-dimensional, we assume a dominant direction of the heat flow. In this case, we assume the heat flow to predominantly be horizontal. In reality, though, heat flow occurs in three dimensions, and air movement can change the dominant direction easily. In our example, heat passes through the walls, where it meets a thermal elevator if the walls are not capped at the top, which will fast track it to the outside. Although the calculations assumed that there will be no heat loss, because the adjacent units are equally heated, air movement in the cavity changed the dominant heat flow direction, and there is nothing in the way to stop the heat escaping upwards. Two-leaf masonry walls to the exterior are another place where this can occur. We must not forget this when we check the defences against heat loss, or U-value calculations will be grossly misleading in these cases.

Still air is a good insulator. If, in contrast, air is moving, it loses insulating properties, even if this movement is in a closed loop. For example, setting two window panes several centimetres apart does not make a good double glazing, because air roller processes in the gap may in fact accelerate the heat transfer.

To get your insulation layers to perform as intended, encapsulate insulation closely on both sides with air impermeable layers, eliminate voids and communicating cavities within the thermal envelope, and leave no gaps behind or between insulation materials.

2.6 THERMAL MASS

Thermal mass (comprising dense materials exposed to the sun, such as exposed concrete floors) is often considered important, if not essential, for an energy-efficient home. However, for a well-insulated home this is not necessarily the case. Although the mass is most often found within the thermal envelope, rather than being a part of it, we will briefly discuss its role here. Adding extra thermal mass is rather expensive, and not needed to keep the heating energy demand low in a Positive Energy Home. Every house has thermal mass. By ‘extra’ we mean the addition of dense materials with no structural purpose. Overall, the importance of thermal mass for a lower heating demand of houses shrinks with their insulation level. The better the insulation and airtightness, the less benefit is derived from thermal mass. In a poorly insulated building, thermal mass can make a real difference. But in a very well-insulated building, additional thermal mass has hardly any role in further reducing the heating demand.

Why is this? Thermal mass needs fluctuating heat inside the building to buffer a surplus, allowing the thermal mass to ‘store’ the energy for later release when the temperature inside the building drops. Therefore, thermal mass can help buffer large variations in air temperature, but, due to the high thermal inertia of Passive Houses, indoor temperatures are very stable throughout the year, negating the need for buffering. Placing a pot of hot coffee behind a window in full sun achieves little because the pot is already warm and has limited ability to absorb any more heat. Similarly, the capacity of already warm thermal mass to further absorb heat is reduced. The high insulation level and greatly reduced ventilation heat loss will leave only a tiny gap between demand and supply of warmth, even on very cold days anyway.

For summer, though, and particularly in hot climates with a large temperature swing between night and day, thermal mass may be a game changer for comfort. For this to happen, the heat that is absorbed during the day needs to be ‘discharged’ again overnight through increased night-time ventilation. If this cannot be guaranteed (e.g. in hot climates where the temperature swings are unpredictable or mild), thermal mass can be very difficult to control and can result in overheating of the home. In a cold to moderately warm climate, houses with appropriate external shading, especially of east- and west-facing windows, should not need extra thermal mass to stay comfortable year round.

Although thermal mass can be beneficial in certain situations, the first priorities for the design of a house should always be a high performance thermal envelope with excellent airtightness and effective shading.

SUMMARY

For the home to offer effective protection from the elements, it needs to have three uninterrupted functional layers: weathertight, thermal insulation and airtight. The performance of these layers must undergo tests on the drawing board, the computer and in the field. Once these layers are lined internally and/or externally, gaining access to remedy any remaining faults is prohibitively expensive and, if flaws persist, they will impact negatively on the wellbeing of the insufficiently enveloped people for a very long time. They therefore need to be thoroughly tested before it is too late! A house that is missing patches in the thermal envelope is like a poorly wrapped gift: an embarrassment.

Light and sunshine are important for a good life, but transparent areas in the thermal envelope need very careful design, so that the amount of light and sunshine that gets into the house can delight, rather than create discomfort. Windows are the most critical element in the thermal envelope – getting them right is paramount for the creation of Positive Energy Homes!

Make an optimised thermal envelope the highest priority in designing and building a Positive Energy Home. You can always put more solar collectors on your roof later, but the thermal envelope is the most crucial factor for a healthy and comfortable home, and its performance is locked in for a very long time!

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CHAPTER 3

Fresh air home delivery

A breath of fresh air! Not just an occasional allocation, but a constant home delivery service, with no noise or draughts attached. Can you say no to this? In this chapter, we investigate ways to ensure a steady fresh air supply as a key ingredient of healthy living.

Fresh air needs to be supplied and distributed consistently to manage pollutants and moisture. But is there a conflict with thermal comfort when we let fresh air in? We will reveal how to avoid bad compromises, and tame windows and natural forces to deliver positive outcomes.

But first, why is an effective exchange of air in our homes important? Great care is devoted to households' supply of clean water. With a daily breathing rate of 15–20 m^3, we are inhaling significantly more air than we are ingesting water per day. In Chapter 1, we highlighted the importance of good indoor air quality for our wellbeing. We should care about clean air in our homes at least as much as we care about clean water! So, how can we ensure a regular supply of fresh air into our homes?

When ventilation relies solely on natural forces, we are dealing with what are called 'free-running' buildings: 'free' as in following pressure differences created by either wind or stack effects. In mechanically ventilated buildings in contrast, fan power forces air to move. Hybrid strategies may entail the only occasional use of mechanical forces, or leaving one side of the air exchange equation (either supply or extraction) without mechanical pressurisation.

Just as you can do your laundry manually, you can operate windows manually as a means to get fresh air in. But why would you do this if a machine can do a much better job, more thoroughly, far more conveniently, while using less energy (and water) in the process? For your laundry, this machine is called a washing machine. For your fresh air needs, the best machine for the job is called a heat recovery ventilation system. Well-designed and installed systems offer superior comfort and consistency of air exchange, along with low energy consumption. This chapter covers the design, installation and benefits of such systems and their use in conjunction with windows or in hybrid mode to deliver fresh air efficiently and effectively year round.

As a quick reminder, though, before we dilute air contaminants through ventilation, we should try and minimise the pollutants in our home. In Chapter 1, we analysed some practical limitations of this approach, but it should be our goal to avoid pollutant-emitting substances and processes wherever possible.

3.1 ACTIVE VENTILATION WITH HEAT RECOVERY

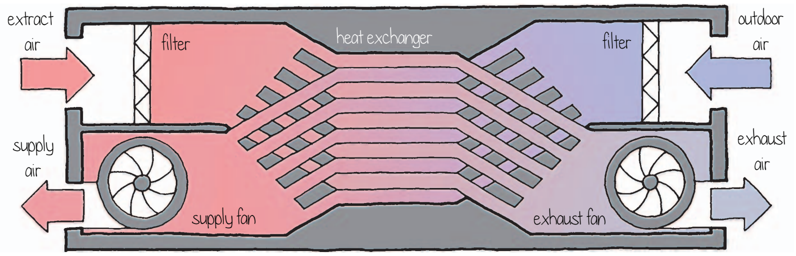
To deliver an effective and predictable turnover of air within the home we need active means to supply and exhaust it.

When well distributed, the volumes of air required to maintain ideal interior air quality are relatively low: about 30 m^3 per person per hour are sufficient. For most houses, this is equivalent to turning over the volume of air in the house every 2 hours (0.5 air changes per hour). Only a fraction of this air is needed for breathing, with ~0.45 m^3 per person going through our lungs every hour. The bulk of the fresh air provision dilutes harmful substances in the air, so that the air that ends up in our lungs is beneficial to our health. Another job of the fresh air supply is to avoid moisture build-up inside our homes.

One great benefit of using fan power to get fresh air is that the supply can easily be filtered, which allows for the removal of dust, pollen and other substances from outdoor air before it gets inside. This is particularly good news for people who suffer from allergies, or live in areas with poor outdoor air quality.

In leaky buildings, the addition of heat recovery ventilation can provide benefits to indoor air quality (although with less predictable results), and the heat recovery will also provide some preconditioning of the incoming air, and improve thermal comfort. But it is in well-sealed homes, such as Passive Houses, where the system comes to its own. The energy for running the heat recovery ventilation system will, in this case, be far less than the energy required to compensate for ventilation heat loss. Depending on the severity of the climate, the energy recovered by an efficient system can be 10 or even 20 times the energy needed to run the system. For every kilowatt hour invested in running the very efficient fans, you get multiple kilowatt hours of thermal energy back. The reason why ventilation systems are sometimes frowned upon (because they allegedly consume more energy than opening a window) are then turned on their head: a well-designed heat recovery ventilation systems saves far more energy than it consumes!

An airtight thermal envelope is needed for the ventilation system to perform at its optimum. If make-up air can enter through leaks, it will not pass through the heat exchanger, and therefore will not be pre-warmed. Plus, the heat in the outgoing air will not be donated to the air that leaked in, and some heat contained in the outgoing air will go to waste. In addition to improving the effectiveness of heat recovery, better airtightness also improves the air quality in the home. How so? Uncontrolled leaks or resulting pressure differences may upset or short-circuit the distribution of air throughout the home. Because the leaks are uncontrolled, there is no way of knowing where

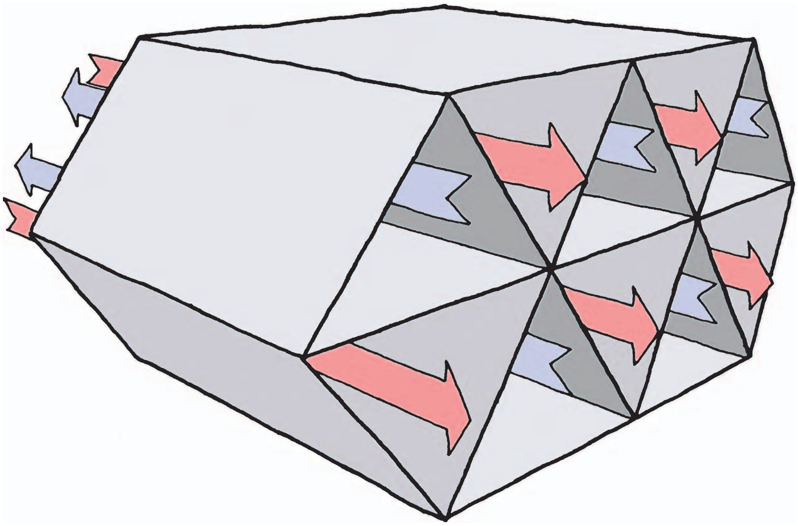


Basic heat recovery schematic.

This highly efficient heat recovery air handling unit for residential use has the size of a bar fridge.

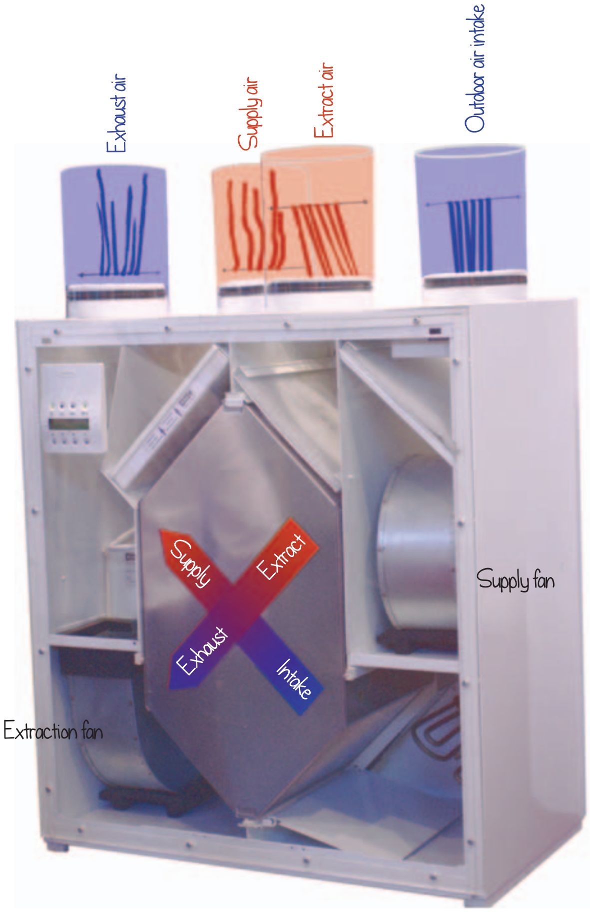
they will occur. For example, they could be in places where not much fresh air is needed, such as in the laundry or next to an extraction terminal. Plus, the quality of air entering through leaks will be unfiltered and of questionable quality. Although airtightness is not the reason to have a ventilation system, airtightness and mechanical ventilation go together well. In fact they are a perfect match!

How does heat recovery ventilation work? A heat recovery ventilation system operates with two fans: one supplies air to the rooms where people spend most of their time, the other extracts air from rooms where odours and moisture originate. Those fans typically run very efficiently using direct current motors. For a 150 m^2 home, the combined fan power can be less than 60 W for nominal operation. Both supply and extract air are forced through a heat exchanger: a device with a very large surface area that enables the outgoing air to donate warmth to incoming air. In most systems, the air streams are kept completely separate (e.g. using a specialised membrane that permits the heat to transfer but not the contaminants). The principle is the same as with a radiator to cool an engine: the large surface area, often in a honeycomb structure, enables the engine to discharge heat to the environment. In heat recovery ventilation systems, the large surface area enables the stale air to donate warmth to the incoming air.

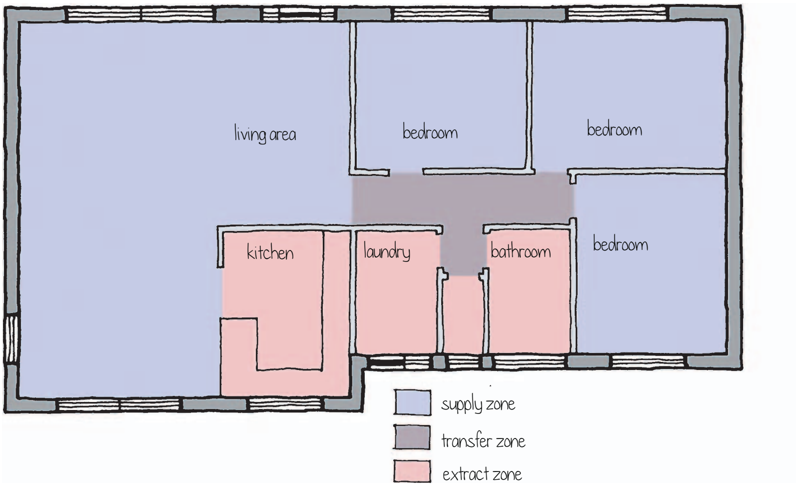


Section of a counterflow heat exchanger core. Stale air (red) and fresh air (blue) are passing by each other in a honeycomb structure. The stale air donates warmth to the fresh air.

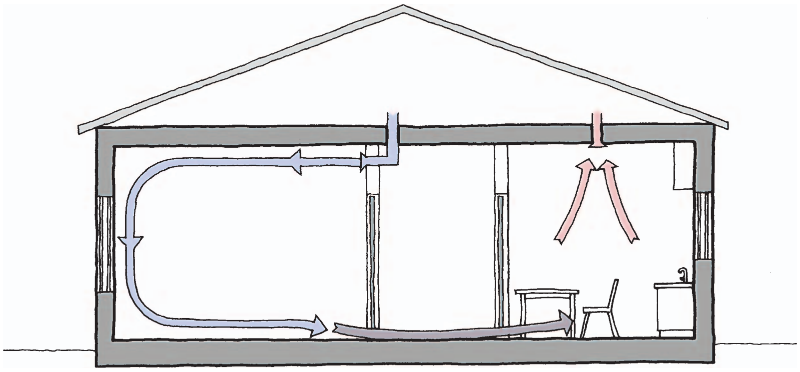
Rather than supplying and extracting air to every room, the distribution of air is cascading: the air supplied to bedrooms, for example, moves to bathrooms and kitchens, and gets slightly less fresh on the way. This is, however, countered by a significantly higher air change rate for kitchens



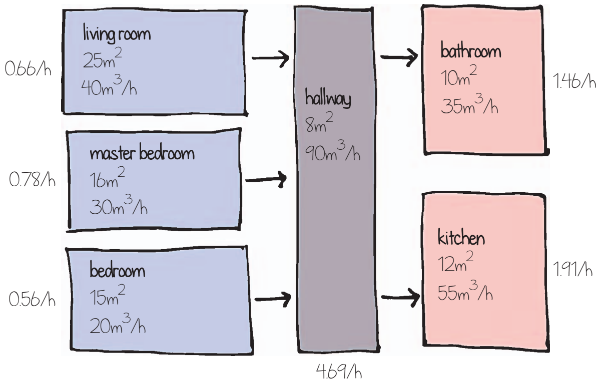
Cross-section through an air handling unit. Two fans force airflows to meet in the heat exchanger (middle).



Example of supply, extract and transfer zones.



Cascading ventilation system. Air is supplied to spaces where people dwell, such as living and bedrooms, where it mixes with stale air. It is then transferred to kitchen and bathrooms, where it is extracted.



Supply rates and outcomes for rooms. For example, 40 m^3/h supplied to the living room of 25 m^2 (or 60 m^3 at 2.40 m clear height) will result in an air change rate of 0.66/h; 55 m^3/h extracted from the kitchen will lead to an air change rate of 1.91/h there. Even though some of the freshness of air is 'used up' on the way, the higher change rate means that the air is still of sufficient quality in kitchen and bathroom. No other extraction is needed for kitchens and bathrooms.

and bathrooms, securing a satisfactory outcome. Some rooms, such as hallways, will have neither supply nor extraction valves. Here, air transfers from a supply to an extract zone. Every room in a house where people dwell needs to be associated with a ventilation zone. Bedrooms are undoubtedly in the supply zone, hallways typically in the transfer zone and bathrooms and kitchens in the extract zone. The zoning of other rooms can depend on the layout and usage. For example, in a open plan layout, a living room can form part of the transfer zone, if sufficient supply of fresh air from the bedrooms can be secured.

3.2 WHAT IS IMPORTANT FOR DESIGNING A HEAT RECOVERY VENTILATION SYSTEM?

Ventilation systems are certified by the Passive House Institute in Germany. Over 100 systems were certified in the small appliances range (suitable to typical residential) alone in October 2015. However, the availability of systems in your location may still be severely restricted, because most systems originate from Europe. There is no requirement to use certified components, but the benefit of doing so is that the performance of these systems has been rigorously checked, and that the results of these measurements are well documented.

Measures such as frost protection and filtration are all integrated into the testing procedure, and the outcomes for noise, electrical consumption, operational range and heat recovery efficiency are ready to be imported into the Passive House Planning Package (see Chapter 8), which enables predictable conclusions for the performance of your home. Furthermore, for comfort, the certification safeguards that the temperature of incoming air that is supplied around the home will not drop below 16.5°C without heating, even at –10°C outdoor temperature.

Heat recovery ventilation unit installed in the basement of this terraced house.

For heat exchanger efficiency, it is most important that the cold incoming air and the warm outgoing air spend quality time together. A very large surface area of the membrane between the two air streams is needed. Small interwoven channels of air or folds in the heat exchanger plates create this large surface area.

The highest efficiency is achieved when the two air streams flow in opposite directions, called counterflow, through the heat exchanger. This configuration maximises the time the two mediums spend together, and provides consistent temperature difference across that length of the heat exchanger, which increases the leaving temperature of the incoming air. These units can achieve sensible or dry heat transfer rates of 85–99% without any cross contamination.

Other common configurations for air-to-air heat exchangers include cross flow, which is typically less efficient. Basically, the air streams do not have time to be intimate if they are only crossing paths at one point, so less warmth is transferred between them.

In the heat exchanger, outgoing warm air passes by a surface that is cooled by incoming outdoor air. Condensation may occur. This condensate needs to be safely drained away to avoid contamination of the exchanger.

Other types of heat exchangers use high surface area ceramic as a heat-absorbing material, over which the two air streams are alternatively passed. That is, warm outgoing air soaks heat into the material. After ~30 s, the airflow is reversed and the cold outside air depletes the reservoir of warmth – and then the cycle repeats. Because the air only flows in one direction at a time, to maintain the air balance, these systems often operated in pairs with one unit supplying air inwards while the other facilitates the outward flow.

When heat is recovered, but not moisture, as in the above examples, there is a risk that indoor air may become too dry in winter. Because the air is continuously exchanged and incoming cold air warmed, the relative humidity can drop to below 30% occasionally. This may not be much of a problem, because dust-free dry air is tolerated far more than dusty dry air and, through the filtration, the incoming air will be very clean. Nonetheless, if this becomes an issue, there are ways to counter the effect. First, try increasing indoor humidity levels (e.g. by drying your clothes inside). If this does not increase the relative humidity, the ventilation system can temporarily be run at a lower air change rate, but not below 20 m^3 per person per hour.

It is also possible to recover the moisture in air, and with it the latent heat, which further increases the heat recovery efficiency. The systems may use heat wheels, where the outgoing air is passed over a heat-absorbing material such as a metal wheel, which is then spun around in the path of the incoming air allowing the absorbed heat to warm it. Moisture is transferred with air, which can help to manage humidity. Because the two air streams are exposed to the same surface, there is, however, the potential for contamination in these systems. If, for example, the extract air contains organic compounds from cooking, some of these may be absorbed to the wheel and be transferred to the incoming air. These systems are often referred to as enthalpy heat exchangers or ERV. With the number of rotations, the humidity transfer can be controlled.

A similar effect can be achieved with a plate exchanger and a semi-permeable membrane, which lets water molecules through, but no other contaminants in air. It is not easy to control the amount of humidity recovery via this process and particularly during the shoulder seasons, there is a risk of retaining too much moisture.

3.3 FILTERS

Would you like some pollen with your fresh air? Particles or mosquitoes? No – well, you need a filter. Incoming air in heat recovery ventilation systems is commonly filtered. The filter can be integrated with the air handling unit, or be in a separate box slotted into the intake air duct. For Passive House systems, a fine filter with F7 mesh is required. This will trap most of the particles and pollen, and all of the mosquitoes. For other types of allergies, such as a spore allergy, it is recommended to use an even finer filter. F9 will retain over 95% of mould spores, so why not use the finer filter as a default? The finer the net, the more particles you catch, but if these particles are not a problem for your indoor air, than all they do is clog the filter faster. A finer filter also adds resistance, and should therefore only be used if necessary. Extract air should also be filtered, not to keep the neighbours happy, but mostly to keep the heat exchanger clean. If filters are installed at extraction points, rather than at the air handling unit, they also contribute to preserving a dust-free duct network. Filters require cleaning or changing around once a year, depending on prevailing conditions and frequency of use.

Range hoods in the kitchen should operate in circulation mode instead of being connected to the outdoors. If they were, they would imbalance the system needlessly when in use. They would also be a potential air leak when idle. While the extraction valve in the kitchen will take care of fumes and excess humidity, range hoods still have a place to filter out fat and particles from cooking and frying before they can choke the ducts. This should happen as close to the source as possible so that polluted air is straining through a filter directly over the stovetop.

Air filter. If the material reminds you of the filter in your vacuum cleaner, you are not mistaken (Photo: Melitta).

3.4 GROUND HEAT EXCHANGER

In cold or hot climates, using the ground as a secondary heat exchanger may be a good idea. In winter in a cold climate, the temperature of the ground at sufficient depth will always be higher than the winter average ambient air temperature. In this situation, the main purpose of using a ground heat exchanger is to increase the temperature of the incoming air and to ensure that there is no risk of freezing at the heat exchanger. This risk of freezing will be higher the better the heat exchanger performs and, interestingly, pertain to the exhaust side of the heat exchange, which after passing to a highly efficient heat exchanger may be well below freezing temperature. The temperature of the incoming air is no direct concern, because very cold outdoor air will not carry much moisture. But with a low temperature of incoming air, the outgoing, moist air will be cooled severely. This will be more so in highly efficient heat exchangers, such as those used in Passive Houses, as more heat is squeezed out of the outgoing air. But this entails a higher risk of freezing than with poorly performing systems. For example, an 80% efficient heat recovery system will tolerate –4°C incoming temperatures without freezing, but a 95% efficient system requires temperatures of –2°C and above to safely prevent freezing.

Conversely, in climates with hot summers, the temperature of the ground at sufficient depth will be lower than the air temperatures on warm days. In this case, the ground can be used to pre-cool the supply air. A medium cooled by the ground also allows for passive dehumidification of the incoming air, because the incoming air on passing through a colder coil will offload some of the moisture.

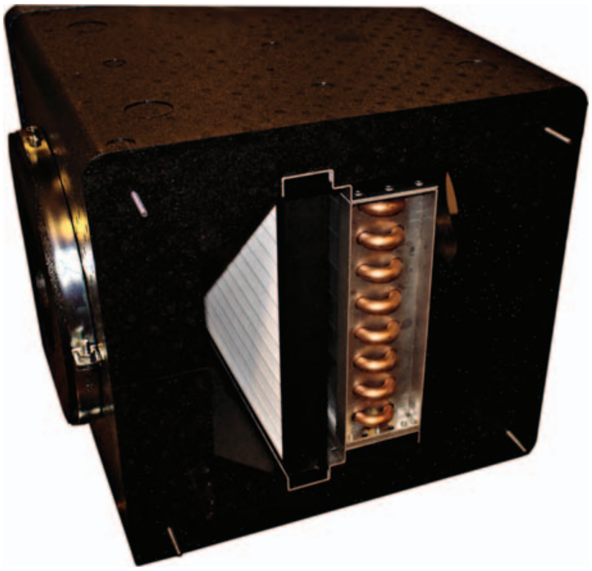
3.4.1 Air-to-air ground heat exchanger

In its simplest form, a ground heat exchanger is a long supply air tube that passes through the ground. Typically, there is a trade-off between cost and efficiency: the deeper the duct is buried, the higher the efficiency will be, but this comes at higher installation cost. Putting ducts at 1–2 m depths is often a good compromise. For a house, ~40 m of tubes need to be laid with a gradient and a drain. The tubes need to be completely tight, and it should be possible to access them for maintenance. Although mould formation is a concern in a configuration like this, particularly as warm air is drawn through the tubes in summer, investigations on actual in use system have not detected these problems.

Using an air-to-air ground heat exchanger is best suited for air handling units that are close to the ground, and is not advisable for an air handling unit that is located in the attic.

3.4.2 Brine-to-air ground heat exchanger

Rather than having air circulating through the ground, a brine-to-air heat exchanger uses polyethylene pipes filled with a water/glycol mixture that loops through the ground. These pipes pass through a heat exchanger coil in the supply air duct to pre-warm or pre-cool air there, before it either enters the heat exchanger (winter situation) or is distributed directly to the rooms



Secondary heat exchanger. Brine circulates through the ground and the copper duct register. Air that flows through this register will be pre-warmed in winter, and pre-cooled in summer.

(summer situation). As a rule of thumb, pipes twice looped around the perimeter of a house (with at least 50 cm separation between them) will typically suffice. These pipes are thinner than the ducts of the air-filled ground heat exchanger (~25 mm nominal diameter), so less excavation is called for to lay them at sufficient depth. It is also possible to install them vertically rather than horizontally. They do not require a gradient or drain, because air is not flowing in them. A small pump suffices to run the loop, and a heat exchanger to transfer the heat from the ground to the incoming air. In summer, incoming air is precooled by passing through this ground-source heat exchanger, which is likely to result in condensate forming. Provisions need to be in place to safely drain this water away. Because the supply air duct that encases the heat exchanger will be de-pressurised, a back-draft valve to the sewer is needed to avoid contamination with sewer fumes. A ground exchanger can also be used in conjunction with mechanical cooling or heating via a heat pump, as discussed in Chapter 4.

3.5 DUCTING

Within the home, air is delivered to the space via supply ducts and returned to the ventilation unit via extract ducts. These ducts need to be very smooth on the inside to avoid friction, noise and dust accumulation. If the ducts are made of plastic, they furthermore require an antistatic coating, which rules out sewer ducts.

The key design and construction principles for an effective and efficient distribution system include:

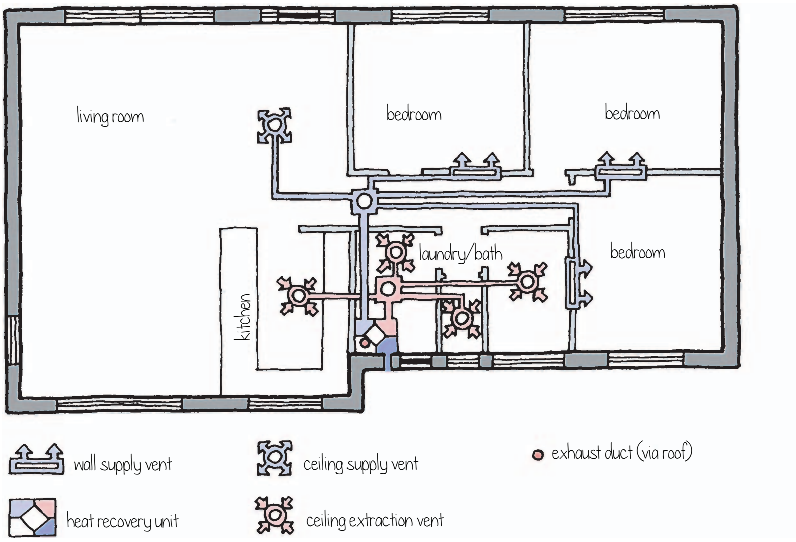
- Layout
  - arrange duct work to minimise sound transfer between rooms or include sound attenuators
  - minimise duct lengths

    - avoid/minimise turns and bends
    - locate outlets to facilitate effective mixing of air
    - ensure access to ducts for cleaning
    - design the layout to avoid ducts crossing as much as possible.
- System components
    - select low-friction ducts, with smooth inner surface to reduce friction and avoid dust collection
    - select duct diameter for optimum air velocity for efficiency and distribution
    - select outlets and inlets to facilitate effective distribution at minimum pressure loss
    - design duct layout to minimise the need for balancing valves
    - maximise the area of filters to reduce pressure loss and extend filter life.
- Installation, ensure that
    - airtight installation is achieved
    - additional bends and constrictions are not introduced
    - the system is effectively balanced
    - ducts are kept clean and dust free (keeping ducts sealed until in use).

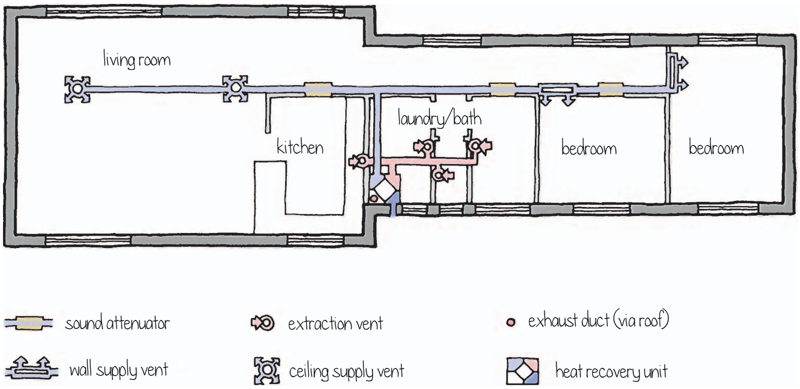
The distribution system begins with a duct that takes fresh air in from outside, and ends with a duct that exhausts stale air to the outside again. Both ducts bridge the building envelope, and transport all the air in the house; that is, they will be the widest and 'busiest' ducts. They will also both carry cold air in winter: the incoming air will be cold outdoor air, and the exhaust air will only be slightly warmer, because the warmth of the stale air from the house is mostly depleted in the heat exchanger. Consequently, these ducts should be really short. The air-handling unit should be placed as close as possible to the building envelope to achieve this. A vapour-tight insulation layer must cover these ducts to avoid the warm room air condensing on them. If the exhaust is facing a neighbouring property, it also pays to slot in an attenuator before the air leaves the building, to avoid potential noise. The exhaust should be away from the intake to prevent short-circuiting, and is best ducted through the roof (unless the roof is too far away from the air handling unit). Exhausting through a wall may lead to increased resistance when the wind is blowing on the façade in question.

The air intake should be away from the ground and sources of pollution (e.g. the garage or compost heaps). It must be ensured that rainwater cannot get into the duct and that small animals are discouraged from entering. They would be filtered out, eventually, but it is best to keep the filters as clean as possible and them alive. In a noisy environment, it may pay to take air in through an attenuator.

Within the house, the distribution of air can either branch from a main trunk into the rooms, or run star-shaped from a manifold. Seam-folded metal ducts are often used for the branching configuration, whereas flexible polymer ducts typically go with the star-shaped distribution. The latter will be the system of choice when space is limited (e.g. in a ceiling), because a smaller duct



Star-shaped ducting layout.



Branching distribution. Sound attenuators are required to avoid cross-talk between rooms.

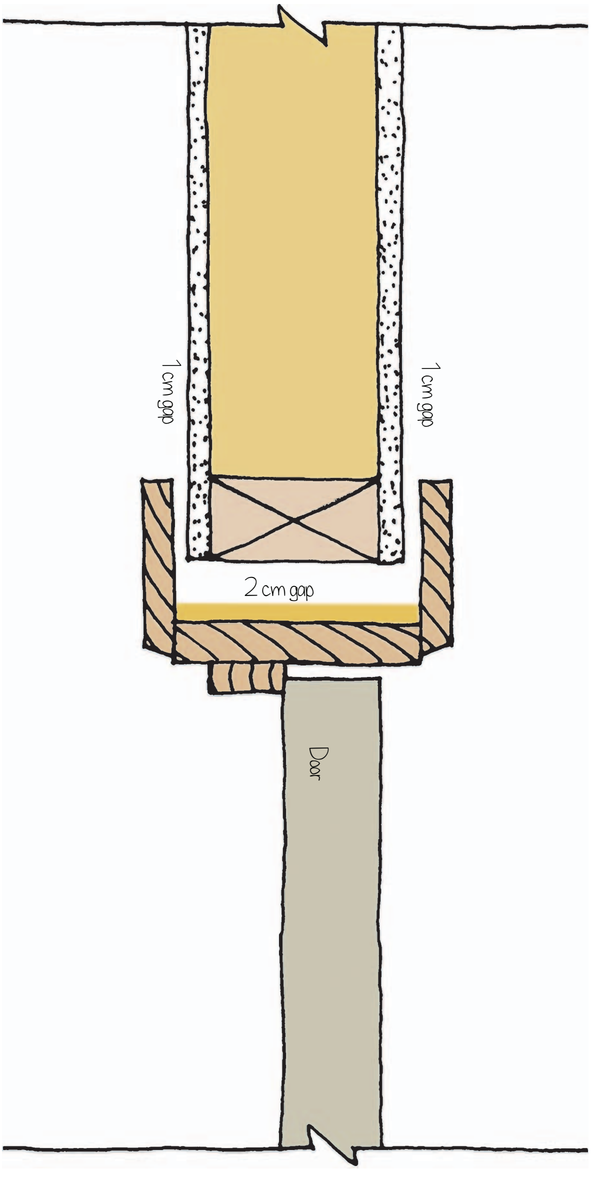
diameter is possible when the duct is only carrying air to one room. Flexible ducts are easier to install, and if the ducts are sufficiently long and meet in a manifold, sound attenuators are not required. However, the pressure drop in a flexible duct can be significantly higher than in a seam-folded metal duct with the same external diameter.

When one duct serves more than one room, such as in the branching distribution in the lower figure above, it may be necessary to install sound attenuators to avoid cross-talk.

3.6 MAY THE FORCE BE WITH YOU!

The fans in the system generate a force that moves air. They will work most efficiently when obstacles in the way of pushing or sucking air around are minimised. Ducts should be as straight as possible to avoid restrictions, which will in turn cause wind noise, and wide enough for the volume of air that needs to be moved through them. Typically 80–150 mm diameter ducting is appropriate for a small residential building. The design needs to reflect this with sufficient space.

If ducts are too narrow or too bendy there will be restrictions, and the fans need to work harder and less efficiently to overcome these. Furthermore, if the resistance to the airflow is on one side of the supply-extract chain only, then a pressure imbalance within the home will result. Should negative pressure be the outcome, then all remaining leaks in the fabric will let air through at an increased rate. If positive pressure results, then the possibility of pushing warm, moist air into building cavities is heightened, leading to a risk of condensation there. It is therefore paramount to preclude large pressure imbalances. Many ventilations system use an integrated automatic flow balancing, which makes one of the fans work harder if a pressure imbalance exists, if, for example, a filter is blocked. The airflow needs to be recalibrated occasionally if this does not happen automatically.



Transfer of air through gaps around the lintel of a door. With an acoustic absorber mat in the horizontal part of the gap, improved acoustic outcomes are possible.

Filters are another place where a pressure drop occurs, but this is unavoidable. However, filters that are black with particles add significant resistance. It is therefore important to keep an eye on filters, and to change them before they become clogged. The additional energy needed to push air through a filter passed its best-before date costs typically more than a new filter. Skimping on filter cost – even from a purely economic point of view – is not sensible. Most ventilation systems will signal automatically when a filter change is due. Have a spare filter ready for when this times comes.

With the cascading nature of the system, other potential places of resistance are transfer openings. Transfer openings allow for the air to pass from one zone to the next, even if indoor doors are closed. Often this is achieved simply by a door cut short. With heightened acoustic requirements, other options to transfer air, but not noise, need to be employed. Transferring air into the bathroom under the door is not the most comfortable solution, because we may stand with wet feet in front of the door, where air is moving fast. Air transfer around the lintel is the better option in this case and anywhere improved acoustic outcomes are required. Proprietary solutions for the transfer of air without sound are also available.

Transporting air to where you need it without ducts is the most ingenious way. It can be done by using what is known as the Coanda effect. Romanian aeronautical engineer Henri Coanda discovered a phenomenon that keeps aeroplanes suspended in air: a fast flowing jet stream next to a surface creates a vacuum that makes the air attach to it. How can we use this for ventilation? If an air outlet is placed ~15 cm below the ceiling, and the airflow directed towards the ceiling, air will travel along the ceiling into the room. Rather than getting an air duct in the middle of a room, you can thereby distribute air to the whole room from a nozzle over the door, and with minimal friction losses.

Using the Coanda effect to transport air has many advantages: it saves on the cost of ducting, it reduces duct lengths and thereby pressure drop, and it leads to better mixing of air. But not all outlets are suited to use the Coanda effect: the best are long throw nozzles that supply air from ~15 cm below the ceiling.

Ceiling and wall mounted air outlet capable of using the Coanda effect (Photo: Lindab).

3.7 USING THE VENTILATION SYSTEM FOR HEATING AND COOLING

Passive Houses are particularly cost-effective if no additional infrastructure is needed to condition the house. Although it may sometimes be advisable to use additional appliances for heating and cooling (e.g. when the layout or usage patterns of the home are not ideal), it is preferable to distribute the required conditioning using the infrastructure already in place: the ventilation system. Because air is a comparatively poor carrier of heat (water, in comparison, has a much higher specific heat capacity than air), the amounts of heat or cold that can be transported in air are fairly limited. Theoretically, these limits can be overcome by increasing the temperature of the air significantly, but there are drawbacks to this practice: unfiltered air at high temperatures will start to smell stuffy, as dust in it combusts. However, this is not so much a problem in houses where incoming air is filtered. Dust aside, the higher the temperatures of air you are transporting, the higher are the delivery losses, and eventually, the supply of very hot or very cold air will also have comfort implications. For this reason, a temperature limit for conditioned air has to be respected. Another strategy for transporting more heat in air is to increase the air volumes above the level that is needed for good indoor air quality. But this is not a virtuous strategy either, because it does not award an improvement for indoor air quality, and the excess volumes that are required consume needless fan power. It may also get a bit draughty as a result. Out of these considerations, design parameters of ~30 m^3/h per person as a fresh air requirement, and a maximum temperature of air of ~50°C emerge. This equates to a maximum of ~300 W per person that we have available to transport heat with air. In comparison, a decent hair dryer has a capacity of 2000 W. 300 W is not much heat on a cold winter's night – but must suffice to keep us warm in a Passive House. That is why we need a thermal envelope and ventilation system to keep the requirements for extra heat very low. How the air can be heated, and what other options for heating exist, is explained in Chapter 5.

The ventilation system can also be used to help with airflows through the home in summer, such as bringing in air when a cool breeze has arrived on a summer's afternoon, or ventilating during the night without risking entry for intruders or mosquitoes. For this, the ventilation system needs to be able to bypass the heat exchanger, using an alternate duct that allows the air to take a short cut. It will then be possible to flush the home with cool air overnight in summer. Many units have this feature built in. For heat/enthalpy wheel systems, stopping the rotation of the wheel allows the air to flow through without pre-heating/cooling from the outgoing air.

Using the ventilation system for active cooling has similar benefits and challenges as using it for heating. Again, the infrastructure for a whole house removal of heat (cooling) is already in place with the ventilation system. But, just as with heating, the amount of cooling that can be distributed has limitations. However, cooling, even in a hot climate, does typically not require a large temperature differential to outdoors, and the problem is therefore less pronounced than with heating.

A ground heat exchanger integrated into the ventilation system can contribute to both, heating and cooling, and even dehumidification.

3.8 FIREPLACES AND BALANCED VENTILATION

It is tricky, but possible, to operate a fire in a house with balanced ventilation. We do not recommend it, though, because there is a distinct possibility to overheat a Passive House using fire, and there are cleaner heat sources available than burning wood. If you are after the romance of a fire, think about an ethanol fireplace as an alternative. But, if you are adamant that a wood fire is what you want, to make it work with a balanced ventilation system, the fireplace needs to source combustion air in through a dedicated duct. Obviously, the fireplace itself and all ducts and flues need to be very airtight. Most are not, so procuring an airtight fireplace and flue system is the first part of the challenge. Connecting a flue (that can get very hot) to the airtightness layer is the next, because polymer products may melt with the temperatures at the surface of a flue, and building codes typically also have requirements for minimum distances to flammable materials. In addition, you need a differential pressure switch that automatically switches the ventilation system off in case of negative pressure in the exhaust flue. A back-draft valve in this flue is furthermore a good idea to prevent combustion gases from entering indoor air when pressure differences due to wind occur. In a nutshell, it is possible, but requires dedication and a rather big budget to have a fireplace in a Positive Energy Home. In severely cold climates, a small fireplace can heat water in a buffer tank, from which in winter domestic hot water and a hydraulic heat exchanger can be fed. The latter can be used to warm the air throughout the enclosure, if placed in the supply air stream. But, again, the additional heat you require in any Passive House is minute, and simplicity in generating it is bliss.

3.9 VENTILATION CONTROL AND USER INTERFACE

Typically, the heat recovery ventilation system comes with three settings: ‘low’, ‘nominal’ or default and ‘high’ or ‘party’. Most units have a touchscreen that easily allows the user to change between settings.

The ‘low’ setting, which basically slows down the fans, is used during periods of absence or significantly reduced occupancy and delivers ~70% of the nominal flow rate. ‘Nominal’ is what will fit most of the time. It is the optimum flow rate for the typical usage. ‘High’ or ‘party’ mode is what you need when you entertain, and the number of people in the house markedly exceeds typical usage. This mode may also be accessible from a switch in the bathroom to boost the extraction of steam. After a preset delay of a few minutes, the fans switch back to default mode automatically.

The setting of this touchscreen control panel indicates that you are currently entertaining and therefore in need of 30% more air than usual (Photo: Paul Wärmerückgewinnung GmbH).

Early heat recovery ventilation systems allowed for a high degree of individual settings, but experience shows that more operations modes merely complicate matters. In fact, most people will only ever use the default mode. In the early days of Passive Housing, there was also an impetus to create individual zones in the houses for a perceived optimum comfort. For example, it was attempted to make bedrooms colder, because the impression was that cooler conditions were needed for a good night's sleep. It is difficult, though not impossible, to have varying temperature zones in a Passive House. The general happiness of Passive House occupants with an even temperature throughout the enclosure, however, is testament to the fact that great comfort and quality of air is what we are really after, and temperature variations are just what we are used to. Although one size does not fit everyone all the time, three operation modes seem to be all the adjustment people need in an already well-behaving house. Choice is good, but more choice is not necessarily better.

To fully automate the supply rate of fresh air, it is also possible to link the fan flow to a CO_2 sensor in the extract air stream. If CO_2 concentrations cross a threshold value, say 800 ppm, the fan speed, and therefore the supply rate, is increased automatically.

3.10 SUPPLY-ONLY OR EXTRACT-ONLY MODE

Many ventilation units can be operated in supply only or extract-only mode, with open windows or doors balancing the airflow. When outside conditions are mild and windows are being used for ventilation but extraction is still required to remove cooking odours or excess steam in bathrooms, the system can be used in extract-only mode. This can also be useful when warm air has built up in the home and the outside air is cool, or to help cool the home overnight during summer. For example, if only the extract fan is operated, a negative pressure will build up in the home, which can facilitate cool air being drawn in through open windows. Alternatively cool supply air may be provided and windows or vents located high on the wall or in the ceiling can be opened to let out warm air from the inside. Strategies to use the ventilation system to assist with thermal comfort are discussed further in Chapter 5.

Supply-only mode can be useful where outside temperatures are favourable, but the air contains dust or unwanted pollen. In this case, the supply fan can be used to bring air into the home via the filter, creating a positive pressure in the home that can be relieved via windows, thereby minimising the ingress of contaminants through the openings.

3.11 SEASONAL USE

As discussed, it is really difficult to get the right amount of air in through windows, or any other kind of opening in the thermal envelope, during the weeks of the year where it is either too cold or too hot outside. However, this changes when the outdoor conditions are pleasant, and the environment is benign – not too polluted, nor carrying allergens. In this case, windows can be left open for very long periods, so that a sufficient air exchange is guaranteed. The ventilation system can be completely switched off during these periods, or one of the alternative strategies already discussed can be used. When the system is switched off for periods of time, regular checks of the filters are needed. They need to be dry on switch-off, and stay dry thereafter to ensure that microbial growth does not occur, which could subsequently be distributed through the home via the ventilation system. This is not a concern in normal use, because the constant airflow through filters will keep them dry.

3.12 PERFORMANCE REQUIREMENTS

Once the distribution system has been optimised, it is important to ensure that the ventilation unit selected has the required fan and heat recovery performance. To assist with this the Passive House Institute provides a list of certified units that comply with the requirements in Table 3.1.

The acoustic performance of the units is also tested, and if they do not comply with acoustic requirements out of the box, then acoustic attenuation and separation need to be factored into the installation, such as additional acoustic insulation being installed around the unit. Eventually, this will lead to the system being inaudible in living and bedrooms, and barely audible in kitchen and bathrooms, wherever the air handling unit may be placed.

Table 3.1. Certification requirements for residential ventilation systems.

Measure	Requirement
Supply air temperature	16.5°C at −10°C ambient
Percentage heat recovered from balanced mass flows of the intake and exhaust air	At least 75% to PHI method
Energy consumed by fan and controls to move 1 m^3	Less than or equal to 0.45 Wh/m^3
Internal/external leakage airflow rate	Less than or equal to 3%
Ability to control airflow rate relative to design flow (100%)	70/100/130%
Noise in living space	Less than or equal to 25 dB(A)
Intake air filter	At least F7
Extract air filter	At least G3

3.13 OTHER MECHANICAL VENTILATION OPTIONS

The optimal solution for Positive Energy Homes is using a centralised, balanced ventilation system with heat recovery. Sometimes, though, and particularly in a retrofit situation, the optimum is not feasible to achieve cost-effectively, so let us discuss other options to deliver good indoor air quality.

3.13.1 Distributed heat recovery ventilation systems

It is generally preferable to use the advantages of a cascading layout of air distribution through the home, because it does not require both supply and extract terminals in the same room. But particularly in a retrofit situation, distributed solutions are worth a consideration, because they do not require ducting, which may be difficult to retrofit cost-effectively. Another potential use for distributed systems are very small apartments, where a central unit may be too large for the space.

Distributed systems use multiple small heat recovery units able to deliver 15–30 m^3/h to manage individual rooms or sections of the house. These units are designed to mount across an external wall or into the ceiling adjacent an external wall with a short duct through the external wall or eave soffit. For larger homes, this requires multiple units, all of which require their own power supply, filters and need to be appropriately sealed into the airtight layer and mounted through the thermal envelope without compromising performance.

These units generally achieve heat recovery by alternating the direction of airflow. In a bedroom, having a pair of units mounted on alternate walls operating in opposite directions to each other, so that one is extracting while the other is supplying, creates balance within the room and effectively shuffles the air within the space. The ducts have to be long enough (~40 cm) to achieve a high efficiency, which either requires a thick wall to start with or additional construction

Distributed heat recovery ventilation unit (Photo: LUNOS Lüftungstechnik GmbH).

to accommodate the ducts. Cutting the ducts short to fit a thinner wall, as is sometimes done, will work – but at the expense of heat recovery efficiency.

Alternatively, single units are available that supply and exhaust at the same time by effectively having two fans mounted in the same box that alternate direction of flow. Such units are designed to direct the flow of air in opposite directions within the room to minimise short circuiting.

As noted earlier, kitchens and bathrooms typically have a higher air change requirement, so larger units may be required in these spaces. Alternatively, where additional extraction is required when in use, these units can be switched to a single direction of flow. For example, a pair of fans may be mounted with one in a bedroom and the other in an adjacent en suite. When the shower is being used the en suite fan may be switched to extract only and the bedroom to supply only. No heat recovery occurs during this mode, however, because this operation is only required for a short period of time, it has a minimal impact on the overall energy balance in all but the most extreme conditions, while allowing excess water vapour to be removed.

These units can be sized for the peak occupancy of the room and switched on and off as required or based on CO_2 levels. This ability to operate them in response to demand can be useful for creating zones within the home, allowing the occupant to manage ventilation and heating/cooling energy in response to occupancy. For example, bedroom ventilation could be turned off or to low during the day. However, because these systems only distribute air locally, they cannot double as central heating or cooling system, meaning that heating and/or cooling needs to be provided to each area of the home.

Quality products achieve heat recovery efficiencies of 85%, provided they are installed with the original duct length.

3.13.2 Single fan systems

Ventilation systems that use only one fan, either to supply or extract air, are another alternative. There are limitations to the usefulness of these systems and, particularly, any form of heat recovery is impossible with using only one fan. The supply air will therefore be cold, which may lead to comfort issues, unless diffusers are placed away from the dwelling zone and preferably over a heat source. But, single fan systems are a relatively cheap and easy retrofit solutions, if the following points are heeded:

- All parts of the system, including grills, attenuator, diffusers, filters are designed to minimise pressure drop, friction and noise, and allow for easy cleaning.
- Air handling units are airtight, and installed to reduce structuraand airborne noise transmission.
- Air transfer openings at internadoors or walls do not create a high pressure drop.
- The airflow rate is easily adjusted. Provisions to regulate ventilation rates are simple and self-explanatory.
- All systems are airflow adjusted with a flow hood (balometer) at in- and outlets during commissioning; systems are well documented.
- Passive vents have provisions for noise attenuation and – as supply terminals – filtering of pollutants from outdoor air. Vents furthermore have means of preventing the spread of fire.
- Supply air terminals are installed to reduce negative comfort impacts: high up in the walabove heat sources, or with a ceiling distribution.
- Air intake and exhaust devices are designed to minimise pressure drop, and positioned to reduce the risk of contamination of supply air.
- A maintenance plan is in place.

Single fan systems inevitably create a pressure difference to outdoors. Which options are available?

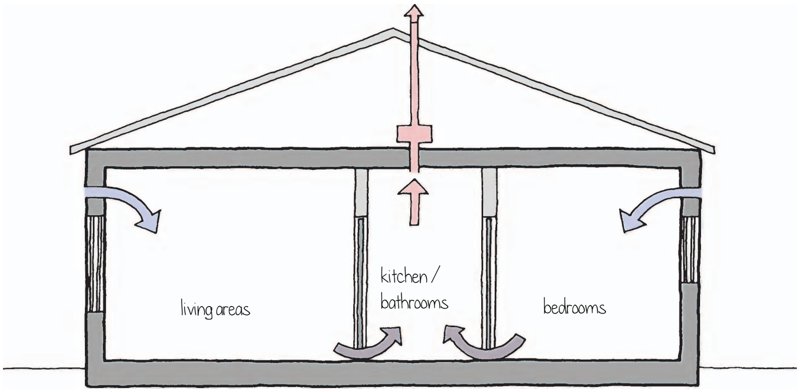
3.13.3 Positive pressure

Positive pressure ventilation uses a fan to continuously push air through ducts into the rooms. It is the most prevalent form of mechanical ventilation in New Zealand. Typically, no attention is paid to the question: ‘where is this air going?’ It is simply assumed that it finds its way through the building fabric somehow. Consider for a moment that this cannot occur: the house would eventually burst (or, more likely, the fan will stop operating, because the pressure inside the house can no longer be overcome). This is risky business. If the air indeed finds its way into the fabric, it will meet a cold layer on its way through it, and condensation is a likely result. Positive pressure systems should therefore only be used in a sufficiently airtight building envelope, and with defined exit terminals in kitchens and bathrooms. That way, air can escape in an orderly fashion. It also helps to give humidity and smells a direct exit route there. Comfort will always be suboptimal with this system, because the supplied air is cold, unless actively pre-warmed. Furthermore, a recovery of warmth from the outgoing air is impossible. On the bright side: it is possible to filter contaminants from outdoor air with these systems.

3.13.4 Negative pressure

Negative pressure ventilation uses one or more extraction fans (sometimes connected to ducts and valves) to accomplish an effective containment and extraction of contaminants from kitchens and bathrooms. The extraction fans create a negative pressure inside and, if used continuously in conjunction with vents as make-up air in living rooms and bedrooms, the system can ensure an effective turnover of air within the home. As the replacement air is sourced from outdoors, this strategy suffers from the same challenges of temperature as air moving into the home through infiltration and windows. This has consequences for the placement of the vents: they need to be mounted high up in the wall, and preferably over heat sources. Moreover, with a leaky home, the distribution of fresh air to where it is needed most is not secured with this system. If make-up air leaks in randomly (e.g. in kitchens and bathrooms) very little air will flow through the vents in living rooms and bedrooms. An airtight building envelope is therefore of utmost importance for air quality outcomes. It is also a precondition for the installation of filters in the trickle vents through which fresh air is supplied, because the pressure there will otherwise be insufficient to pass air through.

Wind, and in higher buildings also stack effect, can work against the fan pressure, and what was designed to be a supply port can occasionally rather leak air to the outside.



Air is extracted from rooms where odours and moisture are generated, and make-up air passively supplied through vents in the wall. Transfer openings at the doors between zones are necessary for directional airflow.

3.13.5 Passive ventilation

Relying on leaks in the thermal envelope is not a sensible approach, because a consistent driver and the 'quality' of the air that creeps in through leaks is doubtful. Getting air in through holes in the fabric, such as trickle vents or windows, is similarly unreliable. Basically, trickle vents and windows are only larger leaks and, as with the smaller leaks drivers for an exchange of air will not always be available. For example, if you leave a window open on a calm, mild day, not much air is exchanged. You either need wind, or a marked difference in temperature or height to make air move naturally. And if you live next to a busy road, you might not appreciate the quality of air on the other side of your window!

In a low-rise building in a mild climate, wind is by far the strongest natural force to move air in and out of houses. The problem with using the wind's capacity is, of course, that you cannot command it. It may blow hard or not at all, or on the wrong side of the building. Holes in the envelope, whether they are cracks, trickle vents or windows, are (particularly in low-rise buildings in a mild climate) not a reliable means to ventilate for this reason. Even if you can control the openings, as with a window that can be opened and closed, you will yield very unpredictable results. Furthermore, because air quality is rapidly declining after every ventilation event, you need to open and close your windows at fairly regular intervals to keep the indoor air fresh. And if this was not challenging enough, outdoor air is not always of pristine quality. Using windows as your mode of ventilation does, however, not allow you to filter pollutants out of air before they can impact on the quality of the air you breathe. On days with little temperature difference between in- and outdoors, and you can leave windows open continuously without leaking energy, window ventilation may be an option, provided no noise, allergy, insect or air quality problems exist. But most of the time windows are unsuited for continuous ventilation.

3.14 POWER OUTAGES

One question that often comes up when mechanical ventilation is discussed: 'but what if there is a power outage – will we suffocate then?' The very short answer is no. You are simply temporarily joining the group of homeowners who have to manually operate windows to get fresh air again. Hopefully, it will not be too long before your ventilation system can be switched on again, because you will otherwise miss the great level of comfort and convenience that comes with an automated home delivery of just the right amount of fresh air that is warmed in winter and cooled in summer. Furthermore, in a Positive Energy Home it is quite simple to add energy storage capacity to easily maintain ventilation through potential outages in the grid.

SUMMARY

The best option to ventilate a Positive Energy Home is a balanced heat recovery ventilation system. It is the most energy-efficient way to secure good indoor air quality and comfort. It is also very convenient, and people who have a well-adjusted system never want to be without it.

CHAPTER 4

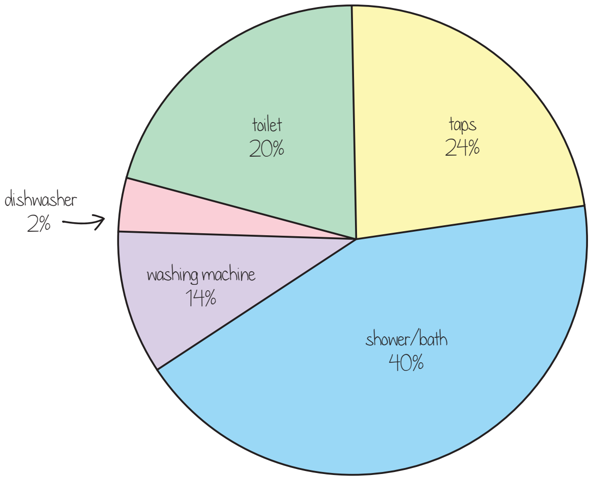
Hot water

Hot water is a basic service within the home and the amount of energy required to heat water is simply determined by the specific heat capacity of water. Unlike heating and cooling energy, where the requirement can be dramatically reduced or eliminated through improving the thermal envelope, the energy required to generate hot water is directly defined by the volume of hot water used by the occupants. With the very low heating and cooling energy requirement in a Positive Energy Home, the generation of hot water can be the largest annual user of energy.

The first step to managing this energy demand is obviously using hot water as efficiently as possible, to reduce the overall volume of water required to be heated. Domestic hot water is primarily used for washing within the home, such as dishes, clothes and ourselves. Unlike services such as heating, cooling and ventilation, which have highly predictable energy demands based on the climate and number of occupants, hot water use and the associated energy consumption is highly sensitive to occupant behaviour, even in a very efficient house. Options to manage use through behaviour and selecting efficient appliances and fittings are discussed in Chapter 7. This chapter focusses on providing the home's hot water demand as efficiently as possible, including minimising heat losses in storage and distribution. As we will illustrate, this goal is easiest achieved by using either a heat pump or solar thermal hot water system, with a highly insulated storage tank and distribution pipes all located as close as possible to the hot water consumption point to minimise storage and delivery heat losses.

How much hot water do we use in the home? A wide range of factors including fitting and appliance efficiency, shower length, tap use habits and frequency of clothes washing all have a significant impact on overall consumption. These variables make it very hard to predict hot water consumption and breakdown between usage categories. More widely studied is total water consumption in the home, with average efficient Australian usage of 112 L/person per day (Arbon *et al.* 2014).

A significant portion of home water consumption is cold, such as for toilet flushing. In showers (and baths) ~60% of the water is hot, making shower duration and frequency a major determining factor of total hot water consumption. For other water outlets, taps, dishwashers and clothes washing machines, the balance of hot and cold water is particularly sensitive to occupant behaviour. For example, clothes washing can be done entirely in cold water. In general, dishwashers use less water and do a better job than washing by hand, but they use mainly hot water, either internally generated in the machine or from the hot water tap. A study of five Melbourne homes measuring hot water consumption over a 12-month period found hot water consumption per person per day of 16–56 L, with an average of 23 L (REMP 2012). In a typical



Average water use breakdown for an efficient home.

home, hot water consumption peaks in the morning between 6 am and 9 am and then again in the evening between 5 pm and 8 pm, coinciding with showers and meal preparation. For heat pumps and solar thermal systems, generation is most efficient during the afternoon when ambient conditions are warm and sunlight is available. Therefore, afternoon and evening water use with a small morning demand can help to maximise efficiency or generation, reduce storage losses and align consumption with energy generation.

4.1 CREATING HOT WATER

The energy required to raise water from tap temperature to a safe hot water storage of around 60°C (to avoid microbial growth) can be easily calculated using the specific heat capacity of water: 4.2 kJ/(kg.K) (at 15°C, 101.325 kPa). In other words, to heat 1 L of water by 1°C, 4.2 kJ of energy are required. It follows that to warm 1 L (1 kg) of water from a tap temperature of 10°C to a storage temperature of 60°C, a temperature increase of: 60–10°C = 50 K, 4.2 kJ/(kg.K) × 50 K = 210 kJ heat energy is required. Therefore to heat the average occupant's daily hot water requirements of 23 L would require: 4.2 kJ/(kg.K) × 50 K × 23 kg = 4.8 MJ or 1.33 kWh.

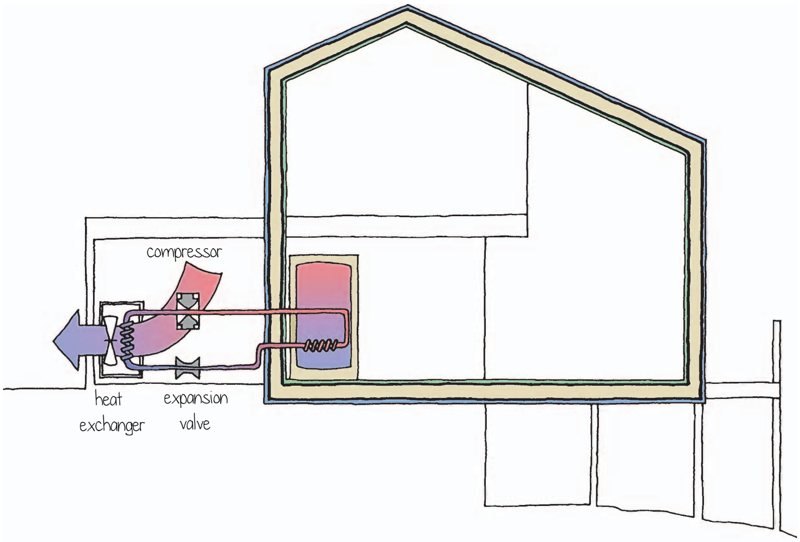
As the amount of heat required to heat a given volume of water is fixed, we need to source this heat as efficiently as possible, and the most effective way to do that is through using a heat pump. Heat pumps allow multiple units of hot water to be generated using 1 unit of electricity. For example, a highly efficient heat pump operating under ideal conditions can produce four units of heat for every unit of electricity consumed, therefore the 1.33 kWh of heat required per average occupant (23 L) could be delivered using just 0.33 kWh of electricity. In regions with consistent solar resource year round, solar hot water systems can be an efficient means of hot water generation. However, in climates where the solar resource is low in winter and high in summer, the solar thermal systems can require large amounts of boosting in winter and generate excess heat in summer that is typically wasted. Resistive electric heating is the least efficient option and should only really be considered for small loads such as boosting a solar thermal system in winter.

4.1.1 Heat pumps

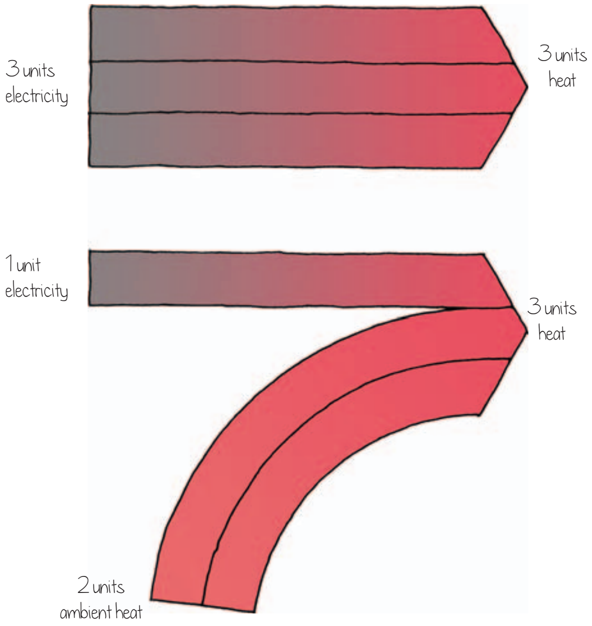
As the name suggests, heat pumps are able to move (pump) heat between spaces or containers. They achieve this by manipulating the temperature of refrigerant within a closed loop, allowing it to collect ambient heat from the air and concentrate in a hot water tank. The temperature of the refrigerant is altered through a cycle of evaporation and compression, where the refrigerant typically changes phases between a gas and a liquid. In a domestic hot water system, a refrigerant at ambient temperature is compressed using an electric motor (condenser), forcing the molecules close together causing them to collide with one another and warm up. This hot refrigerant is then used to heat water by passing it through a coil inside the hot water tank, or through a refrigerant to water heat exchanger, warming the water and cooling the refrigerant. The refrigerant is then passed through an expansion valve causing it to expand/evaporate and cool down, typically to a temperature below the ambient air temperature. In an air-source heat pump, the cold refrigerant is then passed through a refrigerant to an air heat exchanger (a series of metal pipes with metal fins exposed to the outside air) allowing it to be warmed by air passing over the fins, typically assisted by a fan. As long as the refrigerant is colder than the outside air, it is able to collect heat, which can then be concentrated using the condenser to heat water restarting the cycle.

A useful analogy to help understand this process is pumping up a bicycle tyre. When air is compressed in the pump and forced into the tyre the air warms up, which can be felt as it warms the pump shaft and the tyre. If the tyre is then allowed to sit, it will cool to the temperature of the ambient air. By releasing the compressed air within the tyre through the valve, the air will expand cooling it below the temperature of the surrounding air, and will feel cool to the person releasing the valve.

Therefore, unlike a resistive electric element that can only generate as much heat as is available in the energy of the electricity consumed, heat pumps can use electricity to collect heat from the surrounding air, allow them to collect more heat than is available in the energy of the electricity.



Air-source domestic hot water heat pump schematic showing heat being collected from outside air, condensed and used to heat water in a storage tank. Some units have a refrigerant to water heat exchanger between the heat pump and the storage tank.



Energy requirement to heat 3 units of hot water using and electric resistance hot water and heat pump hot water unit.

Domestic hot water heat pump and storage tank (Photo: Faud Abdi).

This makes heat pumps as much as four times more efficient than the electric resistive heating system, and many times more efficient than gas hot water systems that typically have gas to hot water efficiencies of around 65–75%.

4.1.2 Heat pump efficiency

The efficiency of a heat pump is commonly described by its coefficient of performance (COP), which describes how many units of heat the systems can move per unit of electricity consumed.

Because air-source heat pumps rely on absorbing heat from the surrounding air, their efficiency is influenced by the ambient temperature. In warm climates where the ambient conditions are hot, making it easy to collect heat, most heat pumps can achieve very high efficiency, significantly reducing the hot water energy requirements of the home. During cold conditions, when less heat is available in the ambient air, the efficiency of heat pumps decreases and in less-efficient models can drop below that of a standard electric resistive heating unit.

The average efficiency of a heat pump over the year for a particular climate is described by its seasonal performance factor (SPF). As the stated COP is tested under standard conditions, the efficiency over the year (SPF) is normally significantly lower because it takes into account the times when the unit will be operating at reduced efficiency due to unfavourable ambient temperatures. Passive House certification assumes that each occupant will consume 25 L of hot water per day, which if generated using a heat pump with a seasonal performance factor of 2.25 and associated heat losses, equates to ~250 kWh per annum per occupant.

For locations that experience very cold winter conditions, making it very difficult to collect heat from the ambient air, coupling the heat pump to an alternative heat source can improve the efficiency and reduce energy consumption. Some commonly used heat sources include the ground, exhaust air from the ventilation system, large bodies of water and evacuated tube solar thermal collectors. In hot and/or humid climates that require regular cooling using a heat pump in reverse (discussed in Chapter 5), the heat rejected from the cooling system can be used as a heat source.

4.1.3 Components of a heat pump hot water system

Air-source heat pump hot water systems typically come in two configurations: integrated or split. In integrated systems, the condenser normally sits on top of the storage tank. Heat is collected from the air around the unit and the resulting hot refrigerant is used to directly heat the water in the tank by passing the refrigerant through metal coils or metal plates in the tank.

For split systems, the condenser and tank are separate units with heat transferred via insulated pipes. This allows the tank and condenser to be collocated or isolated, providing greater flexibility in locating the condenser; for example, it may be mounted on a wall or roof, while the tank can be on the ground or inside the home. Some units transfer heat from the condenser to the tank using the hot refrigerant, as per the integrated unit. Other units use a small pump to circulate water from the storage tank to the condenser where it is heated via a refrigerant to water heat exchanger and then sent back to the tank. In both cases, the length of connecting pipes should be minimised and the pipes need to be well insulated to prevent heat loss.

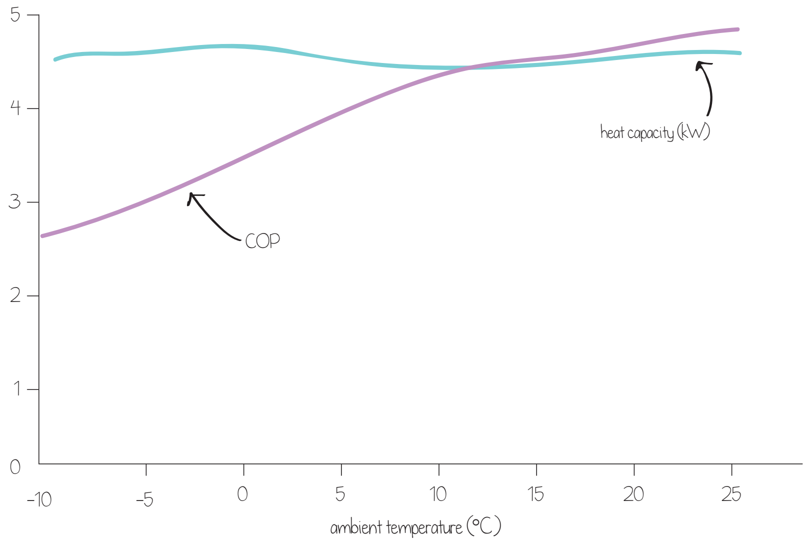
Because the performance of an air-source heat exchanger is sensitive to temperature and requires adequate airflow around the condenser to facilitate effective heat collection, careful consideration of the location is important to maximise efficiency. For example, if the condenser is located in a confined space it will cool the air around it (just like an air-conditioner does), reducing the efficiency of the unit and eventually preventing it from collecting any more heat out of the air. As such, it is important to ensure the unit has plenty of unrestricted airflow and heat can be continuously collected from the surrounding air. In addition to adequate airflow, it is ideal to locate the condenser for a hot water system in a warm location, such as on the sunny side of the home, where it will not be a visual impact and sound generated by the compressor and fans will not be disruptive.

4.1.4 Selecting a heat pump

As with all products, there are a range of domestic hot water heat pumps available of varying quality and performance. Some heat pumps are only suited to warm climates where there is plenty of ambient heat to collect, and during cold periods rely on an electric resistance element to generate heat. For cooler climates, a unit designed to operate under cold ambient conditions is required. As shown in the figure below, high-quality units can achieve heating COPs of greater than 4.5 when ambient air temperatures are above 15°C, and maintain COPs above 2 in ambient conditions of –10°C without reducing heating capacity. These systems have been shown to operate down to –20°C.

All manufacturers will provide a COP for their product, but the conditions under which this COP was measured may vary. For example, all heat pumps operating at ambient temperatures of 30°C will achieve a good COP. Therefore, before selecting a unit for your home, it is essential to ensure that this COP has been tested by an independent party under standard conditions, or better yet been certified by the Passive House Institute. In addition to standard conditions, the manufacturer should be able to provide independent performance test results across a range of ambient conditions, ideally from 25°C to –10°C. All units will have reduced efficiency under cold conditions, but some will perform better than others. This test data can then be entered into the Passive House Planning Package (see Chapter 8) to calculate a seasonal performance factor that can be used to estimate annual energy consumption.

Obviously ambient conditions vary throughout the day, therefore the heat pump selected should have sufficient control to facilitate generation when energy ambient conditions are



Influence of temperature on COP and heating capacity of an example domestic hot water heat pump.

favourable and/or when the home is generating excess power. For example, the unit can be programmed to operate in the afternoon when conditions are typically warmest and solar output is peaking. More complicated control systems may allow for the unit to be activated once ambient conditions reach an acceptable threshold or receive a signal from the inverter advising excess power is available.

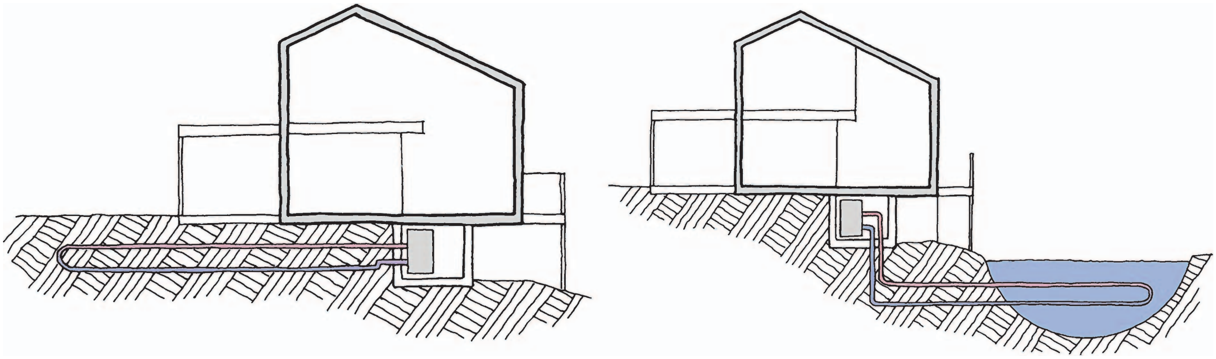
The condenser unit of a heat pump generates noise from the operation of the compressor and fans, which for some units can be disruptive to occupants and neighbours. Quality units have very low operating sound levels below 40 dBA, which when located outside an insulated airtight envelope are able to meet the Passive House certification requirement of maintaining internal noises levels associated with mechanical plant less than 30 dBA.

Like refrigerators and air-conditioners (which are heat pumps, running in reverse) hot water heat pumps use a refrigerant to 'pump' heat. The majority of refrigerants in use are now zero ozone depleting potential. However, many still have high global warming potential, meaning that if they are released to the atmosphere they have a much higher (often thousand fold) greenhouse effect than gases such as CO_2. With that said, hot water heat pumps are now available that use low global warming potential refrigerants, such as propane (GWP 3.3) or CO_2 (GWP 1) as the refrigerant, providing efficiency and low global warming potential in the event of a refrigerant leak.

4.1.5 Ground or water source heat pumps

Where ambient air temperatures are unfavourable for using air-source heat pumps, the ground or a body of water can be used as the heat source (e.g. a brine loop ground-source heat exchanger as introduced in Chapter 3). In these systems, brine is pumped through pipes buried in the ground, allowing it to collect heat when the ground is warmer than the ambient air. The brine is pumped through the pipes and then brought to a heat exchanger where it is used to heat refrigerant in the heat pump. The heat is then concentrated by the heat pump and used to heat water in the tank. This is advantageous because below ~1 m deep the ground temperature is relatively stable year round. In winter, the ground temperature is generally greater than the ambient air temperature, particularly overnight. Therefore, by using the mild ground temperatures, the heat pump can achieve higher efficiency and continue to provide hot water under extreme ambient conditions. With appropriate control, the heat pump can be switched between a ground-source heat exchanger and an air-source heat exchanger, allowing heat to be sourced from the air when the air is warmer than the ground and from the ground when air temperatures are cold.

By extracting heat out of the ground, the ground is cooled over time. Therefore the heat collection system either has to be large enough to be able allow the temperature of the ground to equilibrate with its surroundings or for waste heat from the home to be pumped into the ground during summer to help balance the annual ground temperature. For example, the ground may be used to help cool the home in summer, warming it up, and then used to heat hot water in winter, cooling it down. This will be discussed further under heating and cooling. As you would expect, the addition of a system of pipes to exchange heat with the ground adds significant costs and complexity relative to an air-source system.



Ground (left) and water (right) loops to collect/dump heat for a heat pump or brine cooling coil.

Other potential heat sources/sinks include bodies of water such as a large dam, where coils can be immersed into the water, which, like the ground, should remain milder than the ambient air during extreme conditions. Because water has a high specific heat capacity and is a good heat conductor, heat can rapidly be exchanged between the body and water and the heat pump, meaning a smaller collection area is required relative to a ground collection systems. Like a ground collection system, the body of water needs to be large enough to avoid over-cooling.

Another option is to scavenge heat from other systems within the home, such as waste heat from the ventilation system. For example, during the cold months of the year, the heat recovery ventilation system recovers as much heat as possible from the outgoing air; however, the exhausted air will still be warmer than the ambient. Therefore the outgoing air can be blown over an air-source heat exchanger allowing the waste heat to be collected for hot water generation (see the figure on p. 103). During warm conditions, heat rejected from an air conditioning unit can be used to heat domestic hot water, improving the efficiency of both services. This can be particularly beneficial in primary cooling climates, where the daily hot water demands and cooling demands are synchronised. Although it is possible to engineer a customised system to achieve these outcomes, for domestic applications the most practical and reliable option it to select a package unit, where the hot water heat pump has been integrated with the ventilation and/or cooling system by the manufacturer. This reduces the complexity for the occupant and designer, and, with plenty of Passive House certified units available, reduces the risk of under performance.

4.1.6 Solar hot water

Although the conversion of electricity into heat using a resistive element is close to 100%, the conversion of onsite renewable energy into electricity is generally quite low. For example, a typical solar photovoltaic (PV) panel has a conversion efficiency of around 15%, meaning that the overall efficiency of hot water generation from onsite solar energy is quite low. In contrast, the efficiency of solar thermal collectors such as evacuated tubes (see the figure on p. 202) can be greater than 80% under ideal conditions. The major difference between solar PV and solar hot water is that the later can absorb energy across the entire solar spectrum and from both direct and indirect solar radiation (see Chapter 6). As such, evacuated tubes are able to collect significant heat, even on overcast days.

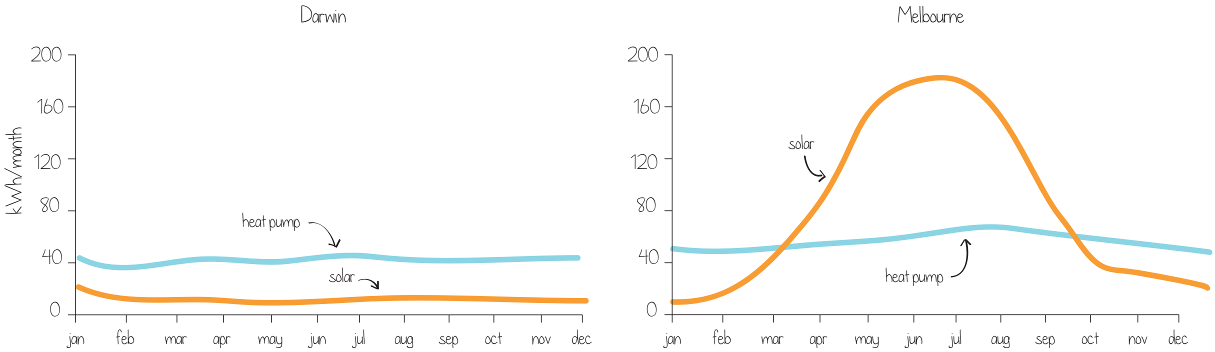
Heat pump hot water systems collect heat out of the ambient air that has been warmed by the sun, making them indirect solar collectors. However, because heat pumps require electricity to collect heat the overall efficiency of hot water generation using solar energy is limited by the efficiency of the solar photovoltaic. For example, using 15% efficient solar photovoltaic panels with a heat pump operating at a COP of 4 (400%), the overall solar energy to hot water conversion efficiency would be 60%.

The disadvantage of solar thermal hot water systems is that if the hot water generated is not required then it is typically wasted (unless it can be used for an alternative purpose such as heating a pool). In contrast a heat pump-photovoltaic (PV) system only uses the amount of electricity required to meet the hot water requirements and any excess electricity can be used for other services in the home, stored or exported to the grid. Furthermore, when there is not enough solar energy available for the solar hot water system to meet the hot water demand of the home, then electrical energy is required to meet the difference. This can be achieved using electric resistive element or through coupling to a heat pump.

As domestic hot water demand is reasonably constant throughout the year, deciding whether a solar hot water system is appropriate for your home can come down to the consistency of the solar resource in your area. For example, in areas closer to the equator where the solar resource is similar year round, then the system can be reliably sized to meet the hot water requirements of the home, with only a small amount of electric boosting required and minimal excess heat generation.

For locations further from the equator with significant variation in solar resource throughout the year, sizing the system to minimise the requirement for boosting will typically result in significant excess heat generation in summer. Alternatively, sizing the system to meet demand in summer will result in significant boosting requirement in winter, when solar PV generation is lowest. As such, for regions with significant annual variation in solar resource, or for homes that have low summer hot water demands and high winter demands, a heat pump is required to achieving optimum efficiency.

For optimum efficiency, a heat pump and solar thermal system can be combined, but unless you expect to have very high hot water consumption then the efficiency gains of installing both



Seasonal energy consumption solar thermal and heat pump for tropical (Darwin) and warm-temperate (Melbourne) climates.

typically does not justify the additional cost. For example, where a heat pump is being installed to provide efficient winter hot water heat, the cost of adding additional PV panels to provide electricity to the heat may be less than adding a solar hot water system and the associated plumbing. In Melbourne, the electricity requirements of a typical home's hot water requirements via the heat pump is roughly equivalent to the generation capacity of a 1 kW solar array.

In theory, combining a solar thermal collector with a heat pump is straightforward, with the solar thermal preheating water, reducing the work of the heat pump to maintain tank temperature. However, it is important to source a system or tank designed for this purpose and check with the heat pump provider that doing so will not void the warranty.

The details of solar hot water collectors are discussed in Chapter 9.

4.1.7 Electric resistive hot water systems

Electricity is the flow of electrons through a conductive material. When transporting or distributing electricity, it is essential to minimise resistive energy losses through the use of highly conductive materials such as copper. However, when electricity is passed through less conductive materials such as nichrome (an alloy of nickel and chromium commonly used for electric heating elements) that has a resistance around 100 times greater than copper, the resistances causes the energy carried by the electrons to be converted into heat. Electric heat elements are very cheap, easy to control and reliable, so the simplest method of generating hot water heating is through the use of an electric heating element in a storage tank.

The conversion of electricity into heat is highly efficient at close to 100%. However, even when powered by high efficiency (20%) solar panels, the overall solar to useful heat efficiency of is too low to be the primary source of hot water for a Positive Energy Home. With that said, resistive heating of water can be an acceptable cost-effective method to top up solar or heat pump systems during extreme weather events, when the electric element is only required to produce 10–15% of the home's overall hot water requirements.

In all of the systems discussed so far, hot water is stored in a tank ready for use. Most tanks are tall and thin, allowing the water in the tank to stratify, with hot water accumulating at the top ready for use in the home, with cold water pooling at the bottom ready to be heated. This stratification can help to reduce heat loss from the tank as only the top section of the tank need to be kept at high temperature (~60°C). Even so, over the course of the year heat loss can account for as much as 20% of the system's energy consumption. Instantaneous electric hot water systems only generate hot water when required, therefore eliminating storage losses and provide great flexibility for variable loads such as boosting hot water temperatures from a solar thermal system. However, instantaneous heating of water creates very high instantaneous electrical demands, which can be beyond a standard domestic electricity connection and are beyond the instantaneous output of a typical solar photovoltaic system. As such, these systems are not generally practical for domestic or renewably powered buildings.

4.2 HOT WATER SYSTEMS

Obviously there is more to providing hot water than just heating water: it needs to be stored ready for use and distributed around the home with as little heat loss as possible.

4.2.1 Tank and pipe insulation

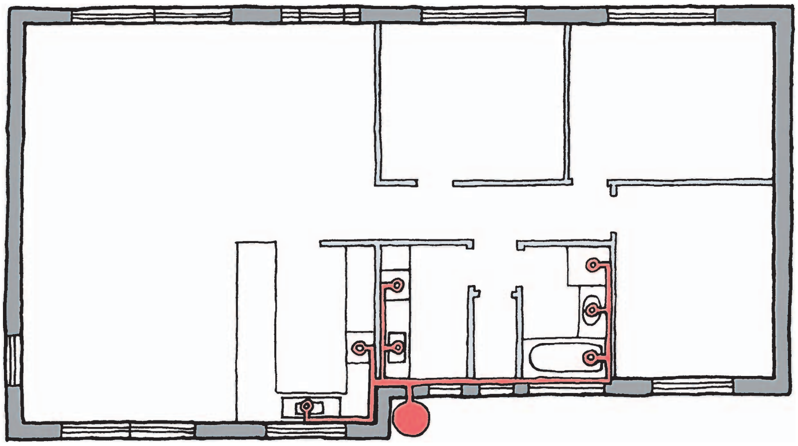
Domestic hot water temperatures are significantly above the ambient air temperature, with the WHO recommending tank temperatures reach 60°C at least once a day to avoid the risk of legionnaires' disease: a serious bacterial infection. But warming the water sufficiently to eliminate bacterial growth means that large amounts of heat loss can readily occur from poorly insulated tanks or distribution pipes. Even if the tank is located inside the thermal envelope, the losses are problematic, because, at least during summer, they can contribute to the risk of overheating. As such, ensuring that insulation is included around tank outlets, valves and pipes right up to the point of use is essential. The thickness of the insulation on domestic hot water pipes should be at least twice the internal diameter of the pipe, with no exposed pipe from tank to tap.

Example of retrofitted hot water tank and hot water pipe insulation (Photo: John Loveless).

Most hot water tanks will come with a certain level of insulation: normally polyester integrated into the unit. Many manufacturers do not state the amount of insulation, but energy rating schemes may require a rated/declared kWh/24 h, which is a measure of how much heat is lost in kWh over a 24 h period. This rating is typically stated as an absolute value, meaning that larger tanks will have a higher value due to their size. Obviously selecting a unit that has the lowest value for the tank size required is ideal. In most cases, the manufacturer-provided insulation is inadequate and additional insulation should be added around the tank. For split heat pumps or split solar system where the storage tank is stand alone this is easily achieved by placing the tank on an insulated base such as styrofoam and wrapping the entire tank in an insulated blanket ~100 mm thick or enclosing in an insulated box with equivalent insulation properties. Once the tank is insulated, it is surrounded by warm potentially warm air, therefore the cold inlet pipe must be insulated with a vapour tight insulation material from the point where the tank insulation starts right up to the tank to ensure condensation does not occur on the pipe. For integrated heat pumps, the condenser and fan must remain exposed, but a layer of insulation can be added to the storage component of the unit. Adding insulation to integrated solar systems where the tank is located on the roof can be more complicated, but, given the tanks are exposed to the weather, is equally, if not more, important.

4.2.2 System layout

The location of the tank relative to the hot water uses is also important to minimise distribution losses and pipe works costs. When a hot water tap is turned on, hot water is drawn from the tank out to the tap. If the tap is a long way from the tank then a significant volume of water has to flow through the pipe before the hot water reaches the point of use. This not only increases the surface area for heat loss to occur, it also results in a significant volume of hot water sitting in the pipe once the tap is turned off, which will cool down and need to be replaced when the tap is turned on again. Therefore the energy used to warm this water is wasted. Ideally the storage tank will be located in a central location adjacent to the hot water demands of the house, minimising the distance between storage and consumption. For example, in a two-storey house, having the hot



Example home layout and tank location to minimise hot water distribution lengths.

water tank in an insulated cupboard in a laundry, adjacent to the kitchen and bathroom, with the upstairs bathroom located directly above, minimises the pipe lengths, associated installations cost and heat loss. As discussed earlier, co-locating these air extraction rooms also minimises the length of extraction air ducts and helps to isolate any potential noise associated with service areas, such as washing machines, from the living and sleeping areas of the home.

4.2.3 Tank sizing

Sizing the tank to allow for both evening and morning peaks can help to reduce the need for boosting. Alternatively, shifting the daily hot water demand to the afternoon or the evening can help to optimise the efficiency of generation and storage. For example, using the washing machine in the afternoon, having showers and washing dishes in the evening, leaves only a small morning hot water demand. This allows the hot water generated in the afternoon to be used, minimising storage losses overnight and leaving the tank ready to be heated during the day.

The size of the hot water storage tank required is influenced by daily consumption and the intended method of hot water generation. In warm climates where the efficiency of the heat pump is relatively consistent day round, the tank only needs to be sized to allow enough hot water to avoid running out when people are showering. Storing less hot water reduces storage losses. Where hot water is going to be generated once a day and then stored, such as in cold climates where it is beneficial to operate the heat pump in the warmest part of the day or where solar hot generation is being used, tanks are generally sized to hold 1.5 days of home hot water requirement. For example, if the home is designed for four occupants using around 50 L of hot water per day then a tank of around 300 L should provide enough hot water to meet demands between generation cycles. It should also be noted that the capacity of the tank is determined by the location of the heat source, with only the water above the source reaching temperature, meaning tanks may store less hot water than their total capacity. In solar hot water systems and split heat pump systems where the hot water is circulated between the tank and the heat pump, mixing allows the entire tank to reach temperature. This can be beneficial for collecting more heat during the day, but it also increases storage losses, so needs to be balanced against your system design and climate.

4.2.4 System control

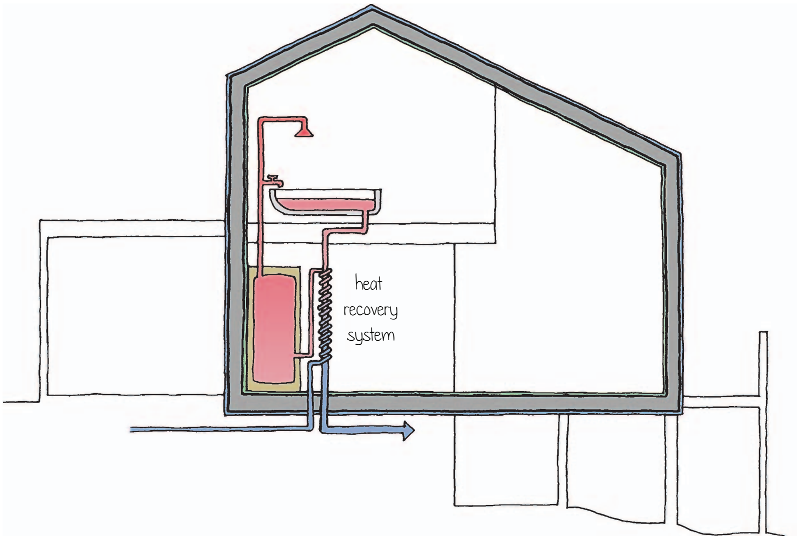
Air-source heat pumps operate most efficiently when the ambient conditions are warm. Therefore programming the heat pump to operate at the warmest part of the day (typically, the afternoon) maximises the efficiency of hot water generation. When the heat pump is powered by solar PV, generating hot water when the PV output is high, typically in the middle of the day when home energy use tends to be low, allows onsite energy to be directly used rather than exporting to the grid or a battery. Hot water generated at these times can then be stored in the tank ready for use during the evening peak. Depending on usage patterns, storage tank size and hot water requirements in the morning, heating water once a day at the efficiency peak in the afternoon may be sufficient to meet the needs of the home.

Solar thermal systems are most efficient at operating when the water temperature is low. For example, when cool domestic water enters into the system, the difference in temperature between the hot water collector and the water is greatest, maximising efficiency. Furthermore, once the tank is heated, any additional solar heat collection is wasted. Therefore, the ideal scenario for maximising solar heat collection is to start the day with a cool tank, allowing the system to operate efficiently and collect as much heat as possible throughout the day. On a good day, enough hot water is generated from the solar collector and stored in the tank to meet the evening peak and morning demand, with the solar hot water system only boosted at the end of the day if there has not been sufficient solar radiation to get the tank up to temperature.

One option to minimise operation of the heat pump in the coldest part of the day, such as the early morning, or make the most out of a solar thermal system, is to use a storage tank with two temperature sensors. One temperature sensor can be located at the top of the tank, which only activates the heat pump or electric booster when the lower part of the tanks has been exhausted, and then keeps only the top section of the tank hot, maintaining the hot water supply to the home. The second sensor located lower down in the tank and is only activated during the day when temperatures are warm and the sun is out, allowing the majority of the daily hot water requirement to be generated as efficiently as possible.

4.2.5 Heat recovery systems

Further efficiency can be realised through using waste heat in drains to preheating incoming cold water. For example, using a heat recovery system such as copper pipe wrapped around the shower drain, allows incoming cold water to be preheated by the outgoing warm water. Passive House certified hot water heat recovery units are available (see the figure below).



Representation of a hot water heat recovery system, showing heat being collected from waste hot water flowing down the drainpipe.

SUMMARY

The supply of hot water is a simple, but fundamental, service in the home, which can become the largest user of energy in a Positive Energy Home. The first step in reducing the energy required to minimise the volume of hot water required through selection of water-efficient appliances and fixtures, as well as establishing efficient usage patterns.

The amount of energy required to heat a particular volume of water is fixed, but there are several options for heating, the most efficient of which is through the use of a heat pump. Unfortunately, not all heat pumps are equal and particular care needs to be taken in selecting a unit suited to your climate and that will live up to the manufacturer's efficiency claims. Solar thermal hot water systems can also offer an efficient hot water supply for regions with consistent solar exposure year round. For climates with high summer and low winter sun, the winter boosting requirements can make solar hot water with an electric resistance boost a less efficient option than an efficient heat pump.

Once heated, it is essential to avoid heat loss from the storage tank and distribution pipes. This is achieved through providing generous insulation for the storage tank and pipes, and minimising distribution lengths from tank to tap.

Because hot water generation is such a large component of home energy consumption, ensuring that the system performs as expected is crucial to achieving positive energy, so we strongly recommend selecting a performance certified, or at least independently verified, hot water service.

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CHAPTER 5

Heating and cooling

5.1 CREATING A COMFORTABLE HOME

In many homes, poor insulation and airtightness results in rapid uncontrolled transfer of heat across the thermal envelope. These houses are bottomless pits into which energy needs to be constantly poured in an attempt to maintain comfortable conditions. Typically this results in air conditioning being the largest consumer of energy in the home, adding up to an energy requirement that is physically impossible or economically prohibitive to meet through onsite generation. To create a home capable of a positive energy balance, we need to dramatically curb the uncontrolled transit of heat in and out of our homes, and then manage the remaining heating and cooling requirements through a combination of passive solutions and super efficient active systems.

With an effective thermal envelope (Chapter 2) heat transfer is very slow, meaning the response to outdoor temperature is minimised. This drastically reduces the amount of heating and cooling required to maintain comfortable conditions. Heating of the home can then be achieved through a combination of capturing sunlight and occasionally actively adding heat, which is easily distributed around the home via the ventilation system. Where heating requirements are very low, electric resistance heating, using a simple electric element in the supply air duct, is the simplest and cheapest method of heating the home. Like hot water generation, heat pumps offer greater efficiency, but, unlike hot water that has a constant large heat demand, the relatively small heating demands of a Passive House warrant the additional complexity and cost. As such, heat pump conditioning systems are best suited to homes that require both heating and cooling, or where a single heat pump can be used to provide both heating and hot water. Keeping the home cool is achieved through excluding solar heat when not required, managing internal heat sources, purging excess heat via windows and/or through the ventilation system and occasionally actively removing heat. Actively removing heat can be done through the use of a ground- or water-body-source heat exchanger or through a cooling heat pump, typically reverse cycle to provide the home's heating and cooling requirements. Through implementation of these strategies, guilt free renewable powered comfort can be enjoyed year round.

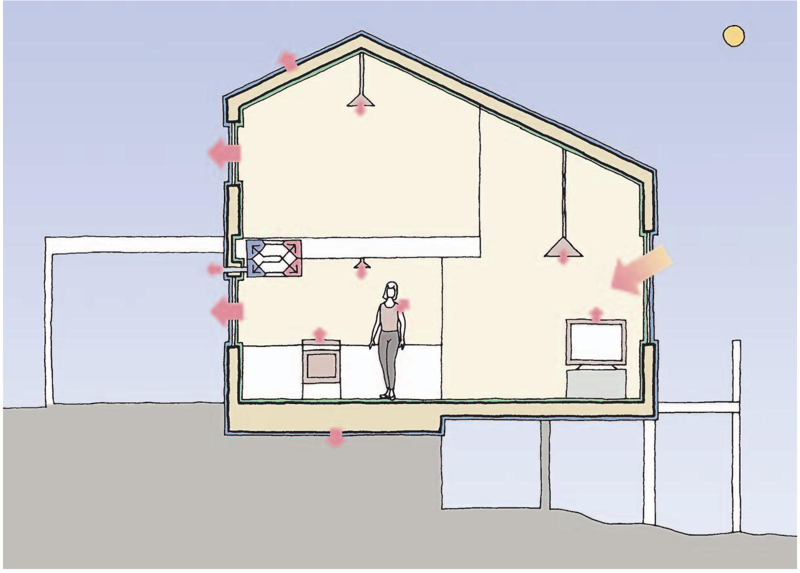
In this chapter, we explore these strategies for managing heat flows in the home, starting with capturing heat to keep it warm and then options to exclude and remove heat to prevent overheating.

5.1.1 Keeping the home warm and cosy

In a Passive House, the uncontrolled heat flows across the envelope are small, so the heat contribution from internal heat sources becomes more significant. For example, heat generated by occupants, refrigerators, televisions, cooking and hot water all add heat to the space. During cold conditions, these heat sources can be beneficial, and internal heat gains can mean that heating is not required for all but the most extreme winter weather. When it's cold outside, excess internal heat generation can be easily managed through opening of windows or purging heat through the ventilation system, bypassing the heat exchanger. As such, it can be tempting to use appliances or lights to help heat the home, but during warm conditions, this heat can readily build up inside the thermal envelope causing the home to overheat. Therefore, although unavoidable internal heat sources such as the occupants can be helpful to keep the home warm in winter, it is essential to maximise the efficiency and sensibly manage appliances to reduce the potential for overheating and the reduce the overall energy demand of the home.

HEATING WITH SUNLIGHT

The collection of a controlled amount of solar heat through windows can be the primary source of heating in a Passive House. In a traditional home, typically any solar heat gain in winter is welcome because heat is rapidly being lost across the envelope so the risk of overheating is low. However, for an effective building envelope, the daily heat flows due to conduction and infiltration are very small relative to the heat carried in sunlight. For example, an equator-facing window in Victoria, can receive over 400 W/m^2 on a clear winter's day. This means that, for a 150 m^2 Passive House with a peak heating demand of 1500 W, 3–4 m^2 of exposed equator-facing clear glass would be sufficient to heat the whole house, even if the ambient air temperature were below zero. Therefore, on a milder winter's day with ambient temperatures around 10°C, 3–4 m^2 of exposed



Heat flows in the home during cold weather, showing potentially useful radiant solar heat gains through the window, waste heat released from appliances and people, and conductive heat losses across the thermal envelope and through the windows. By minimising heat loss and managing passive heat gain, the need for active heating can be minimised.

glass could quickly cause the house to overheat. Obviously a small amount of excess heat gain in winter can be quite pleasant at times, and excess heat is normally readily managed through bypassing the heat recovery system or opening a window, but is important to ensure that any direct solar heating can be easily managed to prevent overheating, particularly in the seasons outside of winter.

First thing in the morning, temperatures are typically at their coldest and the house may be cooler than normal due to overnight temperature setback. Therefore, the collection of early morning sun, which has considerably less energy than midday sun, may be a useful easily controlled source of heating. For example, on a clear morning, an east-facing window is likely to receive around 100–200 W per m^2 of low angle solar energy from around 9 to 10 am. With suitable control, an appropriately sized window can provide a useful morning boost in temperature. Through the use of external blinds, the amount of sun entering the home can be managed to prevent overheating as the day warms up and the internal heat gains in the home increase with occupant activity. On overcast or low sun days where the available solar energy is much lower, it can be beneficial to have a larger area of exposed window with the ability to completely retract shading devices to maximise solar heat collection.

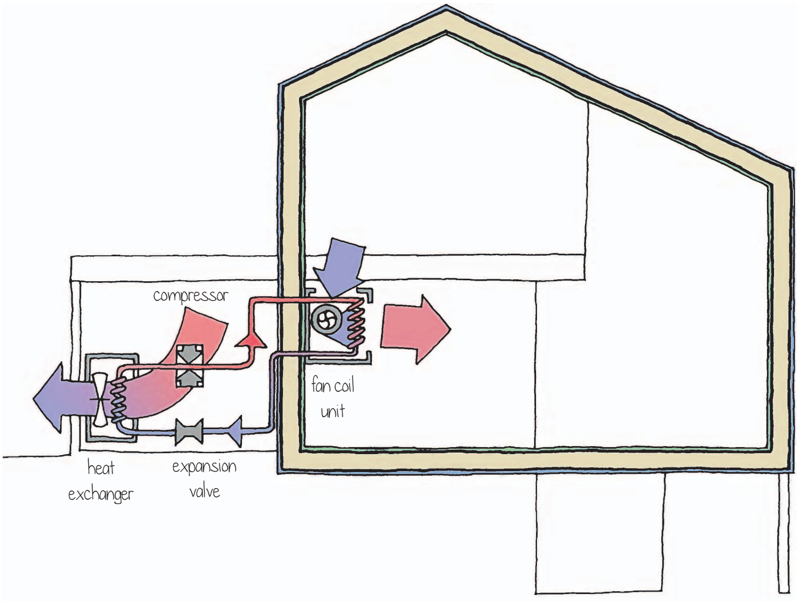
Establishing the right balance between, passive solar heat gain, solar control and daylight harvesting can be challenging, but tools such as the Passive House Planning Package combined with a daylight modelling plug in to 3D modelling tools such as SketchUp can help make this task a lot easier. Balancing daylight and heat gain is discussed further in Chapter 6.

ELECTRIC RESISTIVE HEATING

For mild climates or very high performance envelopes with low ventilation rates, or where temporary local heating is required, small heating loads may be met through the use of resistive heating. Although less efficient than a heat pump for small infrequent loads, resistive heating is a cheap and simple solution. An example of this is the temporary heating of a bathroom where higher temperatures may be desirable after showering when the skin is wet and exposed. A small radiant panel or an electric towel rack is typically more than enough in combination with the heat from the hot water of the shower to heat the room to a cosy temperature. Where resistive heating is used as the primary heat source for the home, the simplest method is to include a heating element in the supply air duct. As discussed below, this option is far easier to purchase, control and install, as well as being cheaper and much less complex than integrating a heat pump with the ventilation system. With that said, electric resistive heating should only be used where the heating requirements of the home have been minimised and the complexity and cost of a heat pump are not warranted.

HEATING WITH A HEAT PUMP

When there is not enough sunlight available to heat the home, using a heat pump is the next most efficient method of providing heat for a renewable energy powered home. As discussed in Section 3.1, a high efficiency heat pump is able to provide two to four times more heating than an electric



Representation of an air-source heat pump for direct heating and cooling of internal air – often referred to as a split system or a reverse cycle air-conditioner.

coil for the same energy input, when ambient temperatures are above –10°C. Heat pumps are commonly used in standard homes in the form of a split system reverse cycle air-conditioner. In this configuration, the condenser is located outside and a head unit or fan coil unit is mounted on the wall or in the ceiling of a living space providing heating as required. The condenser unit is equivalent to those used for heat hot water, but, rather than heating water, domestic split units pipe the hot refrigerant to the fan coil units, where it passes through a series of metal coils and a fan circulates room air over the coils, warming it up. The refrigerant that has been cooled by the room air then passes back to the condenser to collect more heat.

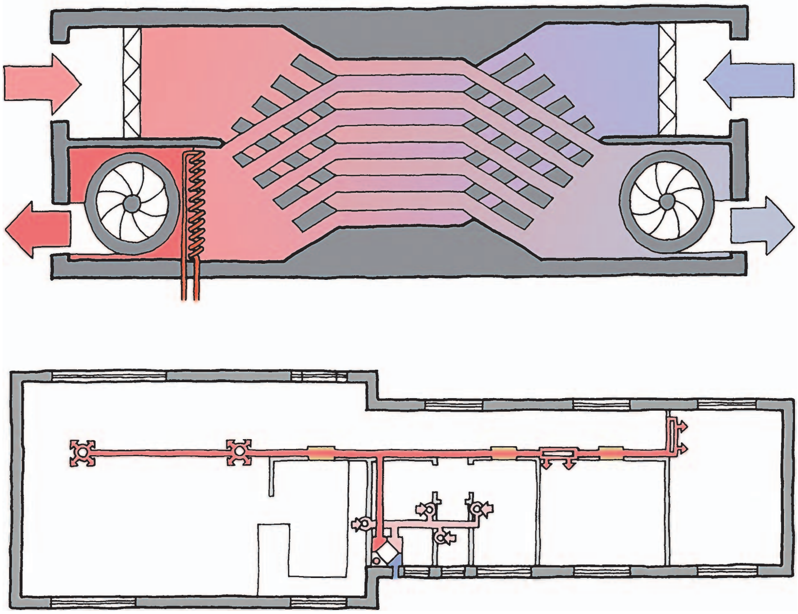
As per our example of solar heating above for a 150 m^2 Passive House home, the peak heating requirements will be in the order of 1.5 kW. Typical small split systems have heating capacities of 2.5 kW or greater, meaning a single unit can readily provide the heating requirement of the entire home, making an efficient off the shelf split unit an economical, easy to control and flexible source of peak heating. However, in most climates, peak heating will only be required during the coldest periods of the year and generally only for a few hours of the day, such as first thing in the morning. For the majority of the time the heating requirement of the home will be a fraction of the nominal peak due to milder ambient conditions, solar heating and internal heat sources. Therefore even the small split system will be operating at a fraction of its capacity the majority of the time. For a basic model, small loads results in the unit cycling on and off, which can be distracting for the occupant and is not ideal for the unit or energy consumption. More sophisticated units have variable speed compressors that allow the unit to function efficiently across a broad output range, and deliver efficient part load efficiency. Therefore, when selecting a split system, ensure that it can operate efficiently over a range of heating demands. For example a quality 2.5 kW rated split with variable output may be able to efficiently provide heat output from 0.6 to 3.9 kW. Finally, the unit standby power needs to be checked to ensure that there is no unnecessary power consumption when not in use.

5.1.2 Delivering heat to the home

USING THE VENTILATION SYSTEM TO DISTRIBUTE HEAT

As noted, for many homes the heating capacity of a small reverse cycle air-conditioner (heat pump) with a single head unit will be sufficient to provide the home's heating requirements. However, providing the entire home's heating requirement from a single head unit can result in the area around the unit becoming too warm or drying. In general, direct exposure to concentrated hot dry air can be unpleasant, especially in a home that is otherwise stable for temperature. One of the great benefits of a well-insulated and sealed home is that the conditioning systems can be subtle, allowing conditioning to be delivered without the occupant even noticing. As such, the best way to deliver and distribute heat is through use of the ventilation system. The ventilation fans are already operating to provide fresh air, so all we need to do is add heat and it will be distributed throughout the home.

This option allows for more even heating across the home relative to localised heating, because all of the supply air is gently heated rather than air in one room being overheated and then mixed. This reduces the occurrence of discomfort and local over-drying of the air. It also removes the need for an additional fan and the associated energy and noise, which is required in the split system to re-circulate room air over the coil. However, one of the disadvantages of using the ventilation system to provide heat to the home is that under peak heating conditions, heat cannot be added to the home without also providing fresh air. Therefore, during peak heating times, if only one occupant is home, the ventilation system may need to operate at an airflow rate designed for four occupants to facilitate sufficient heat delivery. This may result in the system bringing in and heating/drying more outside air than required for ventilation purposes. Due to the small heat



Heat distribution via the ventilation system, showing the heat recovery ventilation system with an integrated heating coil (top) and the resulting heated fresh air being distributed out to the living areas via the ventilation supply ducts (bottom).

flows across a Passive House Standard envelope, the period at which the system is required to operate at peak heating is typically small. In the event that the occupant chooses to operate at lower fan speed, it will likely take several days for conditions within the home to become uncomfortable, by which time ambient conditions are likely to have improved.

For small heat loads, heat can be easily and cheaply added to the ventilation system using an electric coil, which can simply be switched on and off either by the occupant or by a thermostat as required. In contrast, heat pumps need to maintain a balance of heat between the condenser and the heating coil to avoid the refrigerant cycle getting out of balance. In a split system, the fan on the fan coil unit responds to the heat delivery from the condenser, ensuring enough heat is being rejected from the coils at a rate that keeps the refrigerant cycle balanced. In the event that insufficient heat is been shed, then the head unit instructs the condenser to stop or slow down, preventing the system getting out of balance. When the heat pump heating coil is integrated into the supply air duct, the ventilation fan has to balance airflow over the coil to keep the heat pump happy while ensuring the right volume of fresh air is being provided to the home. This is easily achieved by selecting a ventilation system and heat pump that have been integrated by the manufacturer into a single unit or are designed to be coupled together with a common control system. Combining a ventilation system from one manufacturer with a heat pump coil from another manufacturer requires the consideration of an experienced engineer or contractor and appropriate controls.

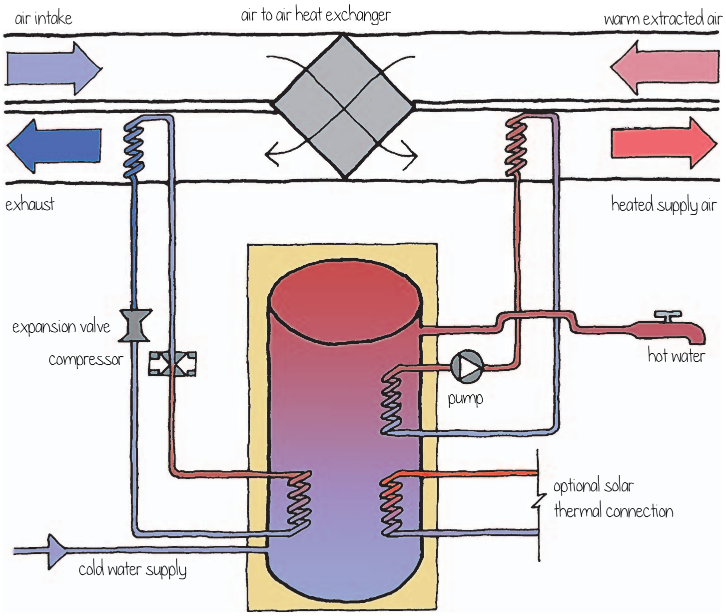
Integrated systems also offer the advantage that the heat coil has been sized for the ventilation rate of the unit, and typically offer in much smaller capacities than a standard split unit, which is ideal for the low heating requirements of a Passive House. This avoids inefficient short cycling of the heat pump that is common for oversized split units. The other advantage of such units is that

Example of a combined domestic hot water and heat recovery ventilation compact unit (see figure on p. 103 for schematic) that recovers waste heat from the exhaust air to heat hot water via a small heat pump (Photo: Zehnder Group).

a reverse cycle heat pump can be used, allowing the ventilation system to also provide cooling and dehumidification, as discussed further in Section 5.2. The disadvantage of these systems is the additional cost and limited availability in some areas.

A third option for heating the ventilation air is to use a hot water coil, which has none of the heat balancing challenges of a refrigerant coil. As such, a standard off-the-shelf hot water coil to be easily added to the supply air duct downstream of the heat recovery unit with heat supply easily controlled by a small pump. Obviously, a hot water coil requires a source of hot water, which can be supplied indirectly from the home's domestic hot water tank, removing the need for a separate heating system. This is typically achieved by including a closed hot water loop between the hot water tank and the heating coil in the ventilation system. Water within the loop is heated by passing it through a coil (heat exchanger) within the hot water tank, which is isolated from the domestic hot water to prevent any potential contamination. The hot water is then circulated to the ventilation-heating coil by a small recirculating pump, which is controlled by a thermostat measuring the air temperature of the home or the supply air. For example, when the home temperature drops below the set temperature, the pump circulates hot water from the heat exchanger in the tank through the coil warming the supply air. Once the home is warm again, the pump turns off. This configuration avoids the complexity of integrating a refrigerant coil with the ventilation system, and allows heating and hot water to be achieved by a single efficient easy-to-service system. It also avoids short cycling of the heat pump because the tank acts as a buffer and allows heat generated in the warmest/peak solar generation part of the day to be stored for use when heating is required.

When designing such a system, the heating coil needs to be sized to provide the home's peak heating requirement at the water temperature supplied from the hot water tank (~55°C). Likewise, the heat exchanger within the tank needs to be sized to match the heating coil capacity, and the



Schematic of a combined hot water and heat recovery ventilation unit with the generated hot water used for domestic purposes and to provide heating to the supply air.

storage tank and heat pump need to be large enough to provide the heating demand of the home and the domestic hot water requirements simultaneously. A typical hot water heat pump system has a heating capacity of around 4 kW, which should be able to easily meet the peak heating and general hot water requirements of the home. In the event of someone pouring a large bath, depleting the hot water tank when peak heating is required, the thermal inertia of a Passive House will mean that if the coil heating capacity is temporarily reduced the occupants are unlikely to notice in the time it takes the heat pump to generate more hot water. Alternatively the storage tank size can be increased to provide a buffer between heating and hot water demand and provide additional heat storage to meet overnight demands or extended cold periods (see Chapter 9). To allow for sufficient storage without over-generating in the non-heating months, it is possible to use two interconnected hot water tanks – one with the heating loop heat exchanger in it that can be isolated during the summer. Direct heating tanks are also available, where the both the domestic hot water and heating hot water are isolated from the storage water, with both directly heated on demand by via large heat exchanger coils within the tank. This configuration avoids the potential for contamination of the domestic hot water and provides the flexibility to use the stored heat for hot water or heating as required.

RADIANT HEATING

In traditional homes, radiant panels or under floor heating can be a very comfortable means of heating a space. However, in a Positive Energy Home, the heating requirements are normally very low, meaning that large systems such as underfloor coils, which have slow response times, can easily overheat a space and consume more energy than required to keep occupants cosy. In most cases, the high costs of these systems are not warranted for the small heating requirements. The exception to this can be where a small radiant electric heater is used to top up temperatures in the bathroom to make conditions comfortable when hopping out of the shower or bath.

5.1.3 Heating control

Like a standard heating system, a simple on/off switch and an adjustable thermostat is typically the most user friendly and practical control method in a Positive Energy Home. With consistent internal surface temperatures and gentle heat distribution through the ventilation system, heating to 20°C is normally sufficient to maintain comfort in winter. Obviously higher temperatures can be achieved if desired, but will require higher energy consumption and a larger renewable energy harvesting system. Generally, temperature sensors should be placed in a transfer zone, somewhere between the supply and exhaust zone. For example, if air is being supplied to the bedrooms, transferring through the living area to the kitchen where it is exhausted, placing the sensor in the living area would be sensible.

More sophisticated control can be used that integrates the heating/cooling and ventilation system to allow greater levels of automation and efficiency. However, as always, greater complexity adds costs and requires greater input from the user.

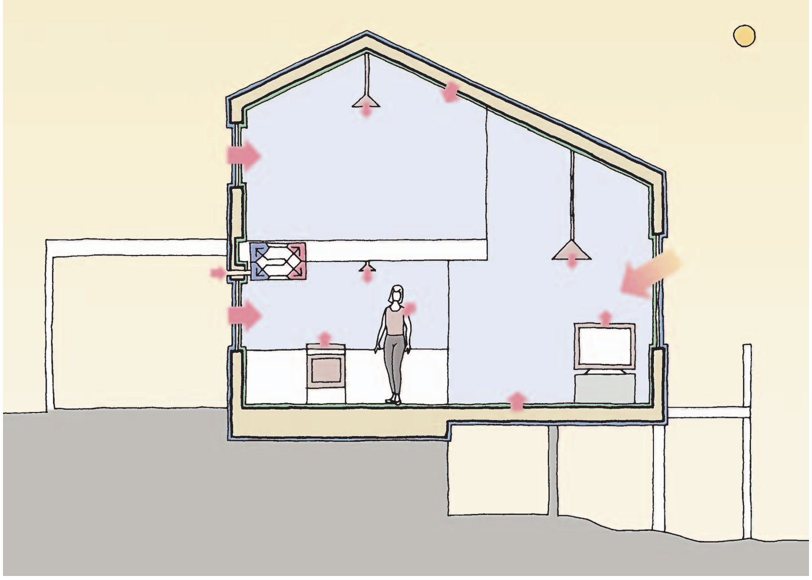
5.1.4 Heating and humidity

In winter, when cold dry air is brought into the home and heated, the relative humidity of the air can drop below comfortable levels and cause over-drying of occupants and the home. During cold dry periods, this can be avoided by temporarily lowering the ventilation rate of the home and allowing moisture levels to increase from occupant and water use within the home. Strategies may include increasing the moisture levels through the use of indoor plants, which transpire moisture into the air, or drying clothes inside (see Chapters 1 and 3 for more detail). Adding moisture through the use of steam humidifiers is energy intensive and difficult to regulate due to the need to heat the water sufficiently to create steam. If additional humidity is required, an atomiser humidified can be a more efficient means of adding moisture to the air.

In a climate with very cold winters, an enthalpy heat exchanger may be a better choice of heat recovery, because it is also capable of recovering moisture from outgoing air, which helps to maintain a more comfortable moisture range indoors (see Section 3.2).

5.2 KEEPING THE HOME COOL AND DRY

Our bodies generate heat as a by-product of their functions, which needs to be rejected to the environment to prevent us overheating. If the ambient temperature is close to our body temperature, there is not a large enough temperature differential for us to effectively reject excess heat and we feel hot. In general, temperatures of up to 25°C provide a comfortable temperature differential between our bodies and the surrounding air for the level of activity and clothing commonly experienced within the home. For most people, short periods of higher temperatures are quite acceptable and indeed can be enjoyable for climates that are cool for much of the year,



Heat flows in the home during hot weather, showing non-useful radiant solar heat gains through the window, non-useful waste heat released from appliances and people, and conductive heat gains across the thermal envelope and through the windows. Unlike heating where heat losses and passive heat gains can be balanced, in hot conditions all of the excess heat that enters the home needs to be actively removed.

but it is beneficial to have the option to keep our homes cooler if required. Passive House certification requires that the home is able to maintain temperatures below 25°C for 90% of the year. For many climates, this can be achieved without the requirement for active cooling. Where active cooling is desired or required, the occupant, working within the energy budget of the home, can regulate the internal temperature to suit their preference.

Just like for heating, creating an effective thermal envelope and airtight layer is essential for preventing unwanted heat gain in summer, particularly on hot days where ambient temperatures are above 25°C. But, just as the envelope is effective at keeping unwanted heat out of the home, it also traps internal heat gains, which eventually need to be purged from the home to prevent overheating.

Key strategies for preventing overheating in a Passive House include:

- solar control through external shading and if appropriate low solar heat gain glass (see Chapter 2)
- minimising internal heat gains from appliances, lighting and hot water (see Chapters 4, 6 and 7)
- heat purging through the ventilation system or windows orientated to collect cool breeze (see Chapter 3)
- actively cooling the home using a heat pump or a heat sink.

Active cooling comes into play, when the first three strategies of keeping the home cool are no longer effective. Let us briefly look at the first three options, before focussing on active cooling.

5.2.1 Managing solar gains

As described in Chapter 2, there is a wide range of operable shading options, both automated and manual, to help managing solar heat gain through windows. Automated systems are typically more expensive and require more maintenance but reduce the reliance on the occupant to remember to use them. Where manual systems are employed, it is important to design them for ease of use. For example, you should choose a system that can be operated from the inside or providing convenient access through operable windows or arranging doors or balconies to allow easy access to the exterior of the window without having to walk all the way around the home.

Many shading options, such as awning blinds, have a significant impact on daylight harvesting. Because solar control is an essential part of creating a comfortable home year round, it is important to orientate windows and select shading systems to minimise their impact on access to views and daylight throughout the year. As discussed in Chapter 2 (and later in Chapter 5), windows on a north–south axis experience less low angle sun during the warm months of the year, making them easier to protect from unwanted solar heat gain without losing useful daylight (see figure on p. 133).

5.2.2 Passive heat purging

During warm conditions, heat needs to be removed from the home to prevent overheating. When external conditions are cooler than the interior, excess heat can be removed by using windows and doors and/or the ventilation system. These conditions may be available even during the warm season: at night-time.

To achieve effective airflow through the home, multiple openings are required. A single open window or door in a home will only achieve local air exchange and provide limited heat purging. Therefore, place multiple openings in appropriate locations to facilitate flows through the building harnessing prevailing breezes. Consideration should be given to providing openings adjacent internal heat sources, such as the ovens and stoves.

In warm areas next to deserts or in cities, avoid orientating openings towards large heat sources and prevailing hot winds, which are often dusty as well as hot. Ideal orientations are towards gentle breezes of favourable temperature, such as towards a sea breeze or summer breezes that pass over a cool garden or wetland before reaching the home.

Multiple openings can also be useful for taking advantage of cool night-time temperatures, so place them in secure locations facing away from potential rain, such as a sheltered door with a secure screen or a high inaccessible window under a building eave. Generally casement or inward top tilting windows are best for capturing airflows.

5.2.3 Active heat purging using the ventilation system

The ventilation system can also be used for purging heat. Many units have a heat exchanger by-pass that allows cool outside air to be brought in and warm inside air to be pumped out. Alternatively, using the ventilation system in supply only mode in combination with an open window or door can actively draw in cool air and push warm air out, which can be an effective means of cooling the house after a hot day or pre-cooling in the morning before a warm day. Using the ventilation system in supply mode, rather than extraction mode, has the benefit of filtering the incoming air and ensuring the cool air is evenly delivered to the living spaces.

Furthermore, using the ventilation system in extraction mode with open windows can be useful for extracting excess heat out of high heat source areas such as kitchens when a lot of cooking is taking place or when there are extra people in the house. For such occasions, it can be useful to have a boost mode on the ventilation system.

As discussed in Section 3.1, another option is to pre-cool the incoming air by drawing it through a cool basement, or series of pipes buried in the ground. For example, on a hot day, warm ambient air can be drawn into a pipe buried in the ground, allowing it to be cooled by the stable ground temperature, before being passed to the ventilation system and into the building. Given the small cooling requirements of a Passive House standard home, in many cases this can be enough to maintain comfortable conditions. Obviously, the installation of the pre-cooling air path adds cost and complexity to the home and requires additional fan power to pass the air through the system. It also introduces the potential for contamination of the air in the event that microbial growth occurs in the pipes or basement during the cooler months of the year.

A brine heat exchanger avoids the potential contamination through passing a brine solution through a series of pipes in the ground and using it to cool the air via a heat exchanger, such as copper coils in the air duct. The heat exchanger coil can also act as a dehumidifier of incoming air, because moisture in incoming air will condense at its cooler surface. As noted earlier, a brine ground-source heat system also has the potential to be a source of heat for the domestic hot water/heating system when ambient temperatures are cold and, as discussed below, can be a heat sink for a heat pump cooling system when the brine itself is not cool enough to meet the cooling demand of the home.

5.2.4 Ceiling fans

Movement of air against the skin increases the rate of heat loss from the body, cooling us down. Ceiling, wall or pedestal fans do not cool the air, but, by creating air movement they can increase comfort in summer. With no air movement, temperatures above 24–25°C feel warm, but, with air movement from a fan, temperatures of 27–28°C can be quite comfortable. Therefore the use of an efficient ceiling or wall fan can delay the need to switch on active cooling, ideally until such point that the outside air has cooled sufficiently to use purging to cool the home. Like all appliances, ceiling fan come in efficient and energy hungry models. DC motor fans are readily available with efficiencies of 400 m^3/Wh (0.0025 Wh/m^3) on high speed and >1500 m^3/Wh (0.0007 Wh/m^3) on low speed.

5.2.5 Heat pumps

Heating and hot water heat pumps capture diffuse heat from the ambient air or an alternative heat source, such as the ground or a water body, and concentrate it to create useful temperatures. For cooling, the heat pump operates in reverse: collecting heat from air inside the home and then pressurises it at the condenser concentrating the heat so it can be rejected to the outside air or alternate heat sink. The cooled refrigerant then passes through an expansion valve, lowering the pressure typically causing the refrigerant to change from a liquid to a gas (evaporate) and cool allowing it to be used to cool the home. This is how both air-conditioners and refrigerators work. Reverse cycle heat pumps are able to provide heating in winter and cooling in summer, with quality models achieving high COPs for both heating and cooling.

Like heating of a home, active cooling via a heat pump can be delivered to the home through the ventilation system or through direct cooling of air within a room using a recirculation fan coil unit. Using the ventilation system removes the needs for an extra fan, allows for even distribution of gentle cooling throughout the home, dehumidification of the incoming air and quiet operation, where as a wall-mounted unit allows for direct cooling of a living space, with easy demand-based

Table 5.1. Example of performance specifications for high performance reverse cycle split systems (Source: Daikin 2016).

Cooling mode		
Rated capacity	2.5 kW	3.5 kW
Power input (rated)	0.42 kW	0.68
Capacity range	0.6–3.9 kW	0.6–5.3 kW
Outdoor operating range	–10 to 43°C	
Heating mode		
Rated capacity	3.6 kW	5 kW
Power input	0.62 kW	0.99 kW
Capacity range	0.6–7.5 kW	0.6–9.0 kW
Outdoor operating range	–20 to 18°C	
General		
COP	5.81	5.05
Power supply	Single phase, 220–240 V 50 Hz	
Refrigerant	R32, zero-ODP, GWP 675	
Max pipe length	10 m	
Max level difference	8 m	
Indoor sound level (hi/lo)	38/19 (dB(A)	42/19 (dB(A)

control and simple installation. Unlike heating, for most climates, cooling in a Passive House is typically only required for a couple of hours at the peak heat of a hot day, so simply cooling the occupied rooms and allowing the ventilation system to scavenge cooling for the rest of the home may be enough to meet occupant comfort requirements.

HEAT PUMP COOLING OPERATING CONDITIONS AND EFFICIENCY

Just like for heating, the efficiency of an air-source heat pump when providing cooling is dependent on the ambient conditions, with the efficiency decreasing as the temperature increases. Many systems claim a COP upwards of 4.5, with high efficiency units claiming COPs as high as 5.8. However, this only reflects the performance under test conditions and the average performance through the cooling season is likely to be lower. During very hot conditions, such as above 35°C, many air-source heat pumps will begin to reduce their cooling output to prevent overheating. At ambient temperatures somewhere above 40°C air-source heat pumps reach a temperature where they can no longer provide cooling, because they are unable to raise the refrigerant temperature sufficiently above the ambient temperature to reject heat. Large commercial systems use cooling towers or wet pads that use the cooling effect of evaporation to cool the refrigerant, effectively combining an evaporative cooler with a heat pump, allowing them to continue to cool at very high ambient temperatures. This strategy is generally not warranted for the small systems used in a Passive House standard home.

For climates where temperatures above 35–40°C are only experienced for a few days of the year, through sensible management of the building envelope, reducing the ventilation rate and cooling of the home either side of the daily peak the envelope should be able to easily maintain comfortable conditions. For example, before a hot day if the house is allowed to cool down overnight by leaving windows open or purging with the ventilation system, then kept cool by active cooling in the morning, it should easily maintain comfortable conditions through the peak of the day, even if the heat pump is unable to produces further cooling. Further cooling can be added in the evening once peak ambient temperatures have passed.

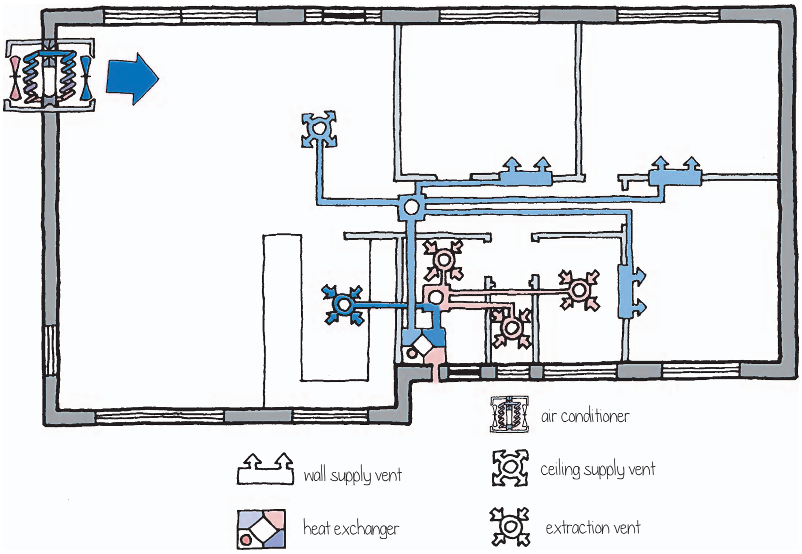
For more extreme climates, heat pumps can be coupled to alternative heat sinks such as the ground or water body, which improves the efficiency and allows it to operate in the peak of the day.

SPLIT SYSTEMS

For mild climates where active cooling is only required for a few weeks of the year and humidity is not a large issue, using a split reverse cycle heat pump system to directly cool the air within the living space can be an economical solution. As discussed for heating, these systems can be uncomfortable where hot air blows directly onto occupants causing drying of the body and the perception of draughts. However, in a warm room, cool air movement can improve the perception of comfort without the need for over-cooling. For example, where a split system providing a stream of cool air into the room, the added comfort of air movement may mean that the room only needs to be cooled to 26°C to achieve occupant comfort. Furthermore, in a well-insulated and sealed home, often internal heat sources such as people, cooking and appliances, which are typically located in the living areas, are a significant source of overheating on hot days. Therefore it is beneficial to locate the cooling unit in the living space where these heat sources typically occur.

When used in a home with a central heat recovery ventilation system, cooling from the living space can be distributed via the heat exchanger, helping to moderate temperatures throughout the home. Where a split system is used for on-demand comfort cooling in the living space, and heating is provided through the ventilation system, such as through a hot water coil or electric element, the split can provide extra flexibility to the heat of the home. For example, during the cold months, general heating of the home to 18°C can be provided across the home via the ventilation unit with the split system topping up the temperature in the occupied area to 21+°C as required. The split can also be useful for boosting the heating system if the home has been left unoccupied and been allowed to cool down. In summer, on a hot afternoon, the living room unit can provide conditioning directly to the occupants and help to maintain stable conditions throughout the home, and then be switched off in the evening when no longer required.

Domestic fan coil units typically come as a head unit that mounts on the wall and draws air from the top of the unit across the coil and blows it out into the room. Ideally, the unit is located to avoid blowing directly onto the occupants and to maximise the distribution of cool air across



Example of home cooling using a split air-conditioner, with cooling provided into the living areas, which are the mostly commonly occupied rooms during the hottest parts of the day, with cooling distributed to the rest of the home via the heat recovery ventilation system.

the area being cooled. For example, locating the unit just below ceiling height with an uninterrupted path across a flat ceiling can harness the Coanda effect to help throw the air across the ceiling, encouraging it to mix with the room air before falling down to the occupied levels. Some manufacturers have designed their units to take advantage of the Coanda effect and claim an air throw of up to 14 m.

Minimising the distance between the head unit and the condenser, and ensuring all pipes and connections are insulated with a vapour-tight insulation material integrated into the airtight layer and the thermal envelope of the home, is essential to prevent condensation and energy loss. The head unit itself must have a condensate drain to allow condensation that occurs on the coil to drain from the unit out of the home. As per the ventilation system, this drain needs to be airtight, so a ball valve or equivalent should be used. Another consideration of these types of units is the noise levels from the fan coil/head unit. The Passive House standard specifies maximum acceptable internal noise levels of 25 dB(A) for acoustic comfort, which is above the high fan speed noise levels for many units.

COOLING VIA THE VENTILATION SYSTEM

For climates where cooling or dehumidification are regularly required to maintain internal temperatures, inclusion of a cooling coil in the supply air duct of the ventilation system can be a practical solution. Where heating in the winter and cooling in the summer are required, incorporation of a reverse cycle heat pump with the ventilation system allows both needs to be met.

Where refrigerant from the heat pump is used directly in a coil to heat or cool the air stream (often referred to as direct expansion or DX coils), the airflow over the coil needs to be managed to ensure the heat pump cycle is balanced. In larger buildings, cold water is often generated to provide cooling to the building, avoiding the control complexity of using refrigerant directly for cooling. For most homes, the extra cost and complexity of inclusion of a cold water system is not warranted, but there are compact units available that provide both hot water and cold water for use in the home.

The inclusion of a cooling coil in the ventilation unit allows for comfortable gentle cooling of the home and for the heat pump to be sized appropriately for the load. For humid climates, this configuration also allows moisture to be stripped out of the incoming air, allowing the air to be dried before entering the home. During warm conditions, our body uses evaporation from our skin to help reject heat, so warm humid air feels warmer than dry air of the same temperature. As such, being able to remove some humidity from the incoming air reduces moisture build up in the home and can provide comfort without the need for over-cooling the air. This moisture needs to be drained away from the coil, so the system needs to include a condensate drain and appropriate valve to prevent air leakage. For most climates, a ventilation system with an integrated heat pump and coil for cooling provides adequate balance of cooling and dehumidification using a standard cooling coil operation.

5.2.6 Dehumidification

Dehumidification occurs when the cooling coil is below the dew point of the air, causing water vapour to condense to liquid on the coil. This phase change releases latent heat that is absorbed by the coil, making dehumidification an energy-intensive process and meaning that a larger coil/cooling capacity is required to dehumidify air than a coil just for cooling. Condensation on the coil also reduces the heat transfer between the coil and the air because the water forms an insulating layer between the metal coil and the air. Therefore, for climates where regular dehumidification is required, the coil capacity needs to be sized for the cooling and dehumidification load.

Some dehumidification can be achieved with a minimal effort by using a brine ground-source heat exchanger in the supply air stream (see Section 3.4.2), but the effectiveness of this technique is limited by the ground temperature. Where this is insufficient, a heat pump can be used to provide cooling to the coil.

For conditions where the air is warm but not overly humid, the ideal situation is to cool the air without causing energy-intense dehumidification. This can be achieved by maintaining the temperature of the coil above the dew point of the air. For most domestic systems, the coil temperature is fixed, so this requires selecting a suitable unit and configuring it appropriately. Conversely, if the air is a mild temperature but uncomfortably humid, the ideal situation is to strip moisture out of the air without over-cooling the air, causing it to be uncomfortably cool for the occupants. One approach to achieving this is to pass a portion of the air over a cold coil: for example, having a coil on one side of the duct, allowing moisture to be stripped out of the air that passes over the coil and then remixing the cooled air with the uncooled air to warm it backup. Both strategies obviously require more design complexity, selection of an appropriate unit, configuration and control.

In consistently humid climates, an enthalpy wheel heat exchanger ventilation system can be used to reduce the ingress of humidity through the ventilation system. In this case, cool dry air exiting the home passes over a desiccant, such as silica gel. The exiting air dries the silica gel, cooling it down. The wheel spins around into the path of the incoming warm moist air, cooling the air and absorbing moisture. The warm moist wheel then spins back into the path of the cool dry exhaust air, completing the cycle. A cooling coil located after the heat exchanger can then trim the temperature and provide further dehumidification of the air before it passes into the home.

In climates that only experience high humidity from time to time, a standard air-to-air heat exchanger heat pump with a cooling coil or a split unit is likely to be sufficient for managing comfort. During a high humidity event, the airflow rate can be temporarily reduced and the thermostat lowered to increase dehumidification of the air.

High humidity events can also be managed using a portable plug-in dehumidification unit, which can be simply switched on or off when required. These appliances condense moisture from the air, generating liquid water and heat as a by-product. The water can simply be poured down the drain, but, like a refrigerator, the heat from the dehumidifier is released into the room, which will put additional pressure on the cooling system during hot conditions. Because dehumidification is an energy-intensive process, it is essential to ensure to select a high efficiency unit and use it appropriately.

For most climates and homes, these approaches should maintain the comfort and health of the home during humid conditions. However, if you are building in a location with consistent high levels of humidity and have particular humidity level requirements for activities such as storing fine art, rare books or commercial printing, then a more sophisticated approach may be warranted. In these cases, consulting a mechanical engineer experienced in managing ventilation and cooling systems for your climate is recommended.

5.2.7 Evaporative cooling

Direct evaporative coolers work by passing warm air over a wet surface causing the water to evaporate cooling the air. This process adds humidity to the air, which then needs to be removed from the home. In hot dry climates, this may be acceptable, but in humid climates evaporative cooling provides limited benefit and adds complexity in the requirement to remove moisture from the home. Indirect evaporative cooling uses evaporation to cool the air then uses an air-to-air heat exchanger that allows the cool moist air to cool hot dry air without moisture exchange, which is then supplied to the home. In general, it is not straightforward to integrate these systems with a well-sealed home or a central ventilation system, and so careful consideration is needed, with some expert advice, before application.

5.2.8 Thermal mass

The use of thermal mass in the home does not change the overall heat balance but can delay when the peak occurs. For example, an exposed concrete slab can absorb a large amount of heat during a warm afternoon, helping to moderate temperatures until the slab reaches similar temperature to the air. At this point, the thermal mass is holding a large amount of heat that will be released back into the house once the air temperature cools down.

In a traditional home with poor insulation and sealing, located in a climate such as the desert that has predictable hot days and cold nights, heat leaks into the house during the day and is absorbed by the thermal mass, keeping the home cool. As cool air leaks into the home at night, the heat is released, moderating the temperature of the home and resetting the thermal mass. In less predictable climates where multiple hot days with warm nights may occur in a row, the charged thermal mass continues to hold the heat preventing the house from cooling down and can cause the house to remain hot well after the outside air has cooled. Under this scenario, cooling the house down requires a large amount of energy to be expended to first cool the thermal mass and then the home.

Within an effective thermal envelope and airtight envelope and shading, the heat flows across the envelope are small and slow, which minimises the impact of external temperature peaks and provides consistent internal temperatures. Therefore a highly effective envelope limits the potential benefits of thermal mass. Thermal mass can help to absorb any excess heat, but without purging or active cooling, this heat will be trapped within the thermal envelope combining with internal heat gains potentially causing the home to overheat. For the heat to be extracted by purging, cool outside air needs to be brought in, to cool the internal air temperature for sufficient period of time to cool the thermal mass. This relies on predictable cool overnight conditions and careful management of openings and ventilation systems by the occupant. For example, where windows are used to allow cool overnight air into the home, there is the potential for over-cooling and discomfort adjacent to the window. Alternatively, if the ventilation system is used to purge the heat above and beyond the ventilation requirement of the home, then the fan energy used to cool the thermal mass may be greater than the cooling energy saved during the hot conditions, which tends to correlate with peak solar output.

Furthermore, the heating and cooling systems of Passive Houses are generally very small, meaning if the mass is overheated or cooled it will take a long period of time to actively adjust the temperature of the mass. For example, if the house has become hot while the occupants are away, it will take an extended period and significant energy to cool the mass.

In general, due to the complexity of design, marginal benefits, unpredictability of weather patterns, reliance on occupant behaviour and potential to have a negative impact on energy consumption and comfort, the addition of mass for thermal management in Positive Energy Homes is something that should only be adopted with careful consideration and experienced expert guidance.

SUMMARY

Heating

Within a Passive House envelope, only small adjustments to the indoor conditions are required to maintain comfort. Active management of the building envelope, through use of windows to collect solar energy, can eliminate for active heating most of the year. Where additional heat is required, the ventilation system is the ideal method of distributing heat around the home via the heat recovery unit. For very small heating demands it is hard to go past the low cost and simplicity of an electric heating element in the supply air duct. For larger heating requirements, the most efficient heating is through the use of a heat pump, either using the domestic hot water heat pump or a reverse cycle unit that can also provide cooling. Heat from a heat pump can be provided to the supply air duct or directly delivered into living spaces using a fan coil unit. For climates where extreme ambient temperatures are experienced, coupling the heat pump to a ground or water heat source/sink can improve the efficiency and seasonal performance of the system.

Cooling

As with all homes, and particularly in a well-insulated and sealed home, managing unwanted solar heat is essential to preventing overheating. When ambient conditions are cool but indoor temperatures are warm due to excess internal and/or solar heat gains, heat can be removed from the home through bypassing the heat exchanger and using the ventilation system to provide cool outside air and extract warm internal air. This strategy can also be used in conjunction with windows. When ambient conditions are warm and the inside is also warm, heat needs to be actively removed from the home to prevent overheating. This can be done using a ground-source brine heat exchanger to pre-cool the ventilation air or using a heat pump in cooling mode to cool the ventilation air or directly cool air within the home. For regions with high humidity, an enthalpy heat exchanger or heat pump cooling may be required to remove excess moisture from incoming air. For dwellings built to Passive House standard, cooling demands will be low and, when covered by a high efficiency ground-source heat exchanger or heat pump, the small cooling energy requirements should be easily met by rooftop solar.

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CHAPTER 6

Light, views and connection with the environment

Light is the primary way in which we interact with the world. It provides us with a direct connection with the surroundings, allows us to navigate around our environment, appreciate physical beauty, conduct fine spatial tasks and helps to regulate our body clock. Illumination is a fundamental service in the home and, when done well, can be a great source of enjoyment and inspiration. In particular, daylight has an important role in helping to regulate our circadian rhythms and moods, as well as providing great colour rendering and daily colour temperature variation. Its many benefits that come without a price tag, making it our first choice in lighting. On the down side, daylight is only available when the sun is up, and direct sunlight can cause glare and carries large amounts of heat with it. Unfortunately, many beautifully day-lit homes suffer from chronic overheating, high cooling loads, glare and cold conditions in winter due to overuse of glass resulting in poor thermal performance (see photo on p. 4). Compared with daylight, electric lighting has the advantage of being easy to control, but it is hard to recreate the many subtle benefits that sunlight inherently provides. Furthermore, electric light obviously consumes electricity, which eventually ends up as heat in the home. As such, to create a light-filled engaging home, we need to optimise our openings to capture the right kind of daylight and distribute it deep into the home (see figures on p. 127), exclude unwanted solar heat gain and then provide engaging efficient and easy to control electric lighting solutions for when the sun is not available.

To meet this challenge, windows need to be appropriately orientated, shaded and individually sized to capture low heat, diffuse daylight in the areas of the home where it is needed. We all love some direct sunlight, especially in winter, but there are times where it can cause overheating and glare, so our home needs to include methods to exclude direct sunlight when required.

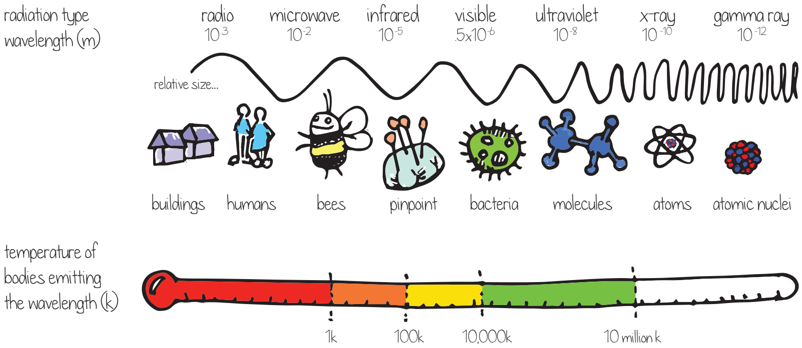
The method of achieving this balance will be different for every location and home, but, as a starting point, the window area of a home should be in the order of 10–20% of floor area, with the majority located on the equator-facing side of the home. Equator-facing windows have access to predictable year-round light and offer the potential to capture useful heat in winter while being easily shaded in summer without undermining the capture of useful daylight. Windows should be located high on the wall with suitable shading from direct summer sun (see figures on pp. 127 and 130). Furthermore, light scattering shelves can be used to block summer sun and bounce diffuse light up on to the ceiling and deep into the home. East- and west-facing windows should be minimised because they are hard to regulate for heat gain and glare without also compromising daylight. Windows facing away from the equator are a great source of diffuse light but offer little potential for useful heat gain, so they can be a net heat loss in winter.

Electric lighting needs to be as efficient as possible to reduce energy requirements and unwanted heat gains. For most applications, this means efficient LED bulbs and high efficacy luminaire. To achieve comfortable and beautiful lighting scenes, we need to ensure the colour quality and temperature of the light is suited to the intended function of the space. Efficiency and texture can be achieved through the use of direct light over task areas such as benchtops and more diffuse or reflected light to fill the space in general areas where general activities such as moving around the home or watching TV are conducted. The lights should be configured so they are intuitive to control and flexible enough to serve a range of functions and lighting scenes, depending on the activities being undertaken and our mood.

In this chapter, we explore how our bodies interact with light and the various light sources available to provide insight into the importance of designing lighting for the occupants. We then cover the design principles of creating a daylight-filled home that doesn't cook in summer and freeze in winter. Finally, we explore the exciting world of creating and controlling light using LEDs.

6.1 HOW WE PERCEIVE LIGHT

What we refer to as 'light' is only a small section of the electromagnetic spectrum. The spectrum includes very high energy short range radiation such as X-rays and gamma rays, which have incredibly short wavelengths (smaller than an atom) and are able to travel through the space between low density matter including our bodies. At the other end of the spectrum are radio waves that have extremely long, low energy wavelengths (10 cm–1 km) that can travel over very long distances, allowing us to communicate around the world and with spacecraft at the farthest reaches of our solar system.

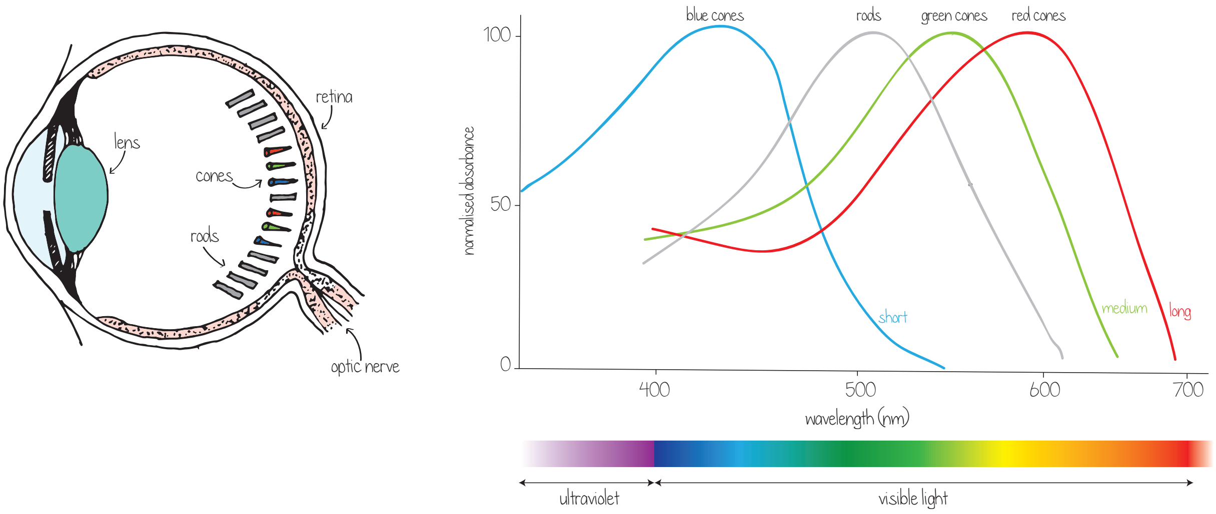


Electromagnetic spectrum, showing the relative wavelength size and black body temperature of radiation emitting surfaces.

The visible section of the electromagnetic spectrum sits between the UV and IR wavelengths. As the names suggest, the UV sits just beyond the shorter wavelength higher energy 'violet' part of the visible spectrum and infrared at the edge of the longer wavelength, lower energy 'red' section of the visible spectrum.

When we stand outside, we feel the range of electromagnetic radiation contained in sunlight as energy absorbed by the molecules of our skin and converted into heat. At the back of our eyes, we have light-sensitive molecules that are excited by specific wavelengths within the visible spectrum. When activated, these molecules stimulate a complicated network of nerves, sending messages to our brain about the wavelengths observed and the relative intensity of the absorbed energy. The brain then does the incredibly complex processing required to convert this information into an image of the world around us. This task is so complex and so useful to survival that the ability to interpret light is thought to have been a major driver in evolutionary brain development, facilitating the emergence of more complicated brain function and what we now call intelligence. We have two types of light-sensitive cells: rods and cones. At the focal point, where the light is most intense, our eyes are lined by cones, which contain the three wavelength-specific light-sensitive molecules that allow us to distinguish different colours of light. Around the cone cells at the periphery of the focal point are rods cells, which are far more sensitive than the cones to the presence of light and allow us to see in low light. Rods are not able to distinguish the wavelength (colour) of light, which is why we can see shapes, but not colour, in very low light conditions. Furthermore, given the location of the rods at the edge of the focal point, our peripheral vision, rather than our focal vision, performs better in very low light conditions. Rods are most sensitive right in the middle (green) of the visible spectrum.

Understanding the nature and functionality of our eyes helps us to design the appropriate lighting scenes for the intended function of the space. For example, where colour is important such as in a home painting studio, the intensity of light must be high enough to stimulate the cone



The human eye contains two types of light-sensitive cells: rods and cones. The three types of colour-sensitive cone cells work together to allow us to see colour across the visible spectrum, while the non-colour-sensitive rod cells allow us to see in low light conditions, with greatest sensitivity in the middle (green) of the visible spectrum.

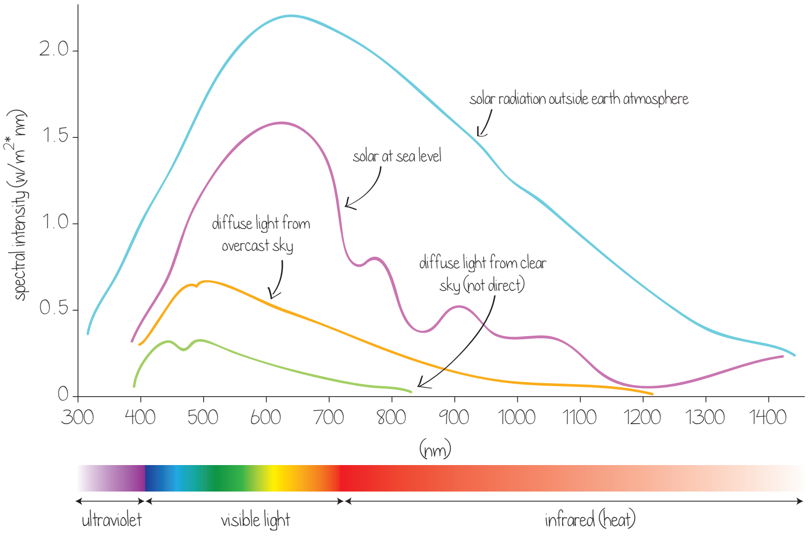
cells and provide consistent balanced intensity across the visible spectrum to allow our eyes and brains to accurately interpret the colour of the painting. When designing for low light requirements, knowing that rods are less sensitive to reds and purples is useful information.

The region we define as the ‘visible spectrum’ includes only the wavelengths of light that can be readily detected by the colour-sensitive cones.

The sensitivity of the three types of colour sensors are centred around blue, green and red. When we look at an object that is blue, the blue sensor is stimulated, sending a message to our brain telling us the object is blue. When all three sensors are stimulated equally, our brain interprets the object we are looking at to be white. When only two of the sensors are stimulated our brain will interpret the colour (e.g. we see simultaneous green and red as yellow). Through analysing the relative stimulation of the three colour sensors, our brain is able to distinguish ~1 million colours across the visible spectrum.

The sun emits radiation across the electromagnetic spectrum, but by the time this radiation reaches the Earth’s atmosphere, much of the short-wave radiation has been lost or filtered by the Earth’s magnetosphere, which deflects the majority of the high-energy radiation (greater than UV). This interaction between high-energy radiation and the magnetosphere causes the spectacular northern and southern lights.

As the sunlight passes through the atmosphere, a layer of ozone molecules at the top of the stratosphere absorbs a large portion of the remaining UV light. Ozone and other molecules in the atmosphere also absorb microwave and significant sections of the IR spectrum, converting the energy to heat. The remaining energy that reaches the Earth’s surface peaks across the spectrum that we define as visible. The sensitivity of our eyes to visible light is therefore effectively an evolutionary signature, resulting from the filtering effect of the Earth’s atmosphere on the radiation from our sun.



Spectrum of sunlight at the upper atmosphere, direct sunlight at sea level under a clear sky, direct light under an overcast sky and indirect light under a clear sky.

6.2 LIGHT INTENSITY AND GLARE

Our ability to focus and interpret images is a function of the amount of light available, the size and contrast between objects, and the time of exposure. Therefore, we can interpret the detail of static objects under lower light by looking at them for a longer period of time, allowing our eyes and brains enough time to collect sufficient light stimulation to resolve a picture of the object. However, to see fast moving objects clearly, we need sufficient light intensity to ensure enough information is collected in the short exposure time available. In general, for very fine tasks or tasks that require clear colour definition, high light intensity is beneficial, whereas, for general tasks, such as avoiding objects as we walk down a hallway, low light, is sufficient.

Our eyes adjust to the variation in light intensity throughout the day and night by adjusting the aperture (opening size) of our pupils. In bright, light the pupil constricts, restricting the amount of light that enters the eye, with the resulting narrow beam of light falling on the colour-sensitive cone cells. In low light conditions the pupils dilate, maximising the intake and angle of light entering the eye, facilitating stimulation of the more-sensitive rod cells. This allows us to see across an incredible diversity of light intensity, from full sunlight with a light level as high as 100 000 lx through to the very low light levels of a moonlit night of less than 1 lx (see Table 6.1). Lux is a measure of the intensity of light in lumens/m^2 (see Table 6.2).

In very bright reflective conditions, the intensity of light can cause discomfort as too much light enters our eye, over-stimulating the sensors, even when the pupil is constricted. Discomfort can also occur when there is significant contrast in the light intensity within our field of vision. For example, if a small patch of sunlight is shining into an otherwise dark room, the pupil may set itself to the average light level, meaning there is not enough light entering the eye to resolve detail

Table 6.1. Example light levels.

Conditions	Lux
Moonless, overcast night sky	0.0001
Moonless clear night sky	0.002
Full moon on a clear night	0.27–1
Typical living room	50
Kitchen bench or desk	320–500
Sunrise or sunset on a clear day	400
Under an overcast sky	1000
Full daylight	10 000–25 000
Direct sunlight	32 000–100 000

Table 6.2. Key terms and performance expectations.

Measure	**Abbreviation**	**Definition**	**Target value**
Colour RENDERING INDEX	CRI	The ability of a light source to produce the entire visible spectrum, where 100 is perfect white light.	>85
Lumens	lm	A measure of visible light output from a light source. A traditional 100 W incandescent light bulb produces ~1600 lm.	Varies with lighting requirement
Lux	Lx	The luminous intensity of light over a defined area, measured in lumens/m^2.	Varies with lighting requirement
Lumens per watt	Lm/W	Lm/W is a common description of the efficiency of a light source, describing the number of lumens a light source produces per watt of electricity.	>100 (lamp)
Lamp hours	LH	Describes the typical number of hours a lamp will operate before failing, or in the case of LEDs, before it reaches L70.	
L70	L70	The number of hours of operation before the output of an LED drops to 70% of its original output. L90 is 90%, L50 is 50%, etc.	
MacAdams ellipses steps	MAC Steps	Because LED strips are made up of a series of LED chips, ensuring there is an acceptable colour variation between the chips is important; this is described by MacAdams ellipses steps.	< 4
Efficacy, of luminaire (fitting)	Lm/w	Efficacy describes the amount of usable light emitted from a light fitting.	> 80 (luminaire)

in the dark areas. At the same time, there may be too much light entering the eye from the patch of sunlight causing over-stimulation. Discomfort caused by high intensity or high contrast is generally referred to as glare. To avoid glare in buildings, it is important to avoid over-lighting and to limit the variation in intensity across our field of view. In general, the intensity of light in the field of view around a task surface should not vary by more than 10-fold.

A small area of direct sunlight reflecting off a glossy benchtop creates discomfort and makes resolving details across the less intensely lit field of vision difficult.

Another common example of glare is exposed light bulbs where the intensity of the lamp is a sharp contrast to the area around it. This can be easily overcome by hiding the light source from direct line of sight, through recessing it, bouncing the light off a mat surface or covering it with a diffuser. Direct sunlight is another common source of glare in buildings, due to its intensity (>30 000 lx) relative to typical indoor light conditions (<500 lx). There are many ways to help manage glare from sunlight, including diffusion before it enters the space through tinted glass or blinds, or using large windows on multiple sides of the room that increase the overall light levels of the space, reducing the contrast. To manage glare and solar heat gain, a useful technique is to capture indirect sunlight through windows facing away from the equator or through the use of light shelves (see Section 6.5 and figure on p. 130) around windows that block direct sunlight and bounce diffuse sunlight up onto the ceiling, distributing even light deep into the room.

6.3 THE COLOUR OF LIGHT

Understanding the colour variation of sunlight throughout the day, and our relationship to it, can help guide sensible layout of buildings and the use of appropriate light colouring to suit the function of the space. As we all know, the sun rises in the east and sets in the west, and as it travels across the sky the ‘temperature’ of the light changes throughout the course of the day and is influenced by the weather.

The temperature of light (in Kelvin) describes the colour balance of white light, with blue-white light described by higher temperatures (5000 K) and red/yellow-white light by lower temperatures (2500 K). Incandescent light bulbs work by heating a tungsten filament to a temperature where it radiates energy as visible light. When the light bulb is switched on and the filament warms up it begins to emit IR radiation; then as it warms further it also emits red/yellow light, then green as it warms further and when the bulb reaches operating temperatures it is emitting light from IR through to blue. For non-incandescent light sources such as LEDs, the colour temperature is not determined by the temperature of the light source, but colour temperature is still used to describe the balance of red and blues in the light. The scientific colour-temperature of the light is at odds to how people traditionally describe the colour of light, where light with a red biased colour balance (below 3000 K, low temperature) described as warm and blue biases (above 5000 K, high temperature) described as cool.

Examples of colour temperature and lamp types. From left to right: a 6500 K (cool white) compact fluorescent; a 3000 K (warm white) LED; and a 2500 K incandescent.

At the top of the atmosphere the colour temperature of sunlight is around 5900 K, under a clear sky K at midday it is between 5500 and 6000 K, under an overcast sky 6500 K, or it can be as low as 2000 K at sunrise or sunset. This variation in colour is due to different parts of the atmosphere interacting with light in different ways. For example, a cloudless atmosphere tends to scatter blue light causing the sky to appear blue. Morning and evening light is warmer, due to the low angle of the sun relative to the atmosphere, the light has to travel through more atmosphere before reaching us, scattering more blue light and shifting the temperature towards the red end of the spectrum. Conversely, clouds tend to absorb more red and infrared, increasing the temperature of the light towards the blue, as such, we tend to associate blue light with cooler conditions.

These variations in colour temperature throughout the day help to set our circadian rhythms. The start and end daylight is typically warm (red) and low intensity (low colour temperature), which is also true of fire and candles. Our brain associates this type of light with rest, so exposure to warmer light before bed helps prepare the brain for sleep. In contrast, mid-morning sun is bright and ‘colder’ (bluer), which stimulates the brain, promoting wakefulness and concentration.

For building design, the most obvious application of these principles include placing bedrooms on the east of a building, which, although sometimes at odds with modern life, fills the room with morning light promoting wakefulness and helping to stimulate the brain. At the end of the day, avoiding blue lights such as computer screens and using warm soft lighting in bedrooms helps to promote sleep. This can also be applied to electric lighting, with brighter higher colour temperature light being used in areas where concentration is required, and softer ‘warmer’ colour temperatures for relaxation areas such as lounge rooms or bedrooms. For multi-use areas, lights with different colour temperatures or fittings that allow the colour balance to be altered can be used to set the colour temperature over the course of the day to suit the function.

6.4 USING LIGHT

Within buildings and spaces light provides many functions:

Light to see by – this is often the first thing we think of when it comes to lighting, and sadly it is often the last consideration in lighting design. Lighting to see by can be achieved through a variety of means, from generic bulk lighting of a space based purely on delivering a particular lux level evenly across a floor plan, to the more considered provision of light where task are being undertaken, such as using pendant lights above tables or a lamp on a desk.

Light for texture and pleasure – light can be used within a space to create contrast and rich patterns that change throughout the day providing variety and stimulation for the building occupants. A great example of this is sunlight that is being filtered through the leaves of a tree, where the patterns ripple with the wind and move around the room as the sun moves across the sky.

Light for texture and pleasure (top), light to see by (bottom left) and light to direct and highlight (bottom right).

Light to direct and highlight – light is often used to draw our attention to an entrance, features of the building or to guide us along a path or through a building. Many churches have great examples of using natural light to direct the congregation's attention towards the altar. Lighting of pathways or hallways can subconsciously guide us through a space. Using light to direct can also be an efficient means of only providing light where it is required, reducing the need for wasteful bulk lighting.

Light to create ambience – the selection of light intensity and colour can be incredibly effective in setting the ambience of a space, which can be varied throughout the day. For example, bright morning daylight in the kitchen and dining room can create a refreshing space to enjoy breakfast and then switched to soft warm light over the table in the evening to create an intimate space for a romantic dinner.

Light to define space – within an open or semi-open area, light can be used to create a sub-space or to separate functionally different areas within a larger space. An example of this is providing pendant lighting or candles at tables in a restaurant to create the feeling of private dining spaces within a large open area. Light can also be used to separate functional spaces within an open area; for example, in an open living space, soft wall and ceiling washing light can be used to separate a relaxing lounge area from a well-lit vibrant kitchen and dining area.

6.5 LIGHTING THE HOME WITH DAYLIGHT

Although much focus is put on the light source, it is only one part of delivering effective, efficient and engaging lighting. The careful selection and placement of windows and light fittings appropriate to the space plays a major role in the comfort, feel and efficiency of the home.

6.5.1 The joy of daylight

Access to daylight in a building is an essential part of creating an engaging positive building. It provides connection to the outside world through views, reference to time of day, current weather conditions, and so on. In addition to the subconscious benefits, exposure to daily light cycles, the constant changes in intensity and direction can be used to create engaging texture and moving patterns within the home that vary throughout the day. The many benefits of daylight have been documented in a wide range of studies, which show positive correlations between learning outcomes in schools, healing in hospitals and sales in shops that are naturally lit.

Obviously, daylight needs to pass through the building envelope via a transparent element. As discussed in Chapter 2, transparent elements generally have lower thermal performance and have the potential to facilitate large amounts of solar heat gain. As shown in the figure on p. 120, direct sunlight contains a significant amount of infrared energy, which provides no lighting benefits but carries significant heat. Because the intensity of direct daylight (10 000–1 000 000 lx) is much greater than the lighting levels required to make a building usable and pleasant (100–500 lx), in most cases there is no need to use direct sunlight to light a space. Indeed, capturing just 3–4% of the available light provides ample lighting for most tasks. For example, 3% of 10 000 lx is 300 lx. The ratio of natural light captured in an area of the home is often described as daylight factor (DF), which is the ratio illuminance available indoors relative to the outside illuminance. For example, if the interior is achieving 300 lx when there is 10 000 lx available outside then the DF would be 3. Building codes typically recommend the following minimum daylight factors (across the majority ~80% of floor area): 2 for kitchens, 1.5 for living spaces, 1 for bedrooms and 0.5 for circulation spaces. As long as suitable glare and heat control is included, we recommend that you target at least double these factors to create a light-filled efficient home, with a daylight factor of around 5 considered well lit.

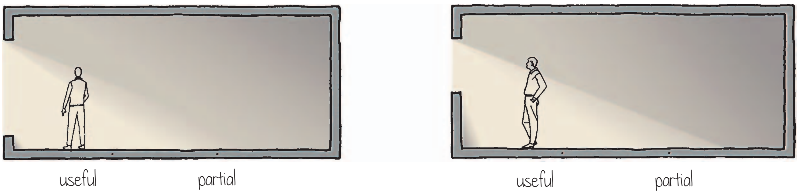
Indirect daylight, which is sunlight that has been scattered or reflected contains very little infrared and much less overall energy (see figure on p. 120). In general, the infrared portion of sunlight is absorbed and converted to heat in the environment in the scattering or reflection process. The other benefit of diffuse indirect light is that it is has a more even distribution of horizontal and vertical light intensity, meaning it can light both horizontal and vertical surfaces at similar intensity, providing very practical light for tasks and minimising glare and shadow issues.

Indirect light is readily harvested from windows facing away from the equator or through the use of light reflecting building elements such as horizontal light shelves or louvred blinds. These elements can also help to create an even distribution of light across the floor plate and help creating diffuse evenly lit task-friendly spaces. Small patches of bright sunshine in areas where detailed tasks are not being undertaken, such as entranceways or sitting rooms, can be useful for creating texture and variety within a space. For example, direct sunlight that has been filtered through the branches of a tree or through an external shading device creates moving patterns over the course of the day that resonate with the human spirit. As such, designing for natural light is part science and part art, both of which require time and a good deal of experience to do well.

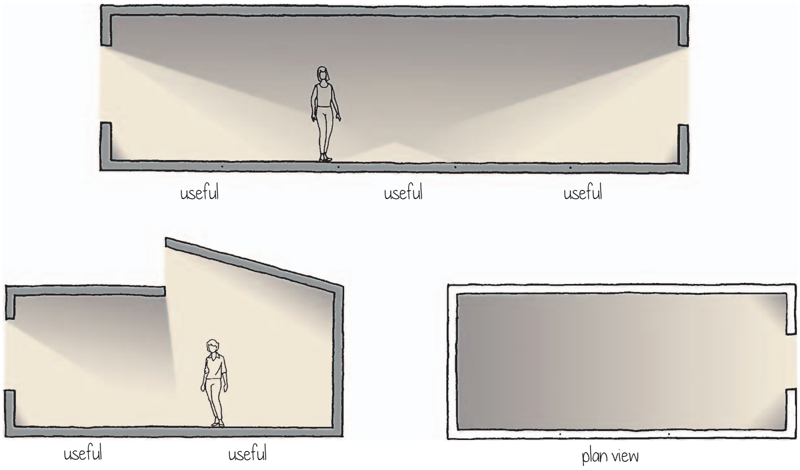
6.5.2 Capturing daylight

The depth to which light is able to penetrate into a room is dependent on many variables, including the time of day, the angle of the sun and the intensity of the light. When designing for daylight, the size of transparent elements is important (discussed in detail below), but the height of the top of the window relative to the roof and floor is the crucial factor in maximising the capture of useful light and the depth to which light penetrates into a space. For example, a small window located high on a wall may be more effective at lighting a space than a larger window that is close to the floor. As a general rule, the penetration of usable light into a space is 2 to 2.5 times the height of the top of the window above the floor, equivalent to drawing a line at an angle of 30°C from the top of the window down to the floor. These are useful design guides for positioning windows and designing the depth of rooms. For example, to adequately light a room during daylight hours using a single window that has a height above the floor of 2.5 m, the room should not be more than 5–6 m deep relative to the window.

The lower section of the window closest to the floor only harvests useful light on the adjacent floor, which is generally adequately lit from higher sections of the window anyway. Therefore floor-to-ceiling windows offer very little light harvesting or winter heat gain advantage over windows positioned 0.8 m above the floor. Furthermore, floor-to-ceiling windows can be quite challenging to manage from both a glare and solar heat gain perspective in summer, requiring



Light distribution into a room is proportional to the height of the window above the floor. Extending the window down towards the floor provides limited additional daylight while increasing the potential for excess solar heat gain and conductive heat loss/gain across the window.



Light from two sides and from high clerestory windows facilitates daylighting of deeper floor plans and provides more even light distribution. Plan view (from above) of a window showing light spreading horizontally from windows at an angle of ~45°.

large shading devices. Large windows can also encourage draughts, with air next to the window cooling and falling down the glass.

In contrast, the width of the window is important for effective light distribution, with light spreading horizontally into the room at an angle of around 45°. Therefore, to create windows for light harvesting and views that are easy to control for solar heat gain in summer and to avoid convective heat loss in winter, wide high windows are much preferable to tall narrow windows. Another key factor in light distribution is the interior surface colour, with windows adjacent to light coloured walls providing far greater light distribution into the space.

LIGHT FROM TWO SIDES

The ideal situation for light distribution is to have natural light available on at least two sides of a room or space, creating a more even distribution and greater consistency across the course of the day (see bottom figure on p. 127). As noted earlier, this also helps to avoid glare through increasing the light levels across the floor and avoiding the perception of a single bright source of light in an otherwise dark room. Where unobstructed windows are provided on opposite sides of a room, if the top of both windows is 2.5 m above the floor then a space as wide as 10–14 m can be effectively lit using natural light for a significant portion of the day.

CLERESTORY WINDOWS AND SKYLIGHTS

Clerestory (or clearstory) windows are effectively windows that are at the top of the ceiling, typically above the standard wall height of the room (see photo below). The use of skylights or clerestory windows can be an effective means of bringing light into deep floor plans or areas of the building that aren't easily lit by wall windows, such as internal passageways. Because the opening is high up, even a relatively small opening can readily provide a large amount of light across a broad area. These types of light openings can be a source of glare if the space is not well lit or openings are small and/or exposed to direct sun. This can be avoided through the use of multiple and/or larger diffuse openings, such as windows facing away from the equator.

Clerestory windows throw light high and deep into the room (see external view of these windows in photo on p. 131) (Photo: David Halford).

Like all windows, these need to be managed for excess solar heat gain and glare. However, given their height and access to unobstructed sky, they can be incredibly effective at harvesting and distributing light around the space using a relatively small window area. The classic application of these type of windows in large spaces is in warehouses, with clerestory windows facing away from the equator in a saw-tooth roof, providing diffuse light across large floor plates. The disadvantages of clerestory windows are that they increase the surface area of the building envelope, increasing costs and the potential for heat loss.

Skylights are an effective source of daylight harvesting. Covering just 10% of the ceiling in skylights spaced at an equivalent distance to the height of the room can provide very high light levels with uniform lighting across a floor plan. However, skylights are particularly challenging to manage for solar control and introduce complications to the creation of an effective thermal and airtight envelope. This can be managed with some effort through minimising their exposure to direct sunlight through shading or orientation and through the use of light diffusers or spectrally selective glass. However, this still leaves the challenges of thermal bridging and preventing air and water leaks. As such, it is preferable to use high vertical windows rather than skylights, which are much easier to integrate into the building envelope and manage for solar heat gain.

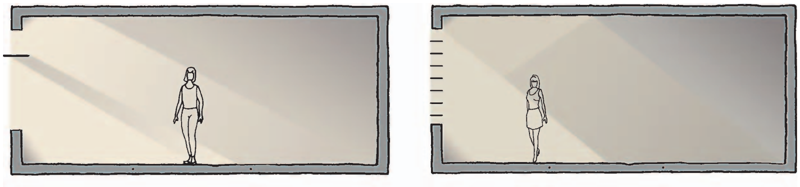
LIGHT TUNNELS

As an alternative to skylights, or as a means of bringing light into spaces that are not adjacent the building envelope, light tunnels or tubes can be used to effectively funnel light into the home. Typically these work by having a dome collector on the roof which funnels light into a reflective tunnel or tube connected to a diffuser on the ceiling or wall. These can be incredibly effective and, although they are not able to provide views to the outside, they can provide many of the benefits of natural light. A great application of this is for spaces that don’t require a visual connection to the outside, such as storage rooms or toilets. Because these elements cross the building envelope their solar heat gain, thermal and airtight properties need to be considered. Like skylights, light tunnels introduce challenges to the thermal and airtight envelope and solar heat gain management, and therefore should only be included with care and experienced consideration.

LIGHT WELLS AND ATRIUMS

In larger or multi-level buildings, voids between levels are commonly used to allow light to penetrate into the middle of a building. Such voids can provide an engaging feature within a building, but careful consideration needs to be given to the management of direct sunlight, and the management of air and heat distribution within the void. In multistorey buildings, buoyant warm air can concentrate at the top of the void, with cool air pooling at the bottom, which can cause temperature differentials between levels resulting in occupant discomfort and disruption to the ventilation system. As such, appropriate shading and air management is an important design consideration for these features.

Light shelves, and light-reflecting horizontal louvres or blinds, help to block direct sunlight and diffuse light into the space.



LIGHT SHELVES

For a window directly exposed to the sky, the intensity of light will be highest adjacent to the window and quickly drop off deeper into the space. Where the window is exposed to direct sunlight, this may create glare within the space. A light shelf is a reflective horizontal surface that is placed adjacent to a window at around three quarters of the window height to reflect diffuse light deeper into the space. A small horizontal awning at the top of the window above the light shelf can be used to block direct summer sunlight. Typically, light shelves are used in conjunction with light coloured ceilings to help maximise the distribution of diffuse light deep into the floor plate. By blocking direct sunlight and reflecting diffuse light across the floor plan, light shelves can increase the usable area lit by the sun and create a more even profile of light intensity. In addition to improving light distribution, by blocking direct sunlight, light shelves can also help to manage excess solar heat gain into the space.

Light shelves can be effective on the outside and inside of the window (or both), and may be combined with reflective surfaces on the ceiling to help direct the light around the room. Shelves can be in the form of a single horizontal element adjacent to the window or a series of smaller louvres, which can be fixed or operable, allowing them to respond to the angle of the sun or overcast conditions.

External venetian blinds can also aid in distributing light into a space, while managing solar heat gain and glare. In particular, speciality blinds are available that allow the top section to be orientated for light harvesting while the lower section can be independently adjusted for glare control.

6.5.3 Orientating windows for daylight

As discussed, the movement of the sun throughout the day and year can be used to create variety and to create enjoyable healthy spaces. To maximise the benefits of daylight, while managing glare and unwanted solar heat gain in summer and useful solar heat gain in winter, solar control needs to be considered for all windows. The easiest solution to this is to provide external shutters or blinds that can be drawn when solar heat gain is undesirable and opened when free heat is advantageous. The downside of this strategy is that blinds or shutters generally reduce the daylight entering the space and rely on the occupant to open and close them, or use an automation system that adds cost and complexity. For north- and south-facing windows, alternative options are available to provide solar control without forfeiting daylight, but this is far more difficult to achieve for east- and west-facing windows.

WINDOWS FACING THE EQUATOR

Equator-facing windows generally offer the greatest potential for balancing solar heat gain and daylight harvesting. When the sun is high in the sky in summer, simple awnings or light shelves can be used to shade direct sunlight because the sun angle relative to the window is relatively constant throughout the day. This avoids the need to close external blinds during summer, allowing plenty of indirect light and views to flow into the home. In winter, when the sun is low in the sky relative to the equator, sunlight can shine in under the shading device allowing useful heat gain. Depending on the window size and height, in most climates an external blind or shutter is still required to allow management of excess heat gain in mid seasons or on particularly sunny winter days. However, through the use of a simple horizontal overhang, the need to use external blinds/shutters can be significantly reduced, increasing the enjoyment of the window.

The depth of the horizontal shading device is proportional to the height of the window. As the most useful light is harvested from the top section of the windows, extending windows down to the floor provides only marginal daylight benefits while increasing the need for solar heat gain control. Most external blinds typically operate top down; therefore even if only the bottom half of the window is in sun the entire window may need to be blocked to prevent overheating, reducing daylight and views. Bottom up blinds can help avoid this issue but this is added complexity for a section of window that adds little benefit.

Spaces that benefit most from equator-facing windows include those that are not overly sensitive to the variation in light throughout the year and benefit from direct sunlight in winter. For example, kitchens, sitting and dining areas, entryways and circulation spaces often work well next to equator-facing windows. Because plenty of light is available from these windows throughout the year, spaces that require good lighting, such as for the completion of detailed tasks, can also work well with this orientation of window. However, including set back or including appropriate glare control, such as blinds, may be required to help manage light levels.

Home designed to optimise light harvesting, winter solar heat gain in the living area, summer solar control and solar electric harvesting (over the bedroom) (Photo: David Halford).

Given their potential for useful solar heat gain in winter, easy solar heat management and daylight harvesting potential, equator-facing windows are the preferred window orientation.

WINDOWS FACING AWAY FROM THE EQUATOR

Outside of the tropics, windows that face away from the equator rarely receive direct sunlight, making them an excellent source of diffuse light, with minimal need for external solar control. However, because these windows do not receive any winter sun, they are not useful for passive solar heating. Furthermore, because they face the cold side of the home they can be a significant source of heat loss. Therefore their size and insulation performance needs to be balanced between heat loss and light harvesting. These windows are ideally smaller than equator-facing windows and placed high on the wall with exposure to the sky to maximise light harvesting. Windows of this orientation suit rooms that do not require high light levels, such as bedrooms. This orientation is also useful for high-level windows, such as clerestory, which can provide pleasant light over deep floor plans, with minimal solar control requirement.

EAST- AND WEST-FACING WINDOWS

These windows provide the greatest challenge in managing daylight and solar heat gain because the angle of the sun relative to these windows changes throughout the course of every day. East-facing windows are exposed to early morning sun at a very shallow angle, which has the highest heat gain potential. West-facing windows have the same exposure at the end of the day, which, when combined with warm afternoon ambient air temperatures, can easily lead to overheating of the home. Overall, balancing between glare and heat gain potential of east- and west-facing windows against maximising the harvesting of useful light is difficult and as such is not always worth attempting.

The easiest way to deal with this challenge is to minimise the area of east- and west-facing windows within a building, in preference for the easier to manage north and south windows. This is obviously not always practical or desirable and there are many options for managing this issue with external shading and blinds. One option is to use a wide short window at viewing level, allowing views out of the home and light in while limiting the time of day the window needs to be shaded (e.g. see the west window in the Parthenay case study in Chapter 10). From a performance and comfort point of view, the best shading solution is retractable external venetians or shutters with horizontal louvres. This allows for the management of low angle sun for glare and heat gain while allowing views and daylight harvesting for the manageable periods of the day when the window is not in direct sun.

With these considerations in mind, some space types can benefit from being located on the east side of the building, allowing them to receive morning sunlight and early morning warmth. These include bedrooms, kitchen/breakfast areas and bathrooms. In addition to capturing light to facilitate the morning tasks that occur in these spaces, exposure to natural light in the morning helps to set our body clocks for the day.

Equator (right side of page) and non-equator (left side of page) facing windows provide good daylight in summer and winter with summer (right image) heat gain management and winter (left image) passive heating easily achieve using a fixed light shelf. East- (right side of page) and west- (left side of page) facing windows have changing light access throughout the day with low angle summer morning and afternoon (left image) sun exposure, making balancing light harvesting and solar heat gain more complicated.

Because west-facing spaces are exposed to low angle sun in the warmest part of the day, the capture of daylight needs to be carefully balanced against heat control, even in winter. Therefore, spaces that do not require much natural light and/or are not overly heat sensitive are best placed on the west side of the building with small heat rejecting windows. For example, garages or storage rooms only have low lighting requirements and can tolerate some temperature variation. In these cases, the use of a high window with a short height that is shaded for most of the day by an external eave may be sufficient.

Placement of main entrances on the west should be avoided because the intensity and angle of afternoon sun can create glare when opening the door from within and a sharp contrast in light levels during the transition from outside to in. West-facing entranceways also tend to overheat, which can make waiting at and unlocking the door unpleasant in summer, and facilitate the ingress of hot air when the door is opened.

6.5.4 Sizing windows for daylight

Because the thermal performance of windows is significantly lower and the cost significantly higher compared with opaque building elements, windows should only be as large as required for effective daylight harvesting and views. As noted earlier, high and wide windows are ideal for daylight and provide a panoramic line of sight out of the home, whereas tall windows stretching to the floor provide only marginal benefits for a large area while requiring additional solar control complexity and cost.

The appropriate size of windows is influenced by a range of factors:

- orientation of the window
- exposure of the window to unobstructed sky

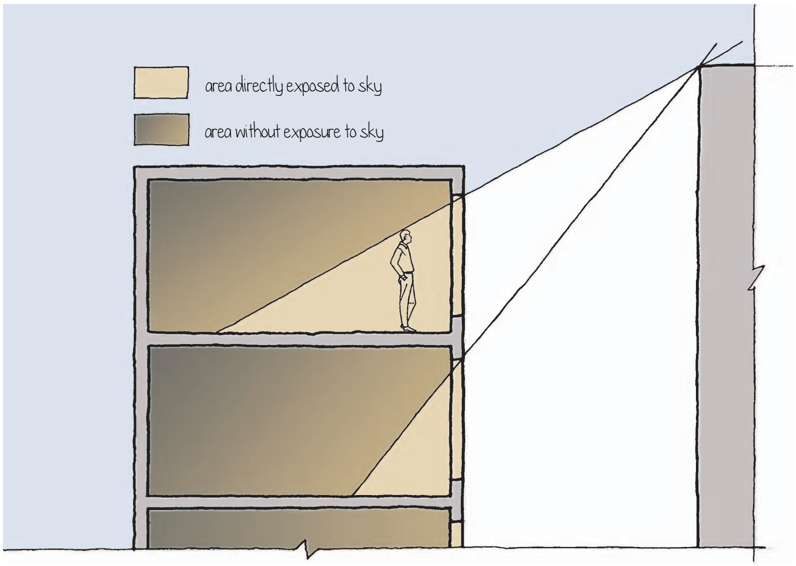
- the interior lighting requirement
- the visible light transmittance of the glass
- the percentage of glass to frame
- the reflectance of internal surfaces
- the total internal area
- how clean the glass is
- the availability of desirable views.

EXPOSURE TO THE SKY

The addition of eaves, shading devices, trees, adjacent buildings, and so on, all reduce the availability of light to a window. Therefore, where obstructions are present, larger windows are required to harvest sufficient light. The amount of daylight entering a room is a function of the exposure to the sky, so an unobstructed high window will provide more light into the room than a low window that is shaded by adjacent objects. In general, a day-lit room will appear dull if more than 50% of the floor area is below the line of sight to the sky.

LIGHTING REQUIREMENTS

Different parts of the home require differing levels of light. Therefore living rooms and kitchens that benefit from more light may have larger windows than bedrooms or hallways that do not need as much light and are not occupied for long hours during the day (see Table 6.4).



The perceived brightness of a space is proportional to the exposure of floor area to the sky (direct line of sight). Spaces with less than 50% exposure to the sky can appear dim and gloomy.

VISIBLE LIGHT TRANSMITTANCE AND GLASS MAINTENANCE

Treatment of glass with low-e coatings or solar heat gain treatments reduces the availability of the light to pass across the glass. As such, windows with a high visible light transmission (VLT) can be smaller and deliver the same amount of light as windows that have a lower VLT due to solar heat rejecting coatings. Similarly, if the glass is dirty, less light will pass through; as such, more regular cleaning of windows that are sheltered from rain or in areas with high particulates such as deserts or by roads can help to reduce window size requirements.

FRAME-TO-GLASS RATIO

Obviously no light passes across the frame and, as discussed, frames are typically the poorest performing element of the window from a thermal and cost point of view. Therefore minimising the frame area can allow smaller windows to be used.

INTERNAL AREA AND SURFACE COLOUR

As you would expect, large areas and darker surface colours require larger windows to light the space. Therefore keeping the home compact and using light internal finish colours can help to create a light space using smaller windows.

ACCESS TO VIEWS

Sometimes the orientation of windows is dictated by the availability of views rather than the sun. A common tendency is to use large floor-to-ceiling windows to capture views. However, the full impact of such large windows are often only appreciated on first impression, with the unobstructed view ignored much of the day, blending into the background. Obviously a great view needs a window to match, but a well-placed smaller window that frames and captures the view from different angles and encourages the occupant to sit down and enjoy the view can be far more enjoyable and engaging over a longer period of time.

Taking all of these factors into consideration, it is possible to calculate the ideal daylight window to floor area ratio for a home. Where the windows are unobstructed, clear and clean and well placed with light interior finishes, window areas as low as 10% of the floor area may be sufficient to fill the home with light during the day. For a typical home with a more complex mixture of variables, larger window areas may be required. For most homes, the energy benefits of capturing daylight are offset by increased heating and cooling energy when windows areas become larger than 25% of the floor area, with only marginal benefits in daylight above this size (CIBSE 1999). With a 25% glazing to floor area ratio, it has been demonstrated that very high average home daylight factors of 7.5% can be achieved. As such, for a well-laid-out and -orientated home, creating a light and engaging space should be achievable with a window area of between 10 and 20% of the floor area. There are a range of daylight modelling programs, which can be used in conjunction with the Passive House Planning Package to help balance daylight and thermal performance (see Chapter 8).

6.6 LIGHT SOURCES

In addition to sunlight, there are many sources of electric light that can be used in a building, all of which have their benefits and challenges. These light sources can be generally broken down into two groups: incandescent and luminescent. Sunlight falls into the first category and LED lamps fall into the second; together these two sources are generally the most efficient and appropriate choice of light for a Positive Energy Home. To provide some context to their advantages, we will discuss the range of commonly available and used light sources and their pros and cons.

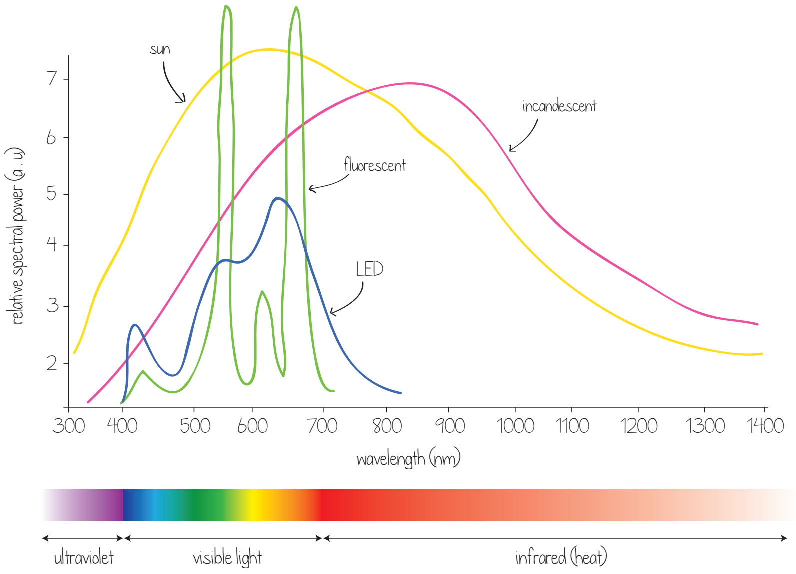
6.6.1 Incandescent

Incandescent light, is generated when a material is heated (often referred to as a black body) up to the temperature that it starts emitting visible electromagnetic radiation.

Light sources in this group include:

1. **The sun,** as we all know, has a very high temperature and as such emits electromagnetic radiation across the visible spectrum. Sunlight is free, rich in colour and provides all sorts of subconscious cues for our body clock. When well harnessed, it is an ideal source of light for Positive Energy Homes.
2. **Flames,** including candles, which generate low temperature warm light rich in yellows and reds, through to gas flames which burn hotter and as such emit high temperature white and even blue light.
3. **Tungsten element light bulbs** are glass bulbs filled with an inert gas or are evacuated, containing a tungsten element that is heated to temperatures of 2800 K (~2500°C) causing it to emit warm white light.

In general, incandescent light sources provide excellent colour rendering, which is a measure of how well the visible spectrum is covered by the light source. For example, the sun has a colour-rendering index (CRI) of 100, producing an even intensity of light across the visible spectrum. In an incandescent light, the filament is heated by passing an electric current through it; as it increases in temperature, the filament will begin to emit visible light in the red part of the spectrum and as it warms further it emits yellows, greens and blues. When it reaches operating temperature, the filament emits all of the wavelengths of light across the visible spectrum giving it a CRI close to 100. When incandescent lamps are dimmed, the temperature of the filament lowers, thus reducing the amount of blue light, shifting the colour temperature of the light towards the red, creating what we refer to as warm light.



Light spectrum from the sun, incandescent lamp, fluorescents lamp and white LED. The sun and incandescent lamps provide excellent colour rendering and include a large non-useful infrared (heat) component.

Unfortunately, the bulk of the energy that goes into the tungsten element is emitted as infrared heat (see figure above). As little as 5% of the energy is converted to visible light, making them very inefficient and very hot. The IR heat emitted from the bulb travels through the air with the light, warming surfaces and people under the light source, which can be beneficial for heating (commonly used in bathrooms as heat lamps), but it can also contribute to overheating in areas when only light is required.

Halogen lamps operate at higher temperatures, moving the light output of the lamp further into the visible spectrum, improving the light quality and luminous efficiency of the lamp. To accommodate the higher temperature and help stabilise the tungsten filament, these lamps use halogen gas within a quartz chamber. The high operating temperatures make them too hot to touch and they need be housed in special fireproof fittings when recessed into the ceiling. Because of this, the use of these lamps can complicate the installation of insulation and make creating an airtight seal around them challenging.

Due to their poor efficiency, short life and potential fire hazard, incandescent lamps are typically not a useful light source for a positive energy building. The only exception to this may be where a very high level of colour rendering or smooth dimming to dark is required. This requirement is becoming less common as the colour rendering and dimming ability of LED improves.

6.6.2 Electroluminescence: gaseous lamps

Electroluminescence is when a material or gas emits light in response to the electrons being excited to higher energy levels by an electrical current or magnetic field. Common examples include fluorescents, high-intensity discharge (HID) lamps and LEDs.

In standard fluorescent and high-intensity discharge lamps, electricity is used to create an electrical arc between two electrodes exciting gas molecules within the chamber causing them to emit radiation. In induction fluorescent lamps, the gas molecules are excited by a magnetic field, which can increase the life of the lamp by avoiding the wear and tear of arcing.

In both arc and induction fluorescent lamps, the excited gas is mercury, which emits UV light. The inside of the fluorescent tube is coated with a series of phosphors, which absorb the UV energy and then re-emit the energy as visible light (photoluminescence). To create white light, three to four phosphors (clearly seen as peaks in the figure on p. 137) are used to create an approximation of white light. The selection and number of phosphors determines the colour output of the lamp and the separation between them can determine the colour rendering of the lamp. In general, phosphors in fluorescents provide quite a distinct output of each colour, which appears white to our trichromatic eyes, but, because only specific wavelengths of the visible spectrum are provided, it reduces the ability of our eyes to distinguish between colours.

Fluorescent lamps are relatively diffuse light sources, emitting light over the whole surface of the tube in all directions. Although this diffuse output can be useful for general lighting, their average colour rendering, switching time, efficiency, lamp life and light frequency (potential for flickering) is inferior to a quality LED lamp. Furthermore, as the phosphor coating deteriorates over time the damaging UV output of these lamps can increase and the lamps contain small amounts of mercury, which is released if the lamp is broken, making them a potential hazard. Fluorescents often take some time to reach the internal temperatures required to achieve maximum light output and are sensitive to short cycle (less than 10–15 min) switching, meaning they are not suited to regular short interval switching on and off. Therefore as the price of quality LEDs continues to reduce, and the colour rendering and efficiency increase, there should be no need to use fluorescent lamps in a Positive Energy Home.

HID lamps use a mixture of gases within a small quartz chamber to emit high-intensity visible light as a point source when an electrical arc is established across the gas chamber. Commonly used gases include mercury, metal halides and sodium. Because some of these elements are not gaseous at ambient temperatures, these lamps can take some time to warm up before they reach nominal light output and can require some time to restrike if switched off.

Metal halide HID lamps can achieve quite high efficiency of >100 lm/W and acceptable colour rendering and their high intensity can make them a cost-effective choice for flood lighting, such as lighting a large outdoor area. However, due to the intensity of these lamps and their switching time, they have limited general lighting value within a Positive Energy Home.

6.6.3 Electroluminescence: solid state LEDs

Light emitting diodes, LEDs, are made from semiconductor materials that, when subjected to an electrical current, emit directional light (perpendicular to the surface) at a particular wavelength specific to the semiconductor. The semiconductor materials used are equivalent to those used in solar panels, which are effectively an LED operating in reverse, absorbing light and generating electricity. Because the light emitted from a particular semiconductor material is only a single colour, to create white light, either a selection of different coloured LEDs are combined into a single light source or a blue LED is used in conjunction with a range of phosphors that absorb the blue light and re-emit it as different colours across the visible spectrum. This can been seen in the output spectrum from an LED, where there is a peak in blue light corresponding to the direct output from the LED and a broad peak across the rest of the visible spectrum arising from the phosphors. By creating an even spread of light output across the spectrum, LEDs provide superior colour rendering compared with fluorescents.

LEDs come in both dimmable and non-dimmable versions, with the dimmable versions typically attracting a cost premium. It is also important to select a dimmer switch suited to LEDs. Unlike incandescent lamps, the colour of the light does not change as the lamp is dimmed. Furthermore, because of the nature of the light source, standard LEDs will not dim below around 10% of their rated output, and will pulse rather than dim any further. However, speciality LEDs are available that facilitate colour change and dimming to black, for applications such as a home theatre.

Because LEDs are solid state, with no moving parts, no arcing and operate at low temperatures and voltages, they have very long operational lives. Furthermore, unlike the other types of light described, LEDS emit highly directional light, perpendicular to the surface of the LED. The ability to control the direction of the light can increase the overall usable light (efficacy) for directional lighting applications such as spot or surface lighting.

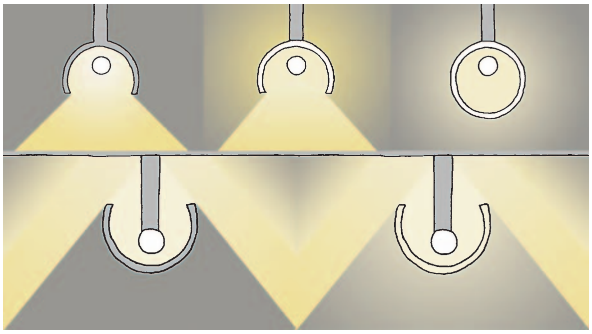
With their long life, versatility and efficiency (see Table 6.3), LEDs have become the ideal light source for creating a Positive Energy Home. Like all appliances, there is a wide range of quality in LED products available, so it is important to understand the key performance metrics to help select the best lamp for the light scene required.

6.7 LIGHTING WITH ELECTRIC LIGHTS

Other than daylight, the most efficient way to light a space is through the use of exposed lamps (bulbs). This approach is often applied for infrequently occupied spaces such as storerooms or garages, where the sole function of the light is to navigate through the space and identify objects. This strategy typically creates unacceptable levels of glare for occupied spaces.

Table 6.3. Comparison of lighting types used in buildings, 2016.

Lamp type	Efficiency (Lm/W)	Lamp life (h)
Incandescent	7–20	750–2000
Halogen	12–20	2500–3000
Compact fluorescent	46–65	6000–15 000
Fluorescent tube	80–95	20 000–30 000
HID metal halide	69–100	14 000–11 000
LED	25–150	25 000–200 000



Luminaires house and direct the light out of a lamp, with direct lighting potentially causing glare. Diffuse and indirect luminaires provide softer more even lighting but reduce the overall efficiency of the light source.

To create engaging comfortable spaces, light is normally provided via luminaires (lamps and fittings). Other than being a visual feature within the space, luminaires are used to house the lamp, direct, spread and diffuse the light, and manage the glare from the light source. In most cases, these functions reduce the total light output of a fitting, but through using the light effectively, selecting the right fitting can reduce the overall power required to light a space increasing the efficacy. For non-directional light sources such as incandescent, fluorescents and HID lamps, reflectors are often incorporated into the fitting to direct the majority of the light in the desired direction. For directional lighting applications the directionality of LED lamps is an advantage, but, where diffuse light is required, LED light needs to be passed through a diffuser or bounced off a surface to spread the light, which incurs some losses.

In most cases, the efficiency (as well as long life and colour quality) of LED lamps offset the efficiency losses associated with diffusion of the light by the luminaire, making them the most efficient choice for most home lighting requirements. Because the performance of LEDs is sensitive to heat, the peak intensity of LED lights can be limited by the ability of the luminaire to dissipate the heat away from the LED. For large spaces, such as lighting the back yard, this can mean that multiple LED fittings spread around the space are required to achieve the equivalent output of a single HID fitting.

Glare from luminaires is described by a unified glare rating (UGR), which effectively quantifies the intensity of the luminaire relative to light within a space (background luminance). A UGR value of <10 is ideal; with no significant glare, UGR of 10–20 can be acceptable depending on the function of the space (hallways, etc.) and values of 20–30 or above are generally unacceptably high for buildings. Because glare is relative to the ambient light available, to calculate UGR the output of the light fitting needs to be modelled within the space it will be used, typically by a lighting design specialist. In the absence of this modelling, we recommend the use of light fitting where the light source is not directly visible to the eye. For example, direct view of the light source (bulb) is obscured by the fitting, the light source is angled away from the eye or is covered by a diffuser.

6.7.1 Task lighting

Because our ability to see is a function of the intensity of light available and the size of the object, areas that require the highest light levels are generally those where detailed tasks are undertaken. This lighting requirement is most efficiently achieved by using dedicated and directional light over the task area. For example, a task lamp on a desk or a light directly above a sink allows the required light to be achieved where needed, without over-lighting the entire room. When using this type of light, it is important to ensure that the light can reach the surface without obstruction by the user and to avoid exposing the light source to the line of sight. For example, lighting a kitchen bench or sink from the ceiling or wall above the bench with a suitable shade or diffuser, ensures that the user does not create a shadow on the bench, which commonly occurs when the light is located in the centre of the ceiling above the standing area.

It is also important to consider the angle of the light relative to the task surface and, where multiple surfaces or different orientations need to be lit, that there is a sufficient mixture of vertical and horizontal light. For example, lighting a kitchen bench using directional light from above is effective for the benchtop but may make it difficult to resolve detail in the cupboards below the bench. As such, using multiple light sources on different angles or a diffuse light to complement the task lighting is necessary. One way to achieve this is by complementing directional task lighting with a fitting that reflects light off the ceiling and bounces it around the room, or a pendant that provides diffuse light in all directions.

DELIVERING ENOUGH LIGHT

In general, the recommended light levels (see Table 6.4) for tasks are specified in lux, which is lumens per m^2 at the working surface. For general lighting, the amount of light in lumens, required can be roughly calculated by multiplying the area by the desired lux level: for example, a 10 m^2 room lit to 200 lx would require ~2000 lm. With this number in hand, we then need to consider the lumen output of the fitting, the light distribution from the fitting and the location and the distance of the fitting from the working surface.

For example, if a light bulb emits 500 lm, and the fitting reduces this by 20%, lowering the useful output to 400 lm with a directional light distribution that creates a circle of light with an area of 1 m^2, at a distance of 1 m directly below the fitting, the light level will be close to 400 lx.

Table 6.4. Illumination levels for typical tasks.

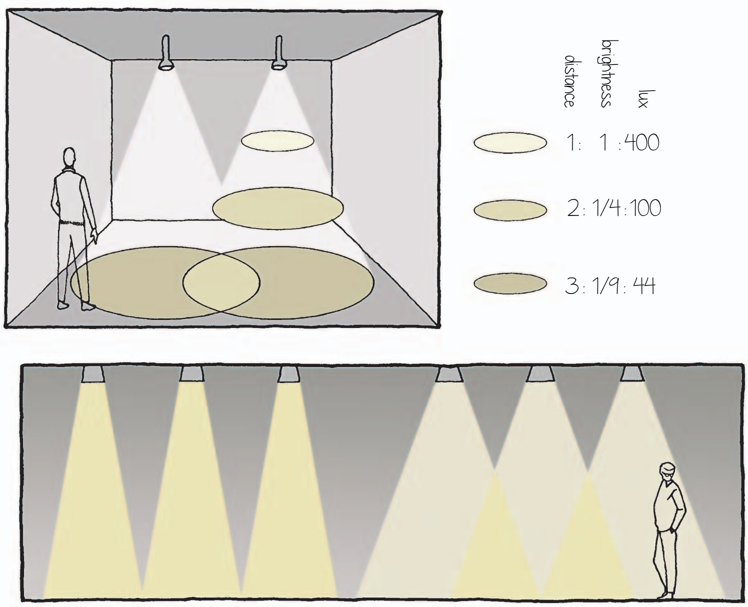
Activity	Example activity	Room	Illumination (lux)	Target W/m^2
Low detail tasks	Circulation	Hallway	40–80	1
General coarse detail	Dining, watching TV, changing	Bedroom, dining, bathroom, living room, kitchen	100–200	2–3
Medium detail task	Reading, writing, typing, food preparation	Home office, kitchen benchtop, bathroom vanity	250–400	4–5
Fine detail task	Sewing, fine drawing	Workshop, studio	500–1100	6–13

Therefore a task lamp with a lumen output of 400 lm with a height of around 1 m above the desk will provide ample light for tasks such as reading and writing.

If we move the light fitting further away from the working surface, the intensity of the lux levels decrease as the lumens from the light are spread over a larger area. For the example luminaire above with an output of 400 lm that has a directional light distribution of 1 m^2 at a distance of 1 m, at a distance of 2 m above the work surface the light distribution area would become 4 m^2 (2^2), giving a lighting level of 100 lx. If we move the fitting to 3 m above the working surface then the light distribution area would become 9 m^2 (3^2), providing a light level of ~44 lx. This fall off with distance is referred to as the inverse square law.

Obviously, every light source and fitting has a different light distribution and most quality manufacturers will provide a light beam angle or light distribution (polar) curve. This allows the area and shape of light distribution at a given distance (ceiling height) to be estimated. These can be used to assess the required lumen output and the number of lights required to light a space. Light is additive, so if the light distribution area of light fittings overlap the light intensity of the overlap area will be equivalent to the sum of light from each fitting. For example, if the light fitting described above provided 44 lx at a distance of 3 m, two of these lights next to each other would create 88 lx in the overlapping area. Using multiple fittings, rather than one intense fitting, can help to reduce the potential for glare, creating a more consistent lighting scene and provide greater lighting level flexibility (see figure below). For example, half the lights can be switched off for a lower lighting level.

The maintenance factor of the fitting and the lamp also need to be considered, with the build-up of dirt and reduced output from the lamp reducing the available lumens over time. As such, allowing for some depreciation in output is required when designing to specific light levels.



Light intensity decreases by the inverse square of the distance from the lamp. Lighting is additive, so where the output of lights overlap the light level is the sum of the contribution from both light sources. Therefore the desired lighting for a surface can be achieved using individual lights or by overlapping multiple less-intense lights.

6.7.2 General lighting

General lighting within a space to allow us to move around and conduct non-detailed tasks such as watching television or socialising can be achieved using lower light levels. This type of lighting also lends itself well to creating texture within the space. When working with lower light levels, it is preferable to use indirect or diffuse light to avoid creating glare and shadows that may reduce the functionality and reduce the perceived volume of the space. For example, in a living area, a pedestal lamp can be used in a corner away from the window to provide diffuse light through the shade and reflected light off the walls and ceiling filling the space with diffuse, indirect, glare free, warm light. This light can be used to balance bright daylight from the window or top up the far side of the room during times of low daylight. Bouncing light off one corner of the room can help to create soft texture within a room. Lighting the ceiling can increase the overall perception of light within the room and visually open up the entire volume of the space. Using diffuse wall washing light can also be effective for using only a small amount of light to offset the perception of darkness in an area or room that is not being used, allowing it to be left lit using only a small amount of energy (see photo below).

In contrast, the common use of bright evenly spaced down lights over open areas, typically delivers only a bright floor where the least amount of light is required. This lighting choice can

Lighting in a Passive House, Wanaka, has electric task lighting and daylight in the bay window, indirect light washing the walls behind the television creating volume and diffuse light, with general down lighting in the hallway (Photo: Simon Devitt).

also result in glare and create the sense of darkness around the ceiling, shrinking the room and reducing the perceived brightness of the space. Therefore using a smaller amount of light effectively, rather than carelessly bulk lighting a space can increase functionality, texture and perceived brightness of a space while reducing energy consumption.

6.7.3 Lighting control

The most important feature of a lighting control strategy is that people can easily understand it. Simple light switches, logically laid out can often be more effective than complicated control systems because the occupant can readily engage with the switch and turn off the light when no longer required. The challenge with manual control is that we are stimulated to turn on lights when it becomes too dark, but there is no trigger to switch off a light when we leave a room or when there is sufficient daylight to light the space. Task lighting can assist with this, because as when the light is specific to the task we are more likely to turn it off at the point of use when no longer required. In contrast, for general room lighting we may not be consciously aware of the light being on and switches are more likely to be remote from the light, making it less likely to be switched off when not required. In all cases, making the switches accessible and meaningful to the light being used is important: for example, at the point of use for task lighting or at the point where you are most likely to enter and leave a room for general lighting.

Automated control can be useful in large spaces of variable occupancy and where there is little ownership (i.e. where people don't feel empowered to turn off the light or are worried it may impact on the next person). An example of this is external entranceways where you need the light to be on before you reach the switch, but once inside will not notice if the light is left on. Common occupancy sensors used include passive infrared sensors (PIR), which detect movement through the infrared energy put out by the heat of our bodies. This means they are able to detect us in darkness and should not be activated by movement of objects that are at ambient temperatures, such as the branch of a tree. In areas where the sensor may be obscured by objects, such as in bathrooms, PIR sensors are sometimes combined with a microphone that detects sound within the space.

Active detectors include ultrasonic and microwave sensors, which work in the same way as the echolocation of bats, by sending out high frequency ultrasonic waves (or microwaves) and detecting changes in the reflected signals. These sensors can increase sensitivity to movement, but in some cases can interfere with hearing assistance devices and are typically not required in a home setting.

Occupancy sensors all use a small amount of energy when in standby mode, which over the course of a year can become significant. As such, where their application is warranted, it is useful to also have an accessible switch allowing the sensor to be switched off when not required, such as during the day or when the light is not required for a period of time.

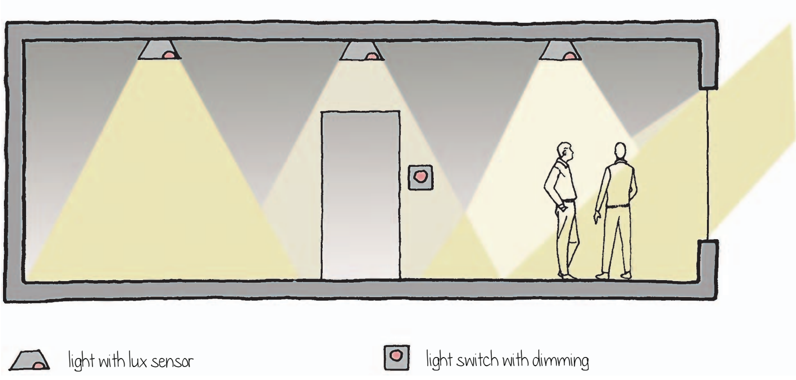
INTEGRATING ELECTRIC AND DAYLIGHT

Light from multiple sources is additive, for example if a space next to a window has light level of 400 lx from daylight, if electric lights designed to deliver 300 lx are turned on then the overall light level will be 700 lx. To take advantage of this it is useful to position and zone lights so that they can be turned on and off in response to the ambient conditions. In large spaces, this may mean having lights around the perimeter of a room adjacent to windows on a separate switch/circuit to the rest of the lights, or having a lamp in the corner furthest from the window to top up this area when the main lights are off.

As our eyes rapidly adjust to the ambient light levels, we are unlikely to notice a gradual change in light level such as increasing daylight in the morning, which provides no prompt for us to switch off the lights. Where automated daylight control is used, using lux sensors to dim the electric lighting in response to the available daylight can create a seamless transition and maximise the energy savings. This is useful where the switching off of lights may be distracting, but it does increase the cost and complexity of both the sensor and the light fitting. For light fittings to dim in response to light levels, they require a dimmer and a lighting controller such as a DALI (digital addressable lighting interface) card and a DALI lux sensor. In most areas of the home, it is normally sufficient to simply have the lux sensor to switch off the light when there is suitable daylight. Lux level sensors generally contain a small photoelectric cell (solar cell) that generates an electric current in the presence of light activating the switch. Often light and occupancy sensors are combined into a single device.

SUMMARY

To create engaging and efficient homes, they should ideally be designed to collect natural light. The use of daylight needs to be carefully balanced against glare and excessive solar heat gain. This



Lux level sensors and dimming control can be used to dim lights or switch off where there is sufficient daylight, creating a smooth and consistent transition between daylight and electric lighting.

can be achieved through the use of high windows facing away from the equator and suitable shading or light shelves to maximise the collection of diffuse light. For most applications, quality LEDs lamps, with appropriate colour temperatures and colour rendering are the most efficient and reliable source of electric light. The selection and placement of appropriate light fittings is equally important in maximising the enjoyment of the space and minimising energy consumption. Finally, the placement of lights and switches is important to encourage the efficient management of lights within the home.

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CHAPTER 7

Appliances

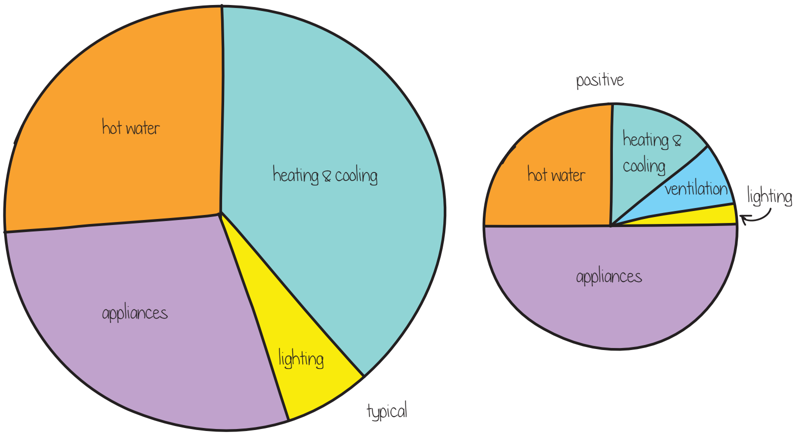
An enjoyable home with a surplus of energy is within easy reach when you adhere to the principles outlined in the previous chapters. Unlike comfort, ventilation and light, which are basic services used by all, appliance energy consumption is typically dependent not only on the efficiency of the appliance but the preferences and lifestyle of the occupant. Therefore, in selecting appliances and sizing of the home's renewable energy system, it is important to decide what will allow you to best enjoy your home. For some people, appliance use will be only a small part of their home energy consumption due to their lifestyle and commitment to energy efficient behaviour, such as cooking light meals on the stove, switching everything off after use and having short efficient showers. As a result, they will only require a small solar array to meet the associated energy demands. For those of us committed to having a Positive Energy Home, but whose main hobby is not saving energy, investing in efficient appliances and a larger renewable system may be preferable.

The majority of the energy consumed by appliances ends up as heat in the home, so minimising appliance energy consumption, particularly during warm conditions, is important to avoid overheating and the need for cooling. For example, vacuuming the home on a hot afternoon will cause you to warm up from the activity and add significant heat to the home, which may then need to be removed by the cooling system. Therefore managing appliance energy consumption is a combination of selecting the most efficient appliance for the task, selecting the most efficient model practical and then adopting efficient and practical usage habits. The great advantage of a Positive Energy Home is that it provides a meaningful target and incentive to maintain these habits, knowing that your energy efficiency habits contribute to making your home an energy producer.

In this chapter, we explore the efficiency and use of a range of common appliances and then tackle hot water use in the home.

7.1 APPLIANCE RATINGS

In most countries, major appliances and hot water fixtures are rated and labelled with their energy and water efficiency. Appliance energy consumption is estimated using standardised usage patterns, allowing comparison between models. In most cases, ratings provide annual energy consumption and a rating that is relative to the size of the unit. However, this can be misleading



Example energy consumption by category for a typical and Positive Energy Home.

when comparing between differently sized units. For example, a large television may have a high efficiency rating but may still use significantly more power than a less efficient smaller model. This is true for many of the major appliances. As such, the first step is deciding what size refrigerator, television, washing machine, and so on, is right for you.

Local energy ratings are a useful guide for selecting between locally available appliances and are common for large appliances such as refrigerators and washing machines. In many regions, smaller appliances are not rated, in which case referring to European energy ratings (see Table 7.1) or using product energy efficiency rating websites may be helpful. Be aware, though, that different countries may use different boundary (testing) conditions for their efficiency ratings, which makes cross-country comparisons difficult.

As noted these ratings are based on a standardised usage pattern, which can be useful for predicting annual energy consumption of appliances such as refrigerators that are always on. However, the energy consumption of most appliances is directly proportional to their use, thus in addition to selecting the right size and efficiency, selecting features that facilitate efficient use can be just as, or in some cases more, important.

Table 7.1. Summary of power usage by appliance: examples of best in class annual consumption based on EU energy ratings.

Appliance	Type	Inefficient	Efficient	kWh per
Refrigerator	350 L frost free	340	185	annum
Dishwasher	13 place settings	290	194	annum
Washing machine	8 kg front loader	250	137	annum
Television	107 cm screen	48	48	annum
Range hood	90 cm	138	30	annum
Vacuum	cylinder	60	26	annum
Computer	laptop	30	13	annum
Oven	71 L fan forced	0.88	0.52	cycle

7.1.1 Instantaneous and stand-by power

Like all electrical powered devices, total energy consumption is the product of instantaneous power in watts and usage time in hours (see examples in Table 7.2). For resistive heating appliances, such as a toaster or kettle, the instantaneous power demand can be very high, but they are typically only used for a couple of minutes at a time and only a few times a day. Large energy users such as washing machines and dishwashers have varying instantaneous energy demands, depending on where they are in their cycle, with total energy determined by how many and the type of cycle used. Finally, there are the relatively small instantaneous energy demand appliances such as computers or clocks, which may be left on for long periods of time or 24 h a day. Furthermore, the majority of appliances with electronics or chargers consume power when not in use, meaning they are consuming energy 24 h a day. Many efficient appliances are designed to have low standby power of less than 1 W, but, over the course of a year, multiple devices in standby mode can add up to a significant energy consumption, especially relative to power consumption in a low energy home. As such, it is important to not only turn off appliances such as computers and televisions when not in use, but to switch off the supply of power to them when they will not be used again for a period of time. Similarly, chargers for laptops, phones, and son on, often consume power even when not charging and should be isolated from the power supply when not in use.

Isolating from the power is easily achieved where the appliance has an integrated power isolation switch. Alternatively, configuring wall switches so they are easily accessible at the point of use, such as having the power point on the wall above the washing machine, makes it effortless to switch off once the cycle is complete. Using power boards with a readily accessible master switch can make it easy to isolate appliances that are used together, such as a computer and

Table 7.2. Example power (watts) demand of common appliances.

Appliance	In use	On not in use	Stand-by
Clothes washer	600–2400	5.8	<1
Clock radio	4	–	2
Laptop	20	–	2–0.2
Television LED	100	–	3.5
DVD/DVR	20	8	2
Toaster	600–1200	–	0
Modem	6	4	4
Cordless phone	3.5	3.5	2.4
Microwave	1300	25 (Open)	3
Stereo	20	9	5
Phone charger	3.7	2.2 (Charged)	0.25

monitor, with one switch. Entertainment systems, on the other hand, may benefit from a power board that allows each device to be powered or isolated as required. For appliances such as dishwashers that often have a hard to access power point, an inline switch can be used, which is effectively an extension lead that plugs in between the appliance and the power point, with a switch at the end of it that can be conveniently located for easy switching. To automate the process, there are also smart extension leads available that cut power to the socket once the appliance goes into standby mode.

7.2 CLOTHES WASHING MACHINES

Washing machines generally have energy ratings that allow comparison between models of equivalent size. However, there are many factors that contribute to the overall energy consumption of the clothes washing process including:

- amount of washing done
- size/weight of the load
- orientation of the drum
- efficiency of the motor
- cycle programs available/selected
- amount of hot water consumed
- how the hot water is generated
- how dry the clothes are at the end of the wash
- how the clothes are dried.

7.2.1 Hot water generation and cold water cycles

In machines that heat the water internally, heating energy can constitute as much as 80% of the total machine energy consumption. As such, selecting a machine that minimises hot water consumption and has a cold wash cycle is essential for reducing the high energy consumption of clothes washing. In a Positive Energy Home, it is likely that hot water will be generated through either a heat pump or a solar thermal system, which are far more efficient than the resistive elements within the washing machine. Selecting a machine that has a hot and cold-water connection makes it easier to use the more efficiently generated hot water, noting that some units do not give you the option, coming with only a cold water connection point.

7.2.2 Wash cycles

Given the significance of hot water energy in the washing process, selecting a machine that has a cold-water only option is very useful (with an appropriate detergent) for reducing energy consumption. Many machines offer a range of temperature options, allowing the appropriate temperature to be selected for the nature of the load. Some machines also offer an economy mode that uses strategies such as only using hot water when required and allowing longer soaking times to reduce the mechanical washing requirement. Another useful option is a short-cycle mode that reduces water consumption and washing time for lightly soiled clothes.

Many machines also allow the speed of the spin cycle to be selected, which can be useful for balancing spinning energy against drying energy. Obviously having a range of options allows the most appropriate cycle to be selected for the requirements of the clothes being washed, facilitating reduced energy consumption. Machines that offer more sophisticated controls include electronics that typically still have a small power draw when not in use. In this case, having an easily accessible power point above or next to the machine allows the machine to be conveniently isolated from the power when not in use, which will eliminate standby losses.

7.2.3 Size and weight of the load

Washing machine capacity is generally described by its load weight. This determines the maximum capacity of the machine. In general, larger machines are more efficient per unit weight, but unless a full load is required for every wash, using a large machine to do a smaller load is normally less efficient. Some machines detect the size of the load and adjust the water requirements and cycle accordingly, but selecting a machine size that suits your typical load, and operating it fully (but not over-) loaded is the most efficient choice.

7.2.4 Orientation of the drum

Front loading washing machines have a horizontal orientated drum, which allows the clothes to be easily and gently turned over, generally reducing the wear and tear on clothing, extending their usable life and use significantly less energy than top loading machines. Because clothes are rotated between top and bottom, the drum only has to be partially filled with water to wet all of the clothes. Where hot water is being used, this allows a significant reduction in water consumption, reducing heating energy. Reduced water volumes also reduces the weight in the drum and, as such, the energy required to spin it. In general, front loaders have longer cycles because it takes longer to mix all of the clothes through the water. Horizontal drums also allow for faster spinning speeds.

7.2.5 Efficiency of the motor

Besides water heating, the motor is the major energy consumer within the machine. Electrical motors can readily achieve efficiencies greater than 90%, and it is now common for washing machines to use high efficiency DC motors. The efficiency of the motor may not be stated, so investigating and comparing the non-hot water energy consumption of the machine is a useful indicator.

7.2.6 Spin cycle and drying clothes

Most machines nominate their peak spin cycle in revolutions per minute (RPM). A higher spin speed is able to extract more moisture out of the clothes, but, as you would expect higher speeds and longer spin cycles consume more motor energy. When drying clothes outside in hot dry climates, over-spinning of clothes may not be beneficial because clothes readily dry when hung out on a line or clotheshorse. However, in cooler or humid climates, where clothes may be hung out to dry inside or in a dryer or drying cupboard (see below for details), reducing the amount of moisture in the clothes reduces the moisture that needs to be removed from the home and heating energy required to dry the clothes. In general, extra spinning reduces the drying time with only a small mechanical energy penalty.

When external clothes lines are not practical, a clothes drying cupboard interconnected with the home ventilation system may be a practical alternative. Clothes are hung within the cupboard and then air from the home is drawn through the cupboard over the clothes and out through the ventilation system. By actively drawing air over the clothes, drying time is reduced, which, if used in conjunction with a high speed spin cycle can dry the clothes in a few hours, without the excess heat and damage to clothes common to heated dryers. In climates where heating of the home in winter results in dry air, drying of clothes on a clotheshorse in a supply air room of the home can help to raise humidity levels.

Electric dryers that use resistive elements to heat the air are an inefficient method of drying clothes consuming very large amounts of energy and generating considerable heat within the home. Heat pump clothes dryers are far more efficient and are an acceptable option where lines or drying cupboards are not practical.

7.3 DISHWASHERS

Dishwashers typically use in the order of 0.5–1.6 kWh per load. Like washing machines, the major energy consumption within a dishwasher is heating of hot water. As such, selecting a unit that is appropriately sized for the requirement and that has low water use is essential. As with washing machines, some dishwashers have only a cold-water intake and do all of the heating internally using electric elements. When the home has an efficient hot-water system, selecting a dishwasher that has a hot and cold water intake with a (economy) cycle designed to only use hot water when required and minimise internal heating element use can reduce overall energy consumption of dishwashing. Alternatively, mixers are available that enable a hot water connection with only one connector to the appliance. Some units also allow the temperature of the wash cycle to be selected, which can be useful for fragile glassware and reducing energy consumption. Light soiling cycles or soil sensing machines can also be useful features for reducing hot water consumption and cycle time.

The other significant energy consumption within a dishwasher is during the drying cycle where electric elements are used to heat the dishes. Some dishwashers have the option to skip the drying cycle, allowing the user to open the dishwasher and allow the dishes to air dry, reducing energy consumption. Other units are designed to draw air through the machine to dry the dishes.

In most cases, a well-loaded efficient dishwasher will use less energy and water and do a better job than all but the most efficient of hand washers. With some scraping of dishes, most dishwashers do not require pre-rinsing of the dishes if the machine is going to be run shortly after loading. Pre-rinsing with hot water obviously increases energy consumption and negates the benefits of the dishwasher, so where some amount of pre-rinsing is required it should be done with cold water and assisted with a dish brush.

7.4 TELEVISIONS AND ACCESSORIES

In general, LCD televisions using LED back lighting provide the highest efficiency. Within the LCD (LED) category, the size of the screen is the major determining factor of energy consumption when in use. Unlike the appliances discussed so far, when in use televisions typically only have one setting. It follows that the annual energy consumption has a direct correlation to how often the television is in use. Some televisions have power management settings that monitor occupancy within the room and switch off the screen while maintaining the sound when no one is present. It then switches the picture back on when occupancy is detected or switches off the television if no-one returns. This may be a useful feature for listening to programs while conducting some other task at the same time.

Most modern televisions have relatively low standby power consumption of less than 1 W, but because this power is always being consumed it can add up to a significant amount of energy over the course of a year. As such, having an easily accessible power isolation switch for the television and peripheral devices is useful and helps to reinforce energy saving habits. In many cases, peripheral devices such as PVR, DVD, sound systems etc. are not always required when the television is on, so having a power board with individual switches making it easy to only switch on the devices required and avoids unnecessary standby-power. This is particularly relevant for peripheral sound systems with power speakers or Wi-Fi enabled devices that may have significant power consumption in operation and standby mode, and may only be required when watching particular content.

This is also true of stereos and radios that can have surprisingly high standby energy consumption and typically do not come with an energy rating. Therefore, selecting devices with an inbuilt power isolation switch or having an easily accessible wall or power board switch to allow them to be switched on and off when required is essential. A classic example of this is clock radios that only use a few watts of energy, but, because they are always on, over the course of the year their energy consumption adds up. As such, if this is an essential item for your home, ensure you select a model with low standby power (<1 W) and be sure to switch off the device if you are away for an extended period of time.

7.5 COMPUTERS, TABLETS AND NETWORK DEVICES

Because laptops and tablets have been optimised to maximise battery life, they generally have significantly lower energy consumption to perform the same task relative to a desktop computer. For example, a laptop can use as little as 15 W, whereas a typical desktop computer uses in the order of 30–40 W, plus 20 W for the external monitor. Charging of batteries introduces some energy losses; as such when using laptops or tablets at a fixed location or for long periods of time, it is ideal to connect them to the power source rather than operate on battery power then recharge. Most computer manufacturers do not provide useful energy consumption information, but there are several websites available that allow comparison between devices.

Once an efficient system has been selected, it is important to establish sensible behaviour, such as shutting down and switching off at the power point when not in use. Most operating systems will have software to automate a shutdown. It is also useful to set up practical power management settings within the device, such as switching off the screen, going into standby mode and disconnecting from the network when not being used for a short period of time. As noted earlier, many charging devices consume power when not in use, so isolating them from the power source when not in use is ideal.

Modems and routers are typically left on for long hours so, like all such devices, selecting an efficient model and setting up a convenient method of switching them off when not required is useful for power management.

7.6 VACUUM CLEANERS

Vacuum cleaners are typically power hungry and used for an extended period of time per use, translating to significant power consumption. For example, a typical cylinder vacuum with a peak wattage of 1600 W consumes 1 kWh after around 40 min of use at full power. In many countries, vacuums do not come with an energy rating, but many international models are rated under the European scheme. This scheme rates the vacuum for energy consumption, effectiveness of cleaning carpets and hard floors, total noise levels and dust emissions, which can be a useful guide for selecting the right machine for you. In general, upright vacuums consume less energy than cylinder machines, because a short straight tube connects the motor and the suction point rather than a long, flexible rough tube.

Energy, and indeed the time, required for vacuuming can be reduced by simple strategies and behaviours to reduce the need to vacuum. A major source of contaminants and dirt in the home arises from the soles of our shoes, so not wearing shoes in the home or having a walk off grill and mat at the entrances to the home can help to reduce the need for vacuuming. Another major source of dust and particles is through air ingresses, which is all but eliminated in a sealed home with a filtered ventilation system. During mild periods, dust can be minimised by ensuring windows are not exposed to dusty winds or by using the ventilation system in supply only to filter incoming air, creating positive pressure that pushes air outwards from the windows can help reduce dust ingress. Other simple strategies include using a broom for hard floors and avoiding the installation of carpets or rugs that shed fluff or pill.

When in use, like all appliances, only switching it on when in use and switching it off when pausing to move furniture reduces waste. Emptying the machine or ensuring the bag is not over full, and cleaning or changing filters reduce pressure loss and energy consumption. Many models of vacuum have multiple motor speeds, which allows the energy consumption to be reduced when less suction is required, such as vacuuming a hard floor rather than carpet. Using the appropriate fitting for the task at hand can also help to reduce vacuuming time and energy consumption.

7.7 REFRIGERATORS AND FREEZERS

For a typical home, refrigerators are always switched on and are therefore a large energy consumer, even if rarely accessed. As the name suggests, refrigerators use a refrigerant-based heat pump to remove heat out of the cold compartment inside of the fridge and dump it into the room. The overall energy requirement is influenced by the size for the refrigerator, efficiency of the heat pump, how well the refrigerator is insulated and how much heat is allowed into the fridge through opening the door and adding warm food.

Typically, large refrigerators are more efficient per unit of refrigerated space due to their smaller surface to volume ratio. However, cooling a larger space uses more energy overall. As such, selecting a refrigerator/freezer to minimise energy consumption is a matter of selecting the most efficient model for the most appropriately sized refrigerator for your needs; that is, the smallest practical size. It is also important to note that different configurations of refrigerators may have different energy rating criteria. For example, side by side fridge-freezers may be rated differently to top or bottom mounted fridge-freezers; as such, be sure to check the average annual energy consumption as well as the energy rating.

In general, refrigerators are insulated using vacuum panels, which allow high levels of insulation to be achieved without making the walls of the refrigerator impractically thick. Like a home, ensuring the door is well sealed so cold air cannot escape is crucial. Opening the door allows the cool air inside the refrigerator to fall out, increasing energy consumption. This is exaggerated for the freezers, where the air temperature is typically minus 18°C, resulting in rapid exchange of heat when the door is open. Some freezers minimise this through the use of clear plastic doors, or drawers for each shelf to prevent the cold air falling out when the door is opened. Reducing the air volume of the fridge or freezer can improve the energy consumption by minimising the air that can exchange when the door is open. For example, filling unused space with water containers adds thermal inertia helping to prevent heat loss when the refrigerator is opened. As a user, reducing the amount of time the refrigerator is opened and avoiding putting hot objects into the refrigerator helps to reduce energy consumption. Where frozen food needs to be defrosted, moving it from the freezer to the fridge the night before helps to keep the fridge cool and reduces the need to defrost the food in a microwave.

Like air-conditioners, the temperature around the refrigerator has a direct impact on the energy consumption of the unit. Heat build up around the heat pump reduces the efficiency of heat rejection and high temperatures around or direct sunlight on the refrigerator increases heat transfer across the insulation of the unit. As such, locating the unit is in a cool location away from direct sunlight and heat sources helps to reduce energy consumption. For example, the refrigerator should not be located adjacent to cooktops and ovens. It is also essential to ensure that there is adequate space and opportunity for airflow around the refrigerator to ensure the heat from the unit does not build up. Therefore enclosing refrigerators in cabinets should be avoided unless there is a suitable heat extraction system.

7.8 COOKING

In a low energy home, cooking of food cannot only be a significant energy user in itself, it can also be a significant source of heat and contaminants. Like most appliances, the efficiency of the cooking device and the method of use both influence the overall energy consumption.

7.8.1 Cooktops

Combustion in the home is a major source of contamination, increasing the ventilation requirement and is generally an inefficient means of heating. For gas cooktops as little as 40% of the heat energy in the gas is transferred to the food, with the majority passing up and around the saucepan. In contrast, a resistive electric cooktop transfer heat directly from the element to the pan increasing the efficiency up to 74%. However, due to the thermal inertia of the element and the requirement to transfer heat from the element to the pan, the ability of these cooktops to rapidly change temperature is poor.

Induction cooktops work by using a magnetic field to directly heat the saucepan or fry pan. This direct transfer of energy to the cooking surface means that the cooktop itself is a smooth easy-to-clean surface that is not directly heated reducing the chance of burns to the user and food spills burning onto the cooktop. By transferring the energy directly to the cooking surface induction avoids the waste heat increasing the efficiency up to 84% and reducing waste heat being released into the home (Lawrence Berkley National Laboratory 1998). The direct transfer also facilitates excellent temperature control and responsiveness at the cooking surface, making these cook tops the ideal choice for a Positive Energy Home. The only disadvantages are that they are generally more expensive and the pans need to be magnetic (contain ferrous iron), meaning that aluminium and copper pans are not suitable.

In general, cooktops are a relatively efficient means of cooking/heating liquids or small pieces of food (high surface area). Using a lid can reduce cooking energy 50–85% and stirring to help distribute the heat throughout the food can reduce cooking energy by 3–15%.

For food that typically takes a long time to cook, such as beans, lentils, meat stews, and so on, the cooking time and energy requirement can be dramatically reduced by pre-soaking and using a pressure cooker. These speciality saucepans pressurise under heat, raising the boiling temperature of the water, allowing much higher cooking temperatures within the liquid to be achieve. For beans, pressure cookers can reduce the cooking time from hours down to less than 10 min. For meat stews, cooking so the meat falls off the bone or so it is tenderised, which takes hours in a normal pan or a slow cooker, can be achieved in less than 30 min. Pressure cookers can also allow larger foods, such as a leg of lamb, to be cooked on the cooktop, which is far more efficient than the oven.

With that said, it still takes time for the flavour common to slow cooked food to soak in. As such, using a pressure cooker to reduce cooking time, and then leaving the food in the cooker for the flavour to permeate, and then reheating for serving can be an efficient and effective means of cooking these type of foods.

7.8.2 Range hoods

Use of the range hood when cooking oily foods is important to avoid contamination of the ventilation system, filter and heat exchanger. As discussed in Chapter 3, recirculating range hoods should be used in centrally ventilated homes and regular cleaning of the range hood filters helps to improve performance and reduce pressure losses across the filter. Although not always correlated with efficiency, noisy range hoods are less likely to be used by the occupant, so selecting a quite model is important to encourage use and the resulting air quality benefits.

Range hood energy consumption is influenced by the airflow rate, the pressure loss across the filters, the efficiency of the motor, the energy efficiency of lights and, as always, how often long it is used. European ratings provide information on the energy consumption of the fan, lights, grease filtering and noise level: all important factors in range hood selection.

Although airflow rate is a useful indicator, it is not always an effective guide to the capture effectiveness of the hood. A well-designed hood can achieve higher capture effectiveness at lower airflow rate than generic higher flow units. The location and height of the hood relative to the cooking surface is also important, with most manufacturers providing a recommended height of installation that should be followed to ensure effective capture. Other factors that can influence capture effectiveness include the location, number and size of pans on the cooktop and the proximity of the hood relative to potential airflows such as windows, doors or air vents of fans, which can disrupt the airflow around the hood. For example, an open window next to a range hood can disrupt airflow on windy days reducing the capture effectiveness.

7.8.3 Electric ovens

Like cooktops, electric ovens are typically twice as efficient (electric to heat) than gas ovens, but the overall efficiency of transferring the electrical energy to heat in the food can be as low as 14% due to heat losses from the oven and the heat required to heat the thermal mass of the oven. Like the home, selecting an appropriately sized model with good insulation and low thermal mass reduces heating energy required improving the efficiency of cooking. This also gives the added benefit of reducing excess heat escaping into the home and, through using insulated oven doors, such as triple or quad glazing, reduces the heat and chance of burns through the glass. Again, like the home, minimising heat loss through keeping the door closed as much as possible reduces total energy consumption.

Ovens cook the food by convection (transfer of heat from the hot air to the food) and by transfer of radiant heat from the element to the food (grilling/broiling). Radiant heat transfer does not require the whole oven to heat up with the radiant heat transfer directly to the food, but the radiant heat cannot penetrate far into the food so it is typically only effective for thin food. Convection heats the food more slowly, allowing the heat to transfer into the food without burning the surface. From an efficiency point of view, using an appropriate setting within the oven for the type of cooking being done helps to reduce energy consumption. For example, using a combination of fan convection to circulate the heat, and a radiant element on the top to help crisp the food, or from the bottom for food such as pizza, can help to reduce cooking time and energy consumption.

Because ovens are far less efficient, using a cooktop or microwave to pre-heat food can significantly reduce the oven cooking time and overall energy consumption. For example, parboiling potatoes on the cooktop significantly reduces baking time in the oven while still achieving the crisp baked result.

7.8.4 Microwave ovens and combination convection ovens

Microwave ovens work by exciting molecules such as water within the food, directly generating heat inside the food by friction, which is an efficient way of delivering heat into thick moist food. The conversion of electricity into microwaves is ~65% efficient, making the overall efficiency of energy transfer to the food around 50%, which is much higher than a convection oven. Obviously by heating the food from the inside, crisping and drying of the surface does not occur. As such, for large volume solid food such as roast meats, using a combination microwave and convection heating, either sequentially or combined microwave convection oven can reduce the cooking time and improve efficiency while delivering the crisp surfaces that we expect from a convection oven.

7.8.5 Other cooking appliances

KETTLES

In a kettle, the electricity is converted to heat in the element that is in direct contact with the water, meaning nearly all of the energy goes into the water. Furthermore, the heat causes convection within the water, creating effective heat distribution within the jug. However, significant energy can be wasted when the kettle is overfilled. As such, kettles are an efficient means of heating water when used appropriately.

COFFEE MACHINES

Like kettles, coffee machines use electricity to heat water and/or milk to make the coffee. Units that only heat the required amount of water and milk are obviously more efficient. Units that heat a large amount of water to build up steam for milk frothing can consume a considerable amount of energy. Units that agitate the milk while warming are generally more efficient. Like all appliances, only switching them on when in use is essential to avoid wasting energy.

RICE COOKERS AND SLOW COOKERS

Like kettles, these appliances use electricity to directly heat the element in contact with the food, reducing energy wastage associated with heat transfer. Where these appliances are well insulated, they can deliver more of the heat to the food, making them a relatively efficient means of cooking.

SANDWICH MAKERS AND ELECTRIC FRY PANS

Again these units heat the element in contact with the food and often have some insulation to help focus the heat on the food. Selecting a unit that is an appropriate size for common use and carefully managing their use (avoid excessive preheating, and switching off straight after use) helps to reduce energy consumption.

TOASTERS

Toasters with vertical slots have very high instantaneous power demands and release quite a large amount of heat out the top of the toaster. However, in general, they are only used for a very short period, so their overall energy consumption is relatively low. Obviously, using a four-slice toaster to toast two slices is very wasteful so selecting the right size unit is sensible. Horizontal toasters/grillers with insulation can help to trap the heat in the unit, improving the overall efficiency.

7.9 HOT WATER FITTINGS

In a Positive Energy Home, hot water consumption can be the largest user of energy. It is also one of the most sensitive to occupant behaviour, especially after efficient dishwashers and washing machines have been selected.

A key behaviour in reducing hot water consumption is getting into the habit of using cold water wherever possible, such as when pre-rinsing dishes, washing fruit and vegetables, soaking clothes, brushing teeth and washing hands. Measurements of hot water distribution events (hot tap is opened) in Melbourne homes found that nearly half are less than 1 min and less than 1 L, accounting for 15% to total hot water use. Considering pipe volumes, many of these events may not even be delivering useful hot water to the tap. Presumably these events arise from short hand washing or item rinsing events, where hot water is being called for without being required, such as turning on a mixer tap in the default half hot-half cold position. As such, selecting taps and tap locations that encourage the default use of cold water can help to reduce hot water wastage. Some single lever taps provide cold water in the default, middle position. Furthermore, selecting low flow taps with an aerator or flow restricting spray nozzle helps to improve the wetting ability of the tap and reduce water consumption. For rinsing taps, such as kitchen or bathroom basin taps, flow rates of 4 L per minute are readily available. Where the tap is used for filling a bath or trough, a low flow tap is no advantage and will increase the time it takes to fill the bath.

In most homes, the largest user of hot water is the shower. There are many very low flow showerheads, with a variety of effective and enjoyable showerheads available in the 9 L/min range. There are also a selection of ultra-low-flow showers, delivering as little as 5 L/min, but many of these do not deliver an overly satisfying shower experience. The ideal low-flow showerhead achieves effective wetting and pressure to create an enjoyable and effective shower.

Low-flow showerheads typically come in two forms:

1. Non-aerating heads that restrict the water flow and squeeze it through small holes: this produces a pressurised, massaging water spray. These suit people who prefer a higher pressure shower. A variation on this are shower heads that collide fine high pressure streams of water together mid air, to create an effective wetting spray.

2. ‘Aerating’ heads that mix air with the water to create a softer, bubbly, shower.

Depending on your personal preference, a quality low-flow shower head can typically deliver an enjoyable shower with as little a 6.5 L/min (rated), with a lower volume if the taps are only partially turned on. As this is often a matter of personal preference, the ideal scenario is to be able to try the showerhead before selecting or taking a recommendation from someone with similar preferences.

Even with an effective showerhead, the shower is a significant user of hot water. In the design of a Positive Energy Home, forecast hot water consumption is a major component of estimating total energy consumption, with the frequency and length of showers being the major uncertainty. There are a range of innovative strategies for developing a sensible shower routine that may work for you, including showerheads with built in timers, or flow shut-off switches that allow you to stop water flow when washing hair or soaping up. However, in general, installing a quality low-flow head and getting in the habit of having short showers is the most effective method of minimising hot water consumption.

At a typical shower water temperature of 40°C, the mixture of hot to cold is ~60% hot (60°C) and 40% cold water (around 10°C). Therefore a 6.5 L/min shower head uses around 4 L/min of hot water, or 20 L total, for a 5 min shower. If the hot water was generated using an efficient heat pump or solar hot water system, this 5 min shower would consume around 0.25 kWh of energy. In contrast a 9 L/min shower head running for 10 min using hot water from a resistive electric heater would consume ~10 times more energy. This highlights the importance of having sensible length showers in addition to using an efficient showerhead and an efficient hot water heater.

7.10 HOME ENERGY MONITORING

In a well-designed Positive Energy Home, the building uses very little energy to provide comfort, light and ventilation, which makes it very achievable to live within the renewable energy budget of the site. Managing the remaining energy consumed by appliances can be assisted through the use of an in-home energy monitoring system that provides real-time energy consumption and generation data.

In a Positive Energy Home, where heating/cooling and ventilation energy consumption is low, identifying the energy consumption of appliances within the home is typically quite obvious. Simple systems use a current reading loop around the main alternating current electrical feed to the house (downstream of the solar energy input) that sends a signal to a display within the home providing instantaneous demand feedback to the users. For example, switching on the kettle causes a clear increase in power consumption. Regular feedback on how energy is consumed can be incredibly useful for identifying standby power and helping to develop efficient habits, such as switching off appliances at the power point at the end of the day or when going out.

More sophisticated systems are also available that allow multiple circuits to be monitored, logged and displayed, such as solar generation, lighting, hot water, heating/cooling and ventilation, and plug loads. This can help the occupant to not only understand instantaneous appliance energy use but also their consumption over the day. It can also provide insight into how to manage the building envelope to minimise energy use. For example, by observing the energy consumption during different weather conditions, the occupant can establish when to open windows/doors and switch off the mechanical system or when to use the blinds to screen out extra sunlight or let in useful heat. It is also possible to install a thermal meter on the output from the

Home energy consumption can be tracked using in home displays or on the web, allowing real-time feedback on energy consumption; kettle off (left) and kettle on (right).

hot water system to monitor hot water consumption, which is useful for understanding usage habits and monitoring the efficiency of the hot water system. For example, where electricity in and hot water out is measured, the efficiency of the system can be monitored throughout the day and year to find the best control strategy or to call your supplier/installer if the system is not meeting the performance expectations.

Where power monitoring is connected to an in-home display or connected to the network allowing the data to be displayed on a computer, cumulative energy can be displayed, allowing energy consumption to be tracked against energy generation. For example, daily and annual energy consumption and generation can be plotted next to each other providing regular reinforcement of efficient behaviour and allowing the occupants the live within their renewable energy budget. Obviously, consumption and generation vary throughout the year based on the weather and solar resource, but over time the user will learn the nature of their home allowing them to enjoy it in their way. For example, they may find that they are using their television or oven less than normal, leaving some excess energy to enjoy a longer shower here and there.

It is important to remember that, although these devices can be quite useful, they consume power and are typically always on collecting data. As such, it is worth considering whether a more sophisticated system with data logging is something you will use over an extended period. It is also important to ensure there is a means to easily switch the system off when not being used or switch down to a data collection only mode.

SUMMARY

In a Passive House, appliances and hot water become the major energy consumers. Therefore, to make it easier and cheaper to achieve positive energy, it is a relatively simple matter to select efficient appliances fit for the service required, and adopt good habits to ensure the energy consumed is put to work rather than wasted. For most people, living in a Positive Energy Home will not only be healthy and comfortable, it will also create a sense of pride, which makes the small task of managing energy in the home something to be enjoyed.

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CHAPTER 8

Toolbox

There is a lot you can do with a screwdriver, but we would not recommend using it for chopping wood or spreading paint on your walls. With the right tools, the job of designing healthy, comfortable and energy-efficient houses is straightforward. Yet, with tools that are not up for the challenge, it can easily become an aimless toil.

Changes on paper or the computer are far less complicated and expensive than they are in the tangible world. Luckily, the tools to keep us on track are available and accessible. Following the Passive House certification process, guides you through most of them automatically.

8.1 DESIGN TOOLS

All models are wrong – but some are useful. Design tools have to strike a balance between accuracy and usefulness. A perfect model of a building will be just as chaotic as real life. Instead of aiming for authenticity, we should therefore simplify our problem by stripping it down to core concepts that are easier to grasp. Writing this book is a continuous attempt at doing exactly that. However, there comes a point where simplifications are no longer corresponding to the dilemmas of the real world, but rather become meaningless contractions. If I am allergic to hazelnuts, it does not help me to know that the muesli bar I am about to ingest may contain tree nuts. Knowing exactly what tree nuts could be in it can be a matter of survival in this case. Simplifications are necessary for our comprehension of the world around us, but we need to make sure that these simplifications remain useful. For building design tools to be practical, the simulated outcomes need to closely resemble the outcomes observed in use, so that the effect of any changes can be suitably anticipated. At the very beginning of a building process, future homeowners and their designers can exert a great degree of influence on outcomes. Once in the building phase, results become increasingly fixed, and the opportunity to leverage them cost-effectively rapidly falls. With cost and quality in mind, it is in the design phase where we need to spend most effort to get it right. Both the capital costs of erecting the building and the life-cycle cost are locked in at this stage. Good design takes time, and is an iterative and collaborative process. A designer experienced with Passive Houses will be able to guide you through the stages smoothly, and will use the right tools for the job.

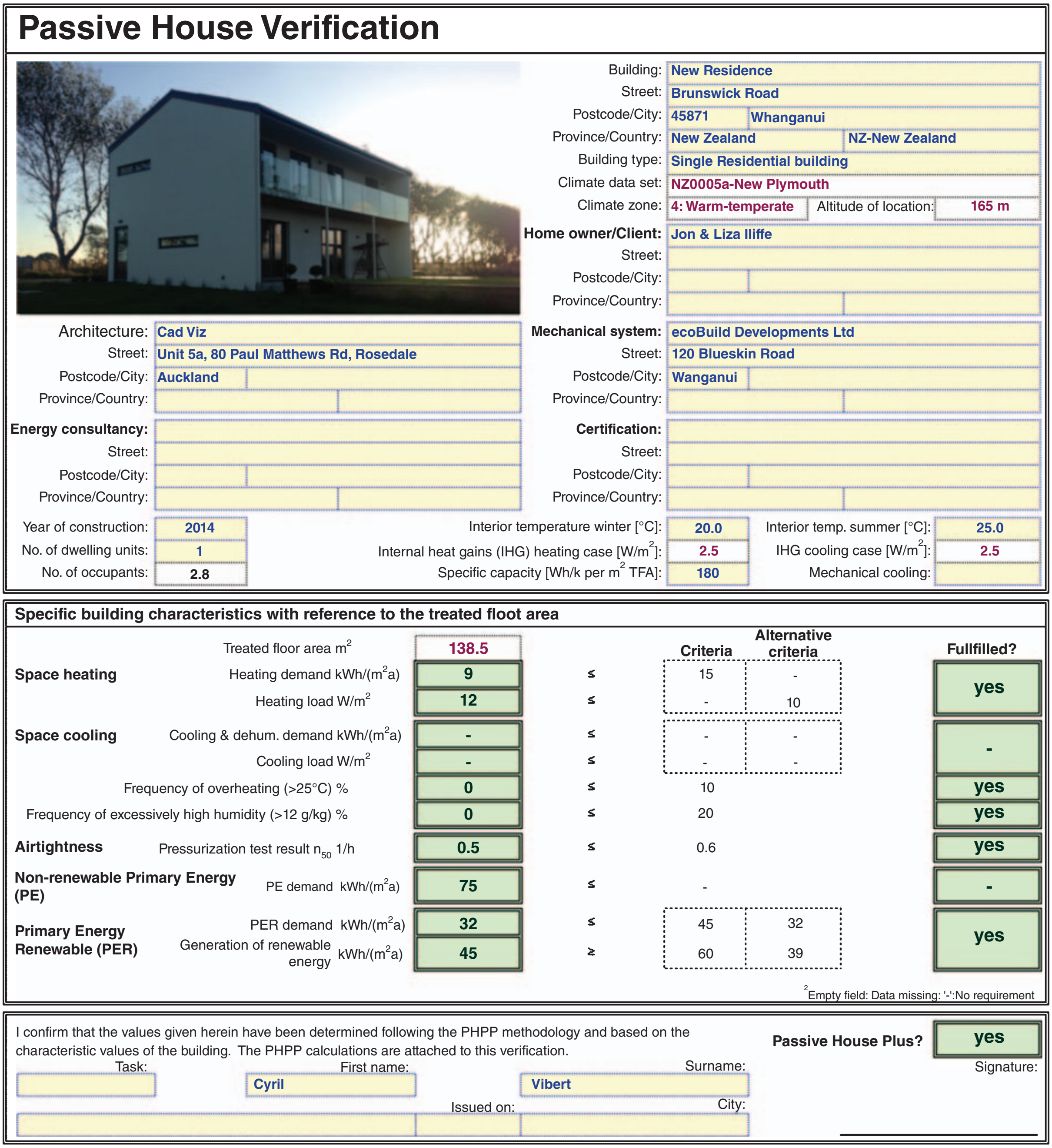
A screwdriver is very good for fastening screws, and can also be used to open cans of paint. But do not try to use it for tasks it was not designed for!

8.1.1 Passive House Planning Package

Very few codes or standard compliance methods are useful as design tools. The Passive House Planning Package (PHPP) is an exception. It is not only effective for demonstrating compliance with Passive House goals, but, more importantly, it is the ‘Swiss knife’ of energy-efficient housing design. Essentially, PHPP is a very sophisticated workbook full of spreadsheets that work together beautifully and transparently. It is cost-effective, and anyone who can work with spreadsheet software and has an understanding of building science (which hopefully you have after reading this book) can use it intuitively.

The downside of PHPP is that it is very data hungry. To obtain results that are accurate enough for the optimisation of the building, a raft of details need to be entered. However, these are all details that need to be considered in the construction of a home. PHPP just makes you consider these details upfront (where it matters) rather than accepting whatever happens to be in stock at the local store or what was used on the last job. For some details, there are drop-down menus to choose from, but often the exact construction or window frame available for the project in question will not be contained in the drop-down menu initially, in which case the entry needs to be created.

Because PHPP uses spreadsheets, all algorithms are completely transparent, and any changes immediately impact on the results. This makes it easy to play around with variations to find the optimum for the house at the location it is in. PHPP has been evaluated in the field, and was found to deliver results quite close to the measured reality. Most energy assessment tools have only been tested against other simulations, where a rather wide bandwidth of deviation from reference results is allowed. PHPP is the only tool that went through both testing phases successfully. The method PHPP uses is largely based on the international standard ISO 13790, Energy performance of buildings, which has been independently tested for its degree of transparency, robustness and reproducibility, with validation exercises demonstrating that the uncertainties produced by its algorithms are within an acceptable range. PHPP itself has also been validated against the results of a dynamic building simulations software. On top of this, it has credits few other tools have: it has been evaluated empirically. Post-occupancy evaluations regularly find good agreement with the calculated results. An example of comparative tests is given later in this chapter.



Passive House Verification

		Building:	New Residence
		Street:	Brunswick Road
		Postcode/City:	45871 Whanganui
		Province/Country:	New Zealand NZ-New Zealand
		Building type:	Single Residential building
		Climate data set:	NZ0005a-New Plymouth
		Climate zone:	4: Warm-temperate Altitude of location: 165 m
		Home owner/Client:	Jon & Liza Iliffe
		Street:	
		Postcode/City:	
		Province/Country:	
Architecture:	Cad Viz	**Mechanical system:**	ecoBuild Developments Ltd
Street:	Unit 5a, 80 Paul Matthews Rd, Rosedale	Street:	120 Blueskin Road
Postcode/City:	Auckland	Postcode/City:	Wanganui
Province/Country:		Province/Country:	
Energy consultancy:		**Certification:**	
Street:		Street:	
Postcode/City:		Postcode/City:	
Province/Country:		Province/Country:	

Year of construction:	2014	Interior temperature winter [°C]:	20.0	Interior temp. summer [°C]:	25.0
No. of dwelling units:	1	Internal heat gains (IHG) heating case [W/m^{2}]:	2.5	IHG cooling case [W/m^{2}]:	2.5
No. of occupants:	2.8	Specific capacity [Wh/k per m^{2} TFA]:	180	Mechanical cooling:	

Specific building characteristics with reference to the treated floor area

				Criteria	Alternative criteria	Fullfilled?
	Treated floor area m^{2}	138.5				
Space heating	Heating demand kWh/(m^{2}a)	9	≤	15	-	yes
	Heating load W/m^{2}	12	≤	-	10	
Space cooling	Cooling & dehum. demand kWh/(m^{2}a)	-	≤	-	-	-
	Cooling load W/m^{2}	-	≤	-	-	
	Frequency of overheating (>25°C) %	0	≤	10		yes
	Frequency of excessively high humidity (>12 g/kg) %	0	≤	20		yes
Airtightness	Pressurization test result n_{50} 1/h	0.5	≤	0.6		yes
Non-renewable Primary Energy (PE)	PE demand kWh/(m^{2}a)	75	≤	-		-
Primary Energy Renewable (PER)	PER demand kWh/(m^{2}a)	32	≤	45	32	yes
	Generation of renewable energy kWh/(m^{2}a)	45	≥	60	39	

^{2}Empty field: Data missing: '-':No requirement

I confirm that the values given herein have been determined following the PHPP methodology and based on the characteristic values of the building. The PHPP calculations are attached to this verification.

Passive House Plus? yes

Task:	First name:	Surname:	Signature:
	Cyril	Vibert	
	Issued on:	City:	

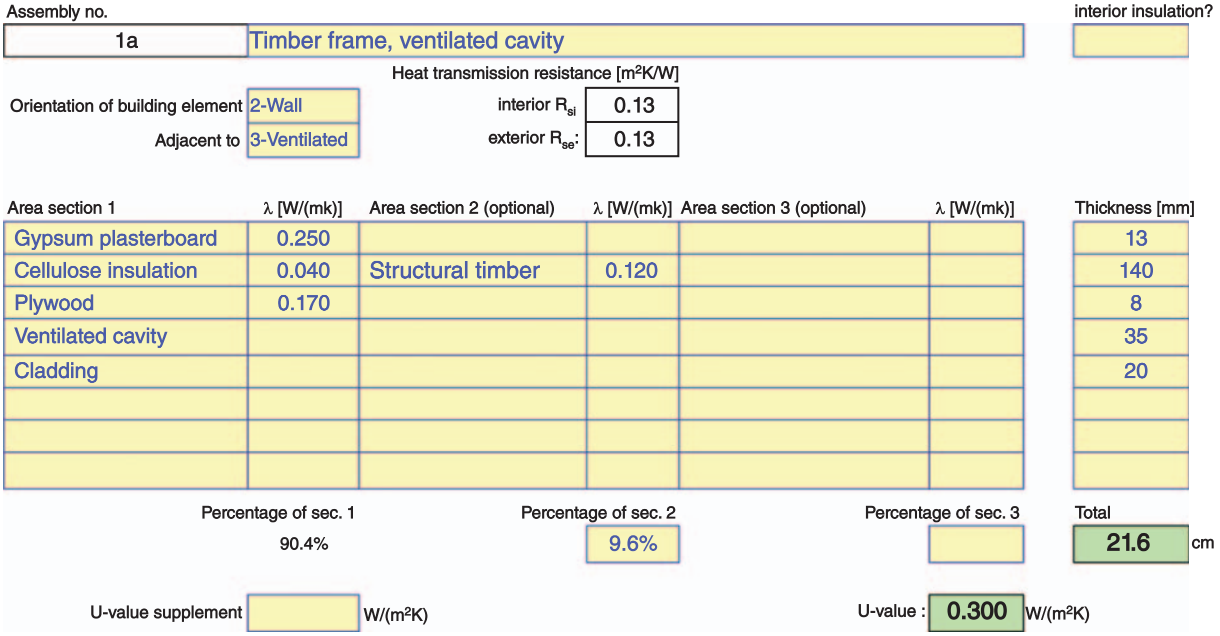
Passive House Planning Package verification worksheet, where the results of other worksheets are aggregated.

The tool is also under active development, factoring in real-life experiences of its users. It is not foolproof on its own, but, used in a certification process, it is as good as an effort to predict the performance of houses gets without turning the design of a house into a full-blown research project. However, the overriding factor for the accuracy of PHPP and other tools is the reliability of input data. For Certified Passive Houses, the plausibility of input data will be rigorously checked by the building certifier already in the design stage. These checks are not about ticking the right boxes: the fundamentals for the performance of the building will be scrutinised. Indeed, the certification process is more of an independent design review to help optimise the built outcome, rather than a formulaic test score.

DesignPH, a plugin for the popular CAD software SketchUp, adds visualisation to PHPP. It enables PHPP details to be input directly from the geometry and components drawn in SketchUp in three dimensions. You can also place your building on a ‘real’ site, which helps with a realistic shading assessment. This is where the fourth dimension, time, comes in: when the SketchUp model is placed on the actual building site, you can evaluate the sun path and the effect of shading over the year. Moreover, the graphical nature of this analysis makes it even easier to quickly check the impact of changes, or to see what happens if you turn the house 45°C on the site. With the right plug-ins, it is also possible to use the SketchUp model for a daylight analysis.

8.1.2 International standard ISO 6946:2007

The methods of the international standard for the assessment of the thermal resistance and transmittance of building elements, ISO 6946:2007, are embedded in PHPP. This standard is maintained and regularly reviewed by a group of international building scientists. As far as the one-dimensional, steady-state assessment of the heat loss factors through opaque building elements goes, ISO 6946 does a very good job. Although complex tools are available that calculate



Assembly no.: 1a — Timber frame, ventilated cavity

interior insulation?

Heat transmission resistance [m²K/W]

Orientation of building element: 2-Wall — interior R_{si}: 0.13

Adjacent to: 3-Ventilated — exterior R_{se}: 0.13

Area section 1	λ [W/(mk)]	Area section 2 (optional)	λ [W/(mk)]	Area section 3 (optional)	λ [W/(mk)]	Thickness [mm]
Gypsum plasterboard	0.250					13
Cellulose insulation	0.040	Structural timber	0.120			140
Plywood	0.170					8
Ventilated cavity						35
Cladding						20

Percentage of sec. 1: 90.4%

Percentage of sec. 2: 9.6%

Percentage of sec. 3:

Total: 21.6 cm

U-value supplement: W/(m²K)

U-value: 0.300 W/(m²K)

The thermal bridge effect of regular structural timber elements in an insulation layer can be calculated with the methods of ISO 6946:2007. The calculation of the timber content has to be fairly accurate, though, and consider all timber that bridges the insulation layer, including studs, top and bottom plates, and any horizontal bracing pieces.

heat loss through the building fabric dynamically and in all dimensions – taking ever-changing outdoor conditions and the three-dimensional nature of heat flow into account – the simplifications contained in ISO 6946 are, in addition to being easy to apply, still useful. Only in exceptional cases is it necessary to get more accurate results for houses. Whatever tool you use, you have to know its limitations. Although ISO 6946 is good enough to calculate regularly occurring thermal bridges in a construction element, such as studs in a timber-framed wall, the results of this calculation will only be accurate enough if the difference in thermal conductivity between the bridging material and the insulation around it is not too large. Timber studs are no problem here, but the effect of steel studs in an insulation layer are beyond the capabilities of this method.

Building code compliance tools often take the simplification process too far, and therefore lack the sophistication needed for an optimisation of the thermal envelope. Code compliance tools are frequently unsuited for any other purpose, such as designing a well-performing house cost-effectively.

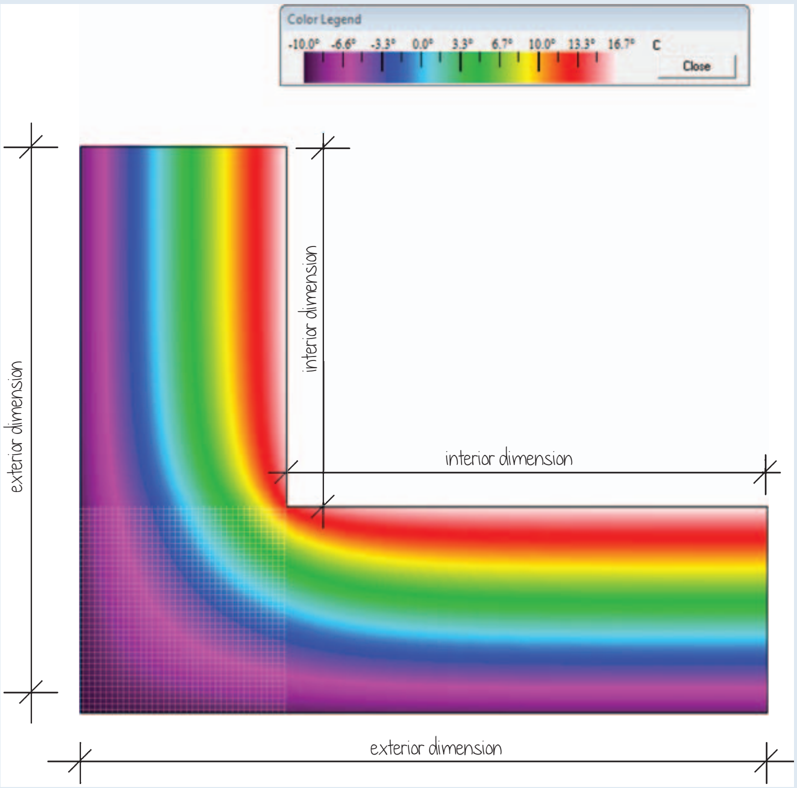
8.1.3 Thermal bridge software

Thermal bridge software picks up where ISO 6946 leaves you: U-value calculations are one-dimensional, which delivers a result that is accurate enough for the assessment of the heat loss to the outside when heat flow in one direction dominates. As an example, in the middle of a wall that is bordering outdoor air, the heat flow in winter will be predominantly in the horizontal direction. U-value calculations reduce the three-dimensional heat flow to one straight line between warm and cold areas, which serves well as a simplification for the building element in isolation. Even the effects of many regular thermal bridges can be accounted for in this manner. However, with building elements assembled, a dominant heat flow direction at joints can no longer be prudently assumed. This is where a tool that deals with more than one dimension is needed. The aim is then to estimate the additional heat loss that was not already assessed in the one-dimensional U-value calculations.

Negative thermal bridge values

Depending on the dimensioning system used to calculate heat loss through the fabric, the difference at corners can sometimes be negative; that is, the two-dimensional heat flow is less than the sum of the parts suggested. One-dimensional heat flow calculations based on exterior dimensions of the building, measure the exterior corners twice. This is a prudent hypothesis, because the geometrical thermal bridge effects at corners are typically accounted for that way. Yet, particularly with thick walls, such as you get with straw bale construction, this can lead to a severe overestimation of the heat loss at corners. With a two-dimensional evaluation, this can be corrected. Assessments for building code compliance frequently use interior dimensions to calculate the heat loss through the envelope. In this case, heat loss at corners is overlooked entirely, and every corner needs to undergo a separate thermal bridge analysis for a complete appraisal of the building's heat loss.

An exterior corner is a geometrical thermal bridge, as can be seen by the lower interior surface temperatures. When using exterior dimensions to assess the heat loss through the thermal envelope, the corner is counted twice, and the additional heat loss thereby typically acknowledged. However, if interior dimensions are used, heat loss at the corner is entirely unaccounted for. In this case, to calculate the total heat loss, a separate thermal bridge assessment is necessary for every corner.

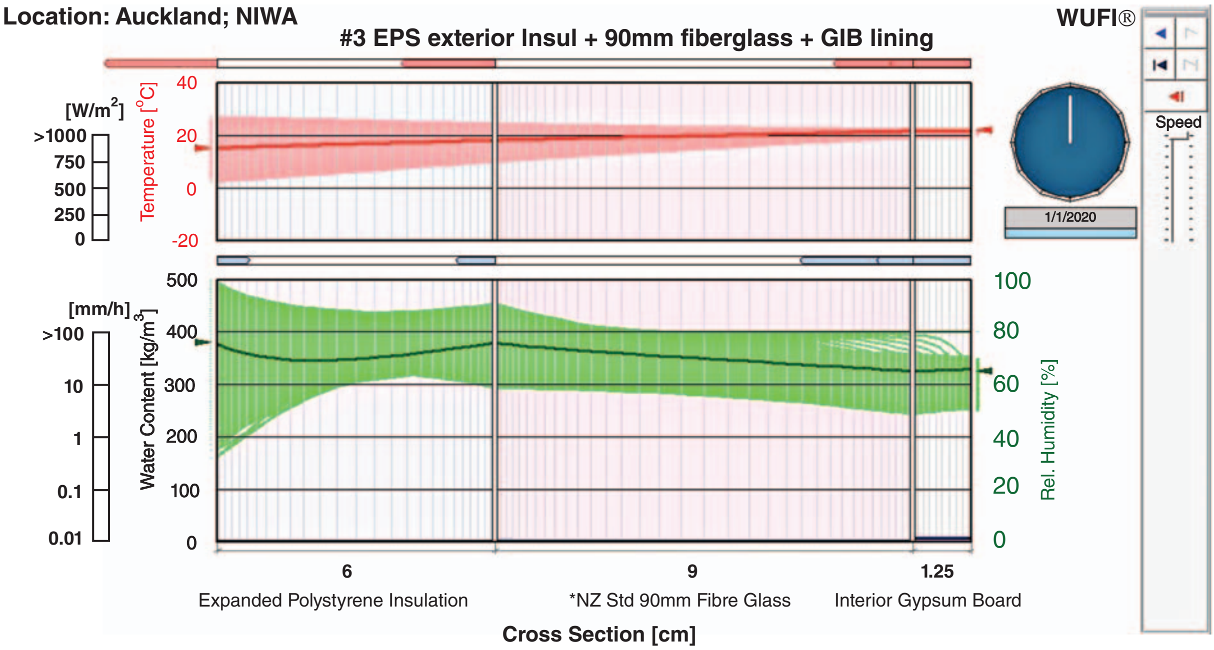


Rarely does adding a third dimension significantly add to the accuracy of the model. After all, any joint model is only ever a segment of the whole house, and therefore only a slightly lesser simplification. The additional information obtained by adding a third dimension is typically insignificant. One day it may become possible to model the heat flow of the whole geometry of a house conclusively in three dimensions – but we are not there, yet. However, in most cases, two-dimensional modelling of a section is accurate enough to help us rearrange the construction, and thereby getting a better result.

A large number of commercially available thermal bridge analysis software is available for conducting this analysis, but there is also one tried and tested tool called THERM that can be downloaded free of charge from the website of the Lawrence Berkeley Laboratories in the United States. THERM has a long history, and looks old school because of this. It is also not quite as convenient to use as some of the commercial software, but, it calculates accurately, and is widely used by building scientists because of this.

8.1.4 Coupled heat and moisture transfer

When moisture is excluded from the calculations, which it regularly is in methods that assess heat transfer through the building envelope, the algorithms can be relatively simple. This changes with moisture in the mix, because there are mutual dependencies. To complicate matters further, even material properties may change significantly with moisture and temperature impacting on them in



Using WUFI, a time-lapse video is created to assess the heat flow and moisture build-up of any modelled construction in a selected climate over time (Figure: Jason Quinn).

tandem. There are a couple of commercial software packages available for assessing the coupled heat and moisture transfer in buildings, of which WUFI is the most widely used. In WUFI, you can model a construction in a specific climate, and then do something that resembles artificial ageing. A film is created that indicates how this construction will fare over time, whether moisture will accumulate in it, or whether moisture loads impacting on the construction from the inside or outside are able to dry out over time. In a continental climate, where heat and moisture flows in winter are more predictable because of the more constant gradient between indoor and outdoor temperatures, a WUFI analysis may not be necessary. Likewise in warm climates, where the interior is not artificially cooled. In all other cases, and particularly for retrofits, an assessment of the coupled heat and moisture transfer is advisable. Ageing a construction virtually is preferable over a real world experience of moisture building up in cavities or at surfaces over time. Plus, on the computer screen, it is easily possible to check what-if scenarios and adjust the design accordingly to avoid damaging the fabric in the future.

8.1.5 Coloured pencil

Using a coloured pencil or felt pen to trace the functional layers of the thermal envelope in a print-out of sections and plans sounds basic, but it is nonetheless a very effective exercise. Not only does it allow you to visualise any issues with gaps, it also prompts you to plan in detail all the necessary connections. These need to be drawn up to construction detail – preferably in three dimensions – and all materials need to be carefully specified. Sequence drawings may further be needed, and tied to a scheduling tool, such as a Gantt chart. Taking your builder on board at this stage is likewise a good idea to check whether the detail is actually buildable, or whether there are better alternatives. Services also need to be considered at this stage, particularly where penetrations of the thermal envelope are required. And before you detail any penetration through the thermal envelope, ask yourself: ‘can it be avoided at reasonable cost?’

8.2 QUALITY ASSURANCE TOOLS

What we learn from mistakes is mainly not to repeat them. Looking for what went well and what did not is the first step in a process of continuous improvement. And it is here where house design typically lacks. Photogenic abodes are far more interesting in publications than well-performing houses (although there is no reason for a home not to be both). Time after time this results in outcomes that are no longer architecture, but rather large-scale sculpture. Architecture needs to delight – but not just the eye. Other senses deserve to be pleasantly stimulated as well. The sense of heat and cold on our skin, the sense of hearing and smelling are not depicted in the glossy magazines that announce another architectural award winner. It is left to the reader to imagine whether the experience of living in the house contributes to their wellbeing.

In most cases, clients are typically paying the bill of the designer long before they had a chance to appreciate the feel of their home. Furthermore, many designs are one-offs. This situation leaves no chance to learn from mistakes and, even if a designer may occasionally reflect on their mistakes, they will not tell anyone about it. The best results are obtained when the art and science of building come together in a collaborative respectful design team or in the mind of someone with many years of experience in both.

Because a house is for most of us the greatest expense we ever make in our lives, we desperately need to make sure that our house works out. Investing in tests in the design stage sets us on the right path, but things can still go wrong later. What needs to happen to get the best outcome possible?

8.2.1 Passive House Planning Package

PHPP has already been discussed as a design tool, but it doubles as a quality assurance tool, if the workbook and accompanying drawings, results of other calculations (such as thermal bridges), and further required documentation (such as material data) are forwarded to a peer review. This is what happens in the Passive House certification process. Another trained pair of eyes goes over the drawings and calculations and points out errors, misconceptions, causes for concern and opportunities to improve. What is being picked up may impact negatively on the long-term performance of the building, and is therefore vitally important information. It pays to go through this process at the design stage so that required changes are still easily enacted.

Once all documents are checked, and all concerns considered, the building gets the tick to go ahead. Sometimes, though, there are stumbling blocks in the building process: materials that were assumed to be available may have a shortage, and need to be substituted, or the ground turns out to require a particular treatment that was not envisaged. Any required changes of the certified design need to be documented and implemented in PHPP to check their effect, and to trace the compliance with performance goals.

At critical stages, photos need to be taken, to demonstrate, for example, that the insulation was indeed fitted gaplessly in every cavity, and that the details drawn up to avoid thermal bridging were followed in the process. This not only supports certification, but also provides a chance of continuous improvement.

One performance target that can only be assumed in the design stage is the degree of airtightness of the thermal envelope. This is therefore one of the physical tests required to ascertain that the house will be healthy and comfortable to live in.

8.2.2 Blower-door test

The blower-door, as described in Chapter 2, offers a valuable diagnostic of the effort to avoid leaks in the building fabric during construction. There is in fact a 'blower-door light' for exactly this purpose, which is cost-effective and easy to handle on a building site by the builders to do *ad hoc* tests of airtightness. But once the building is ready for delivery to the new owners, a compliance test has to be conducted by an experienced tester. The maximum air change rate allowed is 0.6/h at a 50 Pa pressure difference. Typically, it is carried out by someone who was not involved in the building process. A strict protocol needs to be followed during the test and its documentation. But that is not all. Because the exchanged volume during the test is referenced to the exchangeable volume of the house, this has to be unambiguously calculated based on dimensions in the drawings, which are verified on site. Whoever does the test must not only take full responsibility for following the testing protocol to the letter, they must also sign for the accuracy of the volume calculation.

As a quick example to demonstrate the importance of an accurate calculation of the internal volume: if the average of depressurisation and pressurisation tests comes up with a volume of 180 m^3/h exchanged at 50 Pa, a building with 300 m^3 internal volume complies with the maximum change rate of 0.6/h, but a building with 303 m^3 internal volume does not, even if rounding is taken into account. With a clear height of 2.7 m, the difference amounts to only 1.1 m^2 floor area misaligned. For this reason, the volume calculation requires great care, and the result needs to be reproducible.

Passive House blower-door testing requirements

The air change rate n_{50} is calculated from a measurement of the airflow rate (volume per hour) at 50 Pa. The test is carried out in accordance with European Standard EN 13829:2001. The airflow rate is divided by the internal volume of rooms enclosed by the thermal envelope. The calculation for this volume has to be well documented, and done room-by-room. Typically, the only openings that may be sealed for the test are the outdoor air and exhaust air openings of the ventilation system. All other potential leaks, such as range hoods, cat flaps and so on, are to be left as in use. To avoid taking potential leaks in the ductwork into account, the temporary seals should be installed at the outdoor intake and exhaust air ends of the system that are at the thermal envelope.

The airflow rate is measured over a range of pressure differences from ~10 and up to 100 Pascal. The ambient pressure difference between inside and outside needs to be deducted, and differences in the density of air be accounted for. This will happen automatically with modern testing equipment after a calibration phase. The airflow at exactly 50 Pascal is calculated from a minimum of five measurements within the tested range. Most blower-door testing kits will automatically take hundreds of measurements in this range. Both, positive and negative pressure ranges are evaluated to achieve the value at 50 Pa. The average of the two is used to determine compliance. The test can only be conducted under favourable weather conditions. To obtain reliable results, it must not be too windy or too hot outside.

While the blower-door is depressurising the house, your skin readily detects fast moving air, which will be the result of smaller leaks. Larger and more diffuse leaks will not create the jet-streams that are easily perceived with your hands, but they can still be visualised with an infrared camera or theatre smoke. If smoke is used, it pays to notify the local fire department beforehand, as concerned neighbours may otherwise call them to extinguish a putative fire.

8.2.3 Ventilation system

During construction, it is important to inspect whether ducts on site are protected from water, dust and debris. Ducts need to have a cap on both ends to achieve this. They also need to be stored in a dry place. Although air in a ventilation system is filtered, you want the initial conditions to be as fresh as possible, rather than starting out with construction dirt accumulated in your ducting. When interior doors are installed, look for transfer openings. Are they letting enough air through or are they blocked by carpets or furniture? When a door undercut is used as the cheapest way to enable air transfer, you need a gap that is wider than 1 cm to the finished floor – including any floorboards or carpets.

The next step in assuring a well-behaved ventilation system requires measuring if airflows are as designed. The ventilation system is dimensioned to deliver sufficient amounts of fresh air where they are needed, and extract pollutants and moisture at the source in kitchens and bathrooms. The extraction and supply volumes have to be balanced. A remaining negative pressure will add unwanted infiltration, while a remaining positive pressure will increase the risk of moisture being pushed into cavities, where it may meet a cold surface and condense. But in addition to the balancing act, a thorough commissioning process is also necessary to ensure that the designed supply air volumes are actually getting to the rooms where people need them if they are to stay healthy. If the results are not satisfactory, the flow rates need to be adjusted until they are. The unscientific, home-made options to test airflow requires a large plastic bag of known volume, such as\ a 60 L rubbish bag, taped to a metal or cardboard ring, to keep the mouth open. In case of a supply diffuser, you would flatten the bag, put it over the diffuser, and count the seconds it takes to fill the bag completely. For example, if your rubbish bag can hold 60 L, and it takes 6 s to fill it, your flow rate is 10 L/s, or 36 m^3/h. This also works in reverse with an inflated bag over an exhaust grille, but you need to add 1 s to your count in this case. However, this is only

A flow hood.

the cheap and cheerful, low-tech method to get an idea of what is happening. Your installation technician should use a flow hood or balometer for the process that produces more accurate results.

What is really going on in your bedroom?

When designing the flow rate for a bedroom, take everyone who sleeps there regularly into account! A bedroom that we measured had an accurate flow rate for the two person occupancy it was designed for. However, a large dog was also sleeping there, and the cause for higher than expected CO_2 concentrations overnight. After the flow rate was adjusted to account for the fresh air requirement of the dog, CO_2 concentrations dropped to healthy levels.

8.2.4 Window tests

While windows are surprisingly opaque when it comes to assessing their performance with the naked eye, some detail can be revealed looking at them with, and in, the right light. A candle or light placed in front of an insulated glazing unit at night (or against any black background) will reflect the light at every surface. For double-glazing, you should see four flames reflected, and for triple glazing six. If surfaces are coated with a low-emissivity film, the colours of the reflected flames should differ. The reflections from the coated surfaces should have a red-bluish tinge.

The flame is reflected with a red tinge on surface 2 and 4 (from the inside), suggesting that this is where the low-emissivity coating was applied. This is an old window, and with modern triple glazing you rather expect the low-emissivity coating to be on surface 2 and 5.

Looking in between the panes: if you see a shiny metal, you are likely to have an inferior edge spacer. What you want to see is the plastic surface of a polymer-composite bar, which conducts markedly less heat than the aluminium typically used.

You also need to check visually that the sealant gaskets at corners are durably connected. A lazy tradesperson may have pulled the sealant around the corners rather than cut them at a 45 degree angle and glued them together fabricate a durable corner. Pulling them around the corner stretches them too thinly. It will negatively impact on their ability to seal properly, and should not be tolerated. During installation, it is also important to check that the insulation is consistently installed up to the window housing or frame, with no unplanned thermal bridges or air gaps. High-performance frames are one of the few cost premiums in a Passive House, so ensuring they have the chance to perform is a worthwhile investment of time.

8.2.5 Thermography

In Chapter 6, we explained that infrared sits just below the visible light sector in the electromagnetic spectrum. Infrared is heat energy emitted by all objects warmer than absolute zero. Heat energy is typically invisible, but it can make an appearance if lenses that are receptive for infrared radiation are used. Only a few years ago, cameras for heat detection were horrendously expensive, and difficult to operate: for example, liquid nitrogen was required as a cooling liquid to obtain useful pictures. Nowadays, smartphone add-ons are capable of producing infrared pictures of reasonable quality, and professional tools are similarly easy to use and cost effective. Although it still takes some experience to operate these tools correctly for the analysis of complicated situations, using an infrared camera to detect air leaks during a blower-door test is as easy as taking snapshots with a typical camera.

We have all seen the colourful infrared images of houses taken from the outside, but these are actually not very telling. Particularly with cavity walls or ventilated façades, a picture taken from

Thermal camera revealing where the installation of insulation has been missed in the wall between the top of the window and the ceiling.

inside is far more informative. But, even though the quality of readily available infrared cameras has markedly increased in recent years, to reliably detect thermal bridges or gaps in the insulation layer, it is still advisable to take the picture with sufficient temperature difference between in- and outdoors and preferably at night-time to exclude the effects of areas warmed by the sun and reflected infrared radiation. Strong winds will change the exterior surface temperature of affected areas, and thereby what you see on the display of your camera, so aim for a calm winter night as the best opportunity to check for thermal bridges. Another consideration is the emissivity of the surface: for example, a high emissivity matt black surface will read a very different temperature to a shiny metal surface even though the surfaces may be the same temperature. Most cameras have an emissivity setting to adjust for different surfaces, but it can be hard to compare them in the same image. Similarly, windows can be challenging, with infrared radiation passing through them and reflecting off their surfaces. For both low-emissivity surfaces and windows, placing some black tape on the surface and allowing it to equilibrate to the temperature of the object can provide a clearer image of the temperature and heat flows. Like all checks, infrared images have the best value when it is still possible to remedy any faults easily: that is, before the construction is lined.

8.2.6 Easy measurements at home

Temperature and humidity indoors are easily monitored with inexpensive tools. A solar powered thermo-hygrometer (be careful: do not place this in direct sunlight) that detects the temperature and relative humidity of its surroundings is a good option for direct readings. Inexpensive USB data loggers are more suited for summary assessments: for example, to check how temperature and humidity change during the day. They need an external sensor or have an inbuilt battery to allow remote logging, because otherwise the proximity of the computer may skew the readings. You can also use the thermo-hygrometer to find your personal comfort range, and adjust services accordingly. Consult with your designer if your expectations are not being met. More expensive are data loggers that also include CO_2. It is, however, worth it to also keep an eye on CO_2 concentrations in the rooms where people dwell. Monitoring CO_2 concentrations is great for testing whether the ventilation strategy is successful. The logger can be moved week-by-week. It should ideally be placed in the breathing zone – that is, on the bed table in a bedroom, and higher up in other rooms. It is a good sign if values stay below 1000 ppm at all times, but in a very polluted environment this may not be possible. In any case, indoor concentrations of more than 600 ppm above outdoor concentration should not be tolerated, and the ventilation system should be adjusted accordingly.

8.2.7 In-situ U-value measurement

Quite often, the calculated and measured U-value are worlds apart. This may be due to underperforming insulation materials, a faulty installation or an underestimation of thermal bypass processes. The result of this performance gap: houses need a lot more energy than they were calculated to require to stay healthy places to live. Thermography and blower-door testing can detect some of the faults, but how exactly they will affect the performance can only be roughly estimated. Measuring the U-value of elements in the thermal envelope gives a clearer picture, but to date these measurements require special skills, effort and equipment. There are signs that this may change in the near future, with the development of more cost-effective and accessible measurement devices.

U-value measurements in the real world are a valuable tool in the kit, particularly to keep manufacturers of glazing units honest. Here, the performance largely depends on things that are invisible, such as the gas filling between the panes, and the coating of surfaces. Currently, there is very little you can do but believe the manufacturer, with the exception of the flame test already discussed. And research shows that some manufactures of glazing units are taking short cuts, and failing in-situ tests. If indoor and outdoor air temperatures are known, and the interior surface temperature can be measured (e.g. with an infrared thermometer) a plausibility test for the U-value is possible. A multiplication of U-value and temperature difference, divided by the film-coefficient for the surface will result in the difference between surface temperature and interior air temperature. As an example, if the U-value of a glazing configuration is given as 2.0 W/(m^2K), and it is 20°C inside and 0°C outside, the product of U-value and temperature difference will result in a heat transfer of 40 W/m^2. The coefficient for the extra resistance of air at the interior surface is 7.69 W/(m^2K) in this case. The result of the division is 5.2 K, and the expected temperature at the interior surface of the glass therefore 20–5.2 = 14.8°C.

How to calculate the interior surface temperature of a building assembly

Multiplying the U-value with the temperature difference from in- to outside to get the heat transfer is the first step. Mathematically: $U \times \Delta t = q$, with U in W/(m^2K), ΔT in K and q in W/m^2. The result of this multiplication needs to be spread over the heat transfer coefficient at the interior surface, which represents the inverse of the surface resistance, to get the temperature drop between room air and surface. The interior surface resistance for horizontal heat flow is in ISO 6946 assumed to be 0.13 m^2 K/W. Inverted, this amounts to 7.69 W/(m^2K).

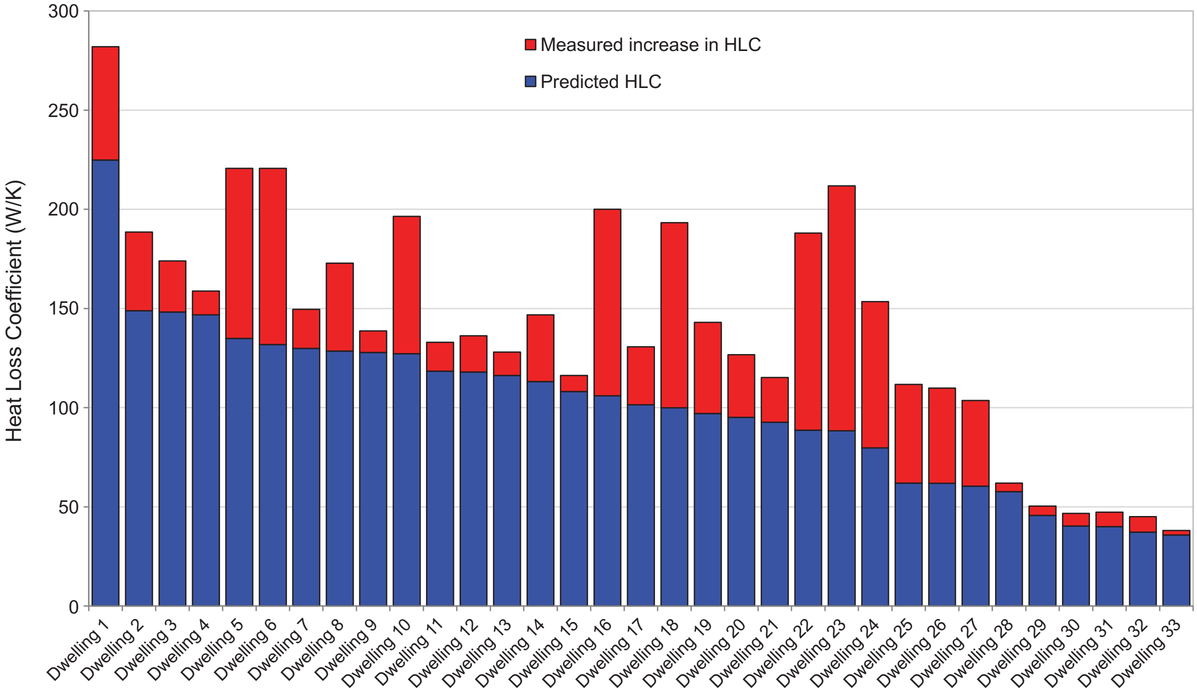
For downward heat flow, as can be assumed for a floor, this value would be 5.88 W/(m²K), and for upward heat flow, if a roof was considered, the figure was 10.00 W/(m²K). The complete formula looks like this: $(U \times \Delta T)/h = \Delta K$, where h is the heat transfer coefficient.

Note: if you are checking whether the surface temperature is a concern for mould formation, a lower than typical heat transfer coefficient is assumed as a safety margin.

Although this check is suited as a plausibility test, it is not very accurate, because, for example, the film coefficient is only an approximation of the average conditions at that surface, and infrared thermometers are typically not very precise either. But it may serve as an approximation to check whether the glass is performing as required until more accessible tools for this task become available.

8.2.8 Co-heating

Co-heating is a post-construction performance test. This test is not for the typical homeowner, but a good way for professionals to check whether design processes result in desired outcomes to complete the learning circle. Basically, the thermal envelope is put on trial, and all random influences on its performance – including the occupants, who have either not yet moved in, or need to be placed elsewhere for the duration of the test – will be excluded. A high internal



Co-heating test results. All 33 houses were supposedly energy efficient, but the average heat loss for the Passive Houses (the last six houses) was only about a quarter of the average heat loss of the other houses; the gap between measured and predicted performance is also markedly narrower with the Passive Houses (Figure: Johnston D. Personal communication. 2016, Leeds Beckett University, Leeds, UK).

temperature is maintained over a few weeks, and evenly distributed throughout the enclosure with fans. The daily heat input of the unoccupied dwelling is recorded, which must equal the heat lost through the thermal envelope. In order to maintain a sufficient and one-directional temperature gradient between in- and outdoors, the test is carried out during winter months. The building is prepared as it would be for a blower-door test, so that the intended openings for the switched-off ventilation system are sealed. In fact, a blower-door measurement is performed before and after the co-heating test to exclude in-and exfiltration heat loss as well. All external parameters, such as wind, sunshine and temperatures are documented, and the totals adjusted for these. The results can then be compared with the predicted outcomes based on calculations.

Typical houses, and even houses that were self-proclaimed performing better than the building code required, were no stellar performers in tests conducted by Leeds Beckett University and other researchers in England. The gap between the predicted and actual performance of the thermal envelope was vast. Not only did the Certified Passive Houses perform markedly better, the intervals between expectations and measured values were also narrower. Johnston and Siddall (2016), who presented these findings, concluded that the fabric of Certified Passive Houses delivers what it says on the tin. We recommend that all designers check this occasionally!

SUMMARY

For any job, it is important to have the right tools. The job of designing and building healthy and comfortable homes requires a set of tested tools for any chance of success. The Passive House certification process mandates the use of most of these tools. Arguably, following this process is even more important than aiming to reach the certification thresholds, because thresholds without a robust means of verifying them are rather meaningless. For professionals, using these tools and a vigorous feedback loop will also lead to continuously improved outputs.

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CHAPTER 9

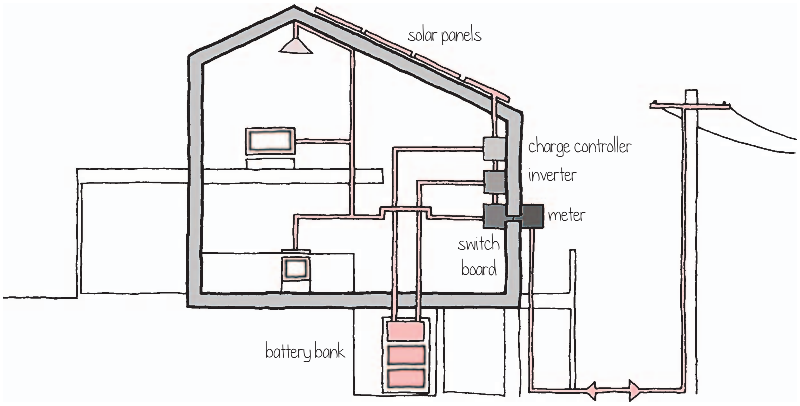
Energy generation and storage

The final part of creating a Positive Energy Home is collecting more energy than the home requires through onsite renewable energy flows on site. Again, we need to stress here that this step is only sensible after the previous steps have been implemented. You do not solve the problem of leaking pipes by adding a rainwater tank. Similarly, we need to plug the energy leaks in our houses first, before we consider generating our energy requirements. For urban areas, the two energy flows generally available are wind and solar.

One of the obvious advantages of wind is that it is able to generate power both day and night. At a large scale in the right location, wind turbines are a highly effective and economical source of clean energy. The amount of power generated by a wind turbine is proportional to the wind speed, frequency and local wind quality. In urban environments, wind quality is often quite low due to friction and turbulence generated by the surrounding landscape and buildings. This often results in relatively poor and unpredictable power generation for small-scale urban turbines, meaning that careful investigation and analysis is required before including this type of generation in the home energy balance. Where the house site may not be appropriate, but the region has good wind resources, a community wind scheme may be an option, where the community co-operative sponsors the development of a medium-scale wind generation facility in the area to provide renewable power. The Hepburn Wind Project in rural Victoria is an example of this approach and is discussed in Chapter 11.

In contrast, generation from solar photovoltaic (electric) systems is relatively reliable and easy to predict even in built-up areas, although it is only available during the day. Generation of heat' such as a solar hot water system' is even more reliable because heat can be collected from indirect solar radiation, allowing these systems to collect useful energy even on cloudy days. Given the complexities and constraints of wind power and the availability in urban areas, the relatively rare availability of micro-hydro suitable watercourses, decreasing costs and diversity, for the majority of homes the collection of solar energy is the most practical and economic means of achieving positive energy.

In most cases, the home will interact with the electricity grid allowing it to share its excess energy generation and draw energy when onsite energy is not available. In regions with hot summers, peak generation from domestic renewables such as solar corresponds with peak or



A grid interactive solar PV system with storage.

heavy grid demand, meaning that the excess solar can help to support the grid during the afternoon peaks. As such, being a part of the grid and an active contributor and user can help to increase the proportion of renewable power beyond our homes. With storage added to the system, helping to smooth out local generation and consumption peaks, home generation systems can become a useful part of a renewable energy grid.

Local energy storage can help to smooth out peak and troughs in onsite power generation, such as when a cloud passes over the home solar generation drops down. Excess power can also be stored to meet evening peak loads within the home, meaning more of the power generated on site can be used in the home. Indeed, as our electricity grids change, with more homes generating their own power and the grid becoming more reliant on renewable sources, domestic energy storage becomes an important component of a clean energy network. For this purpose, inverters (the device that manages the interface between generation and the home) are now available that offer integrated power storage, allowing greater flexibility in the management of generation, storage, consumption and export/import.

These integrated systems typically only have a small storage capacity, allowing for the short-term smoothing of generation and demand. For larger requirements, dedicated storage units are typically used. For remote areas, where grid-connection costs are high, the combination of a super efficient home with adequate energy storage makes it possible to operate independently of the grid without compromising comfort and lifestyle. With that said, energy storage does add considerable cost to the home and introduces conversion losses that need to be accounted for in calculating the annual renewable energy generation capacity of the home. Furthermore, the renewable energy system also needs to be oversized to facilitate powering of the home and charging of batteries.

The most common method of energy storage in homes is through the use of batteries, which provide practical storage for a few days or a week. For regions where there is a mismatch between seasonal generation and demand, such as in higher latitude regions that have peak generation in summer and peak consumption in winter with low generation, a more long-term storage solution, such as pumped water or energy to gas, may be required, as discussed further in Chapter 11.

9.1 ONSITE RENEWABLE GENERATION

As already noted, typically the most reliable and predictable energy source available is solar energy falling on or around the home. Direct solar energy can be collected in a variety of ways for use in the home. As discussed in earlier chapters, the collection of daylight to light in the home is an essential component of creating and engaging an efficient home. We can also use the sun's energy directly for heating the home through our windows and drying clothes on a clothes line. More active uses of the sun's energy include the generation of electricity through solar panels, the active collection of heat through solar thermal systems and the indirect collection of solar heat from the air, ground or bodies of water using heat pumps.

The sun's energy is also captured by plants and stored as biomass. As discussed earlier, the combustion of biomass/fuel to power the home is a relatively inefficient process. In a well-built Positive Energy Home, the introduction of combustion adds considerable complexity, waste, contamination and cost. As such, other than in extreme climates, we believe that the use of biofuels in the home should be limited to the far more valuable function of powering the occupants. Indeed growing food onsite is a key component of creating a positive energy lifestyle, which is explored further in Chapter 11.

A crash course in electricity

The electricity we use to power our homes is effectively the energy from the movement of electrons. This energy is created through the generation of an electrical potential, which causes electrons to move through a conductive material such as a copper wire. The flow of electrons is described as current, not dissimilar to the volume of water flowing through a pipe, and the electrical potential driving the electrons is described as voltage, analogous to the pressure from a pump pushing water down the pipe.

The energy (measured in watts, W) in electricity is a combination of the current (I, measured in amps) and the voltage (V, measured in volts). Just like friction in a pipe, electrons experience resistance as they flow through a wire, which results in the conversion of electrical energy to heat. Therefore, electricity with high current (I) and low voltage (V) will experience greater resistance losses compared with low current high voltage electricity, even though they may transfer the same amount of energy. As such, electricity is generally transported at high voltages, and then stepped down via a transformer to lower more practical and safer voltages for use in the home. Conversely, solar cells (and batteries) output low voltages that need to be increased (either through combining cells in a string or using an inverter/transformer) for practical use in the home and exporting to the grid.

When the negatively charged electrons flow in one direction through a circuit from a point of negative potential to a point of positive potential it is called direct current (DC), whereas in alternating current (AC) the electrical potential is constantly being swapped causing the electrons to flow backwards and forwards. Devices such as solar cells and batteries generate direct current and appliances such as LEDs, electronics and DC motors consume direct current. Resistive devices such as kettles or incandescent light bulbs can use either, and inductive devices such as an induction stove, induction motors and fluorescent lamps require AC power. One advantage of AC power that makes it convenient for distribution is that it is relatively easy to adjust its voltage to suit the need, using a transformer. Therefore, due to the varying requirements of devices and the different properties of the two types of electrical current, in most homes electricity is regularly being converted between DC and AC.

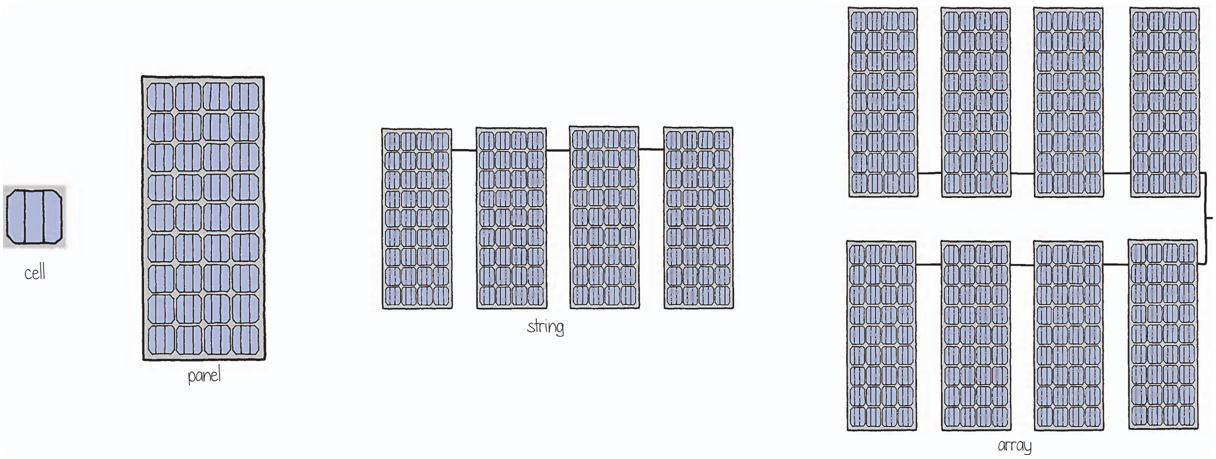
9.2 SOLAR PHOTOVOLTAIC SYSTEMS

Due to their reliability, simplicity and high-quality power generation, solar photovoltaic (PV) systems will form the basis of the majority of Positive Energy Homes. The basic components of a solar PV system are the solar panels and the DC/AC inverter. Some systems also include an energy storage component, either integrated into the inverter or as stand-alone storage units

9.2.1 Solar cells

Photovoltaic panels are made from semiconductors, which, when exposed to sunlight, produce electricity. Within a typical silicon solar panel, two layers of semiconductive silicon are sandwiched together. The top layer is doped with an electron rich (n-type) element such as phosphor and the bottom layer with an electron poor (p-type) element such as boron, creating a p–n junction. When placed together, electrons at the junction between the two layers migrate from the top layer to the bottom creating a small electrical field between the two layers. Once the electrons have found a comfortable location between the two layers, this creates an equilibrium state that is maintained until exposed to sunlight. The absorption of sunlight excites the electrons into a conductive state causing the electrical field to push electrons out of the bottom layer of silicon into a metal plate at the back of the panel. This creates a voltage potential across the cell, allowing the electrons to flow through an external circuit, where the energy carried by the flowing electrons can be harnessed to power the home. The electrons then flow back to the top layer of the panel via a network of metal conductors, resetting the system.

Solar panels are made up of a series of interconnected solar cells (see figure below) where the (square) cells can be easily seen within the panel. The voltage generated across a single solar cell is typically less than 1 V, so multiple cells are combined into a solar panel and wired together in series to create a more useful voltage (e.g. 12 V). Cells are typically wired together in parallel with other 12 V series in a combination that facilitates the desired voltage and current output.



A solar cell, panel, string and array.

9.2.2 Solar panels

Solar panels are a collection of interconnected solar cells housed together in a robust and easy-to-install unit. To achieve this, the cells are coated in a protective layer of plastic, then sealed between a layer of low reflectivity/absorption (low-iron) glass or plastic and a supporting glass, plastic or metal back. Many panels also have a metal or plastic frame for added support and ease of installation. The final part of the solar panel is the electrical connectors (wires) that are typically fitted with male and female 'plug and play' connections that allow easy interconnection with other panels or back to the inverter.

PANEL EFFICIENCY

Peak power output (see Table 9.1) is measured under standard sunlight, equivalent to 1000 W/m^2 (1 kW/m^2). Therefore, dividing the peak output in watts of the panel by its area in m^2, gives W/m^2, and then dividing this number by peak solar 1000 W/m^2 gives the % efficiency of the panel. For example, if a solar panel has a peak output of 250 W and an surface area of 1.6 m^2, then it is able to generate 156 W/m^2 (250 W/1.6 m^2). Therefore, by dividing its peak output (156 W) per m^2 by

Table 9.1. Technical terms for solar panels.

Term	Symbol/units	Explanation	What is this used for
Rated (peak) power	W p or kWp	The maximum power output from the panel under peak sunlight (equivalent to insolation of 1 kW/m^2).	To calculate expected system output using local solar insolation data.
Temperature at rated power	°C	This is the temperature of the panel during peak power testing, typically 25°C.	As a reference for calculating system performance at expected operating temperatures.
Temperature coefficient:	%/°C	The rate at which output decreases per degree of temperature increase.	Estimating power output at typical operating temperatures.
Nominal voltage	Vn/volts	The voltage that the panel is designed to be used at.	System design.
Voltage at peak power	Vp/volts	This is the voltage measured across the panel when the panel is producing peak power.	Calculating power output.
Current at maximum power	Im/amps	The maximum current available from the panel at peak power.	Calculating power output.
Open circuit voltage	Voc	The maximum voltage available from the panel with no load attached. Typically 21 V for a 12 V 36 cell system.	To determine maximum voltage for system design and safety rating.
Short circuit current	Isc/amps	Current generated when the panel is short circuited (load by-passed) at peak output, insolation 1 kW/m^2, at 25°C.	To determine maximum current for system design and safety rating.

the peak solar energy (1000 W) per m^2, we can calculate the panel efficiency to be 15.6% (156 W/m^2/1000 W/m^2 × 100%). All panels are tested under standard conditions, and some manufacturers will also provide performance data for lower sun conditions (see figure on p. 187). This can be important if you live in a cloudy region or at high latitudes where your panels will be operating at far less than 1000 W/m^2 sunlight for most of the year.

Typical commercial panels offer efficiencies between 10 and 20%, generally with a cost premium for higher efficiency panels. The value of increased efficiency may be determined by your power requirements and available roof space. For example, higher efficiency panels may be required to meet the power requirements on a small roof, whereas lower efficiency panels may offer lower system costs where plenty of roof space is available.

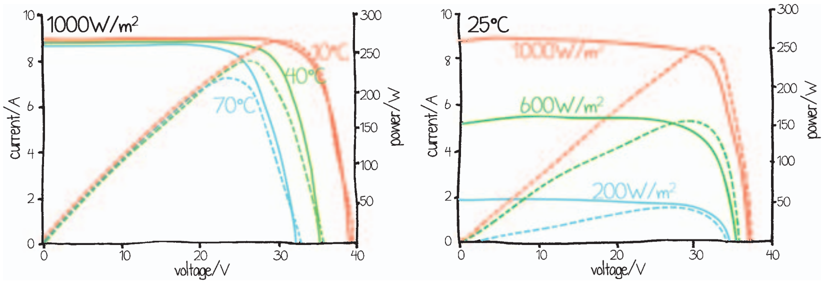
TEMPERATURE COEFFICIENT

As the temperature of solar cells increases the voltage generated by the p–n junction in the cell reduces, which translates to a decrease in the power output of the panel. This decrease in power is described by the panel's temperature coefficient: the percentage decrease in panel output per degree temperature increased above the reference temperature. For example, output from a panel with a temperature coefficient of 0.4%/°C, operating at 35°C (assuming a reference temperature of 25°C), would reduce by 4%. Under direct sunlight with no wind, panel temperatures of greater than 65°C may be experienced, resulting in a 16% reduction in output.

The temperature coefficient varies between panels and technology types. As the majority of solar generation occurs in the warmer summer months, for hot climates reduced output can be a serious concern, making temperature coefficient a key criterion in panel selection. For cold clear climates, this is less of an issue. The panel mounting method can also influence the operating temperature of the panels. For example, panels mounted on frames above the roof have greater airflow around them reducing temperature build up, compared with panels that are integrated into the building fabric and are thus less able to dissipate heat. As such building integration may be less favourable in hot climates due to reduced panel performance. There are also panels available (discussed below) that use water to absorb excess panel heat to improve PV performance and generating useful hot water.

CURRENT-VOLTAGE (IV) CURVES

As with all electrical devices, the power output (W_p) from a solar panel is a combination of the current (I) and voltage (V). The peak current output of the solar panel occurs when the panel is short-circuited (I_{SC}) (electrons are allowed to flow freely), which results in zero voltage. Conversely the peak voltage occurs when the panel is in open circuit (V_{OC}) (electrons are prevented from flowing). Panel performance is typically measured across the full range of currents and voltage between these two extreme points and plotted on a current voltage curve, with current on the vertical axis and voltage on the horizontal. Peak power occurs at the balancing point between peak current and voltage.



Example current voltage (IV) curve for a solar panel showing the influence of temperature on the left and solar intensity on the right.

Most panel manufacturers provide IV-curves for panels under standard test conditions, 1000 W/m^2 at 25°C, giving peak power. Many manufacturers will also provide IV curves across a range of insolation and temperatures, providing valuable information on how the panel will operate under typical conditions experienced at your home. For example, some panel types are less influenced by high temperatures, making them more suited to hot climates, whereas others are less influenced by low insolation making them ideal for cloudier areas or areas in higher latitudes. As such, IV curves can be a useful guide to selecting panels suitable to your area.

9.2.3 Designing a system for your house

PANEL TECHNOLOGIES

Panels are available in a range of shapes, sizes, colours and styles including frameless, to suit your home. The three major technology choices in the domestic roof top market are monocrystalline silicon, polycrystalline silicon and thin-film, the last with a variety of semiconductor materials available.

Crystalline silicon panels are made up of two thinly sliced wafers of silicon sandwiched together to form a p–n junction. Mono-crystalline panels, in which each wafer is cut from a carefully grown single crystal of silicon, have traditionally been the leader in efficiency while being the most energy intensive and expensive to produce. Poly-crystalline panels have a lower manufacturing energy requirement and typically slightly lower efficiency. Wafers are cut from polycrystalline silicon, which require less care and energy to produce, but lack the efficiency benefits of the rigidly ordered monocrystalline wafers. In both types of crystalline cells, as much as half of the silicon is lost during the cutting of wafers and much of the silicon in the wafer is only required to provide structural integrity during construction. The energy pay back period for silicon solar cells is generally around 1–3 years, depending on the manufacturing process and solar resource they are operated under. With a typical operating life of greater than 30 years, they can produce 10–30 times more energy than required to produce them.

Thin film or amorphous panels, which are made from a range of semiconductor materials including silicon, copper, indium, gallium, selenide or cadmium telluride, are made by depositing a thin film of semiconductor onto a conductive surface. It is noteworthy that some of these elements are toxic and require care in their disposal. Thin film panels generally have lower

Examples of panel technologies: at the top, individual single crystal solar cells can be easily distinguished in the monocrystalline silicon panels, with polycrystalline silicon panels in the middle and amorphous thin film silicon panels at the bottom.

efficiency, but require far less semiconductor material to produce, potentially reducing the overall cost of the panel and the embodied energy to around half of crystalline panels. Furthermore, thin film solar panels offer different properties: for example, amorphous silicon thin film solar panels typically have better low light performance than crystalline panels, which can be beneficial in cloudier climates. Thin film panels also come in a variety of colours and substrates, including conductive glass creating translucent panels or plastic for flexibility.

SOLAR PANEL QUALITY

The beauty of a quality solar panel is that it can be placed on the roof and provide reliable electricity generation for the next 25+ years with very little maintenance. Some variations from this scenario include a reduction in output overtime, electrical connection faults or delamination of the panels resulting in reduction in output and/or panel failure. Because there is no practical way for a consumer to physically assess these risks, a common measure of solar panel quality is the warranty offered. Like panel quality, these warranties vary in quality and length, with the ideal warranty covering construction quality and panel output, which in some cases is guaranteed for up to 25 years. As with all warranties, they are only useful if the company offering them is around to honour it. As such, a careful consideration and comparison of the offered warranties and the longevity of the company offering it can provide a good indication of panel quality. This can then form a basis for comparing the quality against the price, to establish the best value for money option for your needs. Most inverters will monitor output and with some basic tracking software you can monitor output over time to check that your panels are performing (see discussion of energy monitoring below).

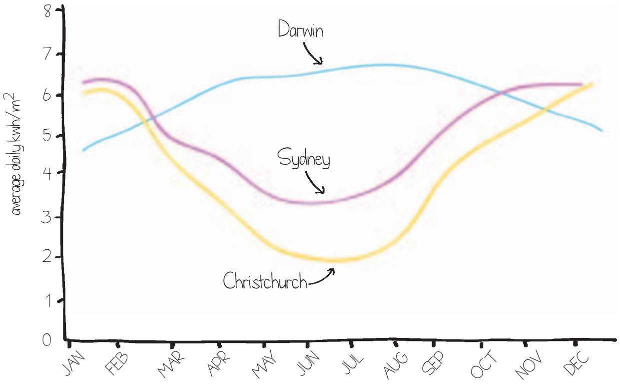
LOCAL SOLAR ENERGY RESOURCE

Given the Earth's predictable path around the sun, taking into account historical weather patterns and measurements, and allowing for some variation due to weather events, the annual solar resource or insolation for a given location is highly predictable. Again allowing for local variations, the average solar energy available in the middle of the day is nominally 1000 W/m² or 1 kW/m² at surface level. This value is used to test the peak output from solar panels: a solar array with a rated 1 kW-peak output solar array will produce 1 kW when exposed to peak sun at 25°C, under standard test conditions. Of course the solar output varies throughout the day and year, meaning less power is produced when less solar energy is available, and obviously no power is produced at night.

Annual insolation data is available for most areas, which is useful for doing detailed calculations, but a more tangible reference for estimating annual solar energy is peak sun hours. Peak sun hours is the average daily insolation expressed in terms of equivalent peak solar energy. For example, if the average usable solar radiation that falls on a site is 5 kWh/m² per day, this would be equivalent to 5 peak sun hours. Across the globe, peak sun hour averages vary from <1 close to the poles to greater than 6 for low cloud areas around the equator. In most regions, peak sun hours vary throughout the year due to the position of the sun in the sky and the prevailing weather (cloud cover). For example, Christchurch, New Zealand, has high peak sun hours in January when the summer days are long, but very low peak sun hours in July with short days and cloud cover. In contrast, Darwin has higher peak sun hours in July than January due to high cloud cover through the January wet season. Alice Springs, which has clear desert sky most of the year, has consistently high solar irradiance year round.

SHADING

Reduction in the incident solar radiation from shadows caused by objects near the array such as buildings or trees, or by self-shading between panels causes a reduction in power generation.



Average daily kWh/m² per month for different locations. For Sydney and Christchurch, solar radiation is higher in summer and drops off in winter, more so for Christchurch which is further from the equator. For Darwin, which is located in the tropics, cloud cover through the summer months reduces available solar radiation, with higher daily solar radiation in the drier winter months.

Given the cost and high value output of solar panels, every effort should be made to provide or find a location that is free of direct shade for the peak generation hours of the day. Where some shading is unavoidable, there are various strategies to help reduce the impact.

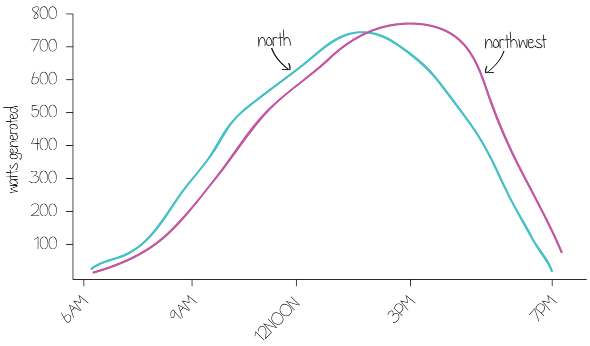
Shading affects different panels in different ways. For crystalline panels, shading of one solar cell within a panel can reduce the output of the entire panel, or even multiple panels depending on how the panels and array are wired. The impact of shading on individual crystalline panels can be reduced by including bypass diodes in the panel, which allow individual solar cells to be bypassed when in shade, but this approach introduces voltage losses and reduces the peak output of the panel. The impact of shading of individual panels on multiple panels occurs when panels are wired in strings back to a common inverter. This can be overcome by using micro-inverters on each panel, allowing each panel to be optimised individually. This configuration, while awarding benefits for shaded systems, introduces greater complexity and requires the inverters to be located on the roof with the panels, hindering access in the event of a failure. Thin film panels tend to have larger, and often longer, solar cells within them, making them less susceptible to spot shading.

AZIMUTH

Azimuth is the orientation of the panels relative to true north. The ideal orientation of panels for peak annual generation is towards the equator, so an azimuth of 0 degrees in the southern hemisphere and 180° in the northern hemisphere. Where equator-facing roof space is not available or impractical, providing the panels are not on a steep tilt angle, good generation can still be

Table 9.2. Monthly and annual kWh generation for a high efficiency (19%) 1 kWp array in Melbourne at a tilt angle of 20°.

	East	North-east	North	North-west	West
January	162	166	166	164	160
February	130	139	142	139	131
March	121	135	137	128	112
April	81	98	104	95	78
May	51	64	68	61	47
June	46	60	64	56	40
July	51	65	69	62	47
August	72	87	90	80	64
September	90	102	105	98	86
October	133	142	144	137	126
November	137	142	143	140	135
December	149	152	153	152	149
Annual	1223	1352	1385	1312	1175



Daily output variation between panels orientated (azimuth) towards north and north-west, in January for a high efficiency (19%) 1 kWp array in Melbourne at a tilt angle of 20°.

achieved for roofs facing anywhere from the equator through to east or west, though with slightly higher variance in seasonal output (Table 9.2).

Orientating the panels towards east or west will change the peak output time of the array. For example, a west-facing panel will have a peak output later in the day than an equator-facing panel. As such, for a home that has a demand peak in the afternoon, variation in the azimuth angle towards west may improve the alignment of generation with demand, increasing the proportion of generated power used directly by the home.

TILT ANGLE OF THE PANELS

The tilt angle of the panels relative to the horizon influences the annual generation and the seasonal generation of the panels. For equator-facing panels, maximum annual generation is

Table 9.3. Monthly and annual kWh generation for a high efficiency (19%) 1 kWp array in Melbourne facing north.

Tilt angle	Flat	30°	60°	Vertical
January	167	160	121	61
February	135	141	117	67
March	120	141	131	91
April	82	110	114	92
May	51	74	81	70
June	44	72	83	75
July	50	76	84	74
August	70	97	102	85
September	90	109	104	78
October	134	144	124	78
November	141	139	108	58
December	155	146	110	55
Annual	1239	1409	1279	884

typically achieved by tilting the panels at a similar angle to the latitude of the location (e.g. at tilt angle of 38° in Melbourne). The tilt angle also influences the seasonal distribution of generation. For example, in Melbourne, flat panels generate significantly more energy in summer than winter, whereas panels with a high tilt angle have a more even distribution across the year (Table 9.3). Therefore the ideal tilt angle can be a balance between maximising annual generation and matching generation against seasonal energy demands for heating and cooling.

On a flat roof, angling the panels on frames adds costs and introduces shading, increasing the space required between panels and increases wind loading. As such, depending on the available roof area, laying the panels flat may slightly reduce the annual output of the panels, but increase the usable roof area, which may allow more panels to be installed increasing annual production. However, laying panels flat can decrease the ability of rain to wash dirt and other debris off the panels, allowing it to build up and reduce output if not cleaned. A pitch angle of at least 10° is recommended to facilitate self-cleaning by rainfall.

In the majority of cases, tilt angle and azimuth are fixed, but through using mechanical tracking systems, the orientation of the panels can be adjusted throughout the day and year to optimise the orientation towards the sun. For example, tilting the panels in winter to capture more sun, while flattening them in summer when the sun is higher in the sky. Tracking of the sun can increase the annual output from the panels, but it adds considerable cost, complexity and maintenance to the system.

It is also possible to integrate panels directly into the building fabric: for example, use them in place of a weather shield such as metal sheets. This can improve the aesthetic of the array and save roofing material costs. There are a range of products available designed for this style of installation or standard panels can be used with appropriate sealing and mounting fixtures.

ORIENTATION AND INVERTERS

Where a central inverter is being used, individual panels are wired together in a ‘string’ with a common connection to the inverter. The inverter then manages voltage and current of that string of panels to maximise the power output, called maximum power point tracking (MPPT). Shading causing a variation in the performance of an individual solar cell or panel within the string can disrupt the output of all of the panels on the same string. This can also be the case where panels on the same string have different orientations, resulting in varied output. Therefore strings should be made up of panels with equivalent orientation and connected to a dedicated inverter for that orientation or to an inverter designed to manage multiple-strings with varied outputs. Where each panel is likely to experience varied conditions, micro-inverters can be used to optimise output for individual panels.

9.2.4 Design underlying structure for solar generation

For the majority of Positive Energy Homes, designing or adapting an existing roof for solar generation is essential to achieving zero net energy. An ideal roof design/selection would include

The roof of the Larch Passive House was designed for economical construction and to maximise unobstructed equator-facing roof area for solar PV and solar hot water collection (Photo: Justin Bere).

a significant area of unshaded equator-facing roof, with a pitch of 10° or more so panels can be laid directly on the roof without additional frames while maximising annual output and assisting with solar panel self cleaning during rain events. This configuration also allows the panels to be wired together into equivalent strings and managed by a single appropriately sized inverter.

The roof should also be designed to create an aesthetically appealing appearance and assist with daylight and passive solar harvesting and solar control. Increasing the pitch off the roof can help to balance annual generation in locations further from the equator, but this needs to be balanced against minimising the overall surface area of the home.

9.2.5 System sizing

Taking all of these factors into consideration (above sections and Table 9.4), along with your local solar resource, allows a surprisingly accurate estimation of annual power generation. There are a range of software packages and websites that do this calculation for you. For example, the PVwatts calculator developed by the National Renewable Energy Laboratory (USA), allows you to calculate monthly and annual output for a proposed array (see Tables 9.5 and 9.6). It even has a feature that allows you to measure your roof space on an aerial photo to estimate potential system size. Once you have a system in mind, the PHPP can be used to forecast annual generation and balance generation requirements against forecast consumption and primary energy requirements.

AREA REQUIRED FOR PANELS

Taking a typical solar panel with an efficiency of 15% into consideration, the peak output of the panel under standard test conditions or 1000 W/m^2 will be 150 W/m^2.

Table 9.4. Other installation and operation factors that influence panel output.

Term	**Meaning**	**What to look for**
Panel temperature	Peak output of the solar panels is typically measured at a panel temperature of 25°C.	Panels are installed to manage heat, with sufficient air-flow around them.
Soiling	Losses due to dirt, snow, bird droppings and other foreign matter on the surface of the PV module that prevent solar radiation from reaching the cells. Soiling is location and weather dependent. There are greater soiling losses in high-traffic, high-pollution areas with infrequent rain.	Most manufacturers recommend cleaning panels to avoid build-up of contamination on the panel surface.
Panel mismatch	Electrical losses due to slight differences caused by manufacturing imperfections between modules in the array that cause the modules to have slightly different current-voltage characteristics.	Using equivalent and quality panels within strings.
Wiring and connections	Resistive losses in the wires connectors in the system.	Avoid excessive wiring and connections.
Age and light-induced degradation	Effect of weathering over time and the reduction in the array's power during the first few months of its operation caused by light-induced degradation.	Output of panels will decrease over system life, allowing for this in energy calculations to ensure positive energy over time. Many panel will come with a output reduction warranty.
Nameplate rating accuracy	Like all devices, the rating given by the manufacturer may be higher than the actual rating.	Ideally, the panels have been independently tested. Where they have not, it may be sensible to allow for some inaccuracy 1–5% to avoid under sizing the system.
Reliability and maintenance	Reduction in the system's output caused by scheduled and unscheduled system shutdown for maintenance, grid outages, and other operational factors.	Over the course of the year the system may be switched off due to faults or maintenance, allowing for this in annual calculations helps to ensure positive energy is achieved. Proactive maintenance outside of generation times can reduce this.

Example panel specifications

Peak power: 200 W

Rated voltage: 24 V

Open circuit voltage: 45.3 V

Short circuit voltage: 6.15 A

Voltage at peak power: 37.8 V

Current and peak power: 5.31

Efficiency: 15%

Dimensions: 1580 × 808 × 35 mm

Power per m^2: 156 W/m^2

Weight: 15.5 kg

Table 9.5. Monthly and annual kWh generation for a high efficiency (19%) 1 kWp array in Australian cities at a tilt angle of 20°.

Month	Melbourne	Sydney	Darwin	Brisbane	Perth	Adelaide	Hobart	Alice Springs
January	166	148	108	153	190	187	157	162
February	142	128	107	126	159	149	132	152
March	137	115	130	135	157	147	111	165
April	104	104	142	115	129	112	88	149
May	68	80	147	95	101	87	58	134
June	64	81	150	94	90	70	49	134
July	69	87	157	110	99	78	58	131
August	90	106	156	129	112	98	79	150
September	105	129	146	144	131	119	98	162
October	144	147	143	143	160	149	129	159
November	143	143	128	146	159	164	136	159
December	153	150	119	156	179	176	155	158
Average	1385	1418	1633	1546	1666	1536	1250	1815

Table 9.6. Monthly and annual kWh generation for a high efficiency (19%) 1 kWp array in New Zealand cities at a tilt angle of 20°.

Month	Auckland	Wellington	Queenstown	Christchurch	Dunedin
January	165	176	165	149	128
February	130	130	137	128	120
March	129	122	125	112	98
April	100	91	90	83	73
May	75	65	65	58	49
June	66	48	54	45	36
July	72	51	66	50	48
August	86	78	84	69	62
September	115	107	112	108	90
October	129	125	135	126	114
November	143	149	152	145	132
December	155	160	169	159	123
Average	1365	1302	1354	1232	1073

Therefore, to achieve a peak output of 1 kW around 7 m^2 of panels will be required. Allowing for access to and around the panels, this typically works out to around 10–12 m^2 of clear roof space per kWp. Every home is different, so the array needs to be sized for the climate and the energy requirements of the home. However, for the purposes of discussion, we would expect a 4–5 kWp rooftop solar array to be capable of making a typical 150 m^2 Positive Energy Home energy positive. This translates to ~50 m^2 of roof area. For a single storey home, this should be easily accommodated on a standard roof configuration such as a simple dual pitch (north–south) roof. However, on a double storey home, the roof design would need to be optimised to make the majority of the roof available for solar.

ACTUAL PERFORMANCE VERSUS PREDICTED

Through the use of quality products and installers, solar panel performance can be remarkably close to predicted. Most generation forecasts use average solar data for your area, which can result in under or over-estimation of annual generation due to weather conditions. This can be accounted for by comparing observed solar generation to measured solar irradiance, either from a home weather station or a local weather agency, and comparing with the region average. For example, if you have an unseasonably cloudy summer, irradiance levels will be down and as a result solar generation will be lower. This comparison can help to identify whether deviations from expected generation are due to the weather, system faults, dirty panels or whether your panels are not meeting their guaranteed output.

9.3 INVERTERS

In the majority of homes and electricity networks, power is distributed as alternating current, whereas solar power generates direct current. In addition to managing the solar panel voltage and current to maximise solar output, inverters convert the direct current electricity to alternating current for distribution throughout the home or to the grid. Many appliances, LED lights and battery chargers convert the AC power back to DC for use and it is possible to distribute DC power around the home for direct use, avoiding the conversion losses of switching to and from AC power. However, this requires DC wiring and specialised appliances, which is currently not common practice, making it impractical for most grid-interactive homes. Where a central inverter is used, the connection between the solar panels and the inverter is DC, so if the battery is located near the inverter, or integrated in the inverter, DC power from the panels can be used directly to charge the batteries (via a controller), and DC power out of the batteries can be converted to AC by the same inverter as the solar panels.

To ensure that quality AC power is delivered to the home, allowing appliances to operate effectively and efficiently, it is important to select an inverter that provides quality sine wave alternating current with high voltage stability. Indeed, a quality inverter can often deliver better

Hybrid inverter including battery storage (left) (Photo: Bosch Power Tec GmbH), 6 kW central inverter (top right) and a micro inverter located on the roof behind each panel (bottom right).

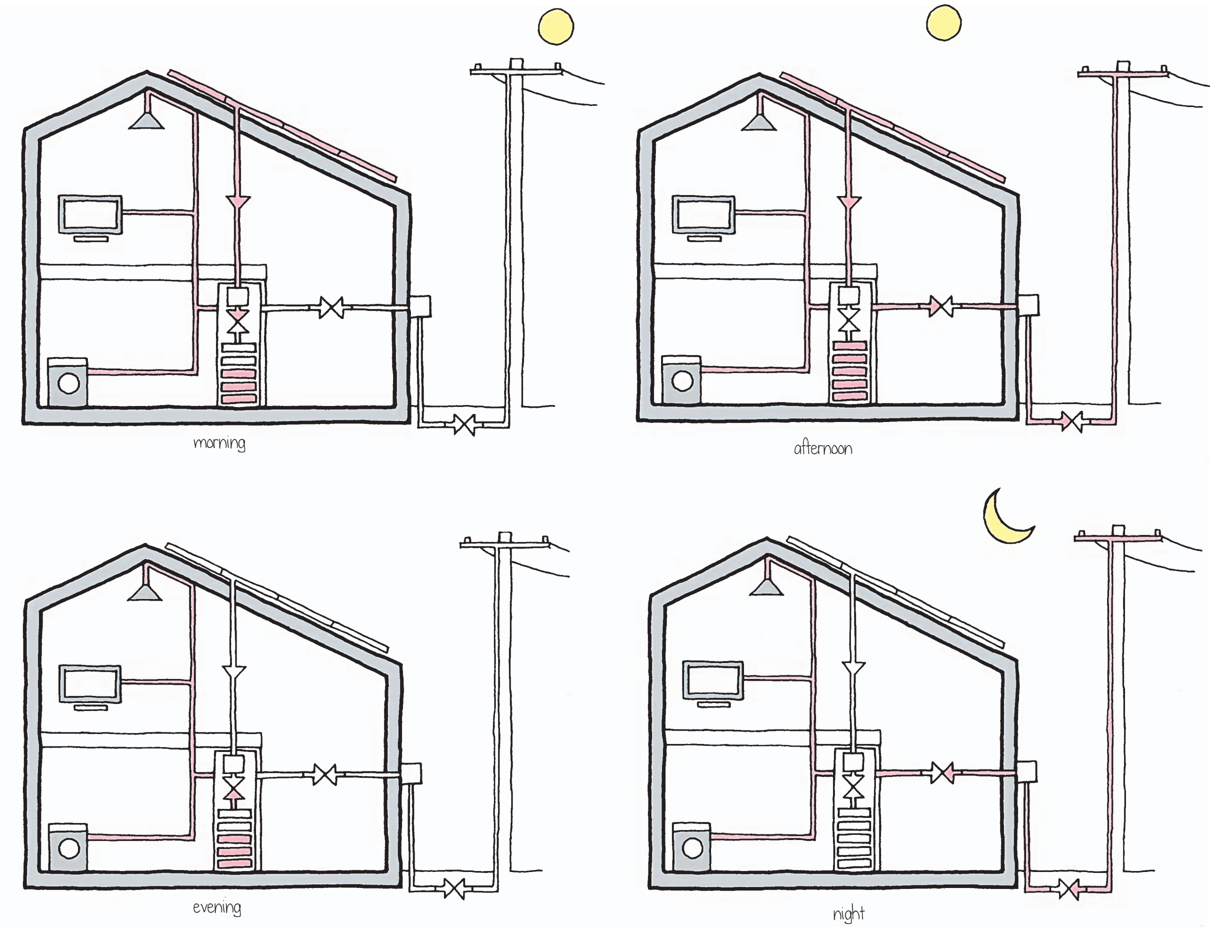
quality power than the grid. Obviously the inverter needs to be able to produce power at the voltage and frequency of your local network.

Given the simplicity of solar panels, inverters are typically the most common point of failure within a home renewable energy system, so, as with panels, ensuring the inverter has a good warranty and originates from a reliable manufacturer is prudent.

9.3.1 Inverter types

The simplest form of inverter is a stand-alone inverter, designed for non-grid-connected system with battery storage. These inverters convert only the amount of power required by the home at any given moment, with the battery storage providing or absorbing the difference between the home energy needs and solar output. In the event that the solar and batteries cannot meet the demand, the inverter will switch off power supply to the home.

Most solar-powered homes are grid-connected and use a grid interactive inverter to convert all of the power generated by the solar system to AC for use in the home or export to the grid when there is excess. When there is insufficient solar output to meet the home's requirements, power is drawn from the grid. In most locations, the inverter will need to be certified as compliant for grid interaction. Other than power and voltage quality, a key feature required for grid interaction is the ability to recognise when the grid has gone down and isolate the home from the grid. Where no storage is included in the system, if the grid goes down the inverter will shut down energy supply to the grid and the home, taking away one advantage of generating your own power: independence. Obviously an important complement to such a system is a two-way utility meter that allows imported and exported power to be measured.



Hybrid inverter operations showing: morning solar generation feeding the home and charging the batteries; afternoon solar generation feeding the home and exporting to the grid once batteries are charged; evening use of the stored battery power; and night-time use of grid power once stored energy has been used up.

The third type of central inverter of interest to Positive Energy Homes is the micro-inverter. As described earlier, these are small inverters, often installed on each solar panel that convert the power from each panel into AC power, as per a standard grid interactive inverter. These inverters allow each panel to operate independently of the rest of the system, which can be useful where there is partial shading of the array or panel have varying orientations of tilt angles. Because micro-inverters convert the solar output directly into AC, there is no opportunity for direct DC charging of batteries.

The final category of inverter relevant to Positive Energy Homes, are hybrid inverters that include integrated energy storage. This effectively means that the inverter has an inbuilt charge controller and battery bank. The storage may only be modest, but enough to smooth out short-term variation in solar output, store excess solar power for evening/overnight use and provide some backup power in the event that the grid fails. This type of inverter offers a range of advantages that complement a Positive Energy Home, so if it is economical in your region we recommend their use.

Some features of these types of inverters that can be useful include:

1. The ability to operate synchronised to the grid or independent of the grid in a Solar UPS (uninterruptable power supply) mode.
2. Web-based interface that allows the user to easily set the mode of the inverter for different times of the day; for example, setting the inverter to maximise storage and minimise export during high generation times, or setting it to minimise grid import during peak electricity rate times. Some of these systems also allow interaction with weather forecasts to help predict generation/consumption and manage storage appropriately.
3. The ability to pass through more power (from the grid) than it is rated to invert, which allows the inverter to sit between the home and the grid and manage all energy supplied to the home. That is, the inverter may be rated to invert up to 4 kW from the solar/battery, but, in the event that the home requires more than 4 kW, the inverter can feed through power from the grid without exceeding its limit. This allows the inverter to manage the solar and battery to maximise consumption of solar generated power and provide uninterrupted supply in the event of grid failure.

9.3.2 Sizing your inverter

As per the hybrid inverters, for stand-alone (non-grid-connected) systems, selecting an appropriate sized inverter requires forecasting of the home's peak energy demand. For example, if you expect to run the dishwasher and washing machine, potentially engaging the hot water system simultaneously, then you need to add up the peak wattage of each of these devices and select an appropriately sized inverter to meet this demand. For stand-alone systems, minimising peak demand through sensible management of devices can reduce the size of the inverter required.

For grid-interactive inverters, the major factor on selecting the size is the output from your solar array. A 4 kW peak solar array will spend the majority of its life generating below 4 kW, so a 3 kW inverter should be able to comfortably manage the system at lower capital cost than a 4 kW or larger inverter. On occasion your array may produce more power than its rated peak, but quality inverters can handle up to 140% of their rated capacity without any significant impact on output. As such, sizing your inverter at or slightly below your array peak output is sensible. From a safety perspective, the open circuit voltage of the solar array should not exceed the maximum allowed voltage of the inverter.

9.3.3 Technical specifications

Table 9.7 lists the technical specifications of inverters for consideration when selecting, many of which are more relevant to stand-alone systems or those that may operate in island mode.

Like all electrical devices, inverters generate heat and are sensitive to weather and dust. Furthermore, for solar systems, the inverter is generally the point of the system most likely to fail

Table 9.7. Inverter technical terms and specifications.

Term	Meaning	What to look for
Peak output – continuous power	The maximum power that the inverter can supply to appliances continuously.	This in the nominal nameplate rating.
Peak output – half hour rating	The power the inverter can supply for half an hour without overloading or overheating.	Inverters can normally comfortably operate above their peak output for a period of time without issue.
Peak output – surge capacity	The power the inverter can deliver for between 1 and 5 s; some are rated for up to a minute.	Typically two to four times their continuous rating, to allow them to start difficult loads such as fridges and other motor-powered appliances.
Idle power	Power that the inverter consumes when it is 'on' but there is no load/generation.	Obviously low idle power is ideal.
Stand-by power	Most inverters should have stand-by mode that is activated after a period of no activity in idle mode.	Typically much lower than idle power.
Minimum load – auto restart	The minimum load threshold to trigger instant response when unit is in stand-by mode.	Usually below 20 W and adjustable in some inverters to suit home.
Total harmonic distortion	Described the quality of the alternating current sine wave.	THD should be below 5%.
Power factor	The ratio of real power flow to the load relative to the apparent power of the circuit, which can be dropped by large inductive loads such as motors.	Appliances typically have minimal impact on power factor, but heat pumps and induction cooktops may, so when in island mode the inverter needs to be able to manage any potential drop in power factor by these devices.
Efficiency	Ratio of DC power into AC power out.	Inverter efficiency typically varies with loads and is often very poor at low loads; as such, sizing the inverter for typical loads with consideration of the half hour rating for peak loads can improve operating efficiency.
Temperature of rating	Like solar panels inverters are rated under standard temperature conditions, often 0–40°C, but sometimes only at 25°C.	If the inverter has not been tested at expected operating temperatures, then some allowance for reduced performance at higher temperatures should be factored in.

and may require replacing over the life of the array. As such, the inverter should be installed in an accessible location where it is protected from the weather (heat, rain and wind) and where will not have a negative impact on the home's heat balance.

9.3.4 User interface and connectivity

Like most electronic appliances, inverters have some kind of user interface such as indicator lights, an interactive display or network connectivity. The inverter should have basic functions displayed to allow easy troubleshooting. Interactive displays on the inverter including parameters such as battery voltage and current, array voltage and current, output voltage and current, and various status and mode displays, can be useful for setup and troubleshooting for a technician or enthusiast. However, for the typical occupant, some kind of network connectivity that allows generation and consumption data to be viewed can be useful for understanding home energy use and achieving positive energy. Hybrid inverters with integrated storage or interaction with storage units can allow for remote scheduling to allow the occupant to maximise generated power use in the home or respond to peak and off-peak grid pricing. Of course, for many occupants these may be features that are used once after installation and never again, and therefore may not warrant the associated cost premium.

9.4 SOLAR HOT WATER

As discussed in Chapter 4, heat energy from the sun for hot water is typically collected two ways:

- directly, using solar hot water panels that absorb solar radiation
- indirectly via a heat pump that absorbs ambient heat from the sun, nominally using electricity generated via solar PV.

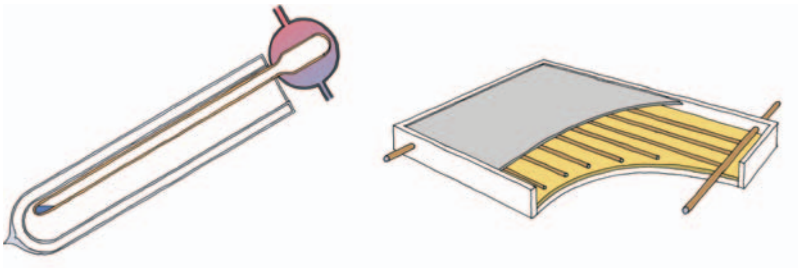
9.4.1 Solar hot water collectors

The most commonly available solar hot water/thermal collectors fall into two categories: evacuated tubes and flat plate.

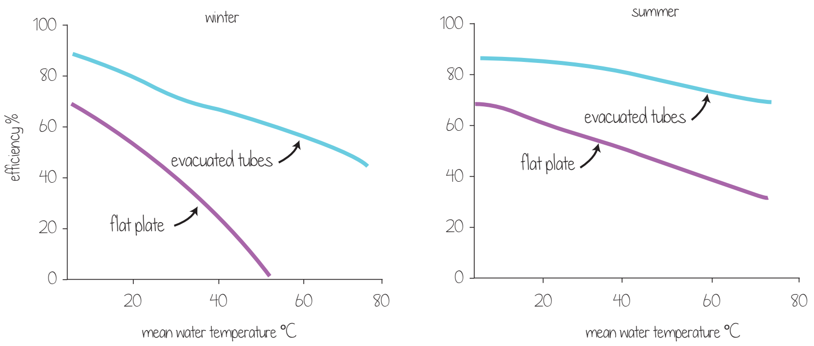
EVACUATED TUBE COLLECTORS

Evacuated tube collectors are made up of an outer borosilicate glass tube with an inner heat tube specially coated to maximise solar absorption. The area between the inner and outer tube is evacuated creating a vacuum, insulating the heat-collecting tube.

Absorbed heat is collected in a heat tube and is transfer to the insulated header at the top of the collector. Many evacuated tubes use a heat-absorbing fluid that turns to vapour when heated. The



Schematic of an evacuated tube solar thermal collector (left, see photo on p. 203) and flat plate solar thermal collector (right, see photo on p. 193).



Seasonal performance comparison for evacuated tube and flat plate collectors in a warm-temperate climate.

vapour then rises up to the top of the tube where it indirectly heats a fluid water in the header. The vapour condenses back to a liquid and drains back down into the tube ready to start the cycle again. Other systems circulate water directly through the tube, passing cold water down through the tube and back up and out via U-shaped copper pipe. These systems are only appropriate for frost-free locations.

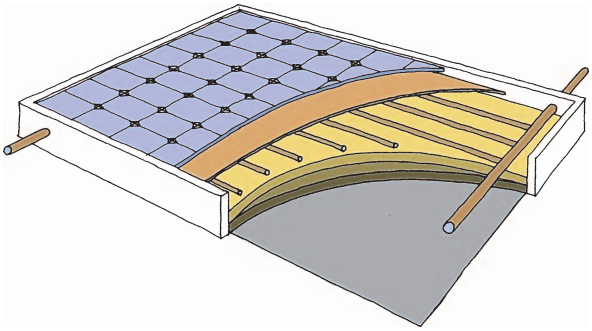
Due to the highly insulated properties of the evacuated tube, the performance of these panels is not overly sensitive to the ambient temperature, allowing them to deliver high efficiency even in cold climates. This also facilitates efficient collection of indirect solar radiation, allowing them to generate useful heat even on a cool overcast day.

Furthermore, because the collectors of an evacuated tube are round, they are less sensitive to sun angle and have more even generation throughout the day, which is known as 'passive tracking'. Depending on the location, this allows for up to 20% more energy collection than a flat plate collector. Like solar panels, the ideal orientation of these systems is towards the equator, but, the round collector makes them less sensitive to variations in orientation. A trial in Sydney, Australia (latitude 33°) found an annual output reduction of only 5% for panels facing north-east or north-wast (equator north), and 16% for east- and west-facing systems (Apricus 2016). This reduction would likely be more significant for locations further from the equator.

Quality evacuated tubes should have passed a hail test, meaning they should withstand reasonable conditions experienced on a roof. However, in the event of damage, some collectors allow for individual tubes to be removed without the need for draining the collector or disrupting the operation of the remaining tubes.

FLAT PLATE COLLECTORS

Flat plate collectors are more like a solar PV panel, with a low absorption/reflectivity glass layer over a collector surface. Typically the collector is a metal (copper or aluminium) plate specially coated to maximise solar absorption. A series of pipes are bonded to the metal plate to collect the heat and the whole system is mounted in an insulated box. The fluid typically flows from the bottom of the panel, allowing the heated liquid/water to rise/flow up to the top of the panel for collection. In warm climates with an equator-facing roof, flat plate collectors can deliver good performance at an economical price.



Schematic of a combined PV-thermal flat plate collector.

HYBRID PV-THERMAL PANELS

Hybrid PV-thermal (PV-T) panels are also available that incorporate a PV layer between the glass and the metal plate, generating electricity and heating water in the one panel. In theory, the cool water influx also helps to improve the efficiency of the PV solar panel, as well as reducing the materials and area required to generate electricity and hot water. In most areas, this technology remains a speciality product and has not received the development and market penetration of conventional PV and solar thermal. Hybrid PV-hot water systems are typically either optimised for PV or for hot water, and may be worth considering where roof space is a premium.

9.4.2 Hot water tank configurations

There are two main configurations: close-coupled and split systems.

CLOSE-COUPLED SYSTEMS

As already noted, for most collectors, heat is collected at the top. If the system storage tank is located at the top of the collector, the heat can be collected via thermosiphon action without the need for a pump between the collector and tank. This reduces the complexity and improves

Evacuated tube solar thermal collector mounted on the roof with the hot water tank located on the ground: a split system. A small pump and temperature controller are used to circulate water between the collector and tank.

system reliability. However, locating the tank on the roof with the collector significantly increases the weight of the system, increasing structural support and roof area requirements. This configuration also leaves the storage tank exposed to the weather and makes it challenging to super insulate. Integrating with a heat pump for boosting also becomes more complicated. As such, although relatively simple in operation, the efficiency limitations and installation complexity make close-couple systems the second choice after split system.

SPLIT SYSTEMS

The second configuration, places the panels on the roof and uses a small pump and a differential temperature controller, to circulate water/fluid between a more traditional hot water storage tank and the collector. This allows easy access and flexible installation of the tank, but adds complexity and energy consumption for the pump and controller. This split system configuration makes it easier to insulate the tank and integrate with a heat pump.

9.4.3 System protection

SNOW AND FROST

In cold climates that experience sub-zero temperatures, the high insulation properties of evacuated tubes make them the obvious choice. Furthermore, there are a wide variety of evacuated tubes that use liquid/vapour heat collection systems that are inherently frost resistant. However, because evacuated tubes are well insulated, the warmth of the panels may not be enough to melt snow off, so, where large amounts of snow are expected, tilting the panels appropriately to help encourage the snow to slide off under its own weight is advisable.

As noted earlier, the efficiency of flat plate panels are more sensitive to ambient temperatures and so are less desirable for cold climates; this is especially true for close-coupled systems where it is difficult to insulate the storage tank. Furthermore, many flat-plates of these systems cannibalise heat to protect the panels against frost damage and prevent snow build up: for example, by recirculating a small amount of hot water through the panel to keep it above freezing and help melt snow. Where panel working fluid is separate from the domestic hot water via a heat exchanger, an antifreeze liquid such as propylene glycol can be added to the water in the collector to lower the freezing point. These systems need to be routinely checked to ensure the antifreeze liquid has not leaked out, increasing the chance of frost damage.

TEMPERING VALVES

At the other end of the temperature spectrum to freezing, the water within solar hot water systems can approach boiling point, so a ‘tempering’ valve needs to be used between the hot water system and the hot water supply to the home to prevent potential scolding. The tempering valve mixes

Table 9.8. Example evacuated tube solar hot water collectors (Source: Apricus 2016).

	AP-20	AP-30 (see photo on p. 203)
Length	2005 mm	2005 mm
Height	136 mm	136 mm
Width	1496 mm	2196 mm
Peak output	1296 W	1944 W
Aperture area	1.88 m^2	2.83 m^2
Gross area	3 m^2	4.4 m^2
Gross dry weight	63.5 kg	95 kg
Fluid capacity	550 mL	790 mL
Ideal flow rate	2 L/min	3 L/min
Home size	1–3 bedrooms	3–4 bedrooms
Storage tank	~250 L	~350 L

the hot water with cold water to ensure the supply temperature to the house does not exceed a preset temperature, typically 50°C.

9.4.4 System sizing

The size of the hot water system depends on the number of occupants and the usage patterns. Table 9.8 provides indicative system sizes required to meet 90% of summer loads in Melbourne, for equator-facing collectors. As discussed in Chapter 4, sizing the system for winter loads results in significant overcapacity in summer and waste heat, so where there is significant variation in the summer and winter solar resource, we recommend the use of an efficient heat pump as the primary hot water generator.

For a typical four person home, around 5–6 m^2 of usable roof area is required to meet 90% of summer load, compared with around 1 kW of solar PV requiring around 7 m^2 to power a heat pump to meet annual hot water requirements.

To maximise winter output, solar hot water systems are often angled at the latitude of the installation site or greater to improve collection of winter sun. Depending on the location of the home, such an angle may cause shading of an area of the roof, so positioning the collectors in a location that is not visually obtrusive and will not cause shading issues for a PV array needs to be considered.

9.4.5 Warranty

Like solar PV, quality is important and warranties can be used as an indicator. Generally, the tanks and collector panels for solar hot water systems are warranted for 5–10 years while the associated pipe work will carry a 12-month warranty only. As for all products, careful investigation of the warranty fine print is important, with some conditions on installation by appropriately qualified personnel, regular servicing and water quality. As for all hot water installations, ensuring adequate pipe insulation is included and properly installed (no gaps or compressions) is essential.

9.5 WIND

9.5.1 Wind energy

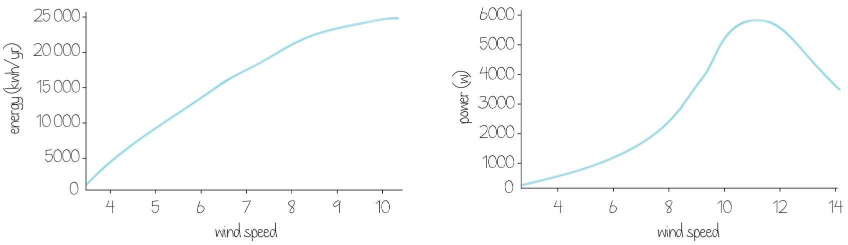
Although it is typically more difficult to use wind energy in built-up areas, let us briefly discuss the options to power Positive Energy Homes.

The energy available in wind is proportional to the cube of the wind speed, meaning that every doubling in wind speed translates to an eight-fold increase in the available power. Friction of wind against the ground and objects causes a reduction in wind speed, therefore wind speed generally increases with height above the ground.

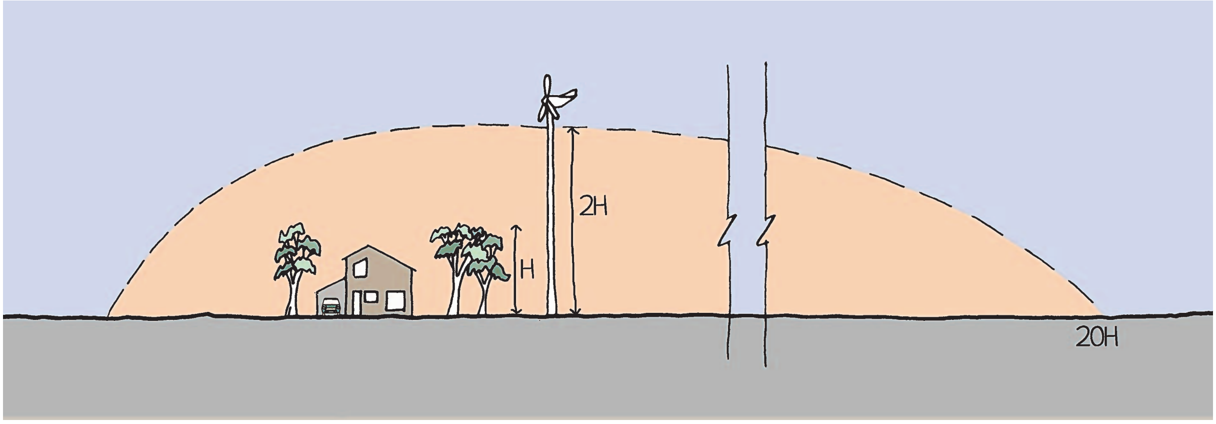
The power available at each site is highly sensitive to wind speed, which in turn is influenced by the local wind resource and terrain surrounding the home. Another key factor in assessing wind potential is the ability to mount the turbine on a tower, well above the worst of the ground friction. Most wind turbines have a cut-in wind speed below which no power is generated. In many urban areas, the average wind speed is less than the cut in wind speed of common turbines.

TURBULENCE

In addition to wind speed, wind turbines are sensitive to the quality of the wind at the point of energy collection. Ideally the wind will be laminar, meaning smooth and straight flowing, such as wind blowing off the sea that is uninterrupted by obstructions. When wind flows over undulating terrain, trees and buildings, friction slows the wind speed and creates turbulence, which disturbs the direction and intensity of the wind. The presence of turbulence has a dramatic impact on the ability of a wind turbine to generate power and rapid changes in speed and direction of the wind



Example of an annual generation and power curve for a 5 kW wind turbine showing the importance of a good average wind speed for useful power generation, noting the cut-in speed of 3 m/s and that the rated power occurs at a strong wind speed of 10 m/s.



Turbulence caused by obstacles can reach twice the height of the obstacles themselves, 20 times the height of the object downwind and twice the height of the object upwind.

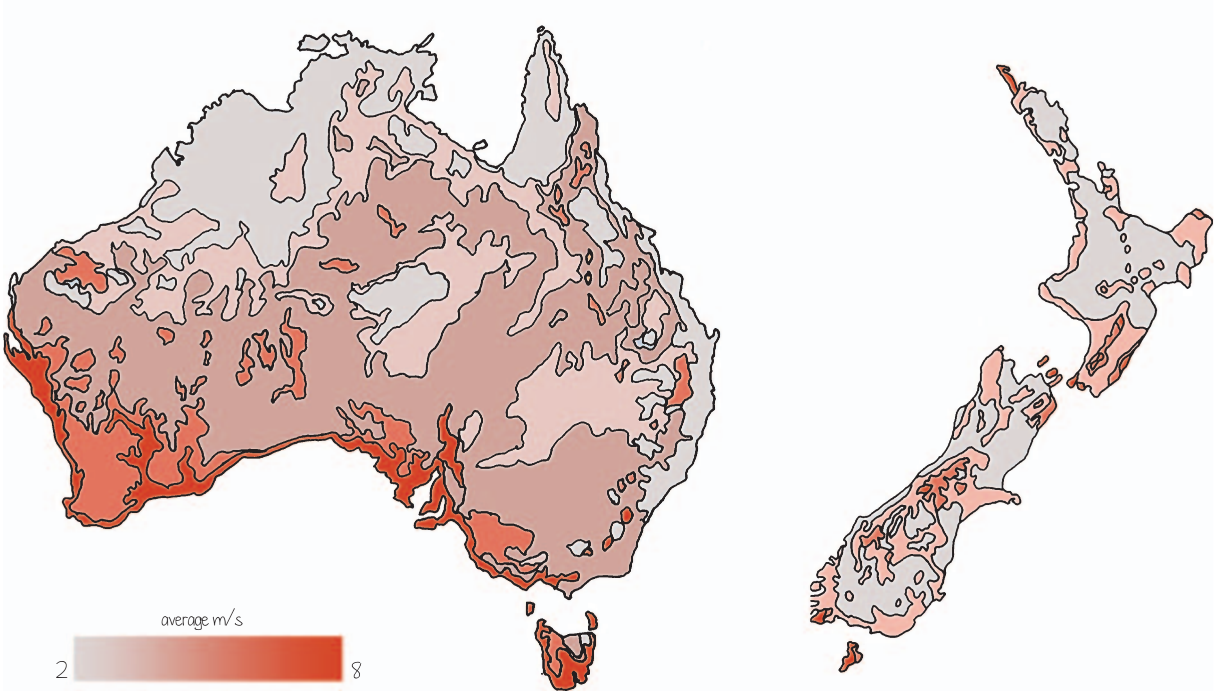
place strain on the turbine, reducing its useful life. In general, mechanical turbulence caused by an object such as a tree or house will extend to double the height of the object causing it and up to 20 times its height downwind of the object. Therefore, even if the area has excellent wind resources, site turbulence may make generation impractical.

As a general rule to avoid turbulence, a tower height of at least 20 m (30–40 m is typically much better) and at least 10 m higher than any object within 150 m of the turbine in the direction of the prevailing wind is required. With this in mind, for many urban sites, the suitability of wind as an economic, reliable source of power for the home can be ruled out, unless a very high tower is allowed by local planning rules. Local planning rules may also have restrictions on turbine noise and blade shadow and light flicker.

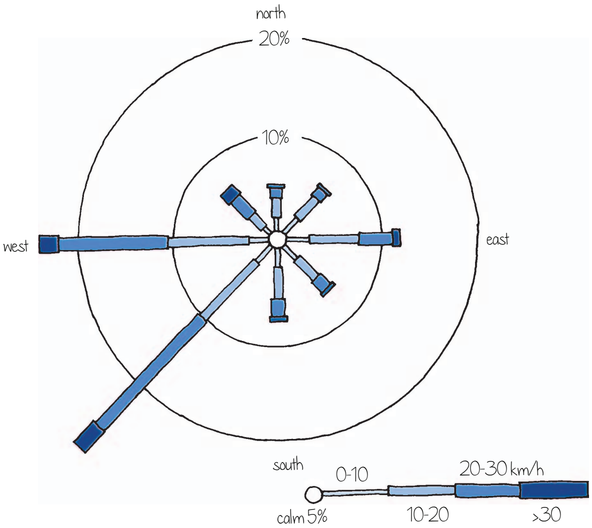
9.5.2 Assessing the wind resource

Assuming a suitable site, such as a clearing on a local hill or exposure to prevailing winds off the sea, has been identified, a high-level assessment of the local wind resources can often be conducted by referring to online wind atlases. These maps can only give an indication of whether the area has a suitable resource and are typically measured well above ground height (e.g. at 65 m). As already noted, wind speeds reduce closer to the ground due to friction and are highly sensitive to local terrain. The direction of the prevailing wind also needs to be investigated, to help identify potential objects that may disrupt power generation. Many meteorological agencies provide annual wind roses (see bottom figure on p. 208) that give an indication of the frequency of wind from each direction over the year. Seasonal wind rose can provide an indication of the availability and prevailing direction of wind at different times of the year.

In the absence of local wind data, these maps can be used to investigate whether it is warranted to conduct site-specific wind monitoring. Where a suitable site is identified and the region has suitable wind resources, monitoring of the wind speed, direction and quality over a 12-month period at the proposed height of the tower is strongly recommended. Wind monitoring normally



Example country scale wind atlas for Australia and New Zealand.



Example wind rose for Perth, Australia, showing the average wind direction and strength over the course of a year.

involves the installation of a data logging wind meter at the site, preferably at the proposed turbine height, but at least 20 m above the ground. This data can then be correlated with nearby weather stations and an assessment of historical data can be undertaken. To warrant further investigation, the site should have an average wind speed of at least 5 m/s at the height that the turbine is to be mounted.

9.5.3 Wind systems

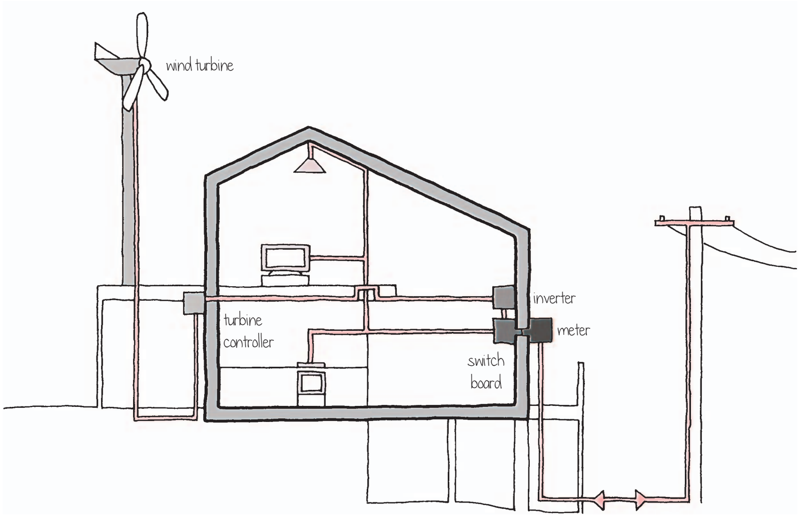
WIND TURBINES

Wind turbines use blades to capture the energy of the air and rotate an electrical generator. There are two common configurations: **vertical-axis,** where the rotor shaft is oriented vertically, and **horizontal-axis,** where the rotor shaft is orientate horizontally. Vertical axis turbines have blades that allow wind energy from any direction to be captured, which can be beneficial in site where direction fluctuates. Horizontal axis turbines typically have two to three blades that capture energy when facing into the wind, which, on domestic-scale turbines, is typically achieved by a trailing wind vane.

As noted earlier, wind speed and quality improves as we move further away from the ground and associated objects, therefore wind turbines are mounted on a tower to position them in clear air. Domestic systems typically use either a freestanding or a guyed tower, depending on the site. The serviceability of the turbine needs to be considered: for example, some towers are able to be folded down allowing easy access.

Choosing a tower height involves finding a balance between increased energy yield at higher height, and increased visual impact of a taller tower, for which it is also possibly more onerous to get planning permission. Obviously, cost will also increase with tower height. Increasing the tower height can increase generation more than it increases price, so taller towers with a small turbine can be cheaper and produce the same amount of power as a shorter tower with a larger turbine.

Just like solar panels a controller is required to manage the turbine and an inverter for converting the power into grid synchronised AC power for the home. These may be separate units or integrated.



A domestic wind system.

Because turbine output is so sensitive to wind speed and quality, we strongly recommend that any wind system includes a data logging wind meter. This allows you to correlate system output with observed wind speed, to monitor system performance and assess the long-term practicality of powering your home from small scale wind.

9.5.4 System sizing/turbine selection

Because turbines are exposed to wind and have high-speed moving parts, for safety and reliability any system considered should have been certified by an independent reputable body.

Unfortunately, the rated power of a turbine tells you very little about the potential power generation, without reference to the wind resource at your site. To determine likely power generation, the turbine's power curve is required, which provides information on the generation potential of the turbine across a range of wind speeds. As you will be basing the assessment of the power generation from this curve, ideally the curve will have been independently tested and verified.

The power curve of a turbine provides a range of information that assists in assessing its suitability for your site:

- The cut-in speed is the wind speed at which the turbine starts to generate power.
- The cut-out speed, is the wind speed at which the turbine will turn itself out of the wind or lock itself to prevent damage during high wind events.
- The rated wind speed is the wind speed at which the turbine achieves its rated power, typically in kW for small turbines. Often the rated power occurs at wind speeds well above those observed at the site of a domestic home.

There are many guides available on the web such as *Home Power* magazine's yearly *Small Wind Turbine Buyer's Guide* that provide useful information for comparing domestic wind turbines.

Using an independently verified power curve and 12 months' worth of hourly wind speed data, the expected annual output of a turbine can be calculated. For more accurate estimations, access to multiple years of wind data is required.

9.5.5 Turbine noise

Noise is a critical issue for small turbines, especially in the urban context, because they will always be placed very close to houses. Noise is generally related to blade tip speed, and turbulence around the turbine, which is why slower moving vertical axis machines tend to be quieter than the traditional horizontal axis ones. For all turbines, the rated noise of the unit and the local wind quality should be carefully considered with advice from an experienced designer/installer to ensure the turbine noise levels are not disruptive to occupants or neighbours.

9.6 STORING HEAT

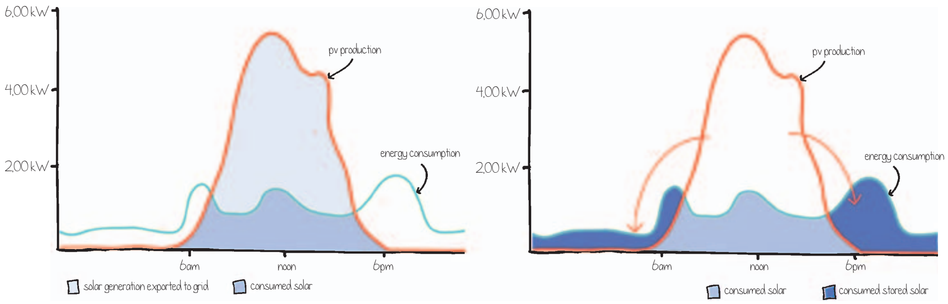
A familiar way to store energy in the home is in a hot water tank, where hot water is kept ready in a super insulated tank for later use. In it, excess energy produced during peak generation time can be stored for several days if not required. Where solar PV is being used to power a heat pump, this allows for hot water to be generated during peak output from the solar panels during the warm afternoon, maximising the efficiency of the heat pump, and then stored for later use. Where heating and domestic hot water requirements are being met from the hot water system, installing a larger hot water storage tank may be beneficial to allow sufficient heat to be stored to meet the overnight hot water and heating requirements. In the event that a small amount excess hot water is generated, it can be used the next day with minimal losses from the tank, but in an ideal situation hot water generation and storage should be balanced against use on a daily basis to avoid energy being wasted as heat loss. Balancing hot water demand, sizing and insulation of hot water tanks was discussed further in Chapter 4.

Many standard homes benefit from the use of thermal mass to absorb excess heat during the day and release it during the evening. This works well for climates that have consistent diurnal temperature swings, such as hot deserts. It also lends itself well to poorly insulated and leaky buildings where heat can easily flow into and out of the home. However, care needs to be taken when using thermal mass to store energy in a well-insulated and sealed home, because once the heat is absorbed it will be trapped in the home unless there is an effective and efficient means of eliminating it. Given the heat flows across a Passive House envelope are very small, typically there is no need for the addition of mass for storing of heat. As such, the use of significant thermal mass needs to be very carefully considered in well-insulated homes, which are unlikely to have the heating and cooling capacity to compensate in the event of overheating or cooling.

With that said, there are a range of building materials available that are well suited to storing sensible heat (or the absence of heat: cold) and latent heat (humidity), which in the right climates, used considerately in moderation may reduce the need for active heating and cooling.

9.7 STORING ELECTRICITY

In most cases, electricity storage in the home will take the form of batteries. Batteries store electricity as chemical energy that can be rapidly released on demand. An alternative method of storing electricity is through pumping water to a high point, storing the energy as potential energy in the water, which can be converted back to electricity via a micro-turbine when required. This may be practical for a rural property with dams or where a header tank is used for domestic water pressure. Other methods of storing electricity include electricity to gas (hydrogen or methane) and capacitor banks, but at the time of writing these technologies are not practical or common in the home.



The addition of battery storage allows for excess solar generation during the day to be stored for use in the evening and overnight. Storage also helps to smooth out short-term variations in solar generation and demand.

Battery storage systems obviously add significant costs and increase annual consumption due to conversion losses interchanging between electrical and chemical energy. For remote areas that are not grid-connected, battery storage is an essential part of balancing the generation and demand, and providing power during periods of no generation. For grid-connected systems, the benefits of battery storage include:

- smoothing and control of grid interaction
- allowing more of the generated power to be used in the home
- potential for supply security when the grid goes down
- potential to become grid-independent.

From an energy community perspective, integrated home energy storage helps to smooth out demand and the intermittent output of domestic renewables, which is an important component of a 100% renewable electricity grid.

9.7.1 How much storage is enough?

Energy storage requirements depends on what the storage is being used for and how actively involved in energy management the occupants are. For grid-connected homes wishing to incorporate a small amount of storage to smooth out short-term spikes in generation and allow more of the homes self generated power to be used to meet the evening peak, then a hybrid inverter with some integrated storage of 1–2 kWh is likely to be the simplest option. In these systems, the inverter also manages battery charging and balances solar, storage and demand consumption. As discussed earlier, some of these units allow for quite sophisticated scheduling to suit a range of energy consumption/generation scenarios and preferences. Because the solar and battery are managed by the same device, the total system can be optimised to maximise output and charging efficiency. Furthermore, the DC power from the solar panels can be used directly to charge the batteries, avoiding additional losses associated with additional connections, wiring and potentially switching between AC and DC power.

For grid-connected homes with regular short-term power outages, again a hybrid inverter may be sufficient to cover the outage, particularly with some minor energy management by the occupants. In the event that the blackout occurs while the sun is out (or the wind is blowing) then the demand on the battery may be quite low, allowing the home to operate as usual. However, if the blackout occurs in the evening, then some minor adjustments to behaviour will extend the period of time that the home can operate on battery power. With a Passive House, the energy flows across the building envelope are quite small, so comfortable conditions will be maintained for an extended period, even if the heating or cooling are switched off or temperature set points are adjusted, which may be an option when operating on a battery. Furthermore, if the home is set up to generate hot water for heating and domestic purposes during the peak generation period of the day, then the hot water heat pump should not be required when operating on battery. In this event, the major energy consumption is by the appliances in the home, which are directly controlled by the occupant.

The size of the inverter required for stand-alone or island mode homes depends on the peak power requirements of the home. For example, if the kettle, oven and air-conditioner are all being used at the same time, then the peak demand will be quite high, whereas if these devices are used in sequence then the peak load will be much lower. Likewise the amount of energy storage required is determined by the size of the loads being used. For example, cooking a roast meal that may require the oven to be on for an hour or more may consume all of the 1–2 kWh of stored energy in the inverter. Alternatively cooking a simple stir-fry will use only a fraction of the energy. As such, avoiding large energy consuming tasks such as roasting, running the dishwasher or washing machine, and switching off unnecessary heating/cooling, appliances and lights will greatly extend the period of time the battery can support your home. Running large appliances during peak generation times maximises the use of self-generated power and avoids the need to run these loads when the home is consuming battery power or purchasing power from the grid.

For the home to operate self sufficiently, enough storage is required to bridge the periods between generation and account for low-generation periods such as cloudy days during winter. Obviously, the daily energy requirements will depend on the prevailing weather at the time and the capacity of your solar array, but, for a Positive Energy Home with an efficient envelope and appliances, the daily energy requirements are very low and predictable. As such, the equivalent of 2–5 days of energy consumption is generally recommended to maintain self-sufficiency, with some minor energy management as discussed above during extended periods of low generation.

For a 150 m^2 Positive Energy Home, average daily energy consumption is likely to be around 12 kWh, so 36 kWh (3 days) of usable storage may be suitable to maintain self-sufficiency throughout the year without any significant compromise to the enjoyment of the home. This peak storage capacity may only be required one or two times a year, so a smaller system requiring less investment may be sufficient if the occupants are prepared to embrace some energy management during low-generation events. The other factor that needs to be considered in designing a self-sufficient system is sizing the solar array to ensure there is sufficient power to charge the batteries in between low-generation periods. For regions with consistent solar resource year round, over-sizing of the system may only be small, but, in climates with poor winter sun, the size of the solar array may have to be much larger to allow for battery charging, taking into account the local climate, solar resource and daily energy use profile during the low solar period. Where the home is not grid-connected, over-sizing the solar system will result in wasted energy in summer. For the Springdale home (see Chapter 10), a 5 kWp solar array should produce enough power for the home to be positive, but, because the home is not grid-connected, they have installed 8.3 kWp for battery charging and meeting peak demand.

Unfortunately, sizing a battery bank is not quite as straightforward as determining the amount of energy storage required. As noted, there are losses associated with charging the battery and losses in converting the DC power to AC. The other major factor is the allowable depth of discharge of the battery bank, which is determined by the impact on battery life of a deep discharge, and varies between battery types and manufacturers. Lithium batteries typically have an 80% depth of discharge, meaning discharge beyond 80% of total capacity should be avoided to prevent compromising battery life. For example, assuming 10% losses and 80% depth of discharge, to deliver 30 kWh of usable storage a battery bank with a storage capacity of 41.5 kWh may be required (30 × 110%/0.8). To add to this complexity, battery storage capacity is often stated in amp hours, which needs to be multiplied by the voltage of the battery bank/system to work out kWh.

9.7.2 System types

As discussed earlier, hybrid inverters incorporate all of the elements required to manage the solar panels, batteries and supply AC energy to the home. For quality systems, each element has been optimised to manage performance and system life. There are also integrated storage units that incorporate all of the functions of battery charging and storage, and are designed to readily interact with standard solar systems and inverters. Again, each element of these units has been carefully matched to suit the others, thus optimising efficiency and unit life. These units typically offer the advantage of being easily scalable and take the complexity and risk out of putting together a reliable, efficient storage system. Where package systems do not meet the requirement of the home or budget, a custom system can be put together with careful consideration of each element, system size, compatibility and potential for future upgrade.

9.7.3 System components

Whether they are purchased as a package or put-together by an experienced practitioner, home battery storage systems require: batteries, a charge controller, a battery management system and an inverter (see photo on p. 218).

BATTERIES

The main component of the storage system is the batteries, which convert electrical energy into chemical energy, storing it for later use. Batteries are made up of cells containing two electrochemically active electrodes with an electrolyte in between them. When charged, the chemicals in the battery are in a high potential energy state, meaning that if connected to an external circuit they will release energy. Effectively, electrons are released from the anode (negative terminal) and received at the cathode (positive terminal) and the electrolyte balances the internal charge by the transfer of ions between the two electrodes. When discharged the battery, chemistry is in a low energy state, which can be reversed by applying an electrical potential in the opposite direction, forcing electrons into the anode and pulling them out of the cathode, restoring the chemistry to its original charged state. Unfortunately, on each cycle the chemistry within the battery is slightly degraded reducing the potential of the cell to store energy. Over time, this degradation reduces the useful storage potential. The extent of degradation per cycle is influenced by a range of factors including the type of chemistry used, the rate of discharge, the depth of discharge and the temperature of the battery. As such, the type of chemistry, the configuration of the battery, how it is used and stored can have a significant impact on the performance and life of the storage system. Therefore selecting the right battery for the task and ensuring the supporting system components are appropriately matched is essential for delivering effective storage.

Battery types

There a range of battery types available using a variety of metals and supporting ions to store electricity. Even within the commonly used and named Li-ion battery group there are a range of different metals used in the cathode, which change the properties of the battery. Once an appropriate battery has been selected, it is important point to ensure that the appropriate charger/charging settings are selected as the charging requirements vary between batteries types.

Batteries requirements also vary between sizes, voltage and over the age of the battery, so mixing different types and sizes of batteries is likely to reduce battery life. Furthermore, the addition of new batteries to an existing bank or changing the voltage of existing batteries banks can reduce their performance.

Battery life

Battery lifespan is generally described in number of cycles, rather than years. Typically this number describes how many cycles the battery can deliver before its capacity decreases by a nominated amount (e.g. 80% of original capacity). The capacity drop factor varies between manufacturers, which can make number of cycles hard to compare. The number of cycles that can be achieved by a battery is influenced by a range of factors, including the type of internal chemistry, the temperature of the batteries, the voltage they are charged at, the rate of discharge

Table 9.9. Relationship between depth of discharge) and number of usable cycles before battery capacity drops below 70% of rated, for a Li-ion battery.

Depth of discharge	Discharge cycles
100%	300–500
50%	1200–1500
25%	2000–2500
10%	3750–4700

and the depth of discharge. As noted earlier, lithium batteries are not overly sensitive to the rate of discharge, but the depth of discharge on each cycle has a significant impact on the life of the battery (Table 9.9). In general, deeper discharge of batteries results in greater degradation of the battery, reducing the number of usable cycles. Therefore, when sizing the system capacity, allowing additional capacity to avoid deep discharges will extend the life of the battery. As discussed earlier, stand-alone storage systems are typically sized for the rare event where there is no significant generation over several days. Therefore, for the majority of the year, the system will only be experiencing shallow discharges with only a couple of deep discharges per year, with minimal impact on usable life.

CHARGE CONTROLLER

A charge controller is an electronic device that regulates the flow of energy into the battery bank from generation devices to prevent overcharging.

BATTERY MANAGEMENT SYSTEM

Lithium batteries must have an effective battery management system (BMS). The BMS monitors each cell in the battery bank during charging and discharging to prevent over-charging and discharging below the minimum voltage point, which can decrease the life of the cell or cause it to fail.

INVERTER

As discussed earlier, an inverter is required to convert the DC output of the batteries to AC power for the home. The inverter normally includes a maximum power point tracker to optimise the voltage of the solar array to maximise power output/battery charging. Some inverters also incorporate a battery charge controller and BMS.

Also included will be safety equipment such as main battery fuses or circuit breakers, temperature sensors for battery monitoring, and current monitoring equipment such as a current shunt or sensor. Like the inverter, storage systems will have a user interface that may range from some indicator lights through to a network enabled display.

9.7.4 Technical specifications

The technical specifications and specialised battery terms are outlined in Table 9.10.

9.7.5 DC or AC system

As already described, for hybrid inverters that have integrated energy storage, DC power generated from the solar panels is fed to the inverter where it is either used directly as DC to charge the battery or is converted to AC for use in the home or export. When the battery is in use,

Table 9.10. Battery technical terms and specifications.

Term	Symbol/units	Explanation	What is this used for
Capacity	Amp-hour (Ah)	Describes the storage capacity of the battery.	To convert Ah to Wh, multiply by the voltage of the battery.
Capacity rating, C-rating	C-number of hours (e.g. C10)	For some battery types, the available capacity is sensitive to the rate of discharge, with reduced capacity at faster discharge rates. Capacity rating nominates the discharge period over which the capacity rating was tested (e.g. C10 means that the rated capacity was discharged over 10 h).	Determining which C rating to use depends on the battery cycle depth each day. If the system discharges over several days, then the C100 rate would be used. If it cycles every day or two then C10 would be used. Lithium batteries have a fairly fixed capacity regardless of discharge, often stating C1 rating.
Voltage	V	Electrical potential of the battery or battery bank.	Multiply V by Ah to get Wh of the battery. Divide by 1000 to get kWh.
Depth of discharge	DoD	How much of the battery's capacity is used each cycle. The depth of discharge per cycle influences the expected number of cycles the battery can deliver over its life.	Manufacturers will provide a recommended maximum DoD to avoid segregation of battery or provide a curve showing the impact of depth of discharge on expected number of cycles (battery life).
State of charge	SOC	Inverse of DOD: the current charge state of the battery.	A DoD of 30% means that the battery has a SOC of 70%.
Charging efficiency/ efficiency	%	The efficiency of converting DC power into stored energy or round trip efficiency which is the percentage of energy out relative to the energy in.	Higher efficiency result in less losses.

DC power is drawn out of the battery and converted to AC by the inverter. This configuration is described as DC-coupling, where the batteries are on the DC side of the inverter. DC-coupling is commonly used for custom storage systems and there is a range of package DC storage units that can be combined with a suitable inverter to deliver AC power to the home. DC-coupled systems can distribute DC power directly to DC-compatible appliances without the need of an inverter, avoiding the conversion losses. For DC-coupled systems, it is essential to ensure that the solar/inverter DC voltage is designed to match the voltage requirements of the battery charger.

The Tesla Power Wall is an example of a DC-coupled storage system that integrates battery charging and management into a user-friendly unit that readily combines with an inverter to provide energy to the home. The power wall currently comes in two models: a 7 kWh daily cycle unit with multiple units able to be connected to provide up to 63 kWh or storage and a 10 kWh weekly cycle unit, with multiple units providing up to 90 kWh of total storage.

Alternating current (AC) coupling is where the DC power from the panels is converted to AC power via an inverter before being sent to the battery, where it is converted back to DC for charging. Obviously this introduces conversion losses, but this type of system allows for the batteries to be charged using alternating current from the grid or an alternative AC source, which may be useful in areas of intermittent supply. The other application of this type of system is where micro-inverters are used for the solar array to help maximise power output from panels that may be subjected to shading or have varying orientations and tilt angles.

Example of a DC storage system (top) showing a Tesla Power Wall, inverter, power meter, switchboard and web box (Photo: Energy Matters), and an Enphase AC storage unit (bottom) (Photo: Enphase Energy).

AC-couple package units are available that have an integrated inverter, charger and management system, allowing the unit to be readily connected to an AC power source. This allows for simple expansion, with additional units readily being connected to AC power, charging and supplying power as required.

9.7.6 Maintenance and upgrades

Most storage systems come preconfigured either as a package or from the supplier along with instructions on any maintenance or checks that need to be done, such as keeping batteries and components clean and free from insect and animal infestation, and checking for loose battery connections. Some systems also come with network connectivity, allowing the system to be remotely monitored by the user or manufacturer.

9.8 PASSIVE HOUSE PLUS

In addition to the comfort, health and efficiency of the home, Passive House certification considers how the consumed energy has been generated, acknowledging that in time our energy systems all need to switch to renewable sources. As such, certification requires that the home can operate below annual energy consumption thresholds and awards higher levels of certification to homes that generate energy on site or nearby. These requirements form a certification framework for the creation of Positive Energy Homes and a renewable-powered future. This is explored further in Chapter 10.

SUMMARY

Through the creation of super-efficient homes, it becomes practical to harvest the annual energy requirements of our homes on site. For most homes, the majority of energy requirements will be harvested using solar PV. Solar thermal can be a reliable heat source for some climates, with wind and micro-hydro typically only appropriate for specific sites. On-site energy storage can help to increase the proportion of generated power that is consumed on site, smooth out our interactions with the grid and shelter us from disruptions in grid supply or even allow us to live comfortable healthy lives independent of the grid. Both generation and storage systems are readily available in a diverse range of products, all of which are quite technical and not necessarily easy to interpret. As such, using an experienced designer and systems with independent certification and good warranties is recommended.

The Alternative Technology Association (Australia) publishes regular up-to-date buyer's guides, for renewable energy systems, storage and efficient lighting and appliances. These guides provide a valuable reference for the state of technology and provide a summary of currently available products in the market.

REFERENCES AND FURTHER READING

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CHAPTER 10

Certification

When we buy a new appliance, we typically invest some time to research its performance. Many of us will also read reviews online to see how other people liked this piece of equipment. Houses are rarely mass produced and, even if they are, the production normally does not happen under controlled conditions all the way. Therefore, we have to treat every house as unique, and while we can enquire about the companies involved in building it, there are no guarantees that the house will perform as we expect. In other words, we have the highest uncertainty with a product that for most of us is the greatest expense we will ever make in our lives!

Although the resale value of houses is determined by many things – such as location, location, location – the value they provide us with while we live in them comes back to one question: are they capable of sheltering us from unpleasant surprises? We include the unpleasantness of paying power bills in this. But there is more to it than saving energy and money: houses can make the difference between life and death – good houses can literally save lives or turn them around.

But how do we know that the house we are about to build or buy is one that leads to an enjoyment of our environment, and keeps us safe from harm? Certification helps.

10.1 PASSIVE HOUSE PROFESSIONALS

Certified Passive House Designers and Consultants have passed a very stringent exam to demonstrate their knowledge about designing Passive Houses cost-effectively. The difference between the ‘designer’ or ‘consultant’ imprint in the certificate simply pertains to a pre-existing qualification: if the Passive House Institute in Germany, who issues the certificates, recognise a design qualification, the title will be ‘Certified Passive House Designer’; otherwise, those who pass the exam have the title ‘Certified Passive House Consultant’. About 50% of applicants do not pass the exam, but there is another pathway to obtaining the qualification. If you are primarily responsible for the design of a Certified Passive House, and document the design and build process extensively, you can demonstrate your skills by doing so, you can claim the title that way. Whichever way the title was obtained, people who hold it have a demonstrated knowledge into the making of a Passive House, typically above that of the average designer. Even designers who are in the business of ‘green’ or ‘sustainable’ design report that their understanding of what it takes to build high-performance houses has benefited greatly from taking a Passive House exam preparation course. These courses are offered worldwide – and increase the chances of success in the exam – but they do not guarantee a win.

As a client, you know that Certified Passive House Designers and Consultants not only have a good understanding of all the topics discussed in this book, they are also trained to look at the economics of energy efficient design, and optimise your house in this regard.

But the people who build your Passive House need to know about airtightness and thermal bridging, too, to deliver the outcomes the Passive House Designer envisaged. Certified Passive House Tradespersons have that knowledge. Their training typically involves hands-on instructions of which materials to use and how to install them, as well as the basics of Passive House design. There is a specialisation for the building fabric and one for services.

Using certified professionals is not a preconditions for getting a building certified, but it offers a level of quality assurance that will likely prove invaluable in the creation of your Positive Energy Home.

10.2 COMPONENTS

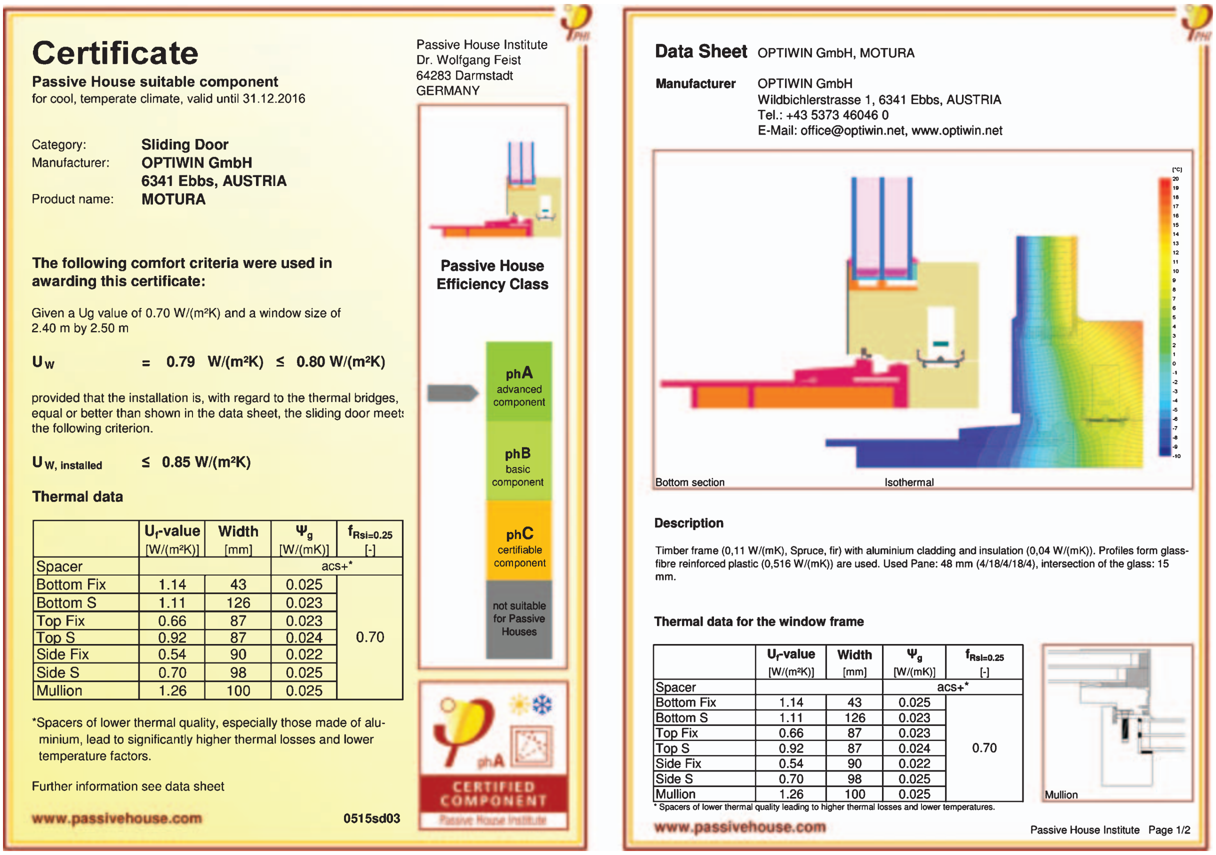
On every muesli bar, you will find a list of ingredients, and an assessment of how they will benefit you – or otherwise (how much energy you obtain out of eating it, how much of your daily requirements to consume certain nutrients will be provided, and what the contribution to your daily intake limit for harmful ingredients is). Compare this with the information you get when buying substantially more expensive building materials or components. Would you not want to know how the insulation material you are about to buy compares to other insulation materials? For a direct comparison, you need to know the thermal conductivity of a product, but you only get this information by default if you live in Europe. It would also be great to have an indication of how the insulation material will perform acoustically or in case of a fire, whether or not it has any structural capacity, and how it will decompose over time. Manufacturers of building materials and components are mostly keeping us in the dark about these features. Doing a good job at designing high-performing houses cost-effectively is hampered by this lack of data.

Many components, such as windows and ventilation systems, are certified by the Passive House Institute in Germany for the use in Passive Houses, but there is no mandatory requirement to use certified components. Like freely choosing your designers or tradespeople, you are free to use whatever material or components you prefer, as long as you can make the case that the performance of a house built with these will pass muster. This is more difficult with non-certified components because you will have to chase the manufacturer for the data you require to demonstrate compliance with the Passive House targets. In another example, there are many things you need to know of a ventilation system to make a sound assessment of the impact it will have on your air quality, noise levels and energy bills. With a Passive House certified ventilation system, all these data are presented. And, because the certifier has no financial interest in exactly this ventilation system selling well, you can trust the stated performance.

There are other institutions who certify building materials, but they have other interests in mind in doing so. They may not look as closely at factors that will determine the energy performance of a ventilation system, for example. To expand on this: if you only measure the ratio of temperature in to temperature out to gauge the efficiency of a heat exchanger, as is often done, then an air leaky heat exchanger will seemingly perform well, because the warm waste air will spill over to the incoming air stream, and increase the temperature there. Of course, this is no merit of the heat exchanger, which is performing poorly because it contaminates the fresh air on its way to the living quarters. The testing methods for Passive House certified ventilations system make it impossible to cheat in that way.

Although all of this certification can at first seem over the top, when you consider that most of us only get one chance at building a great home and then live in it for years, if not decades, taking the time to ensure that the products we choose deliver is time well spent. Therefore it is advisable to use products that have undergone the Passive House certification process, whenever possible – not because the Passive House Institute likes testing things but because they like to know that you are going to get products that you will be happy with.

Products are certified as the optimum for various climate zones. For example, windows that are required in Arctic regions are not optimal for a warm-temperate climate (see figure on p. 42 for a map of climate zones).



Certificate

Passive House suitable component
for cool, temperate climate, valid until 31.12.2016

Passive House Institute
Dr. Wolfgang Feist
64283 Darmstadt
GERMANY

Category:	**Sliding Door**
Manufacturer:	**OPTIWIN GmbH** **6341 Ebbs, AUSTRIA**
Product name:	**MOTURA**

The following comfort criteria were used in awarding this certificate:

Given a Ug value of 0.70 W/(m²K) and a window size of 2.40 m by 2.50 m

U_W = **0.79 W/(m²K) ≤ 0.80 W/(m²K)**

provided that the installation is, with regard to the thermal bridges, equal or better than shown in the data sheet, the sliding door meets the following criterion.

$U_{W,\ installed}$ **≤ 0.85 W/(m²K)**

Thermal data

	U_f-value [W/(m²K)]	Width [mm]	Ψ_g [W/(mK)]	$f_{Rsi=0.25}$ [-]
Spacer	acs+*			
Bottom Fix	1.14	43	0.025	0.70
Bottom S	1.11	126	0.023	
Top Fix	0.66	87	0.023	
Top S	0.92	87	0.024	
Side Fix	0.54	90	0.022	
Side S	0.70	98	0.025	
Mullion	1.26	100	0.025	

*Spacers of lower thermal quality, especially those made of aluminium, lead to significantly higher thermal losses and lower temperature factors.

Further information see data sheet

www.passivehouse.com 0515sd03

Data Sheet OPTIWIN GmbH, MOTURA

Manufacturer OPTIWIN GmbH
Wildbichlerstrasse 1, 6341 Ebbs, AUSTRIA
Tel.: +43 5373 46046 0
E-Mail: office@optiwin.net, www.optiwin.net

Description

Timber frame (0,11 W/(mK), Spruce, fir) with aluminium cladding and insulation (0,04 W/(mK)). Profiles form glass-fibre reinforced plastic (0,516 W/(mK)) are used. Used Pane: 48 mm (4/18/4/18/4), intersection of the glass: 15 mm.

Thermal data for the window frame

	U_f-value [W/(m²K)]	Width [mm]	Ψ_g [W/(mK)]	$f_{Rsi=0.25}$ [-]
Spacer			acs+*	
Bottom Fix	1.14	43	0.025	0.70
Bottom S	1.11	126	0.023	
Top Fix	0.66	87	0.023	
Top S	0.92	87	0.024	
Side Fix	0.54	90	0.022	
Side S	0.70	98	0.025	
Mullion	1.26	100	0.025	

* Spacers of lower thermal quality leading to higher thermal losses and lower temperatures.

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Certificate for level access ranch slider (Figure: Optiwin GmbH).

10.3 NEW HOUSES

A Passive House is a fabric-first approach, and this is universally true across all Passive House classes. In the Passive House system, you cannot balance a poorly performing building envelope with a large photovoltaic array. Although you may get power from the latter, you do not get comfort and health from it. Both are key ingredients of every Certified Passive House.

The requirements for the thermal envelope performance are expressed in thresholds for energy consumption and heating equipment sizing, as well as a maximum value for air-leakiness and thermal bridging (Table 10.1).

Passive House certification also acknowledges performance of buildings beyond the walls, considering that we all have obligations to not only keep ourselves healthy, but also the planet. This means that all energy usage in a house needs to be counted – not just heating and cooling energy, but also energy needed for services, light and appliances. A typical split of energy usage in a Passive House is roughly one third for heating and cooling, one third for domestic hot water, and one third for everything else. We have to account for the whole. But energy used in our homes is typically the tip of the iceberg of our energy needs. Transformation and transportation losses mean that we claim a lot more energy to start with than what we intend to use. This is reflected in a primary energy requirement. What is primary energy? Suppose you want to drink a glass of orange juice for breakfast. You pick three oranges from your garden, which weigh 556 g.

Table 10.1. Thermal envelope requirements for Certified Passive Houses.

Requirement	Threshold
Energy consumption for heating and cooling	15 kWh/(m^2a)
Heating load (relates to equipment size)	10 W/m^2
n_{50}	0.6/h
Thermal bridges	0.01 W/(mK)


Three oranges that together weigh 556 g are being transferred into orange juice; the final product has a net weight of 231 g.

You squeeze 231 g of juice out of them. So: to devour our 231 g of delicious orange juice, we needed to extract about double this weight from nature. These oranges will not be available for any other use.

Primary energy is energy in its raw form. The oranges were the raw source for our orange juice, and like the juice production process, we need to take out a lot more primary energy from nature to be able to consume the power in our homes. There are transformation losses, and transportation losses (some of the juice will stick to the glass, otherwise it would be perfectly clean once emptied), and what we can enjoy is only a fraction of what we needed as raw material.

As with the oranges, the primary energy will not be available for anything else, and making it useful in our household will have consequences for the environment until there comes a time when all energy is generated by renewable means, and there is an abundance of it for everyone and everything requiring energy. The transition to this future is what is envisaged by the new Passive House certification categories.

In this regard, we now have bronze, silver and gold medals in the Passive House certification process, or Classic, Plus and Premium. These categories reflect how much houses contribute to not only the efficient use of energy, but also its generation.

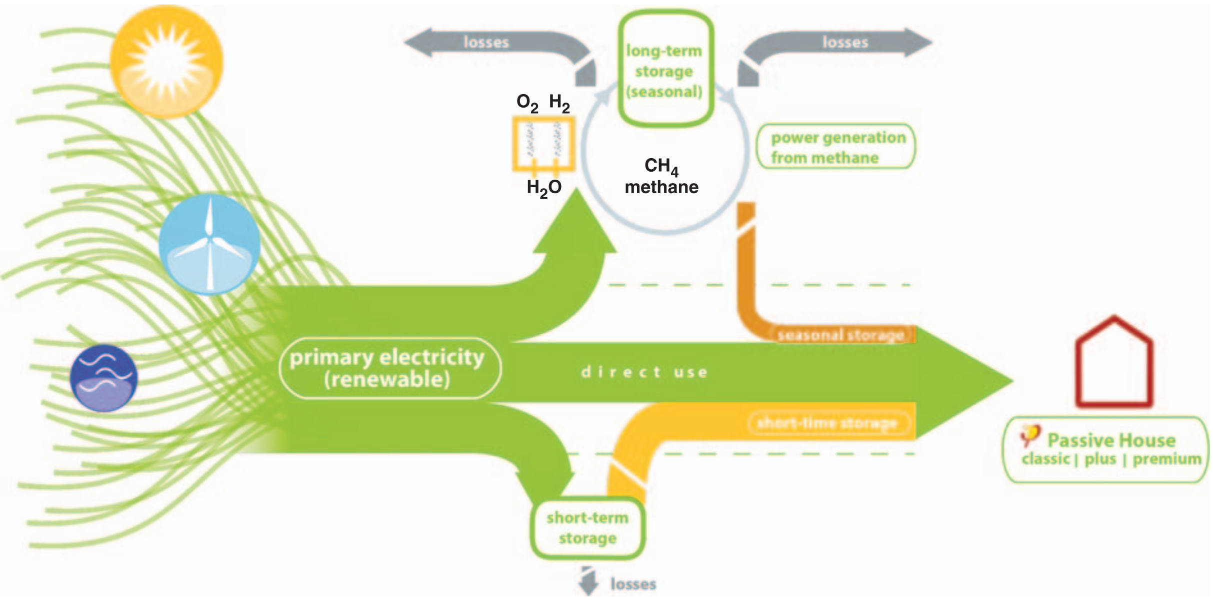
10.3.1 Primary energy renewable (PER) factors

To calculate the overall energy demand of a house, the electrical and non-electrical demand of mechanical systems, including auxiliary energy, plug loads, appliances and lighting, are summed. Added to this is the heating demand for the domestic hot-water production and distribution. If solar hot-water generation is used, the hot water requirement will be reduced by an estimated solar fraction. The uses of devices and services are accounted for as predetermined factors for a particular usage situation, whereby the factor for residential and commercial buildings, for example, will differ. Alternatively, utilisation patterns or a certain frequency is assumed for each service and device, and all these are summed up individually, to result in an overall energy requirement for the house. From there, the impact on the environment is established. From the overall demand for usable energy, the primary energy demand is calculated.

From this perspective, the overall energy demand is geared towards the use of renewable energy sources, anticipating a total divestment from fossil fuels in the near future. Solar, wind and hydro power are assumed to take over, while biomass is considered independently, because there are immediate competing uses as food, fibre for materials and ecosystems. It also requires combustion for its usage as an energy source. Primary energy thresholds are the only aspect of the Passive House standard not concerned with the provision of a healthy and comfortable home – at least not directly. The driver behind these limits is rather an interest in the wellbeing of the planet. It is about limiting the amount of resources we take out of the environment as our fair share – something that will allow everyone to enjoy the same healthy and comfortable conditions in their homes. Of course, eventually, sharing resources more equitably will also contribute to our wellbeing, because it avoids conflicts, human misery and ecological disasters.

Why is it not sufficient to simply generate as much energy as you need over the year? The problem with net zero energy is the tiny word ‘net’. Would it help you to have enough water for the whole year, only most of it will rain down on you in winter, while you need most of it in summer? Without a tank that has seasonal storage capacity you would be pretty thirsty soon. There is no such ‘tank’ for solar power. Even Tesla’s power wall will only be able to store enough solar electricity for a few days. This is not a problem – there’s always the grid where you can draw your electricity from when the sun is not shining for extended periods. As long as you put in just as much energy during summer as you need during winter, you are net-zero, and everything is balanced. But what if everyone did the same? What if everyone generated surplus solar power in summer, and needed electricity from the grid in winter? Where is that power coming from? And what do we do with the huge summer surplus? Until we have viable options for the seasonal storage of electricity, net-zero energy is not the way out of the fossil fuel dilemma.

Primary energy renewable (PER) factors gauge the availability of renewable energy for uses. For example, with solar sources, electricity for cooling purposes is less of a problem, because there is simultaneity between peak cooling demand and peak solar generation. Consequently, the PER factor will be low. This is the opposite for heating. Here, supply and demand are misaligned, and just as you can buy strawberries in winter, but at a higher cost, the PER factor for heating will be higher. Some consumption, such as power for computers and vacuum cleaners has no discernible seasonal variation in usage, and is another matter altogether. How electricity is typically generated in your region will also make a difference. For example, with the high hydroelectricity share in



Some of the regenerative energy will be available for direct use, such as the amount used for the steady amount that light and household appliances consume. What cannot be used immediately, needs to either be stored for shorter periods, for example in a battery, or longer periods, for example converted to gas that can more easily be stored over long periods, and converted back into power when needed. This storage, however, will entail losses (Figure: Passive House Institute).

Table 10.2. Example PER factors from PHPP.

	Auckland	Melbourne	New York
Household electricity	1.15	1.2	1.2
Domestic hot water	1.2	1.25	1.15
Heating	1	1.5	1.5
Cooling	1	1	1.55
Dehumidification	1	1	1.9

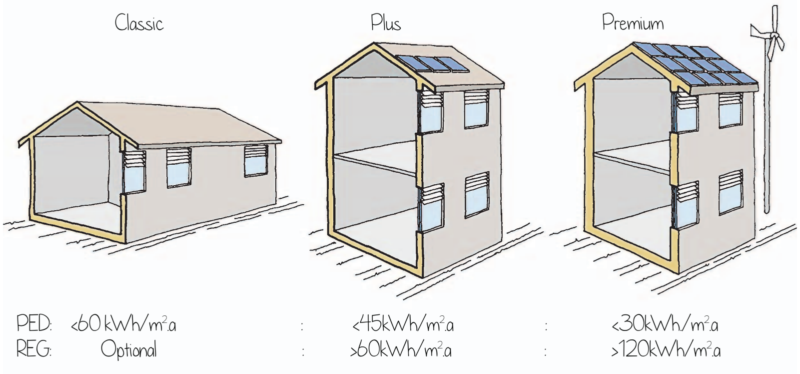
New Zealand, it is easier to balance out peaks in solar generation with another regenerative energy source. It also helps that the hydro lakes are typically at peak capacity in winter.

Ideally, you want to be able to use the energy that you generate instantaneously, because storing it or converting it into other forms for later use incurs losses. To compensate for these losses, you need to produce more energy than what you require for the services you are after. It is really similar to harvesting fruit: renewable energy is best consumed fresh from the field. Although you can pickle your fruit, or turn it into jam to preserve it, this requires containers, additional ingredients, energy and effort to do so. Primary energy renewable factors account for this extra effort, due to mismatches in generation and consumption, as well as conversion, transmission and storage losses in the energy grid.

The factors in Table 10.2 need to be multiplied with the energy that is delivered to the house – and they are only indicative. The PER calculation is integrated into the PHPP and needs to consider specifics, such as energy carriers used other than electricity. Nevertheless, there is a clear signal that complying with PER thresholds for heating, for example, is significantly easier in Auckland than it is in Melbourne or New York, because the energy requirements in Auckland are directly converted to PER, whereas there is a 50% mark-up for Melbourne, based on the reduced availability of renewable energy during the heating season there.

10.3.2 Passive House certification classes

All Passive House certification categories require a very efficient house as the baseline. The consumption for heating and cooling must not exceed 15 kWh/m^2 of conditioned floor



New certification classes for Passive Houses: Classic, Plus and Premium. Primary Energy Demand (PED) pertain to the treated floor area, whereas Renewable Energy Generation (REG) requirements pertain to the footprint of the building.

area per year. This is equivalent to using a 2 kW oil column heater for 75 h per year in a 10 m^2 bedroom. The peak heating power or load must not exceed 10 W/m^2. This means that a 200 m^2 home could be heated by a 2 kW plug-in oil column heater even on the coldest night of the year. And the building envelope must not leak more than 60% of the internal air volume at a pressure difference of 50 Pa.

For Passive House Classic, the only other requirement is that the renewable primary energy demand for all energy use must not exceed 60 kWh/m^2 per annum. Alternatively, the traditional assessment of non-renewable primary energy demand with a threshold of 120 kWh/(m^2 per annum) remains possible. The primary energy allowance shrinks for the higher classes and, additionally, a defined amount of renewable energy needs to be generated either on site, or through a share in a nearby community power generation scheme (see Chapter 11). The latter acknowledges that the conditions for generating renewable energy may not be ideal at the site the house is being built. The requirement for energy generation is furthermore not tied to the conditioned floor area, but rather to the footprint of the house. This considers that the opportunity to generate solar power is typically limited by the available roof space, and while a three storey building may have 300 m^2 treated floor space, the available area of the roof is likely only a third of that. Higher density buildings make better use of scarce resources, most prominently the land they are built on. Although they will not have the highest ratio of on-site generated solar energy per floor area, they help hugely with reducing the environmental impact of urban sprawl. It is therefore only fair that, while the consumption thresholds are tied to conditioned floor area, the generation thresholds are proportional to the building's capabilities.

10.4 CASE STUDIES

10.4.1 Parthenay in Whanganui, New Zealand

Parthenay is the name of the home of the Iliffe family. It is a modest two-storey, four bedroom home overlooking a valley on the outskirts of Whanganui. The Iliffes built and certified their house to Passive House standard. The addition of a 3 kW photovoltaic array on the roof, however, puts it in the current Passive House Plus category. The house needs 32 kWh primary energy renewable per square metre treated floor area, and generates 45 kWh photovoltaic energy per square metre of its footprint each year.

The house not only makes the most out of a small amount of energy, but with four bedrooms and three living areas on only 138 m^2, it is also spatially very efficient. To future-proof its usage, any room can be converted to a home-office or an extra living area with changing occupancy.

Parthenay from the north (Photo: ecoBuild Developments Ltd).

The inner values

U-value of the exterior walls: 0.261 W/(m²K)

U-value of the floor slab: 0.240 W/(m²K)

U-value of the roof: 0.145 W/(m²K)

Mean U-value of the windows: 1.87 W/(m²K)

Heat recovery efficiency: 81%

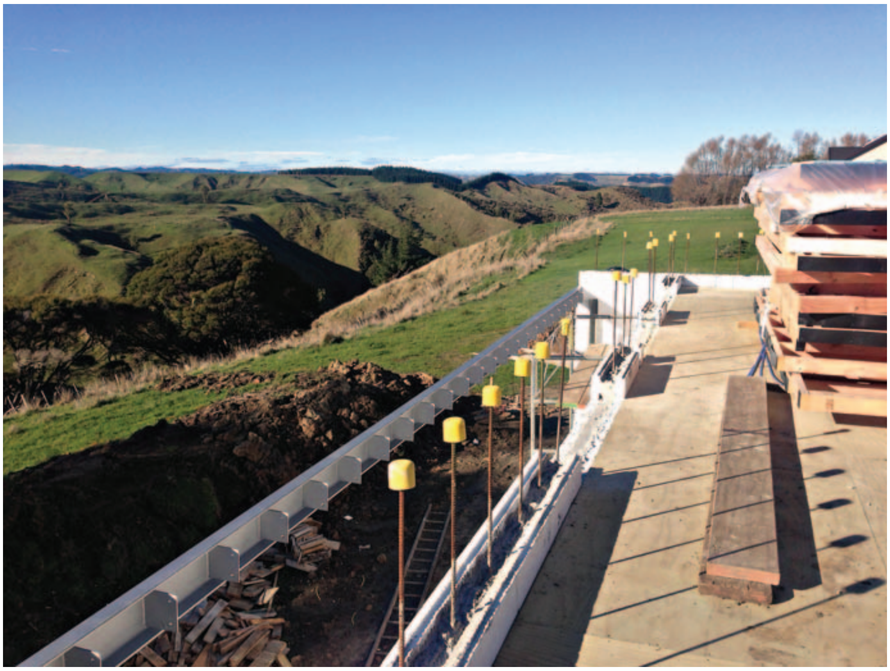
Pressurisation test n_{50} = 0.47/h

PHPP Space heating demand: 9 kWh/(m²a)

Windows are concentrated in the north façade that faces the garden. East and west façades have just sufficient openings for views and light, and the south façade is entirely opaque. This is the side facing the road. It is clad in black metal, which gives the impression of a shed. Clearly, the intention with this house was not to impose itself on the neighbourhood, but rather to concentrate on the inner qualities of positive energy living.

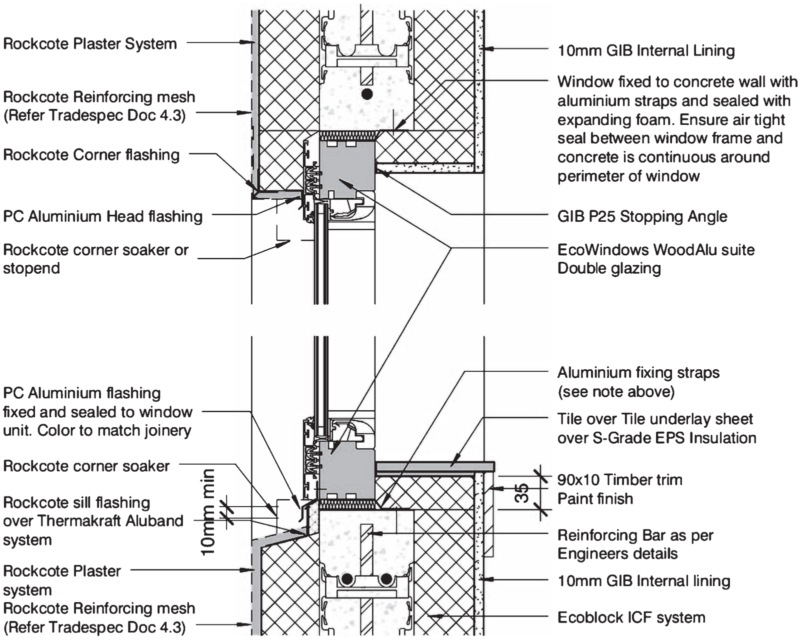
Parthenay from the street (Photo: ecoBuild Developments Ltd).

Outlook from the kitchen to the east. The window is fixed, and the splash back – left transparent over the window area – adds a third layer of glass (Photo: ecoBuild Developments Ltd).



Insulated concrete form blocks are filled with concrete (Photo: ecoBuild Developments Ltd).

The house is pleasantly warm and can be enjoyed year round (Photo: ecoBuild Developments Ltd).



Window installation (Figure: ecoBuild Developments Ltd).

The walls of the house are constructed from an insulated concrete form system. Polystyrene blocks with a hollow core are easily stacked together, and concrete is then poured into the core for stability. In the warm-temperate Whanganui climate, an inner and outer layer of 6 cm concrete was sufficient to achieve Passive House consumption limits.

Mineral wool insulation 200 mm thick is fitted between the rafters of the roof, followed by an extra layer of insulation to the interior.

The concrete floor floats on 150 mm of polystyrene. The insulation is reduced to 65 mm under the footings, which still yields a thermal-bridge-free design ($\Psi = 0.006$ W/(mK)).

Timber-aluminium composite was chosen as the material for window frames. The aluminium faces to the outside as a low-maintenance solution. The wood, however, has the superior thermal properties. Double-glazed, argon-filled transparent areas help with reducing the heat loss.

The airtightness layer for the walls is the concrete. The floor and windows attach to it.

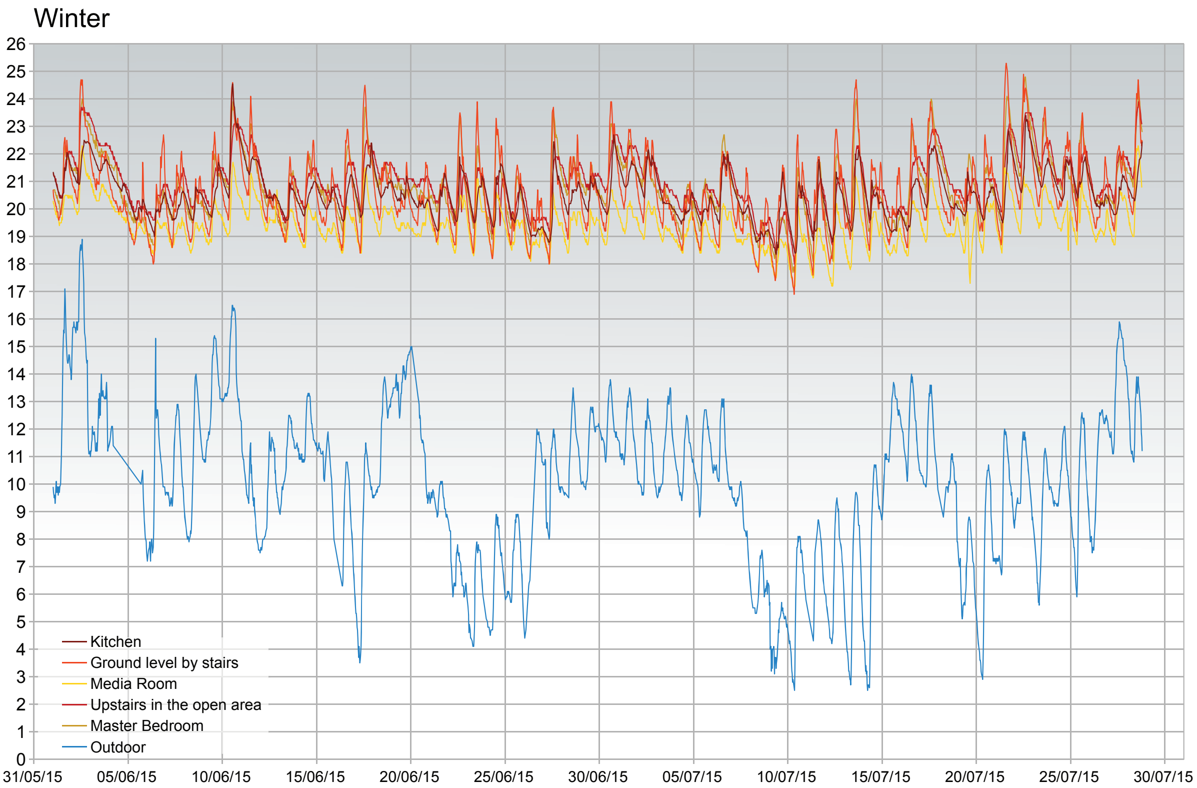
Domestic hot water is generated with an air-to-water heat pump with a 270 L storage tank.

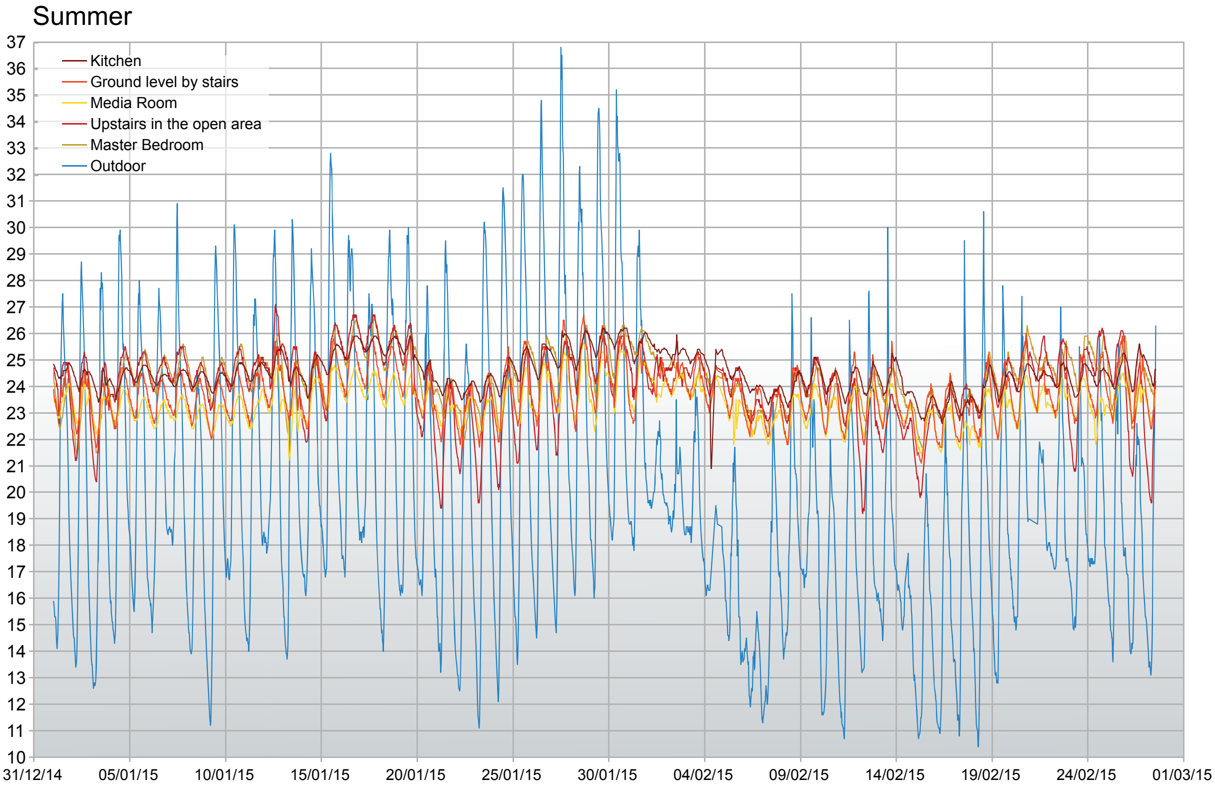
VENTILATION

A very efficient heat recovery ventilation with a star-shaped layout distributes fresh air and the remaining heating requirements.

TEMPERATURE/HUMIDITY RECORDINGS

The indoor temperatures are comfortable throughout the year during waking hours, and decoupled from the fluctuations outdoors. Temperatures are allowed to drop slightly below the comfort range overnight – the heating is consistently switched-off when everyone is in bed.


Winter


Summer

Temperature run (Figure: ecoBuild Developments Ltd).

Jon Iliffe is the co-owner of this home, but his company, eHaus is also in the business of designing Passive Houses. Naturally, he wanted one for himself and his family. ‘This house follows the concept of Passive House very closely and as a result is a joy to live in, no matter what is going on outside: we are always in a peaceful cocoon inside.’

10.4.2 Springdale home, Queensland, Australia

The Springdale home, is a four-bedroom 175 m^2 treated floor area home located in southern Queensland just next to the border of New South Wales, Australia. It is a stand-alone (no grid connection) all electric home, powered from rooftop solar. Located in a mild warm-temperate climate, the combination of an effective thermal envelope, with mainly north- and no west-facing windows, shaded by eaves and external blinds, the home has an incredibly low heating requirement and virtually no cooling requirement. In the event that heating and cooling are required, it is provided by an air-source heat pump system incorporated into the ventilation system, with hot water generated by an air-source heat pump.

Springdale home details

Treated floor area: 175 m^2

Annual electricity consumption: 2053 kWh

Mono-crystalline solar array size: 8.3 kWp

Annual generation: 9727 kWh

Battery storage capacity: 38 kWh

Heat pump size capacity: 3.5 kW heating/4 kW cooling

Heat pump seasonal energy efficiency ratio: 3.6

U-value of the insulate brick exterior walls: 0.09 W/(m^{2}K)

U-value of insulated concrete floor slab: 0.35 W/(m^{2}K)

U-value of the structurally insulated panel roof: 0.16

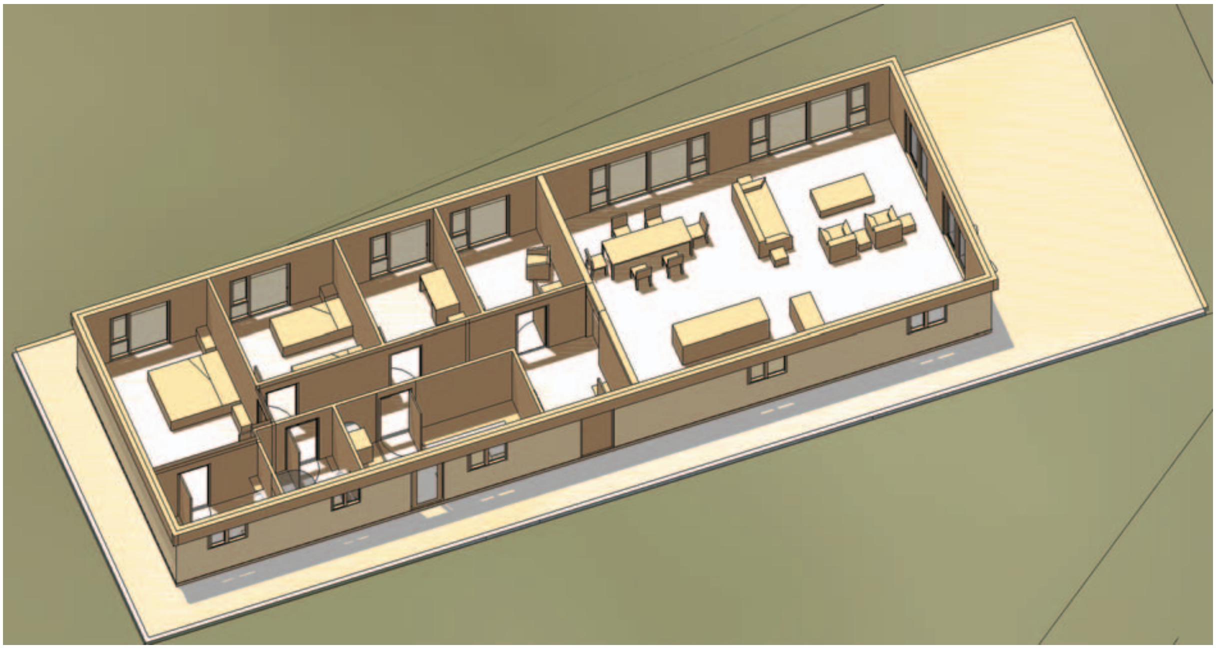
U-value of the windows: 1.4 W/(m^{2}K)

Heat recovery efficiency: 78.7%

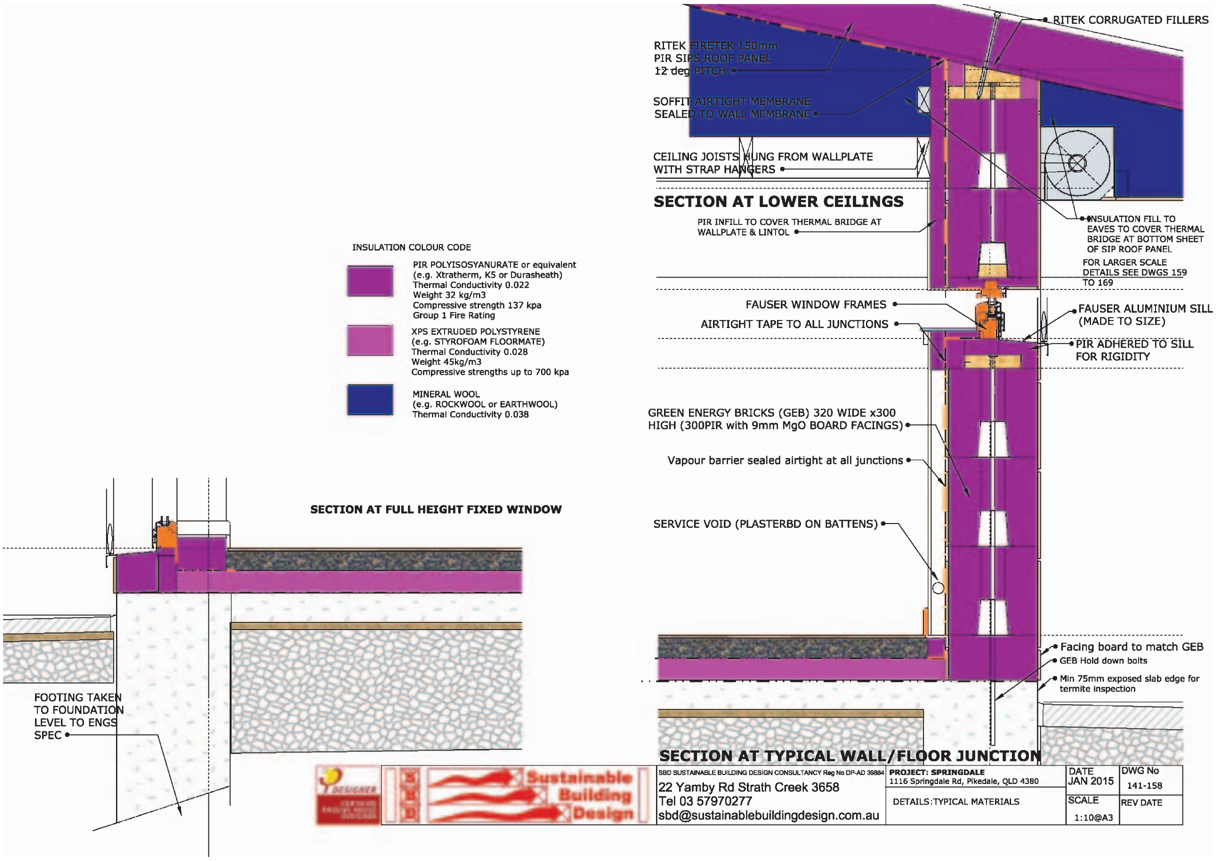
Pressurisation test n_{50} = TBC

PHPP space heating demand: 1 kWh/(m^{2}a)

Passive House Certified Designers: David Halford and Luc Plowman



Springdale Passive House Plus home layout, showing window and room layout optimised for passive solar and daylight management (Figure: David Halford).



Springdale Passive House Plus thermal envelope detail (Figure: David Halford).

10.5 RETROFITS

As stated upfront, this book will not discuss retrofitting the existing building stock in any detail. We will, however, briefly introduce the standard for high-performance retrofits called EnerPHit. It uses the same tried-and-tested processes as Passive House certification, which are the most important part of safeguarding the expected performance, but the thresholds that need to be achieved are slightly relaxed. Things that are easy to get right if you build from scratch become much harder if you have to deal with existing structure. For example, thermal bridges cannot cost-effectively be avoided with an existing structure. And an airtightness layer may not be able to be retrofitted completely gaplessly everywhere.

More difficulty may arise when the building is scheduled, or otherwise of historical importance, and its appearance must not be changed. The certification for retrofits has sensible allowances for these cases. Basically, if you use the Passive House process, and use the best solutions that are economically sensible, you have a good chance of getting this retrofit certified. One thing you will always need to demonstrate, though, is that the health and comfort goals are achieved.

The problem with retrofitting a house is that to do this cost-effectively, you are looking at staging the upgrade of the thermal envelope. Insulation is cheap, but labour and incidentals (such as scaffolding) are not. Therefore, it makes sense to upgrade the parts of the thermal envelope that need some work, anyway. For example, if your interior wall liners look tired or are broken, and you need to replace them anyway, insulation and airtightness can be retrofitted with little additional cost. But if you have to remove an otherwise still well-functioning plasterboard to get to where you want to put the insulation and airtightness layer, the expense will be far greater. For most of us, this will mean that we are not upgrading our houses in one fell swoop, which is what the certification currently requires. However, the problem is acknowledged and step-by-step certification is now also possible.

CHAPTER 11

Positive energy living

Robin Brimblecombe and Kara Rosemeier with Dave Collins

Positive energy living literally taps into the abundance of sunshine and blue sky that is always there, no matter how clouded our thinking gets. Yet this is not a self-help book – at least not the usual type. This book will not save the world, or you. But let us open up a rift to access a better life – for you and everyone on the planet. For positive energy to arise, we need to realise the potential of human environments. The power to move, feed, house, entertain and enrich us, together, and without taking the capacity away from others. Having our cake and eating it – when we require less energy and leave more to go around this becomes a possibility. Energy consumption to meet all our needs can shrink significantly without sacrificing comforts or our health, simply by growing the efficiency with which we use energy. But let us not stop there.

From the 1970s until to quite recently, renewably generated power was called ‘alternative’ energy. What if we could leave the coal, oil and gas in the ground, and not need to burn trees or other biomass – for the power from the sun, wind and hydro to be the standard rather than the alternative? Three things are required to make fossil-free living the new normal:

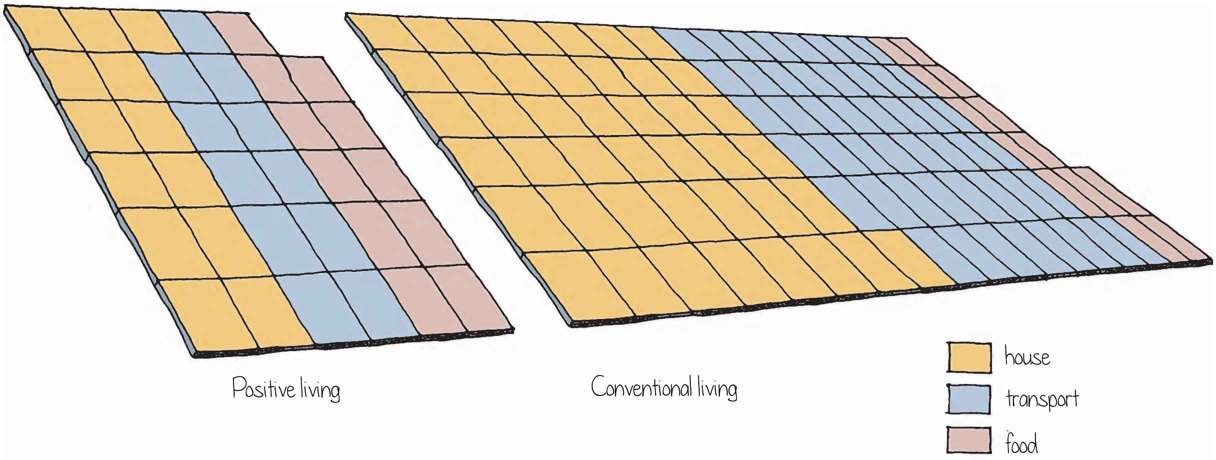
- First and foremost, a dramatic lift in the efficiency of energy use. Buildings – and not just houses – built to the Passive House standard are an example of the mostly untapped efficiency potential of buildings. As we explored throughout the book, using energy smarter has a positive impact on people. There is also plenty of room to improve the efficiency of energy use outside of buildings. Mobility is an example where huge efficiency gains are attainable – with positive side-effects of similar magnitude.
- To further grow the amount of renewable power generation, with many countries well on the way in this regard.
- Lastly, for locations with distinct seasons, we need to balance the discrepancy between peak generation and peak usage. Excess energy harvested in summer needs to be preserved for winter usage.

Once this is done, we need to ask ourselves if we will actually share a surplus of energy freely? We are currently not doing so well at sharing other resources that a minority has in abundance (e.g. money). Will energy be different? Or will a household that generates ample energy simply hoard more freezers, TVs and electric cars? We cannot be certain that everyone is playing ball and keeping things sensible, until we as a society agree on some rules for energy distribution. But the option to give a little without missing out on anything we need is there. Currently, more than a billion of our contemporaries still do not have access to electricity at all. Millions die each year because they are forced to use unsafe fuels for cooking and light. Electricity is an essential part of the life that we should all be allowed to live. It empowers us to communicate, to refrigerate medicine and food, to access information, and to move to places where there are people who can help us. The technologies and resources to leave no one on this Earth behind are available. Using them equitably is what we call positive energy living.

11.1 LIVING WITH POSITIVE ENERGY

As individuals, we typically consume energy directly in three ways: to power our homes, for transport and to power our bodies. With our Positive Energy Homes happily taking care of their energy requirements, it is worth considering how we source the energy to fuel our bodies and meet our transport needs. We also indirectly consume energy through the products that we purchase, but a general discussion about embodied energy of consumer products is well beyond the scope of this book, so other than noting that the easiest way to reduce this energy is to consume fewer items, we will limit the discussion here to energy we have direct control over.

A typical single family Positive Energy Home providing superior comfort and supporting typical occupant behaviour consumes in the order of 12 kWh per day (much lower is possible for energy-frugal occupants) – three to four times less than a conventional home. Similar savings are possible through improving the efficiency of our transport and through growing and sharing food locally.



The number of solar panels required to provide the energy requirements (or equivalent energy requirements in the case of food) for a positive energy household compared with a conventional household.

Embodied energy

The embodied energy of materials is a complicated topic worthy of consideration in all sectors. However, focussing the discussion on building materials, as is often the case, seems arbitrary. The reasons we only touch on embodied energy in this book are discussed briefly below:

- As long as energy is embodied in long-lasting structures, such as buildings that serve a purpose, we do not see it nearly as problematic as when energy is used to create short-lived consumer goods and trinkets with limited usefulness.
- Data about embodied energy of building materials is patchy and often contradictory. For example, we could not find any data for embodied energy of cable sleeves or downpipes, and values for other building materials vary considerably. Life-cycle assessments of buildings typically pick and choose some materials for an analysis without justifying the selection process. Local energy schemes also need to be considered for the whole picture. For example, aluminium in New Zealand is manufactured using a purpose-built hydropower plant. Although we could have a debate about consuming this generated energy for uses other than creating aluminium, the embodied energy of aluminium produced this way is, atypically, rather low. In contrast, Australian aluminium manufacturing is typically powered by burning coal making it pollution and carbon intensive. As such, determining the best products for you home needs to be analysed on a case-by-case basis, rather than using rules of thumb.
- The specific ingredients for energy-efficient houses usually have a very low impact on the overall embodied energy of the project. Decisions about the building's structural elements (e.g. timber, blockwork, brick, concrete and steel) are far more wide-reaching for the overall amount of embodied energy that goes into your home than the choice of the insulation material. No construction method is specific to energy-efficient homes. The outcomes for embodied energy are therefore undetermined.
- While there are certainly differences in the amount of energy required to manufacture polystyrene or cellulose, for example, even a worst case choice of insulation material will normally create a far lower carbon footprint compared with a preference of steel construction over timber. Using locally sourced timber as the structure of a building is therefore typically the most important decision for a low embodied energy content of a building. If you combine this with straw or cellulose as the insulation material, your Positive Energy Home will most likely contain far less embodied energy than all other houses in your street, while simultaneously needing no fossil fuel for its operation.
- Embodied energy is not lost. Even building materials that cannot fully be recycled can have other uses at the end of their life in a building. It is conceivable that landfills of today will become the hardware stores of tomorrow. Fossil fuels depleted to make our houses liveable on the other hand, will not be recoverable in likely future scenarios. The rich chemical value of these compounds is destroyed in the combustion process, making them unavailable for future use.

11.1.1 Getting around using positive energy

Compact urban environments are a precondition to increasing our mobility and access to services without increasing the use of fossil fuels. Apart from enabling us to get to places with body power alone, proximity also makes it easier to share resources.

The poor efficiency of typical fossil fuel powered cars makes transport energy a large part of the typical household energy budget. Electric cars are significantly more efficient in their ability to transport us from A to B, consuming in the order of 1.5 kWh to travel 10 km, making it feasible to source daily transport energy requirements onsite. For example, a 1 kWp solar array in Melbourne,

Photo of Ideal House with electric vehicle charged using excess solar energy (Photo: Murray Durbin).

charging an electric car with a charging efficiency of 80% would provide enough energy for an average daily travel distance of 20 km (~3.8 kWh). A 1 kWp array requires ~7 m^2 of roof space. Still, there are even better ways if only people need to be transported. For example, electric bicycles (e-bikes) are more efficient again, consuming around 10 Wh/km, meaning a 1 kWp solar array could provide enough energy for household members to travel a collective distance of around 300 km per day. To meet the daily transport requirements of an urban household through the installation of a slightly larger solar array is therefore feasible. The occasional weekend getaway may require additional energy, which could be sourced from larger scale wind, solar or hydro installations.

Sharing the vehicle, particularly if it is an electrically powered bus or train, is another great option to bridge longer distances. A total mobility concept, as can be found in some cities, enables the seamless integration of rapid public and last leg private transportation modes. Examples include taking bikes on buses and trains, or the train ticket that also enables you to use an electric vehicle at the train station to easily connect to your origin and destination.

For homes where the tried and true transport methods of walking or riding a push bike are preferred, there are the added benefit of providing exercise and opportunities to interact with the community. Obviously, human-powered transport consumes energy as well, so let us consider how much energy humans consume and where that energy comes from.

11.1.2 Positive energy plates

As shown in Table 11.1, the base energy consumption of an adult is in the order of 2 kWh per day increasing to 4 kWh per day with heightened activity levels. If, like a home or electric car we could charge ourselves from a PV array, a family of four would require around 6–7 kWp of solar PV capacity (~40–50 m^2), assuming 100% charging efficiency.

In reality, we source our solar power from plants, which have a relatively low solar to stored chemical energy conversion efficiency of less than 1%, with only a portion of this energy accessible to us in the form of digestible fruits or vegetables. Although this seems low, it is important to remember that, like a Positive Energy Home, plants are optimised to produce the amount of energy

Table 11.1. Typical daily energy consumption per person by activity type (Source: Hegger *et al.* 2008).

Daily energy consumption	Resting, lying down	Light non-physical work	Strenuous physical activity
kWh/day	2.1	2.9	4.1
kcal/day	1790	2510	3510

they require to live and grow with a little extra stored as carbohydrates to get them through the year and provide for their offspring. The ability of plants to capture solar energy and use water and CO_2 to build complex carbohydrates is nothing short of remarkable. However, because they have evolved to meet their own needs rather than provide us with food, they use the majority of the energy they generate directly and only the energy that is converted to long-term storage is accessible to us. The conversion efficiency of solar to usable energy in food becomes even lower again when the solar energy passes through an animal before being consumed by us.

Given the variables of diet, soil, farming practices and climate, calculating the land required to sustain a family is complex. For the purposes of comparison, a commonly accepted area to support a typical family diet is in the order of 2 acres (~8000 m^2). Along with this area, plenty of time and commitment are required. With an alternate diet, an ideal site and cultivation techniques, the required land can be much smaller, allowing for a meaningful amount of energy to be harvested from the land around your home in the form of food.

If we compare this with the theoretical space required to generate the same amount of energy from solar PV, food energy requires two orders of magnitude more area, making humans relatively inefficient. From this simplistic analysis, we could conclude that it is more efficient to meet our transport requirements through solar powered electric vehicles than solar biomass powered humans or indeed biomass powered vehicles. However, in developed countries most people consume more energy in food than they need to sustain themselves, so putting some of this excess energy to use for walking or cycling has added benefits, because it promotes health and community interaction.

In most industrialised nations, food is cultivated remotely and then processed, transported, stored and displayed for purchase before reaching us, with every step consuming energy. The amount of energy required to source 1 kWh of energy varies with food type, farming method, fertilisers, processing, distance travelled and storage requirements. These factors vary significantly, making it almost impossible to calculate accurately. Table 11.2 provides some examples of energy inputs required to produce and deliver common foods to a cold temperate country (Sweden).

For many people the time, knowledge and available land and water will make growing the majority of their own food impractical. In many cases, it may also not be the most efficient option. However, as can be seen in Table 11.2, sourcing even a small amount of food from our homes can make a meaningful contribution to reducing the energy requirements of food and create a rewarding culinary experience. Given the time and land requirement of growing food, for many homes, productive gardening may be best achieved at a community scale.

Table 11.2. Example energy requirements for delivered food energy in a cold temperate industrialised location (Sweden) (Source: Engstrom 2006).

Food	kWh required to produce and deliver 1 kWh of food	kWh required to provide adult daily energy requirement
Apple local	1.6	4
Apple imported	3.9	11
Milk	2.2	6
Tomatoes, field	7.2	20
Tomatoes, greenhouse	88.0	246
Eggs	3.0	8
Chicken	5.0	14
Tropical fruit	46.0	129
Beef	5.5	15

11.2 POSITIVE ENERGY COMMUNITIES

Although Positive Energy Homes are a step in the direction of more equitable sharing of resources, the power of a community allows for even better outcomes. Sharing houses may not be everyone's ideal situation, but sharing a vehicle, tools or a solar charged electric lawn mower is not that difficult if the structures for it are in place. And why stop there? In the right environments, it is also possible to share energy harvesting systems from vegetable gardens through to ground-source heat sinks and wind turbines.

What is required to share resources effectively is the sharing of data: software that enables you to book the shared car/workshop/lawn mower when you need it, and make it transparent to other users when it will become available again for them to use. A smart-phone app can do this easily. A neighbourhood food co-operative can source items that are not readily produced in the vicinity, and as a member you can trace the available stock on your phone. Is there enough spaghetti in the store for dinner tonight? Or will we have pizza? A quick check on the phone gets this sorted.

Proximity of people is again the key to sharing resources effortlessly. Sprawling urban environments, exclusionary zoning and other planning oddities such as site setbacks and minimum parking requirements get in the way of using the highly valued commodity of urban space more efficiently. The car and lawns take up far too much space that could be used to house and feed people in our towns and cities. There are better ways of solving the problems than the current planning rules. For example: for kids to play, they most of all need other kids – not lawns. And noise issues associated with higher densities are readily avoided if it is possible to achieve effective acoustic separation from the environment in your living quarters, which is a side effect of putting the three functional layers of a Passive House to good use. Cities are organic structures. They need to evolve to thrive – and so does planning.

11.2.1 Shared mobility/accessibility options

Eighty-five per cent of the customers of the car-sharing agency Cambio in Bremen/Germany no longer own a car. They do not need to, because a fleet of cars of various sizes is available to them at the touch of a smartphone app. A dense network of key-lock stations and cars puts almost everyone in the city only a few minutes away from the next shared car. Car-sharing enables smarter use of a resource that would otherwise be idle and only take up space most of the time. But, in Bremen, they now have one better: all-electric cars and e-bike sharing options are also available. These are parked next to a charging station. If car-share schemes are combined with fairly priced annual tickets to a decent public transport network, and safe bicycle and pedestrian lanes, owning a car in the city becomes only a burden. In contrast, getting to where you want to go without needing to find parking, fuel stations and regular maintenance stops lets you experience the flow through urban environments as opportunity and pleasure.

11.2.2 Community gardens for nature and food

For most of us, life is spent indoors, with fleeting exposure to the world as we race between appointments, often down lifeless streets and all too often ‘inside’ a vehicle. In our busy lives, it is easy to forget that we are creatures of nature and the success of our species is intimately tied to our social tendencies. Laying out our neighbourhoods to facilitate alternative means of mobility, not only reduces energy consumption, it provides us with an opportunity to reconnect with the world around us and our neighbours. If we take this a step further and make the spaces between our homes places for nature then the act of commuting also becomes a chance to connect with our origins, making the commute a pleasure or even the reason for our journey.

For many of us, the beauty of nature is enchanting and stimulating, and needs no further explanation. However, given the principles laid out in this book are firmly rooted in science, let us briefly peer beyond this innate feeling and explore the science behind our deep connection to the natural world. For most of our species history, we lived intimately with the natural world and it left its mark on us.

Starting with beauty, which we are told is ‘in the eye of beholder’, it turns out to be in our genes. Each individual has their preferences, but when science pulls apart these preferences and then put them back together to paint a collective vision of what we as a species consider beautiful, it comes out as a picture of a lush meadow, with a waterway flowing through it, some non-threatening animals, a few shrubby trees and a path leading off to some hills on the horizon. Sound clichéd? Well it is, and there is good reason for that: this image represents fresh air, water to drink, food to eat, trees with low branches that we can quickly scramble up if threatened and the promise of adventure just beyond the horizon. With this image firmly stamped in our DNA, it makes sense to create neighbourhoods that connect with our origins and stimulate our sense every time we go outside. Therefore using the spaces between our homes for gardens that hold the promise of spring flowers and bees, trees for fruit and for children to climb, and places for animals to be part of our daily walk to work, is both wonderfully clichéd and stimulating at the same time. Indeed, the science goes further to show that exposure to the sights and sounds of nature reduces our stress hormones levels and quiets our pre-frontal cortex, improving our creativity and concentration.

To achieve this outcome, many communities have done away with the suburban fence, removing the notional boundaries between mine and yours to create open space between our homes, allowing the streets to flow through the landscape rather than define them. This provides an opportunity for an extended ecosystem to develop through the neighbourhood and potential for engaging community space, rather than an incoherent collection of isolated gardens.

Through good planning, these gardens can become more than just the space left between our homes, and provide a broad range of functions to the community, and to nature. For example, allowing for a consistent tract of native vegetation through the neighbourhood creates a connected ecosystem and a corridor for wildlife. Providing communal open spaces between homes, rather than next to busy roads, allows a place for people to meet, have picnics and for children to play and interact. There are many examples of community that have established shared vegetable gardens, where residents can come together to enjoy some fresh air, get some exercise, connect with nature and produce some delicious food. In contrast to isolated backyards, which can become a chore and all too often revert to a monoculture of grass that always seems to need mowing, these communal spaces provide opportunities to learn and share the experience of gardening and get to know your neighbours. They also spread the responsibility of a delivering a successful crop, meaning you can head off for a holiday with the confidence someone will water your prized row of corn if there is no rain while you are away.

11.2.3 Community energy systems

As touched on throughout the book, some technologies are only financially viable at a certain scale or are of a level of complexity that they may not be warranted for the modest requirements of a single home, such as wind turbines, energy to gas storage or ground-source heat sinks. However, at a community level these systems may become viable. For example, where multiple homes are being built on a site, the additional capital cost and maintenance associated with installing a ground-source brine loop with heat exchanger may be viable when shared between homes.

COMMUNITY WIND FARMS

As discussed in Chapter 9, although possible for most residential sites, generating the home's power requirements from wind is challenging and often prohibitively expensive. In contrast, large-scale wind turbines located on a favourable site are some of the cheapest forms of new generation capacity. As such, although wind generation may not be feasible for an individual home, as a community, wind generation can be a viable option. In most cases, this will be a little more complicated than installing a turbine and connecting to the home, because ideal wind harvesting sites are typically remote from residential areas. Teaming up with like-minded people and professionals can still enable communities to harvest wind power.

The Hepburn Community Wind Farm, located at Lenards Hill, ~100 km north-west of Melbourne, is Australia's first community-owned wind farm. The farm comprises two 2.05 MW with a ground to blade tip maximum height of 110 m. The 4.1 MW peak capacity wind farm produced 11.2 GWh in 2014, thereby turning 32% of the peak wind capacity into power. This is enough to provide all of the energy requirements of over 3000 homes built to the principles described in this book. The project cost in the order of $13 million, with the majority of funding sourced through co-operative members and applicants, and the balance made up from government grants and finance, with annual earnings in the order of 14%.

The project was conceived in 2005 by the community group Hepburn Renewable Energy Association and was developed in partnership with the private firm Future Energy. In 2006, the site underwent 12 months of wind measurement, and correlation with historical weather data from the region to predict average wind speeds of 7.7 m/s at the turbine hub height. With a favourable wind resource, Future Energy proceeded to develop the farm, with construction commencing in 2010 and the first output from the farm in 2011. Ownership of the farm was transferred to Hepburn Community Wind Park Co-operative Ltd (Hepburn Wind 2016), a community owned co-operative of around 2000 (majority local) members, each with an equal vote in a co-operative structure. The co-operative has a contract with a private company to operate the farm, with electricity and renewable energy certificates (an Australian Government financial mechanism to support renewable energy generation) generated by the farm are sold to a local retailer who offers the power for sale under a community saver retail product. A portion of the profits generated from the farm are reinvested in the Hepburn Wind Farm Community Fund.

Hepburn was the first community wind farm in Australia, but there are many examples from around the world with a variety of non-profit groups and websites dedicated to supporting community groups in developing renewable energy projects.

Hepburn Community Wind Farm (Photo: Hepburn Wind by Studio Aton).

COMMUNITY SOLAR

The most common method of achieving positive energy in homes is through the installation of rooftop solar PV. This requires a reasonable area of unshaded, appropriately orientated roof area and capital investment on top of the cost of the home. Like community wind farms, community solar collectives or co-operatives can provide an alternative means of sourcing and financing local renewable energy. For example, individual homes may not have sufficient roof space to meet their energy requirements, but across the community other houses may have unused but suitable roof space, which could be managed by a communal initiative to provide power to all the participating homes. Likewise, high-density multi-storey, multi residential buildings may not have sufficient roof space, despite being more efficient than stand-alone homes. Residents may be able to gain access to additional collection area, such as roof space on local community buildings or through a community solar farm.

Around the world there are many examples of solar co-operatives or collectives who have successfully financed rooftop solar or solar garden/farm projects in their local community. Some of the benefits of such programs include:

- gaining access to favourable space for solar arrays, such as the roofs of local homes or community buildings, or land for a solar garden/farm
- economies of scale achieved through combined purchasing power
- access to alternative financing options, such as loans from credit unions or banks with the initial deposit raised through the community or co-operative members
- combined operation and maintenance contracts
- funding of solar for social houses in the community
- combined negotiating power with networks and retailers.

These programs can operate ‘behind the meter’, where homes share power directly rather than through the grid. Where homes are co-located, this avoids the complexity and costs of involving a retailer, but, in many areas sharing power across property boundaries is not allowed by local authorities. Other schemes, such as the Hepburn wind farm, export power to the grid, with an option for members to buy the power from a retail partner.

11.2.4 Community energy storage/renewable energy factors

The Passive House primary energy renewable factors (PER) account for the mismatch between renewable energy generation and energy demand in the home. For each location, these factors reflect the climate and the mixture of renewables within the grid. Cooling in locations such as

Melbourne, where peak solar generation correlates with cooling demand, has a minimal primary energy penalty, whereas heating requirements occur at the time of the year when solar generation is lowest, resulting in a higher factor. This is also true of much of New Zealand, but with large hydroelectric dams and winter rainfall, the grid is able to store and provide renewable energy during the heating season, resulting in a lower renewable primary energy factor. If your location is not fortunate enough to allow the storage of energy in hydroelectric dams, it is difficult to store significant amounts of non-biomass renewable energy across seasons. At a domestic level, the storage of energy in the hot water tank (heat) or batteries (chemical) only allows for a few days' worth of energy. This can help to smooth out the daily mismatch between demand and generation, but is unable to smooth seasonal discrepancies.

Perhaps the most accessible seasonal energy term energy storage option for individual homes is the heat in the ground. As discussed in Chapters 4 and 5, the ground temperature remains relatively stable year round and therefore can be used to collect or dump heat to support hot water generation, heating and cooling. Because the heat flows in a small Passive House are relatively small, drawing heat and dumping heat into brine loop is unlikely to significantly change the heat balance of the ground, with the small energy flows equilibrating with the ground. At a community level where homes are in close proximity, heat flows can be combined and are more predictable, leading to the potential to store heat or the absence of heat (cool) in a community heat well. This requires a common brine loop around the community feeding into the ground, with the larger investment in creating a significant heat well spread out across the community, rather than an individual home. In summer, excess or harvested heat from the homes can be dumped into the heat well and be drawn on for hot water generation and heating in winter, smoothing out the seasonal demand on the grid.

11.2.5 Positive energy neighbourhood

In the year 2003, the first multi-family home of the housing co-operative Wohnsinn in Darmstadt/Germany was ready to be occupied by its co-owners, who either own the right to occupy in perpetuity outright, or pay monthly instalments similar to rent. Democratic decision making and self-government are at the core of this co-operative. The initial community has by now grown to 160 people living in two large buildings. Communal rooms such as a café, workshop, youth and guest rooms are available to all. The project is completely self-governed, and 'jobs' such as janitor, gardener and administrator are all performed by people living in the community. The co-owners come from all walks of life, and there is a good mix of age, ethnicity, family status and levels of physical ability: many apartments were designed barrier-free.

The buildings were constructed to meet Certified Passive House standard. But, on top of this, solar thermal and photovoltaic systems are employed. Many residents are furthermore engaged in a separate co-operative that uses the roofs of parking buildings in the vicinity to generate electricity. A car-sharing agreement completes the picture.

Wohnsinn showing rooftop solar array.

Few members of Wohnsinn would be able to afford living surrounded by positive energy without the power of community. Everyone within the project, and beyond – as surplus energy is fed into the grid – benefits from this pooling of resources towards a communal good.

When we visited in late April of 2013, the arcades that form the outdoor spaces of the uppermost floor were in full bloom. Although there were notional partitions between the units, the dividers were quite porous, and it was easily possible to chat with the neighbours on the next balcony. It emanated that this community of choice had found the right balance of regulation and anarchy to enable an unorthodox, but respectful, way of sharing the spaces outside of the individual living quarters.

11.3 A TALE OF TWO HOMES

Despite the cold winter morning, the neighbours' kids up early making a racket in the street, riding their bikes and playing with their dogs, in your cosy bedroom it is quiet and peaceful. Eventually you stir as some warm rays of winter sun poke through the clouds and bounce around the room, stimulating your senses ready for the day ahead. You sit up refreshed after a great night's sleep to a room full of fresh air. You throw on a T-shirt and feel a twinge of guilt that there is no need for a jumper even though it is so cold outside, but then remember that you have not turned the heater on all year, so you start your day comfy and guilt free.

By the time you reach the living room, the sun has come out over the clouds so you decide to head out on the electric-assisted bike, charged from the rooftop solar, to go and grab some breakfast from the corner organic bakery. As you walk out the front door you get hit by a cold burst of wind and realise it is actually really cold! So you quickly grab a couple of oranges off the tree on the nature strip and head back inside to sit in your sun filled living room and enjoy some fresh squeezed juice and whip up some perfect pancakes on the induction stove.

After breakfast you decide to call your friend who is living on the other side of the world. It has been a long hot summer's day where he is so, he cannot talk long because some friends have dropped by to enjoy the cool fresh comfort of his home. He mentions it has been unseasonably humid but the ground loop cooling system that pre-cools the ventilation air has been doing a great job of taking care of the excess moisture and he has only needed to turn on the air-conditioner once this summer. You ask him how the automated blinds have been working and he jokes that he could not tell you as he does not even notice them. All he knows is that the house stay cools and there is always plenty of light. You laugh and agree that it can be it easy to forget what the weather is doing as it is always comfy in your Positive Energy Homes. Your friend hangs up as a cool change has come through so they are going to open up the house and enjoy a cold drink on the deck. Feeling inspired, you throw on a coat, hit the switch at the door that turns off your appliances and lights and head off to the community garden to check how your winter crop is going.

After a great afternoon enjoying some company and getting your hands dirty planting some snow peas ready for spring, you throw your muddy clothes in your efficient washing machine and have a pleasant hot shower, sourced from your super efficient heat pump hot water system. After your shower, you hang your clothes out in your drying cupboard and flop down on the couch to check out how much power you generated today. In doing so, you notice that the street lights have not come on and through checking the inverter app on your phone you discover that the electricity grid is out, but you didn't notice as your inverter has seamlessly transitioned to battery power. Feeling smug, you head off to the kitchen to cook up some of the veggies you picked from the garden today.

SUMMARY

We can have a future without conflict about scarce energy resources and climate catastrophes if we curb the energy demand that powers our daily lives, and give back more energy to the common pool than we take out. Our lives will not be poorer for it – quite the contrary. But it is not the individual who changes everything. We are in this together and need to collaborate. Positive energy can also flow between people. We share this world and the responsibilities that come with our communal ownership of it. This book is intended to inspire you to demand better performance from new homes, and the people designing, building and approving them. Once you are well housed, shower the world around you with some positive energy!

Find links and further information at <www.PositiveEnergyHomes.website>.

REFERENCES AND FURTHER READING

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