Microgeneration

low energy strategies for larger buildings

Dave Parker

Microgeneration

Low energy strategies for larger buildings

This page intentionally left blank

Microgeneration
Low energy strategies for larger buildings

Dave Parker
BSc CEng FICE FRSA FIQA

ELSEVIER
AMSTERDAM • BOSTON • HEIDELBERG • LONDON • NEW YORK • OXFORD
PARIS • SAN DIEGO • SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO
Architectural Press is an imprint of Elsevier
Architectural Press

Architectural Press is an imprint of Elsevier
Linacre House, Jordan Hill, Oxford OX2 8DP, UK
30 Corporate Drive, Suite 400, Burlington, MA 01803, USA

First edition 2009

Copyright © 2009 Elsevier Ltd. All rights reserved

The right of Dave Parker to be identifed as the author of this work has been asserted in accordance with the Copyright, Designs and Patents Act 1988

No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means electronic, mechanical, photocopying, recording or otherwise without the prior written permission of the publisher

Permissions may be sought directly from Elsevier's Science & Technology Rights Department in Oxford, UK: phone (+44) (0) 1865 843830; fax (+44) (0) 1865 853333; email: permissions@elsevier.com. Alternatively you can submit your request online by visiting the Elsevier web site at http://elsevier.com/locate/permissions, and selecting Obtaining permission to use Elsevier material

Notice
No responsibility is assumed by the publisher for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions or ideas contained in the material herein

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloguing in Publication Data
A catalogue record for this book is available from the Library of Congress

ISBN: 978-0-7506-8470-5

For information on all Architectural Press publications
visit our web site at http://books.elsevier.com

Typeset by Charon Tec Ltd., A Macmillan Company. (www.macmillansolutions.com)

Printed and bound in United Kingdom
09 10 11 12 13   10 9 8 7 6 5 4 3 2 1

Working together to grow
libraries in developing countries

www.elsevier.com | www.bookaid.org | www.sabre.org

ELSEVIER BOOK AID International Sabre Foundation

Contents

This page intentionally left blank

Foreword

There has never been a better time to consider the benefits of microgeneration. Grants are available for many types, government policy is strongly in favour, and the awareness of the urgent need for reductions in CO_2 emissions is widespread. And yet, take up of the myriad of technologies available is still low, and slow to increase. Whilst the reasons behind this apparent reluctance are no doubt complex, at least part of the problem is a lack of clear and readily understandable guidance as to what to do, where to go for advice, how to achieve the goal. This book will, I am confident, go a long way to addressing this shortfall by providing information in a style and format that is engaging and accessible.

Sustainable development, a minority subject until only a few years ago, is now mainstream and the phrase is everyday fare for the press and media. The great advantage of increased exposure of the issues is balanced by the danger of over-use and a loss of interest once the initial concept is grasped. Recent attention given to climate change, heightened by individual events of extreme weather, has awakened genuine concern about what increasing levels of CO_2 may be doing to the world's atmosphere and climatic conditions. The magnitude of the problem, however, may have the effect of turning people away from action – if the problem is so great, is there any point at all in individual action or even local initiatives? Well, the imperative is for action at all levels and particularly within our society here in the UK, where our consumption of resources outstrips almost every other country. Without meaningful actions at individual, community and national level, the UK will have no credibility when sitting in the negotiations for global action to reduce emissions for mitigation of the impacts, and begin the process of adapting to the effects already being noticed.

We are faced with an upsurge in enthusiasm for sustainability, for reducing carbon emissions, and for finding new sources of renewable energy. The great difficulty with this new zeal is finding a way through the baffling array of information, claims and counter claims for all the different options now on offer. It is not sufficient to say that as long as an option delivers some benefit then it is worth doing. There are costs involved and risks, and there needs to be some way of differentiating between the options. At the simplest level, which technologies would yield the best financial return on capital invested? But this is only part of the answer.

We need to know how the technologies compare in terms of their environmental impact, particularly the saving of CO_2 associated with each type. How does biomass compare to solar panels? How dependent does the project become on the source of biomass? Where does ground source heat pump technology sit in terms of carbon saved? Can the power needed for the ground source heat pump system be generated from another renewable source? Do wind turbines work at the scale likely to be affordable for a particular project? How do solar panels for generating electricity compare to direct solar purely for heating? Has the embodied energy associated with manufacture been included in the consideration? How robust is the technology and will it be productive over the full period required for payback of the investment?

In the pursuit of construction and refurbishment projects, the sheer complexity and pressure to deliver are strong disincentives to anyone involved thinking of adding another layer of (initial) cost, risk and complexity. It always seems more than enough of a challenge to follow the current practice in industry in delivering the project. Few project managers and clients go looking for new challenges. But it is those who are prepared to embrace innovation, to apply the principle we are all so ready to endorse, that will make a difference by taking the extra time to design in microgeneration, to find ways of linking savings in running costs to initial capital outlay, and by addressing the planning and regulatory issues as they arise. These few project managers and professionals will set the future of best practice.

Peter Guthrie OBE FREng
Professor of Engineering for Sustainable Development
University of Cambridge

Preface

This is not a book for those still unconvinced of the need to reduce dependence on fossil fuels. It is assumed throughout that the long campaigns waged by others to make the construction industry aware of its responsibility to minimise the impact on modern civilisation of global warming and climate change has been won. This book is for those building designers aiming to reduce their project's dependence on fossil fuels and national energy grids. It is an overview, not a design manual. The focus is mainly on established technologies and those about to become generally available, although some promising technologies currently in the late stages of development will also be touched upon.

So many sources were consulted that it would be impractical to credit them all. Much of the background research was conducted on the Internet. Anyone who tries this will discover that a good search engine will find thousands upon thousands of hits for almost every aspect of microgeneration. A lot will be frustratingly undated, and follow-up research often reveals that the exciting project, piece of technology or prototype installation never came to fruition. Many documents will contradict each other, while definitive figures can be elusive. Using the Internet is much like panning for gold – an awful lot of dross has to be evaluated and discarded for every genuine nugget of up-to-date, relevant and useful information discovered. It is hoped that the reader will profit from the work that went into this book, and, while further detailed research on the Internet will almost certainly be seen as desirable, at least it will be easier to direct it down the most fruitful pathways.

Many observers of the construction industry claim to have observed a recent change in attitude to energy conservation and low carbon footprints. Clients, developers, architects and engineers alike are becoming aware that microgeneration is not some pious gesture; that, unlike carbon offsetting, it can make a real long-term difference to the world our children and grandchildren will inherit. Reliable, developed microgeneration options exist and make increasing practical and economic sense. And for those of a pioneering frame of mind, a number of new technologies that promise even higher efficiencies and even more freedom from dependence on fossil fuel are very close to realisation.

Microgeneration in itself, however, is not the answer to the problem of excessive and unsustainable fossil fuel consumption. It must be coupled with serious attention to the energy consumed in procurement and construction; even then, without some serious long-term changes in occupant expectations there will not be enough of a reduction in energy demand from buildings to make a rapid and permanent change to atmospheric carbon dioxide levels. However, one book can only do so much. This book aims only to answer most of the questions anyone committed to low carbon buildings will have when first considering the opportunities offered by microgeneration.

Reducing day-to-day consumption of fossil fuels for lighting, cooking, heating, cooling and domestic hot water is a key element in any serious attempt to design and construct a truly low carbon building. And low carbon buildings have to be part of our future – if we are to have a future. One day, someone will combine hydrogen from water with atmospheric carbon dioxide to produce a cheap, stable liquid hydrocarbon that can be handled and stored at ambient temperatures and pressures, using only solar energy to power the process. Until then, the incremental approach is the only realistic option.

Dave Parker

List of abbreviations

ATES	aquifer thermal energy store
BTES	borehole thermal energy storage
BIWT	building integrated wind turbines
BMWT	building mounted wind turbines
CdTe	cadmium telluride
CTES	cavern thermal energy storage
CFC	chlorofluorocarbon
COP	coefficient of performance
CHP	combined heat and power
CAES	compressed air energy storage
CIGS	copper indium gallium selenide
CIS	copper indium selenide
DAWT	diffuser augmented wind turbines
DHW	domestic hot water
ELC	Electronic load controllers
ERV	energy recovery ventilation
FDC	flow duration curve
GaAs	gallium arsenide
HRV	heat recovery ventilation
HC	heliostat concentrator
HAWT	horizontal axis wind turbine
HOPE	high density polyethyne
ICS	integrated collector/storage
IC	internal combustion
LED	light emitting diode
MCDB	moisture content dry basis
MCWB	moisture content wet basis
MCFC	molten carbonate fuel cells
ORC	organic Rankine Cycle

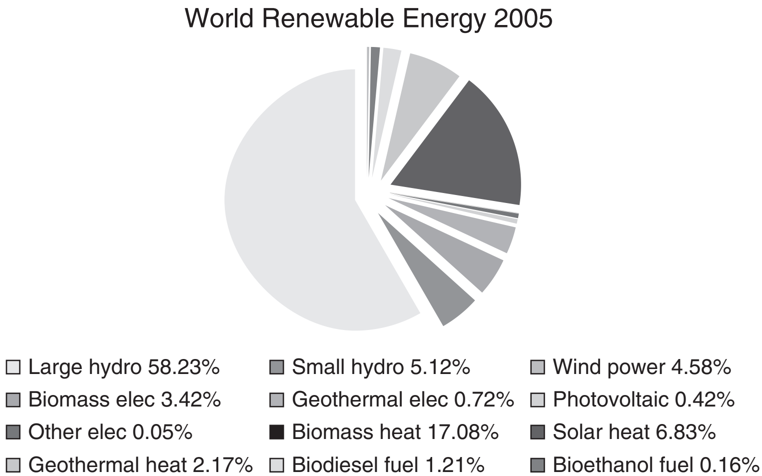
PCM	phase change materials
PDEC	passive downdraught evaporative cooling
PAFC	phosphoric acid fuel cell
PEC	photoelectrochemical cells
PV	photovoltaic
PEMFC	proton exchange membrane fuel cell
RFC	regenerative fuel cell
STTS	short-term thermal store
SOFC	solid oxide fuel cell
SSD	superheated steam dryers
TAP	thermosyphoning air panels
UTES	underground thermal energy storage
URFC	unitised regenerative fuel cell
VAV	variable air volume
VAWT	vertical axis wind turbines

1 Introduction

Modern buildings need heat and electrical energy to perform their design functions. Even today, with climate change widely acknowledged as the greatest threat to human civilisation in its entire history, buildings are being designed and constructed which are, and will continue to be, totally dependent on national energy grids. These grids are still, and for a long time will continue to be, almost totally dependent on fossil fuels. Thanks to political inertia, vested interests and endemic nimbyism, it will almost certainly be several decades before large-scale wind, wave or tidal power make a majority contribution to the energy distributed through national grids.

Nuclear power – if it is to maintain or increase its current contribution – is also a long-term option, assuming uranium supplies continue to be available and the storage of radioactive waste is tolerated. Virtually all the potential sites for large-scale hydropower have already been exploited. In the meantime, therefore, Western industrialised nations are increasingly dependent on fossil fuel supplies from countries with different political agendas, conveyed through pipelines and along shipping routes difficult to protect against terrorist attack. 'Peak oil', the point at which global oil production will begin to decline as reserves dwindle, may be just around the corner – if it has not already arrived – and dwindling supplies and rocketing demand from India and China inevitably mean soaring prices for oil-based products and the energy generated from them.

For the moment and for the immediate and medium term future, energy consumption will equate fairly accurately with carbon dioxide emissions and the greenhouse effect that at the very least is exacerbating global warming and climate change. Buildings of all sizes and types account for about one-third of the energy consumption of modern industrial nations – and up to 60% of the electricity. Of a building's total carbon footprint, up to 50% of the energy consumed during its lifetime is accounted for by the materials used in its construction – this fraction will be inversely proportional to the efficiency of the building's insulation, dropping to around 25% for a poorly insulated structure. Motivation for serious attention to minimising a building's carbon footprint can be a sincere desire to mitigate the effects of climate change – or to insulate the building as far as is practicable from the uncertainties of energy supply from national grids. Achieving total independence from national energy grids is possible – at a price. (Some projects may not have access to such grids in the first place.) Achieving total independence from fossil fuels is also possible but harder, as most buildings not connected to grids depend on fossil-fuelled standby generators. (Such standby generators should also be classified as microgeneration installations.) Significant reductions in dependence on fossil fuels are now very possible, by combining a number of complementary strategies, of which the most visible, if not always the most effective, is microgeneration.



Hydropower is still the biggest source of renewable energy

Generating heat and power at or close to the point of use is theoretically a more efficient use of available resources than centralised generation and the distribution of energy over long distances. Actually achieving efficiency on the micro scale is far from straightforward. A lot depends on the size and effectiveness of the energy store, without which solar and wind power in particular can never be cost effective (see Chapter 15). Retrofitted domestic scale solar water heating systems, for example, normally have only the existing hot water cylinder available as a thermal store, and consequently can never provide anything like all the domestic hot water needed throughout the year. New build homes could include larger thermal stores at ground level or in basements. However, as one moves higher up the building scale, into schools, hospitals, office blocks and the like, the numbers become more attractive. The effectiveness of thermal stores, wind turbines and biomass gasification plants, for example, increases rapidly with size. Several mature microgeneration technologies already exist, with hardware generally available, and others are moving on from the pilot plant stage. Designers now have real choice, and are able to select the technology – or combination of technologies – that will provide the most practical solution for any particular project. But before going down that route, there are two other strategies that must be deployed.

Achieving a low carbon sustainable building involves more than strapping a small wind turbine to the roof of an otherwise conventional building. This is tokenism, or '**greenwashing**'. True sustainability starts with serious consideration of the materials used in the construction of the building. Some materials have much greater embedded energy than others, either because of their method of manufacture or the distance they are transported to site, or the energy needed to handle and place them. Wood, for example, usually looks superior to concrete in this respect, although determining the exact ratio is more complex than it first might appear. Recycled materials are becoming more available and more predictable in performance, and new developments, such as low energy cements and biopolymers, are offering new options. And a material such as concrete may turn out to be desirable in the longer term because of its greater thermal mass. The whole subject is complex and is not covered here, but it should be high on the agenda for any building project aspiring to a low carbon footprint.

Improved insulation is the first step (Courtesy of Passivhaus Institut)

Reducing the post-construction consumption of energy from fossil fuels starts with reducing the building's overall energy demand. Really significant reductions can be achieved by high levels of insulation, by the control of airflows in and out of the building, and by the management of solar gain. Low energy lighting coupled with **light pipes** to conduct natural light into dark corners, the choice of energy efficient appliances and equipment, and the installation of a sophisticated building management system, can help achieve energy demand reductions of 40% or more over conventional designs. A truly green building will also minimise its use of potable mains water, with both grey water and rainwater recycling systems.

Over recent years a number of design philosophies have emerged which all offer ways of attaining a low carbon footprint. One can be summarised as the 'light and tight' solution: developed extensively in Scandinavia, this features largely timber construction with high levels of insulation, high-performance windows, obsessive attention to sealing any potential air leakage through the building envelope and closely controlled ventilation with heat recovery from the outgoing air. In the opposite corner is the 'mass and glass' approach, which is based on a structure with high thermal mass and the intelligent use of solar gain through large windows.

Microgeneration is no longer just for remote sites, like here in the Falklands (Courtesy of Proven Energy)

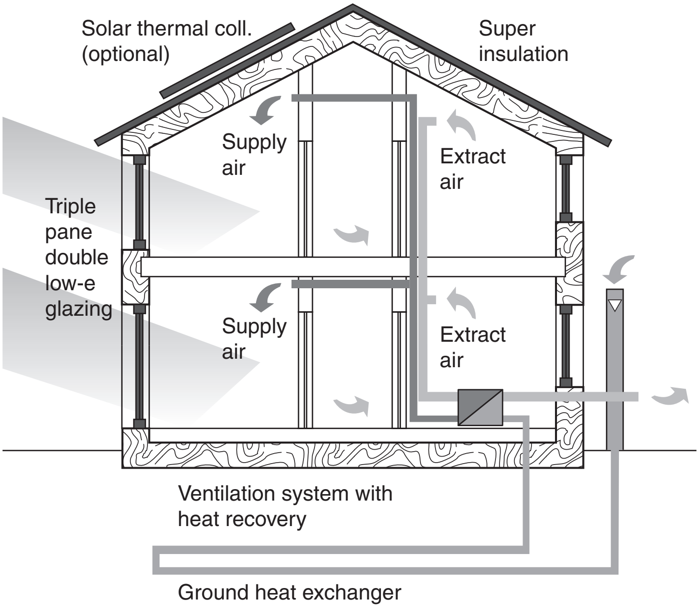
Overlying both these philosophies is the difference between the low and high technology solution. Low technology design features local materials and traditional techniques, such as adobe, green oak, windcatchers, biomass boilers, recycled insulation, solar water and air heating – and a high degree of human intervention in the building's day-to-day operation. A high technology solution may achieve much the same ends by the use of phase change materials as a thermal store, a biomass gasification plant feeding a trigeneration installation (see Chapters 11 and 15), a solar photovoltaic (PV) roofing membrane (see Chapter 4) or a unitised regenerative fuel cell. Or it could be said that the low technology approach is based on tried and tested principles backed up by well proven technology, while the alternative means taking something of a gamble on recently developed technologies which promise much higher performance at greater initial cost.

In moderate to high latitudes, climate change means that summertime cooling in the non-residential sector is becoming as important and beginning to consume as much energy as wintertime heating. Passive, low technology space cooling techniques have been around for millennia, but are not that easy to adapt to current building design preferences. Active cooling, on the other hand, need not necessarily mean conventional vapour compression air conditioning (see Chapters 13 and 15). Part of the problem, however, is the current attitude of building occupants. Over the last 50 years, habits and expectations have changed radically in the developed world. People expect to be comfortable in relatively skimpy clothing whatever the ambient conditions outside may be. This may well be changing, but in the short- to medium-term developers and designers have to look for ways to meet these expectations that allow the carbon footprint to be significantly reduced.

That is not to say that occupant expectations will continue to rise. Public awareness of the risks of global warming is close to the point where politicians and designers alike will have to take note. Gas-guzzling 4 × 4 'Chelsea tractors' and strawberries from the other side of the world are becoming harder to justify. Doubts are being cast ever more loudly on the latest generation of energy-hungry consumer electronics, while low energy lighting and recycled paper are becoming the routine choice. There is a significant and increasing interest in alternative and renewable energy supplies, on the domestic scale at least.

Intelligent use of light pipes can slash lighting costs (Courtesy of Monodraught)

A market for truly low carbon buildings is growing amongst those who will accept some compromises on lifestyle. Commercial developers still doubt the willingness of potential tenants to pay for what is still perceived as a 'green premium' for a low carbon building, but local authorities and organisations with a green agenda are already demonstrating their appetite for the low carbon option.



Light and tight – the Passivehaus approach (Courtesy of Passivhaus Institut)

This is despite the fact that some of the pioneering low carbon buildings have failed to live up to their developers' and designers' expectations. Natural ventilation, for example, can struggle to cope with cooking smells. Maintenance costs have often turned out to be much higher than expected, new technologies such as biomass gasification can run into unforeseen operational problems – and some technologies, such as small-scale wind, have simply failed to produce the energy predicted by their manufacturers. It has often been said that the most cost-effective low carbon technology for buildings is occupant behaviour modification. The argument goes that occupants should be persuaded to routinely switch off computers, printers, phone chargers and lighting when not in use. Also, by turning heating thermostats down a couple of degrees and turning cooling thermostats up a couple, there will be no need for wind turbines or PV arrays. The response, of course, is that behaviour modification is just one string to the bow – improved building design, the use of sustainable materials and microgeneration are the others.

Some clients/end users will prefer to use just one of these approaches. Others will be willing to go the whole way and do everything technically possible to achieve the lowest carbon footprint. For example, some clients will deliberately omit car parking from their projects, even when space permits, although this is more common on headquarters projects than on commercial office developments. The preferred route for most committed clients is a combination of sustainable materials, good design, and serious consideration of the microgeneration options.

Attempts to quantify the economic benefits of microgeneration by calculating payback times are often misleading, and this book will avoid the temptation. A lot of important assumptions have to be made: how prices for natural gas and electricity will change over the medium- to long-term; what support will be offered by national and local governments; how much actual energy will be available from the microgeneration technologies selected. Calculating the building's actual energy needs over a whole year on a daily basis is a major exercise, made even more unpredictable by the, as yet, unquantified effects of climate change over the next few decades. But without a reasonably accurate picture of the peaks and troughs of energy demand, it will be hard to make a sensible decision on the most appropriate microgeneration technology or combination of technologies for the project. Luckily, advanced software that can model energy flows in three dimensions, enabling a much better picture of energy needs to be obtained, is now available. Input from the developers and suppliers of particular forms of microgeneration technology should be treated with caution: there have been some spectacular examples of over-optimism, commercial naivety and scientific illiteracy in recent years.

Technologies which generate electricity – wind, hydropower, solar PV, cogeneration (combined heat and power) – will often have an output profile that is far from an exact match to the building's actual demand for electricity. There will inevitably be times, even with hydropower, the most predictable option, when there is either a surplus or deficit of power available. Storing surplus electrical energy in batteries or similar is rarely as attractive in principle as 'storing' it on a national electricity grid. In an ideal world, surplus electrical energy would be sold to the local electricity supplier when it was produced, while electrical energy would be purchased from the supplier when the on-site generation facility was unable to meet the building's demands. **Net metering** is the generic term used for this type of arrangement; the actual rates for sale or purchase are rarely the same, and can vary without warning as official policy changes. Sometimes only one meter is involved, which runs 'backwards' when energy is exported to the grid; sometimes two, one for incoming energy, one for outgoing.

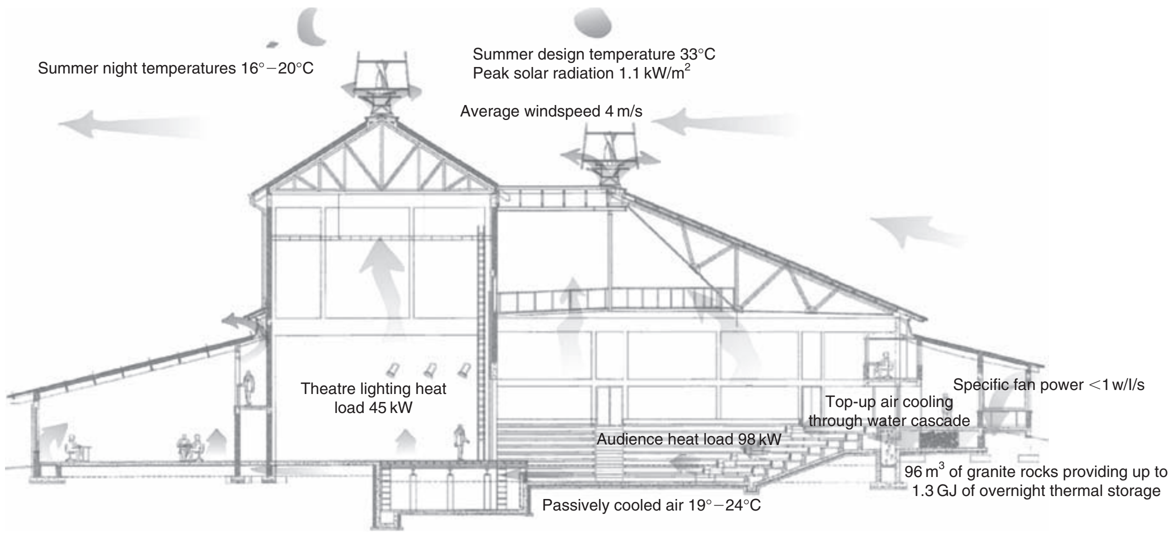
Modern inverters and control systems ensure that any supplies offered to the grid precisely match its requirements in terms of voltage and frequency. However, the attitudes of utility suppliers and national governments to disseminated generation are both unpredictable and variable. In some countries, such as Germany, building owners are offered significant financial incentives to install particular types of microgeneration technology, principally solar PV. In others, official attitudes can be far from encouraging. Worse, these attitudes can change dramatically with time and events, so calculating the long-term economic benefits of grid connection is far from straightforward.

A commitment to a green agenda can produce very effective results (Courtesy of Solarcentury.com)

The practical benefits are obvious. No technology, not even hydropower, is as reliable as national grids (at least for the moment). Back-up generators running on fossil fuels are much more rugged and reliable than they used to be, but capital costs are high, regular maintenance is essential and the installations are even more vulnerable to the vagaries of fossil fuel prices and availability than national grids – even though they will deliver much more of the fuel's chemical energy in the form of electrical power than a national grid ever can. But without a reliable back-up/top-up supply most microgeneration technologies will not be a practical option for most buildings. This is despite the fact that some 'passive' technologies using solar power for space heating and cooling can, in theory, operate without any external energy input; and others, based on biomass, for example, can be self-sufficient. It would be a brave developer who deliberately spurned the opportunity of connection to the local electricity grid.

Advancedsolar photovoltaics still need a grid connection to be effective (Courtesy of Centre for Advanced Technology)

In theory at least, a grid-connected building designed to minimise energy demands by the means outlined above, and equipped with large enough and efficient enough energy stores, could obtain its entire energy needs from microgeneration technologies, using the grid only as an emergency back-up or during maintenance periods. A tall building standing well above surrounding structures and other obstructions could, in theory again, actually become a net exporter of energy. High-level wind turbines operating in clear air are much more efficient and predictable than their small low-level cousins struggling to extract energy from a slower and more turbulent airflow. Cladding on tall buildings can become 'active', incorporating vast areas of PV panels as well as solar air and water heating collectors. A biomass fuelled cogeneration plant could also produce enough heat to supply adjoining buildings. And large, tall buildings also have the increased potential to minimise energy demands. Deep basements can accommodate large thermal stores, high atria promote natural ventilation. Going through the normally complex procedures to obtain permission to extract water from underlying aquifers for cooling purposes is more worthwhile on a large project, as are negotiations with the local electricity supplier. But in practice anything close to the overall balance between energy supply and demand is very



Even in Africa, low energy cooling techniques can be very effective (Courtesy of Arup – Mike Rainbow) hard to achieve, so one of the first decisions to be made on every project is the target percentage of total energy demand that will be assigned to microgeneration technologies.

There is no morally or ethically justifiable minimum percentage, although single figure percentages will smack of greenwashing. One sensible option is to calculate how much energy would be needed to keep the building functioning at the minimum acceptable level if local or national energy grids are out of action, and to provide enough microgeneration capacity to match this. Each project's pattern of energy demand will be unique, and finding the right microgeneration solution will be a complex one-off exercise, one that may throw up some surprising results. But the exercise is usually worthwhile and should become a standard part of the project development process. Be it as a result of government initiatives or for ethical, practical or economic reasons, microgeneration is now firmly on the agenda.

Using a concentration mirror to focus sunlight onto a Stirling engine is still at the experimental stage (credit Schlaich Bergermann and Partner)

2 Passive solar water heating

Ample supplies of hot, clean water 'on tap' are a basic signifier of an advanced society. Ever since ancient times the heating and distribution of **domestic hot water** (**DHW**) has been central to a civilised lifestyle – even if only the rich could enjoy the convenience and comfort that DHW can provide. Over the last century or so, fossil-fuelled DHW systems have become the norm, and the last 50 years in particular has seen DHW usage rocket. Daily power showers have replaced the weekly bath in water heated by coal or crude town gas 'geysers'. Hot tubs are spreading. Washing machines are bigger. At least 30% of the energy demand for a typical modern home is accounted for by DHW needs – this will be much higher in well-insulated homes located where prolonged cold spells are rare. At the same time, the emergence of leisure centres and the like are boosting the need for DHW outside the home. Even offices now have to provide showers for the increasing proportion of their staff who chose to cycle or run to work every morning. Fortunately, replacing some or all of the fossil fuel-derived energy currently utilised for DHW is relatively straightforward. Several well-developed technologies exist, of which the most convenient is usually the most obvious.

It may be more than 150,000,000 km away, but the thermonuclear furnace that is our sun radiates enough raw energy across space to satisfy the needs of human civilisation many times over. Some is absorbed by the atmosphere, but even so, more than a kilowatt can arrive on every square metre of the Earth at the equator. Vast quantities of solar energy reach the Earth's surface even at high latitudes, well north or south of the equator – but there are inherent drawbacks.

Solar power delivery to any given point on the Earth's surface is highly variable. Simple calculations can allow for latitude and the diurnal and seasonal variations in solar delivery – solar energy varies from dawn to noon to dusk, there is obviously much less energy available at high latitudes during winter months – but these give no more than average figures. Unpredictable variations in cloud cover can have major impacts on available energy. Even on a clear day, no more than 75% of the energy reaching the Earth's surface will be direct solar radiation. The balance will be diffuse radiation that has been scattered by the atmosphere, and on days with unbroken cloud cover this proportion will rise to 100%. On a day of broken cloud, available energy levels can vary from minute to minute. As a result, only systems with some form of energy store to smooth out the peaks and troughs of energy capture are practical and economic.

Technologically, the simplest way of utilising the sun's energy is to absorb it into air, taking advantage of the well-known 'greenhouse effect' and using glass to trap infrared radiation from a surface heated by sunlight. Heat is transferred to air between the surface and the glass; the hot air is drawn off for use inside a building. Solar hot air space heating systems have been used for many years (see Chapter 3) and in some installations heat is extracted from the solar-heated air via a heat exchanger to provide DHW. Solar air systems are often the most practical solution in locations where there are very big differences in day and night temperatures – such as deserts – as the solar collectors are immune to the risks of both freezing or 100°C+ temperatures that dog water-based systems. In practice, however, solar hot air water heating systems usually depend on fans and/or pumps, so belong properly in Chapter 9.

The Sunwarm system uses solar heated air for space heating and DHW (Reproduced with permission from Nuaire)

In more temperate climates a water-based solar water heating system is usually the best compromise. Water is a very effective absorber of solar heat. Sometimes this is done directly, sometimes by first heating fluid in a primary circuit that then passes through a heat exchanger. Heated water can then be stored in a well-insulated tank, or in a larger-scale thermal store of some sort (see Chapter 15), and drawn off as needed for a wide range of end uses.

Small-scale solar water heating systems aimed at the domestic market have been available for decades. The technology, originally based on standard plumbing components, has become substantially more sophisticated over recent years. But small-scale solar water heating on its own is far from being the ideal solution for the typical family home, largely because a large thermal store is usually impractical (see Chapter 15). Peak demand for washing and heating occurs on winter mornings, when the water in even the best insulated storage tank is likely to be below optimum temperature. And after a sequence of cloudy days a severe shortfall is inevitable.

Homeowners, therefore, are generally advised that they can expect no more than 50 to 70% of their DHW, i.e. non-space heating needs to be supplied by individual installations, and that they should fit a more reliable standby water heater. This could, of course, use zero or low carbon energy from sources such as mini hydro, or ground source energy (see Chapters 6 and 12), but most individual installations use standby heaters connected to an energy grid.

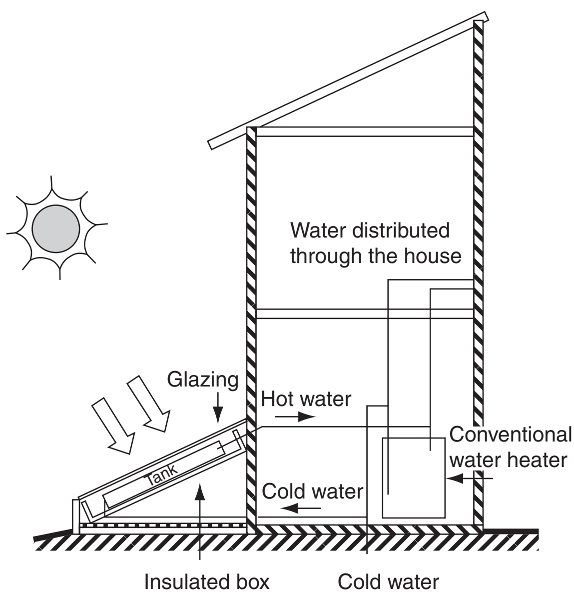
Larger-scale housing developments are more likely to have effective communal thermal stores (see Chapters 15 and 18) and alternative zero or low carbon supplementary energy supplies. Against that must be set the energy losses inherent in a large-scale hot water distribution system, however well insulated. In practice, therefore, it would seem that the most effective applications for solar water heating would be where the demand for hot water more closely matches the availability of solar energy.

Swimming pools are the first obvious case. Public pools need the water in the pool to be maintained at a certain minimum daytime temperature, and there will be a high associated demand for hot water in the showers. Much the same applies to private pools, but they will normally cool down faster and heat up quicker than an Olympic-sized facility, which tends to act as a massive heat sink. Sports and leisure centres, with or without pools, have high daytime DHW needs.

Solar water heating can work very well with swimming pools (Reproduced with permission from Energie Solaire)

Many other public buildings have a demand profile that is more in keeping with supply. Schools and offices need space heating and hot water mainly during the day; care homes and hospitals have high daytime hot water needs but require high levels of space heating both day and night. For larger installations like these there are benefits of scale, which can yield significantly greater efficiencies, but there will also be a need to consider aesthetics, acoustics and safe access for maintenance.

One of the oldest technologies for extracting energy from sunlight and using it to heat DHW is the **integrated collector/storage** (**ICS**) **solar water heating,** or **batch** system. In its simplest form, an ICS system consists of a black painted tank exposed to sunlight and with one face angled upwards. Usually the tank sits within an insulated box with a glazed sunward face. Mains water flows into and out of the tank as hot water is drawn off from the system, and there is usually an internal storage tank with a conventional water heater as back-up. Traditional ICS tanks are heavier than other types of passive solar collectors and are often located at ground level.



Ground mounted batch system

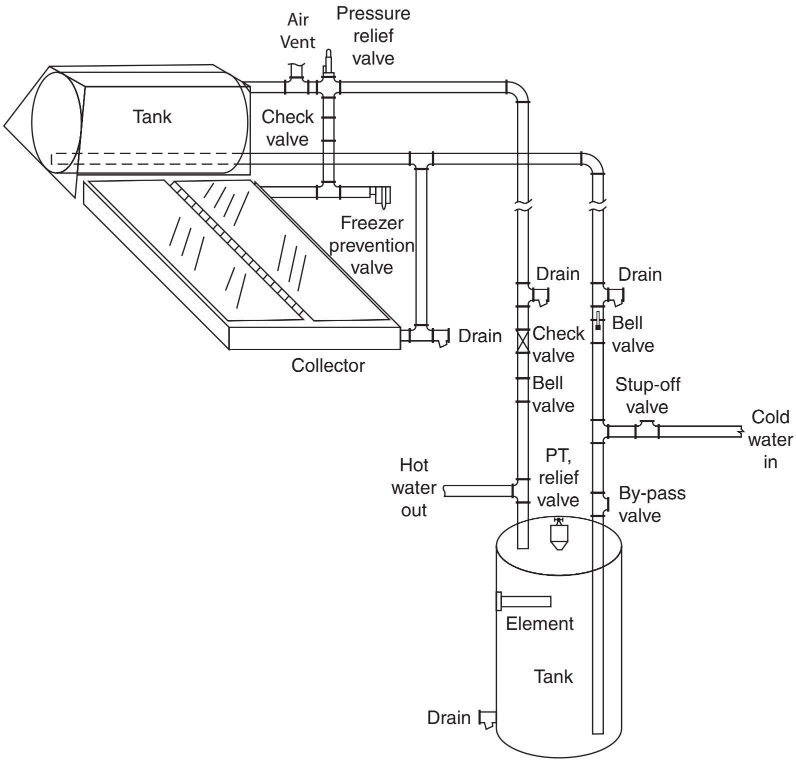
In practice, batch systems are largely confined to mild climates at lower latitudes, due to the risk of freezing during long spells of cold weather. In suitable areas, however, the most practical option for smaller-scale installations would be a modern ICS system, where a storage tank is mounted directly above a more efficient passive solar collector. Several manufacturers supply well-developed systems, but storage capacity is usually limited, making them more suitable for daytime DHW supplies in offices, etc.

Thermosyphon solar water heating is the next simplest option in technological terms. It uses the differential between the densities of hot and cold fluids to circulate a heat absorbing fluid through some form of solar collector. As the fluid is heated in the collector it expands, its density is reduced and it is displaced by denser, cooler fluid entering the collector below it. The heated fluid rises into a thermal store, which may contain a heat exchanger and which must be positioned above the solar collector. Circulation will occur automatically as long as solar energy is available without the need for any form of pump, control system or powered valves, or for any secondary energy supply. If a collector with integral header tank is used, this can be positioned at roof level and used to feed a thermal store in a more convenient location.

Integrated solar collector and header tank (Reproduced with permission from Powertech Solar)

Direct thermosyphon systems use potable water as the heat absorbing fluid, and hence no heat exchanger is required. This eliminates the potential loss in thermal efficiency associated with all heat exchangers. Water will circulate and heat will be absorbed as long as the sun continues to shine, although the amount of heat absorbed will reduce as the mean temperature of the water increases. Hot water drawn off for use is replaced by cold, usually from the mains. Deliberate **stratification** – where the hot water from the collectors is delivered into the top of the storage tank and 'floats' on the top of the cooler water below without mixing – can maximise the availability of domestic hot water early in the morning.

Such simplicity has its drawbacks, not least the risk of the water in the collectors and connecting pipework freezing in prolonged sub-zero temperatures (see below). Potential problems also exist during periods of prolonged sunny warm weather, when the demand for heated water is usually low. In such conditions the temperature of water in smaller scale thermal stores and storage tanks can soon rise to undesirable levels – above 60°C for domestic supplies. The risk of **scalding** is obvious – hot water at 70°C takes less than half a second to cause third degree burns – but, if the temperature begins to approach 100°C, there may be serious problems with high pressures within the system. Safety valves are not always 100% reliable. A number of methods have been adopted to deal with the problem, which inevitably adds to the complexity and maintenance requirements of the installation.



Thermosyphon system using integrated collector and header tank

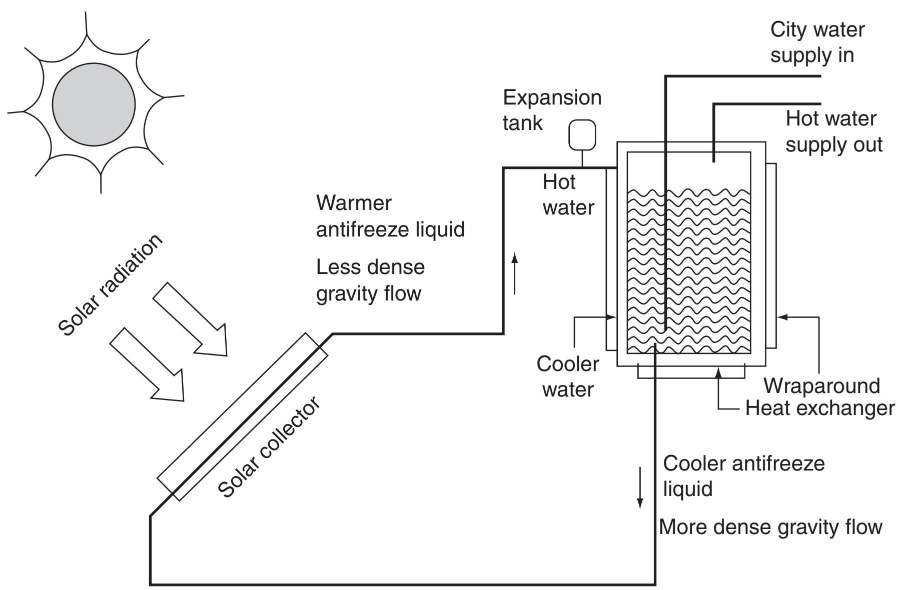
The simplest is to design a system with variable thickness insulation to the storage tank. As hot water from the collectors is added to the tank, the temperature increases from the top down, where the insulation is thickest and heat losses are lowest. As water lower down the tank begins to reach temperatures close to a safety level – usually around 75°C – heat losses through the thinner insulation begin to balance the heat gain from the collectors. Eventually, if the system is well-designed, all the water in the system will stabilise at what is known as the **stagnation temperature**, although some circulation through the collectors will continue. Where flat plate solar collectors are used (see below), their heat collection efficiency almost disappears as the temperature of the water flowing through approaches 100°C, so the additional energy input is easily balanced by increased heat loss in the system.

More efficient evacuated tube collectors (see below) still absorb heat at temperatures close to 100°C, so additional precautions would be needed. These can take the form of '**heat dissipation pipes**', which are basically sealed devices fitted about halfway down a storage tank. They transfer surplus heat to an external radiator – or '**heat dissipators**' – simple water to air heat exchangers on a bypass loop through which the return flow from the solar collector is diverted when the preset temperature limit is exceeded. These should be mounted outside, preferably on the northern side of the building. On larger-scale installations, the solar collectors can have adjustable shading actuated by the same type of temperature-sensitive self-powered units used to control horticultural glasshouse ventilation.

Schools, hospitals, nursing homes and leisure centres have been using thermostatic blender valves to protect hot water users for many years, especially children and the elderly. These limit the temperature of water leaving hot taps in wash hand basins and baths to around 48°C by mixing in cold water as the heated water leaves the storage tank (although 38°C is the recommended maximum temperature for bathing children and the elderly). Blender valves may well become mandatory in the future, even for private homes, but will add complication, restrict flow and increase maintenance.

A further complication is that in hard water areas softened mains water will usually be needed, although on many projects water softening will be desirable for other reasons. Overall, however, the lower cost of installation and minimal maintenance requirements can make direct thermosyphon solar heating systems an attractive option for both domestic scale and larger developments. The most effective installations can be where the solar collectors can be positioned a short distance away from, and below the level of, the main building, feeding into a thermal store at ground or basement level.

Indirect thermosyphon systems capture solar energy in a closed loop primary heating circuit filled with a heat absorbing fluid. The oldest and simplest systems use water with high concentrations of automotive antifreeze, although standard refrigerant fluid is



Basic thermosyphon system with wraparound heat exchanger sometimes used. This heated fluid then passes through a heat exchanger, which could be a simple coil within the main thermal store or a more elaborate and more efficient 'wrap-around' design in which the thermal store is double skinned and the heated fluid flows between the outer and inner skins. Softened mains water is not essential, but the potential for deliberate stratification within the heated water is limited, reducing the availability of hot water in the mornings. Saturation temperatures and pressures within the primary loop can be higher than with direct thermosyphon systems, and similar precautions have to be taken to control storage tank temperatures and scalding risks. Maintenance requirements are higher than with direct systems if antifreeze is used in the primary loop.

A more modern way of **coping with freezing temperatures** is to use burst proof polymer for all external pipework, including that within the solar collectors themselves, or to insulate the pipe network effectively (see Chapter 9). Direct thermosyphon systems using this technology appear to offer a practical and realistic zero carbon alternative for smaller-scale installations, provided precautions are taken against legionella disease (see below).

Passive solar collectors are fixed in position and have no moving parts. Properly aligned and located (see below), passive solar collectors can capture more than 80% of the solar energy falling on them. Two types are readily available.

1. **Flat plate collectors** are generally the simplest, cheapest and most rugged, consisting of little more than shallow weatherproof insulated boxes with transparent lids and internal dark absorber plates backed by sealed piping through which the heat transfer fluid flows. Many variations on this theme are available: the glazing can be one or two layers of high performance glass or polycarbonate, absorbers and piping can be metal or

Flat plate solar collectors are now well developed (Reproduced courtesy of Solarnor) plastic, coated with a range of special 'selective' materials that reduce the radiation of infrared from the collector at night. Some designs are particularly sophisticated, with serious attention paid to aesthetics.

2. **Evacuated tube collectors** usually circulate the heat transfer fluid through copper-filled U tubes or heat pipes in direct contact with aluminium heat transfer fins all located inside the glass tubes from which air has been evacuated between the two glass tubes to minimise heat loss, although more complex and theoretically more efficient variants are available. This type of collector offers higher potential efficiency (up to 25% greater), due to its lower heat loss to the atmosphere and its ability to operate at lower solar energy levels and to produce water at higher temperatures. Against this, evacuated tube collectors are up to three times more expensive than flat plate collectors, due to their more complex technology. There have also been reports of problems with some evacuated tube collectors, with both explosions and implosions occurring, and at least one range of all glass evacuated tube collectors is said to have been taken off the market as a result.

Evacuated tube solar collectors are more complex (Reproduced with permission from Powertech Solar)

...but give higher performance. This example is from Viesmann (Reproduced with permission from Solarcentury.com)

The higher water temperatures possible, however, make evacuated tube collectors the obvious choice if solar water space heating is contemplated (see Chapters 3 and 10). Again, most modern versions are designed with aesthetics in mind, and 'vandal-proof' designs are also available, as are units glazed with ultrasmooth 'self-cleansing' glass. Soaring copper prices could well see solar collectors switch to alternative materials such as stainless steel, aluminium and polymers in the near future.

Actual performance in terms of solar energy collected over the course of a year depends on many factors, most of them site-specific. Latitude, orientation and any shading from nearby buildings, trees or geographical features can influence performance more than collector type. Shading is particularly undesirable between 9 am and 3 pm solar time, when nearly 85% of the daily solar energy is available. Ideally, passive collectors will be aligned with true south, although a deviation of up to 30° east or west would have no significant effect. Angle of inclination – the angle the collectors are tilted up from the horizontal – is always a compromise (see Chapter 9). Other factors being equal, however, and allowing for heat losses within the system before useful hot water is produced, a conventional flat plate collector on average will collect about 400 kWh/m^2 annually at moderate latitudes, a typical evacuated tube collector around 500 kWh/m^2 or more. How much of this energy is available in practice is also a function of thermal store size (see Chapter 15).

Most solar collector suppliers have standardised on an approximately 1.2 m by 2.4 m unit, and larger installations are made up of numbers of these panels plumbed together. Some manufacturers will produce significantly larger individual units if requested. A standard panel, in operation with its tubes filled, weighs in at around 30–50 kg.

Legionnaire's disease, or **legionellosis,** is an unpleasant bacterial infection that kills up to 15% of those unfortunate enough to catch it, usually the old and those who smoke. Infection follows the inhalation of fine water mists or aerosols infected with the **Legionella** bacillus, a particularly tough and persistent organism that can flourish in warm water environments. Luckily, 95% of those infected by legionella develop only the much less serious **Pontiac Fever**, which is usually mistaken for influenza. Legionella flourishes in water at temperatures between 30°C and 45°C, but can survive for years at temperatures not far above freezing and even up to 70°C. All forms of warm water facilities from domestic hot water systems to air-conditioning chillers have been associated with outbreaks of the disease. Only installations where there is no production of aerosols and the water temperature remains permanently below 25°C or above 60°C can be said to be low risk.

Most developed countries have strict regulations on what precautions must be taken to minimise the risk of legionellosis. A common practice is to ensure that water temperatures in all parts of the mains water system reach 60°C at frequent intervals to kill off the bacilli. This is particularly important in systems that use deliberate stratification within the thermal store to maximise higher temperature water availability. The water in the lower part of the tank may never reach temperatures at which the bacilli are killed for weeks at a time unless precautionary measures are taken. These can include regular mixing of the tank's contents using 'destratification' pumps – if the water entering the tank is frequently well above 60°C – or, more commonly, using a low mounted back-up heater to raise the whole thermal store temperature to a level at which the bacillus will be killed on a regular basis – **pasteurisation**. If this heating and/or mixing are powered by a renewable source, such as wind or mini hydro, only a simple control system will be needed. On larger installations the use of ultraviolet sterilisation could be justified, perhaps in conjunction with ultrasound to help remove any biofilms within the pipe network. Regular flushing and sterilisation with chemicals are other options. Precautions should be taken in all cases to minimise the production of the dangerous aerosols.

Passive systems are always worthy of consideration for every project, and passive solar water heating can be a realistic option on many projects, especially when site topology is favourable. Where one of the objectives is to minimise the use of high technology systems – and hence maintenance needs – or where the preference is for equipment with low embedded energy, passive solar water heating can be a worthwhile component in the final microgeneration mix. Its sensitivity to the relative locations of the collectors and the thermal store can make it difficult to combine with some other technologies and may impose architectural compromises, but its simplicity and reliability are very attractive.

This page intentionally left blank

3 Passive solar space heating

As global warming becomes more obvious, the need for space heating in most developed countries will decrease, even as the need for space cooling increases (see Chapter 8). Nevertheless, for many years to come the energy required to keep buildings comfortable for their occupants during the depths of winter will still be a sizeable fraction of the world's energy needs. In Europe currently this fraction is estimated at more than 12%. Even with enhanced standards for insulation and increasingly sophisticated management of passive solar gain, new buildings will still need space heating. Demographic changes are also coming into play. Housing occupancy rates are dropping: there are more and more single-person dwellings, which take a proportionally greater energy share to heat due to the reduced contribution of personal body heat. Low and zero carbon energy sources will have to be utilised, of which the most obvious is the sun.

In theory, hot water from a passive solar water heating system can be used for space heating as well. This would normally be an indirect system (see Chapter 2) with a primary loop transferring solar energy via a heat transfer fluid from the solar collectors to a heat exchanger inside a thermal store containing the space heating water. A true passive solar water space heating system would use pump-free thermosyphonic action to circulate the heated water through a series of wall-mounted radiators or underfloor heating pipes. Underfloor heating (see Chapter 12) is often recommended for all types of solar water space heating as it operates efficiently at lower temperatures than conventional radiators, typically 30–45°C versus 60–90°C.

The problem in practice is that there is a significant risk of air bubbles forming in the underfloor heating pipes and blocking circulation, although the inclusion of a small electric '**purge pump**' – that cuts in when the flow stagnates and circulates the water fast enough to flush out any bubbles – can reduce this risk to acceptable levels. On most buildings there would be an additional need for DHW, so the collectors would have to be proportionally larger, as would the thermal store if high stagnation temperatures are to be avoided. Back-up heaters would not just be larger, but would be likely to be needed more often. In practice, therefore, the most effective way of using a passive solar water heating system to reduce space heating energy demand might be to use it to preheat the feed

Underfloor heating is now well developed and reliable (Reproduced with permission from Nu-Heat UK)

water into some form of low carbon water heater, such as a biomass boiler (see Chapter 7). This could provide both DHW and space heating even on the coldest, most overcast days. An intermediary thermal store would also be needed.

Passive space heating systems using **solar heated air** also have the virtues of simplicity, reliability and low capital cost. Managing solar gain to minimise the energy needed for space heating and cooling is an important part of any building's basic design concept. Tools and techniques include appropriate orientation, the use of shading and high performance glazing, and the utilisation of the building's thermal mass (see Chapter 1). Further contributions to internal comfort during cold weather can be made by utilising dedicated solar collectors to heat internal air. These normally yield temperatures well below 60°C, which can feel subjectively cool to building occupants, so large flows of low velocity air through a number of inlets are to be preferred. This is easily achieved with passive solar air heating systems.

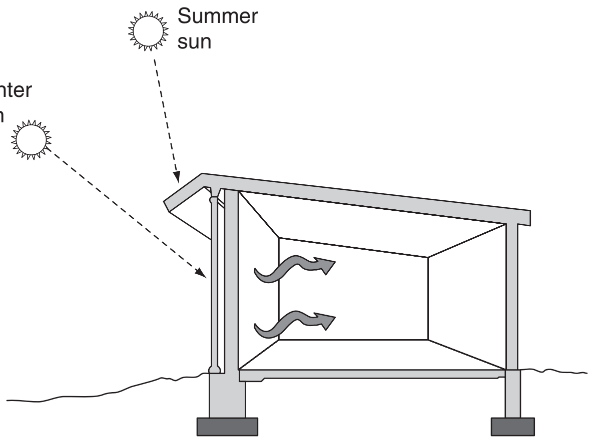
For new build, one of the simplest options is the **thermal wall**. This is a south-facing double- or triple-glazed window that allows sunlight to fall on a massive wall, constructed of masonry, insitu concrete or some form of water container – this latter is often termed a **water wall**. The south facing side of the wall is usually painted black, although a low emissivity, high absorbency material such as metal foil can boost performance significantly. Heat absorbed by the wall during the day continues to be released during the evening and overnight; in fact, the wall becomes a giant storage radiator. Experience suggests that solar heat will take around 8–10 hours to reach the interior of the building through a 200 mm thick concrete or block wall.

Some form of shading, either in the form of an overhang above the wall, fixed louvres on the window or internal blinds, restricts solar gain when the sun is high in summer and maximises it in the colder months. Overhangs and fixed louvres may not restrict solar gain enough during summer mornings and evenings, so blinds or shutters will be the obvious alternative if increased cooling load is to be minimised. Orientation is quite critical. Unlike solar collectors and PV modules, which are relatively intolerant of quite major deviations from true south (see Chapter 9), windows forming part of a passive solar air heating system should be no more than 15° east or west away from true south.

This Welsh house features both passive solar water heating and a Trombe wall (Reproduced with permission from Martin J. Pasqualetti)

The **Trombe wall**, named after its French developer, adds the refinement of air vents at top and bottom of the thermal wall. This allows air to circulate by natural convection from the floor level of the interior space through the space between the wall and the window, where temperatures are higher, and up and out at the top of the wall, where it may be ducted up to floors above. The same principle can be applied to the **water wall**, made up normally of black painted metal or plastic tanks, which usually warm up quicker thanks to internal convection currents and can store up to five times more heat per unit mass than conventional walls. In some applications, architectural considerations might dictate the choice of a translucent water wall, made up of glass fibre reinforced plastic tanks, which would sacrifice some potential efficiency in return for the extra natural daylight penetrating the interior space.

Both thermal and Trombe walls – and the Barra System below – have the problem that a large conventional thermal mass is heavy and so has obvious structural implications. 'Virtual thermal mass', however, can be added to an otherwise conventional building by the judicious use of **phase change materials** (see Chapter 15).



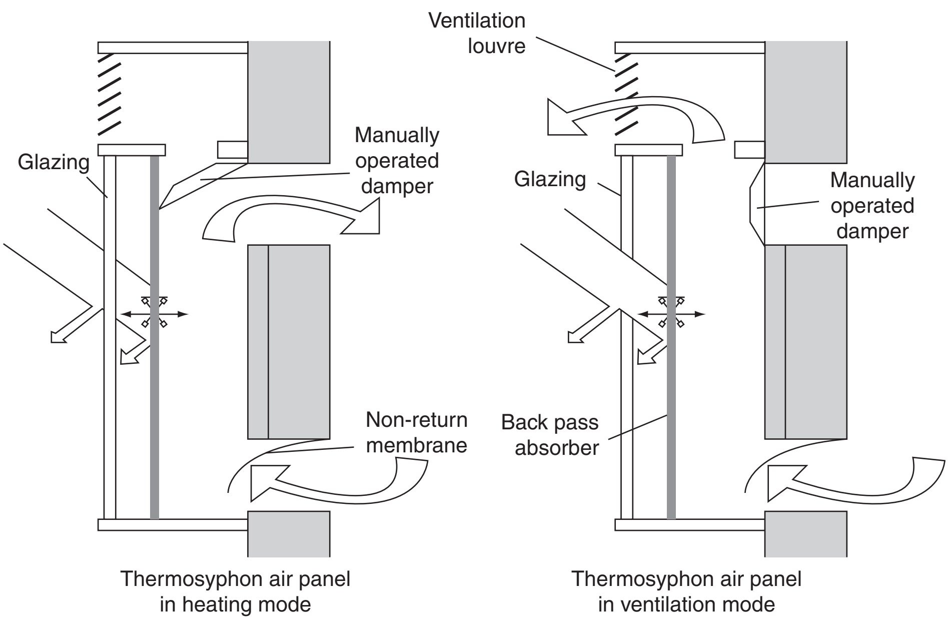
Passive solar design using a Trombe wall

In the **Barra System**, developed in Italy, the air flows from the thermal wall into ducts cast into a heavy reinforced concrete floor slab, converting it into a thermal store that would radiate its heat during evening and overnight. This is said to give a more uniform south–north heat distribution and hence greater comfort for the occupants. A similar effect can be achieved by directing the air along channels in the soffit of a massive long span concrete floor. Refinements like these could supplement thermal or Trombe walls, or partially replace them when such features are inappropriate or impractical. In such cases, the necessary hot air could be generated in externally mounted **thermosyphoning air panels** (**TAP**), also sometimes known as **solar chimneys** (although the term solar chimney is best reserved for the vertical shafts used in many pioneering low energy buildings to extract warm air from interiors during summer) (see Chapter 8).

Roof-mounted thermosyphoning air panels can be unobtrusive (Reproduced with permission from Nuaire)

In principle, TAPs bear a superficial resemblance to the flat plate collectors used for solar water heating. An absorber, usually metallic, sits inside a glazed, insulated box. The absorber heats the air, and the hot air flows out and into the building through vents at the top of the box, to be replaced by colder internal air from vents at the bottom. A backdraught valve prevents cold air flowing in the reverse direction on cold nights. The relatively low temperatures at which TAPs operate mean that thermal losses to the environment are correspondingly low, increasing their efficiency. Various forms of shading or venting to the atmosphere, usually manually operated, can be used to modulate peak heat gain. TAPs are often covered up for the summer months, but they are much less likely to be affected by either high or freezing temperatures than water-based collectors. Some TAPs draw in outside air until its temperature drops below the point at which the TAP is capable of heating it to the internal temperature – this helps ventilation.

One common application of TAPs is to mount them directly below windows, venting straight into the room inside. A practical benefit of all TAPs compared to thermal and Trombe walls is that they free up the interior wall for shelving, etc. TAPs are also widely used on the commercial scale for grain drying and similar activities, which usually take place in late summer while the sun is still relatively high in the sky. These normally heat outside air. In some cases, the TAP is effectively the entire southern elevation of the building. Invariably there will be some form of back-up air heating, and hot air from the TAPs will normally be forced through a network of ducts by some form of fan.



TAPs can aid summertime ventilation as well as heat rooms

The aesthetics of external TAPs can be enhanced by the use of textured glazing or the use of a different dark or black colour for the absorber. Specifying double wall polycarbonate for the external glazing can reduce vandalism risks. Unglazed TAPs are also possible.

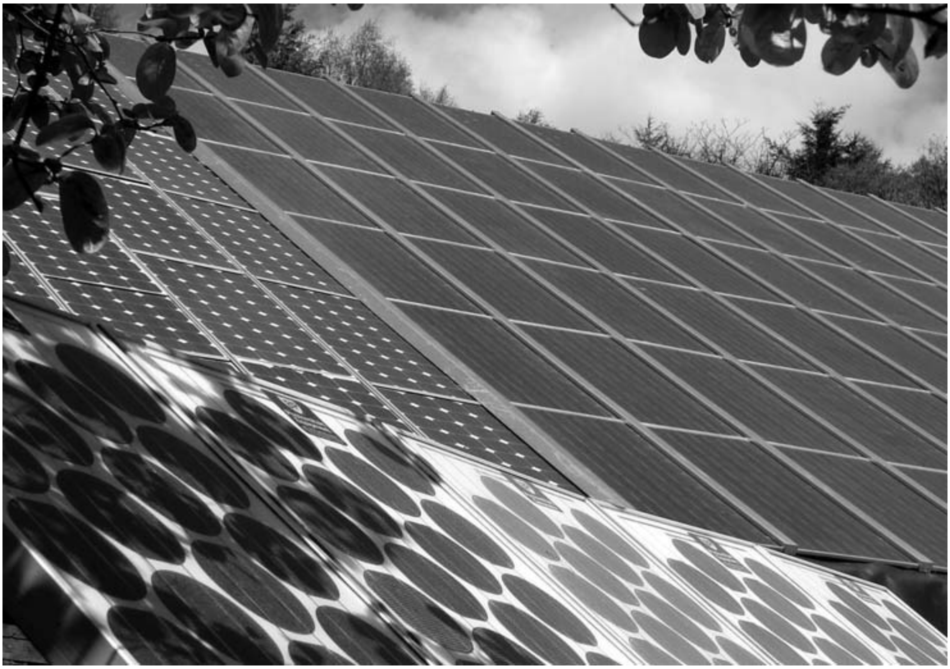
These basically utilise conventional metal cladding as the absorber and circulate air in a cavity between it and the main wall insulation. More sophisticated versions are described in Chapter 10.

The low capital and running costs of passive solar air heating systems, and their inherent reliability, can make them a cost-effective option for many applications. Their main drawbacks are that without a fan to circulate the heated air, it is difficult to ensure even heat distribution throughout the building or to install a cost-effective thermal store in a convenient location. Details of active solar air heating systems can be found in Chapter 10.

In higher latitudes TAPs are best mounted on façades (Reproduced with permission from SolarVenti)

4 Photovoltaics

There is a seductive simplicity about solar **photovoltaic** (PV) technology. No complex machinery is needed, no fossil fuels, power stations or electricity pylons, no energy is wasted in cooling towers or distribution networks. A classic solar PV installation has no moving parts. It is silent, unobtrusive and needs little maintenance. PV cells can be integrated into elegant façades without architectural embarrassment. A PV installation can take up much less space than its solar air or water heating analogues, even though it will



Monocrystalline and polycrystalline solar PV panels at the Centre for Alternative Technology Wales (Reproduced with permission from Centre for Advanced Technology) usually also need a rectifier to convert the low voltage direct current electricity it produces into mains voltage alternating current before it can be utilised. And while most other microgeneration technologies are firmly rooted in earlier centuries, PV is a child of the space age, and very much one of the key technologies for the twenty-first century.

As always, such simplicity comes at a price. Efficiency of conversion is still low. Even the best PV cells currently available commercially can utilise less than 40% of the sunlight falling onto them – and these are far too expensive to use on the large-scale (see below). Fifteen per cent or less conversion is more typical. Cells must be kept cool to reach even these levels; cooling adds to complexity. Cell manufacture is an energy intensive process; indeed, some researchers have suggested that most PV cells on the market will still not produce more useable energy during their lifetime than was consumed in their manufacture. Some of the materials used in some cells are very scarce potentially toxic and need particular care during manufacture and disposal/recycling. Power is only available when the sun is providing energy: like wind and other forms of solar energy, PV is only a practical option for many buildings when a grid connection or some other form of energy store is available (see Chapter 15). Despite these drawbacks, however, the inherent attractions of PV means that it will always be worth considering when determining the best alternative energy technology mix for any particular project.

Physicists discovered that a particular class of material would generate electricity direct from sunlight as far back as the nineteenth century. These were the materials we now know as **semiconductors**, but the first true PV cell, which used selenium, was only about 1% efficient. In the 1950s, however, Bell Laboratories in the USA was researching semiconductors, looking for better performance than could be achieved by germanium, the first semiconductor to be used on a commercial scale. Silicon was to take over once the practical problems of mass producing high purity silicon crystals had been cracked. However, during the research process it was discovered that silicon with certain specific impurities was much more efficient at converting sunlight to electricity than selenium.

Nevertheless, conversion efficiency was still only 6% or so, and the cells were expensive. It was not until the Soviets launched Sputnik 3 in 1957 that real interest in the new technology appeared. Sputnik used an array of PV cells for power; conversion efficiency might have been low but the vast sea of solar energy in which the satellite swam meant that plenty of power was available whenever the satellite was out of the Earth's shadow. Western research was galvanised by this Soviet first. Generous government funds became available, and virtually every satellite and spacecraft launched into permanent orbit in the last 50 years has spread fragile silicon arrays to mark its successful insertion. The International Space Station has the largest PV array ever assembled in space, currently (2007) spanning more than 70 m.

These **first generation cells**, also known as **silicon-wafer based solar cells**, are relatively robust units. Two layers of single crystal or **monocrystalline silicon** form the heart of the cell. One is deliberately 'doped' with a small percentage of phosphorus – this is known as **N-type silicon**. **P-type silicon**, doped with boron, forms the second layer. The two layers are sandwiched between a metallic back contact sheet and a fine metallic contact grid on the upper face. As silicon is basically a shiny silver metal that would naturally reflect a lot of the sunlight falling on it, an anti-reflective coating is applied before the whole cell is sealed below a protective glass cover plate. With an effective anti-reflective coating, one that cuts losses due to reflection to less than 5%, and an efficient front contact grid that blocks as little light as possible, conversion efficiencies as high as 15% are now possible.

Monocrystalline silicon is sliced from highly refined very pure cylindrical ingots, so to minimise waste the slices are usually left circular. A cheaper alternative is **polycrystalline** or **multicrystalline silicon**. Made from less refined square ingots, polycrystalline silicon cells are less efficient than the monocrystalline alternative, but cover a greater area of a normal rectangular PV panel. These two types of cells still account for the vast majority of solar PV capacity installed, but they remain expensive, and research is now focussed on bringing the cost per kilowatt down to more competitive levels.

One of the most significant developments to come onto the market recently is the **SunPower A-300** monocrystalline cell. This has a unique rear contact design that reveals the 5% of the face of the cell normally covered by the contact grid and permits the use of thicker metal in the grid, which reduces resistive losses. Claimed efficiency tops 20%, and the A300 is said to be cheaper and easier to mass-produce than the conventional alternative.

Other results so far include the development of cells based on new semiconductors, or on much thinner films of silicon-based semiconductors such as amorphous silicon, or a combination of both. Generally classified as **second generation** cells, these are significantly cheaper to manufacture than the first generation cells, which usually more than makes up for their lower efficiency – only about 8% in the case of amorphous silicon. Some **thin film** cells use only 1% or so of the expensive silicon that goes into silicon wafer-based cells, saving massive amounts of energy during manufacture. And although overall efficiency is low, thin film cells do work better than silicon wafer cells in low light conditions, and are generally more robust and vandal-proof. One thin film technology now available on the commercial scale is based on **cadmium telluride** (**CdTe**), which is easier to deposit on substrates than most of the alternatives. The perceived potential toxicity of elemental cadmium means that this technology has attracted some controversy, although research to date indicates the risks are low. Efficiency is above 10%.

Significantly higher conversion efficiencies, approaching 20%, can be achieved by multi-layered thin film composites. These have a more complex operating model than the basic silicon cell, and can be tuned more precisely for particular end uses. Both **copper indium selenide** (**CIS**) and **copper indium gallium selenide** (**CIGS**) cells are now in production, although there are long-term concerns about indium supplies. CIGS cell development is focused on replacing as much of the indium with the much more available gallium as possible. Both CIS and CIGS cells can achieve efficiencies of around 11%. Thin film composites can even be deposited on flexible materials such as polymer roofing and textiles.

Moving to conversion efficiencies above 20% requires completely new technologies. Many, such as **quantum dot modified photovoltaics**, have achieved conversion efficiencies above 40% in the laboratory but are still in the development phase. One technology that is available, albeit at a very high price, is based on **gallium arsenide** (**GaAs**) multi-junction cells. Their ability to absorb nearly all the solar spectrum allows them to achieve conversion efficiencies approaching 40%, but their cost means that they have been used almost exclusively in the aerospace sector so far. However, alternative ways of using GaAs

'Flexible' solar PV is now a reality (Reproduced with permission from United Solar Ovonics)

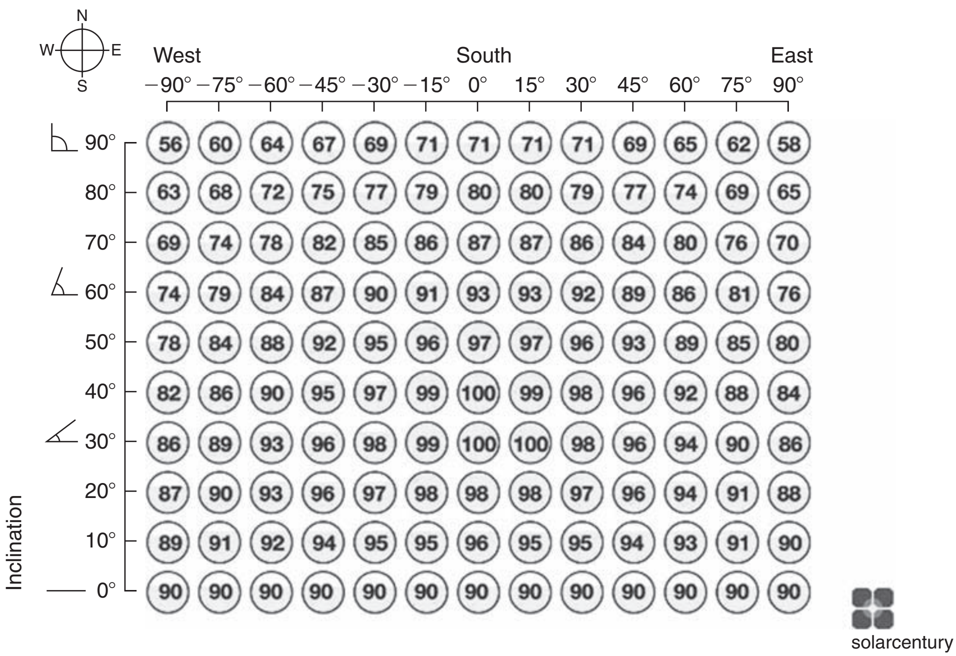
Roofing membranes incorporating PV cells open up new possibilities (Reproduced with permission from United Solar Ovonics)

cells are now coming to the fore, and the technology is very promising (see below). At London's Imperial College, for example, '**quantum well**' GaAs cells, which promise to be significantly cheaper than their predecessors, have been developed – these, marketed under the trade name **QuantaSol**, are aimed squarely at the **concentrating PV** field (see below) and are said to be a cost-effective solution for generating electricity on the larger scale.

Cells based on organic/polymer materials and dyes appear to offer the possibility of acceptable conversion efficiencies and massive reductions in production costs, but their developers have still not solved the problems of ultra-violet degradation and intolerance of high temperatures. Research into the manufacture of much cheaper silicon cell variants is also ongoing.

Other third generation PV technologies include **photoelectrochemical cells** (**PEC**), and those that use nanotechnology, such as **ormasil.** These promise conversion efficiencies in excess of 60%, but there are formidable problems to be overcome before any of these technologies become realistic options in practice.

PV cell conversion efficiency is calculated as the amount of energy produced by a square metre of cell at 25°C exposed to a standard solar radiation, which is taken as the solar radiation falling on a square metre of the Earth's surface at the equator at noon on a clear day at the spring or autumn equinox. Conveniently, this is 1,000 watts. Thus, a square metre of cell with a conversion efficiency of 15% will produce 150 watts of peak power. In practice, of course, the solar radiation falling on a solar PV panel located away from the equator will be far less than this for almost all the time. Research suggests that the effective capacity factor of a fixed PV array will rarely exceed 20%. Thus a rule of thumb figure would be that a square metre of typical PV cell would produce no more than 250 kWh in a year.



Typical PV performance chart (Reproduced with permission from Solarcentury.com)

Crystalline PV cells are usually made up into modules containing either 36 or 72 individual cells; modules are assembled into PV panels and arrays. Module efficiency is usually 1 to 3% lower than theoretical cell efficiency in practice, due to reflection off the cover glass and temperature variations.

Extracting more useable power from the solar radiation available by increasing the conversion efficiency of the PV cell is one option. An alternative is to maximise the amount of radiation falling on the cell. Fixed arrays are usually orientated as close to true south as possible (see Chapter 9), although deviations of as much as 30° east or west are acceptable. Angle to the horizontal is usually the same as the latitude, unless maximum winter electricity output is a priority – in which case the angle should be latitude plus 15°.

Greater energy capture can be achieved by using some of the power generated to drive a single or dual axis tracking mechanism that will keep the PV array pointing towards the sun from dawn to dusk. A single axis east–west tracking installation can yield up to nearly 30% more energy in a year than a fixed array. A dual axis set-up, which also tilts the array to follow the sun's changing altitude, can produce around 40% more, both at the cost of higher capital and maintenance costs. Alternatively, so-called **passive trackers** are now becoming available for solar PV installations. These use the solar-induced expansion of a low boiling point compressed gas fluid (the same principle used in glasshouse ventilation actuators) to keep the panels pointing at the sun, and viscous dampers to minimise wind shake.

A passive solar tracking mechanism
(Reproduced with permission from Leonard G.)

Adding mirrors or lenses to concentrate the sun's rays on the array produces a **heliostat concentrator** (**HC**). In areas where cloudless skies are common, this approach improves the overall performance of all PV cells, thereby reducing the area needed for any specific output. It can also make it easier to justify the use of such high-performance cells as gallium arsenide. In 2006 Australia announced it was planning to build a GaAs-based HCPV installation in northwest Victoria, which, with a projected 154 MW output, would be ten times larger than any other PV plant anywhere else in the world. A conventional flat plate PV installation would use 1,000 times as much PV cell material as an HCPV installation, it is claimed, on the basis that each GaAs cell receives 500 times as much sunlight and is twice as efficient as a silicon cell.

A SolFocus concentrating PV module (Reproduced with permission from SolFocus)

On the smaller scale, companies such as **SolFocus** in the US are now offering developed HCPV panels made up of 16 mirror-based concentrators focussing sunlight onto GaAs cells only 10 mm square. Overall panel efficiency is 17%, and the panel is claimed to be capable of generating 205 W of 40 V electricity at peak. Most if not all HCPV installations include some form of solar tracking as they rely on direct sunlight rather than diffuse light. An alternative approach has been adopted by **Soliant** of California. A combination of mirrors and lenses is used to concentrate sunlight onto the cells, which are mounted in small twin axis tracking units. Modules of 35 of these currently under development measure 700 mm by 2500 mm, generate around 500 W, and are said to be 24% efficient. Soliant hopes to have the technology available in mid-2009.

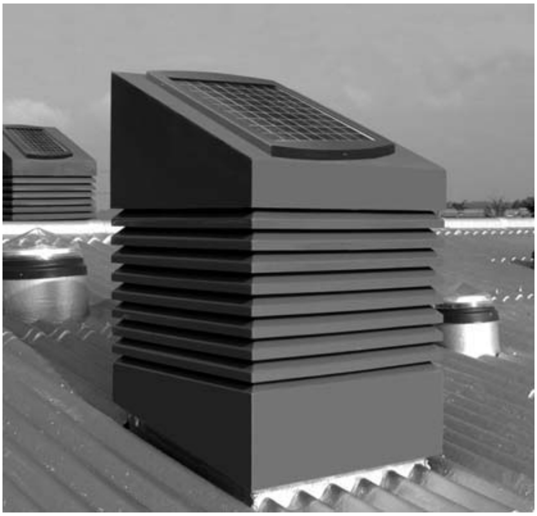
Individual dual axis tracking features in this concentrating PV module under development by Solaire (Reproduced with permission from Solaire)

The Australian installation will be some 35° from the Equator, but it will be in a rural location where there is no risk of shading from adjoining trees, buildings or geographical features. Overshadowing can seriously limit the performance of a PV installation, more so than with solar air or water heating collectors. Low-rise buildings in dense urban locations with many tall buildings would not be fruitful locations for PV. Where buildings are much the same height then a rooftop installation would be indicated, and where the building stands well clear of others – say in an office or industrial park – façade-integrated arrays might be the best option, particularly where the building is relatively tall and the roof area proportionally small.

Façade mounted PV is a practical option in the right location (Reproduced with permission from United Solar Ovonics)

Like all solar technologies, PV is most effective on buildings whose peak power demand is during daylight hours. Residential buildings will need some form of energy store (see Chapter 15), most commonly by connection to the national grid. The latter is not always a straightforward option. Alternatively, the power from the PV panels can be used exclusively to drive the fans and pumps of a solar air- or water heating installation, or a space cooling and ventilation system, or an integrated system that performs both heating and cooling functions. These normally need most power when the sun is shining brightest, so PV is the obvious provider. Many pumps, fans and ventilators now come with integrated

PV panels, greatly simplifying installation. Surplus power could also be converted into heat and passed into a thermal store.



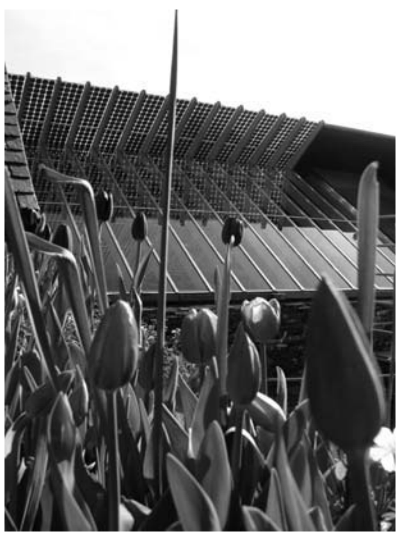
Solar PV powered ventilation is now readily available (Reproduced with permission from Monodraught)

Offices, schools, hospitals and the like can utilise PV electricity as a substitute for, or supplement to, power from the national grid. Converting the low voltage direct current output from a PV cell to mains voltage alternating current requires a rectifier, which at best will be 90% efficient. In many modern buildings much of the electrical energy consumed will be used to power desktop computers – which will convert the mains voltage AC into low voltage DC via internal transformers, which have a typical efficiency of around 40%. So a significant percentage of the electricity generated by the PV cells will be lost as heat: useful in the winter, a nuisance in the warmer months. It would make sense for buildings of the future to have separate low voltage DC circuits powered by PV that would be used directly by computers, low voltage lighting and the like to maximise efficiency.

For all types of PV cell, output is inversely proportional to cell temperature, so keeping PV arrays cool should be a priority. Air is the usual medium; natural ventilation is usually adequate, even in the sunniest locations, although ventilation fans powered by the array are a realistic alternative. In winter the heated air can be a valuable asset: it can be used to back up a space heating system or passed through an air/water heat exchanger to boost domestic hot water supplies. Even in summer the solar energy contained in the cooling air can be tapped for space cooling purposes (see Chapter 13), or captured in a seasonal thermal store (see Chapter 15). Large-scale HCPV installations may be more effective with water cooling – concentrating sunlight by up to 500 times produces very high temperatures at the cells, and although air cooling can work well with smaller HCPV arrays, water cooling is usually the best answer for large installations.

Many recent buildings combine both solar air/water heating collectors and PV cells on their roofs or façades (see Chapter 16). Rain screen cladding and curtain walling systems are available with integrated PV – these are sometimes dubbed '**active cladding**', and can actually be cheaper than some forms of conventional cladding. Glazing with semi-transparent silicon-wafer cells laminated into it is on the market. Cell spacing can be tuned to provide the optimum balance between daylight transmission and electricity generation. 'Transparent' thin film cells have been produced and are being offered by some manufacturers, although the contact grids are still visible. High-performance roofing membranes are

'Translucent' solar PV glazing continues to improve (above and below) (Reproduced with permission from Solarcentury.com)



(Reproduced with permission from Centre for Advanced Technology)

available with flexible thin film amorphous silicon cells laminated in. Solar tiles and slates are another possibility, as are PV arrays integrated into shading louvres. Options like these should go a long way to dispelling any lingering architectural objections to PV arrays.

A typical small office development of 1,000 m^2 floor area will consume up to 200,000 kWh per annum. Assuming that one square metre of monocrystalline silicon PV array can yield 250 kWh annually, meeting say 10% of the building's needs through PV will require at least an 80 m^2 installation. If cheaper technology is preferred, perhaps in the form of a roofing membrane, then two or three times this area might be needed.

Output from PV arrays will decline with time, but how fast, and how long the array will continue to function is still the subject of heated debate. Silicon-based cells can be contaminated by iron or oxygen from the environment; the materials used for encapsulation can be attacked by heat, moisture and UV radiation. The oldest Earth-based solar modules have been in operation for more than three decades without obvious signs of widespread distress, so confidence in the long-term performance of PV cells is still high.

Solar PV is too often seen as an architecturally acceptable symbol of commitment to a green agenda. A small but visible PV array is a quieter alternative to a token rooftop wind turbine, one with fewer structural implications. Size itself is no guarantee that the PV array is not just another greenwash. What matters is the way the output from the array is utilised. If it is genuinely reducing the building's demand for energy from fossil fuels and/or providing an emergency back-up, solar PV is a valid option.

Manchester's CIS tower shows what PV can do in the right context (Reproduced with permission from Solarcentury.com)

This page intentionally left blank

5 Wind power

Mankind has been harnessing the wind for more than two millennia. Windmills have ground grain, drained marshes, sawn timber, and even heated water by churning. The first windmill specifically designed to generate electricity was erected in Ohio in 1888, and in 1931 a 100 kW wind turbine in Yalta, in the former USSR, began feeding power into the local 6.3 kV grid. Wind farms are now seen as the quickest and easiest route to reducing dependency on fossil fuels for national electricity generation. However, controversy still surrounds both their actual effectiveness and their potential impact on the local tourist

Wind farms are becoming larger and more common, but still represent only a small fraction of the world's electricity generating capacity (Reproduced with permission from Michael J. Pasqualetti) trade and/or local wildlife. Generous government subsidies in most developed countries have spurred technological progress, and the latest generation of very large turbines are beginning to live up to the dreams of their adherents. At the end of 2006 the total world wind farm capacity was calculated to be nearly 75,000 megawatts, still less than 1% of world electricity consumption.

At the other end of the spectrum, there has been a parallel blossoming of interest in small domestic wind turbines, usually rated at 100 kW or below. A bewildering variety of designs have been offered, with a number of frankly misleading claims as to their potential performance made by manufacturers. Recently it has become fashionable to have a roof-mounted wind turbine installed, particularly amongst aspiring politicians. Small turbines are even available from DIY stores. More significantly, a number of **building integrated wind turbine** designs are beginning to leave the drawing board. Research into various types of medium-scale wind turbine technologies is beginning to bear fruit. For most projects above the domestic scale, wind energy is now worth considering as at least part of a package of renewable energy alternatives.

Recent experience all over the world has confirmed what the old windmill builders knew well; extracting energy from the wind is never straightforward. These days we have detailed maps of average wind speeds available for many countries, but these are only a starting point. The key to successful wind turbine installation lies in the **micrositing**. Windmills were built on hills, or on flat, featureless, almost treeless plains, where the wind had a good '**fetch**', an unobstructed run through the windmill's sails. Height helps, as wind velocity increases with distance from the energy-sapping ground – although windmills were never built on really tall hills. What is really needed is steady, predictable wind with as little turbulence as possible.

So the most predictable and productive wind farms to date are those built off shore. Wind farms on high altitude moorland also perform well. Least favourable is the urban environment. Not only do closely packed buildings and trees suck massive amounts of energy out of the wind immediately above them, they also generate highly unpredictable turbulence. A typical small wind turbine battered by a turbulent air stream rarely produces enough electricity to make it more than a token gesture to a greener lifestyle. And retrofitted building mounted small wind turbines can also feed unacceptable levels of noise and vibration into the building. On the other hand, some buildings with certain types of roof will see wind speed increase over the roof when the orientation is favourable. This accelerated airflow can be utilised if the installation is correctly designed. Buildings in industrial estates or on the urban fringes could well experience less turbulent flow than those in town centres – but trees can still be a major problem for turbines at low level.

Whatever the location, the same basic laws apply. Available power is related to the cube of the average wind speed. Double the wind speed, and eight times as much power is available. Double the height of a turbine by mounting it on a tower, and average wind speed will increase by around 10% – which implies a 30% plus increase in power generated. Unfortunately, much of the energy generated will come in short bursts at higher wind speeds. Typically, half the total energy will be produced in just 15% of the operating time, making either connection to the national grid or some form of energy store essential for economic operation (see Chapter 1 and Chapter 15). A useful rule of thumb is that wind turbines are worthwhile where the average wind speed is greater than 4.5 m/s – at turbine height. For individual installations it is not enough to depend on average wind speed maps, especially where the local topography is far from flat and featureless. A proper survey measuring wind speeds in various locations on the project site for a whole year would be the ideal solution, as experience has shown that in some locations moving the wind generator less than 50 m can double its output.

By far the most common and most developed way of extracting energy from the wind is the **horizontal axis wind turbine** (**HAWT**). This will typically be a three-bladed design – although versions with anything from one to 20 blades have been tried – with the blades mounted on a shaft that turns some form of electricity generator (see below). This assembly is mounted on a tower. Most designs have the blades rotating upwind of the hub to minimise the effects of the inevitable turbulence downwind of the tower. These blades have to be relatively stiff or mounted well away from the tower or tilted upwards, to minimise the risk of blades flexing under load and striking the tower – which, alternatively, could be raked forward to achieve the same goal.

Old and new – wind turbines and an agricultural windmill (Reproduced with permission from Michael J. Pasqualetti)

Small upwind HAWTs will have a tail vane to turn the blades into wind: larger models will have a wind sensor and a servomotor to ensure alignment, although these can become overwhelmed by a gusty, turbulent airflow, typical of urban locations. Downwind designs do exist, and align automatically, simplifying manufacture and maintenance. The blades on downwind HAWTs can be made more flexible than upwind alternatives, allowing them to flex and spill wind when a gust strikes. Against that, as blades pass through the mast's turbulence the forces on them will vary suddenly, causing extra stresses on the hub.

An established downwind HAWT – the 15 kW Proven 15 (Reproduced with permission from Proven Energy)

All HAWTs suffer from the same problem of asymmetry of blade loading. **Wind shear**, the variation of wind speed with height above ground, usually means that, at any given moment, there will be a measurable difference in air velocity between the lowest and highest points of a blade's rotation, even on a relatively small installation. On the large wind farm HAWTs this difference is considerable. Thus the aerodynamic forces on individual blades will fluctuate significantly as they rotate, and these forces have to be resisted by the hub and tower. Moreover, as the turbine swings backwards and forwards to follow the wind there will be gyroscopic forces acting on the blades, which again will put stresses into the hub and tower, and its foundations. These cyclic and random stress variations have caused fatigue failures at the hub in a number of early HAWT installations.

Better understanding of the forces involved has led to the development of much more rugged designs, and fatigue failures are now rare. The three-bladed option is popular, largely because it minimises cyclic variations. It should be noted that a three-bladed HAWT would only extract around 3% more energy out of the wind than a two-bladed design, at the price of greater initial cost and more complex erection. Medium-sized two-bladed designs with developed versions of the so-called '**teetering**' **hub**, which reduces hub stresses, are now commercially available, although it is claimed they are noisier than equivalent three-bladed designs.

Alternative forms of HAWTs have also been the subject of much experimentation. Small domestic-scale units are now available in the US with two widely separated twin-bladed rotors mounted on the same shaft, one upwind and one downwind of the mast. These co-axial designs are claimed to be significantly more efficient than single rotor designs at low wind speeds, and there are proposals for much larger wind farm sized versions. In Japan a turbine that uses a so-called '**loopwing**' is on the market. This looks remarkably like a giant food mixer lain on its side, and is claimed to be quieter, safer, and more efficient than conventional small HAWTs.

Counter-rotating co-axial designs have also been tried, although none are yet available commercially. Prototypes with both sets of blades on the same side of the tower, and on opposite sides, have shown that they can tap more of the wind's energy over a wider range of wind speeds than a single-rotor design. One experimental installation in California is said to be up to 40% more efficient than a comparable single-rotor system, but at the price of greater complexity and cost.

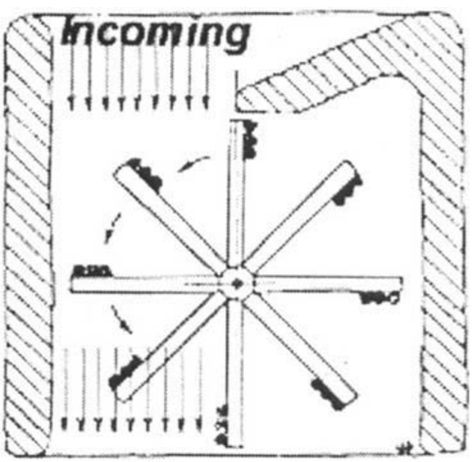
Ducted rotor or **diffuser augmented wind turbines** (**DAWT**) also offer greater efficiency, at a similar price. Surrounding a rotor with a duct that is shaped to accelerate the wind flow through the rotor significantly, is said to enable it to operate at higher speeds in a wider range of wind speeds. In practice, it would seem to make little sense to mount a DAWT on a tower as an alternative to a conventional HAWT. To achieve significant augmentation the duct has to be as long as possible, preferably at least seven times the rotor diameter, which poses a formidable alignment problem in rapidly shifting winds. And for the same cost and material usage a bigger HAWT, which would probably produce more power overall, could be constructed. However, both DAWTs and counter-rotating co-axial HAWTs might have a role to play where turbine diameter has to be restricted for some reason, as they can achieve more power from the same diameter than a conventional HAWT. This can make them some of the more interesting options for **building integrated wind turbines** (see below).

All HAWTs can trace their ancestry back to the earliest European windmills, which were first recorded in the thirteenth century. The most primitive types used fabric sails spread by timber frames, which could easily be furled in high winds. By the time the classic windmill fell out of favour more than 500 years later, the sails were sophisticated aerodynamically efficient fabrications made up of timber shutters that could be adjusted while the sails were in motion. In high winds all the shutters opened to minimise the loads on the system. Modern HAWTs also have to have some form of speed-limiting device to avoid overloading. Earlier medium-sized HAWTs depended on self-regulation; as wind speed and the loads on the blades increased, they began to warp, until turbulence grew rapidly and the blades effectively 'stalled'. This is a noisy process, and large modern HAWTs generally reduce the angle at which the blades meet the wind – the angle of attack – as wind speed increases, to keep the torque at the hub constant. Either individual electric servomotors or hydraulic power is used to accomplish this **feathering** or **furling**, and there will be a back-up system that will furl the blades if main power fails.

Such complexity is really only cost-effective on large installations. A more realistic alternative on medium-sized projects is **electrical braking**, in which electrical energy is drained off into a resistor, which converts the kinetic energy of the blades into heat – which can be utilised for many purposes. This system, also known as **dynamic braking**, allows the turbine to run at constant speed even when wind speeds are high. **Passive pitch control** is used on the **Iskra AT5–I**, a 5.4 m diameter three-bladed HAWT rated at 5 kW; springs in the hub balance centrifugal force from the rotating blades against torque loads from the generator to maintain blade pitch at the optimum setting.

Passive pitch control features on the 5 kW Iskra AT5-I (Reproduced with permission from Iskra UK)

If HAWTs are the descendants of mediaeval European windmills, **vertical axis wind turbines** (**VAWT**) have an even more ancient lineage. One of the earliest applications of wind power was to grind grain, and millstones have a vertical axis. To the Persians, and subsequently the Chinese, it made perfect sense to arrange fabric sails around a central shaft connected directly to the upper millstone. This was some 3,000 years ago. Even then, the windmill builders were aware of the fundamental problem with VAWTs – for part of their rotation

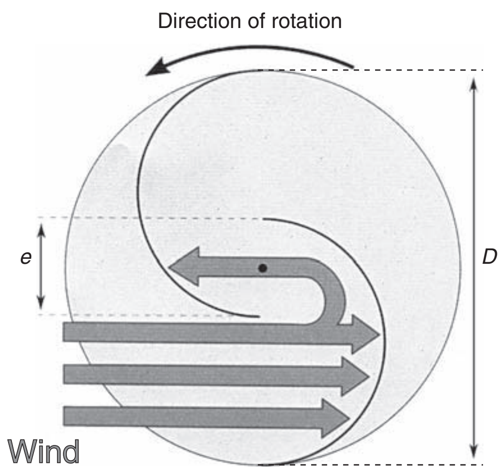


Panemone-based designs have been around for centuries the blades are travelling against the wind. In the Persian **panemone**, a wall shields half the assembly, allowing it to rotate against the wind direction with as little drag as possible.

More sophisticated versions of the panemone are still intriguing wind energy enthusiasts to this day. All VAWTs share the same basic advantages: the heavy generator is at ground level and much more accessible for maintenance, the assembly needs no yaw mechanism to keep it pointing into the wind, and vulnerability to high wind speeds is much reduced. The expensive tower used by HAWTs is eliminated: transport and erection costs are usually much lower.

Against these benefits must be set the inherent drawback of lower overall efficiency due to the drag from the blades travelling forward against the wind for part of the rotation. Efficiency is also compromised by the fact that most VAWTs operate closer to the ground than HAWTs, in a more turbulent and less energetic airflow. The latest designs are all aimed at reducing these drawbacks and maximising the benefits, and most are variations on a number of basic themes.

Simplest of all is the **Savonius turbine**, little more than a sophisticated version of the twin scoop rotors used for anemometers and roof vents. With three scoops or more a Savonius turbine will always self start, and there has been much work done to improve its basic efficiency. Perhaps the most interesting variant is the **TMA** design from the US, originally a 'multi-Savonius' concept with fixed vanes to concentrate the wind on the rotor. This has now evolved into a much simpler and more efficient version, with a slender 'twin scoop' rotor surrounded by three offset 'stators', which both accelerate the wind speed hitting the rotor and act as the main support structure. Claimed advantages include the ability to operate efficiently over a much wider wind speed range than HAWTs and thus to have a significantly higher capacity factor, and to offer no threat to birds and bats.



Principle of the Savonius turbine (Reproduced with permission from Schnargel)

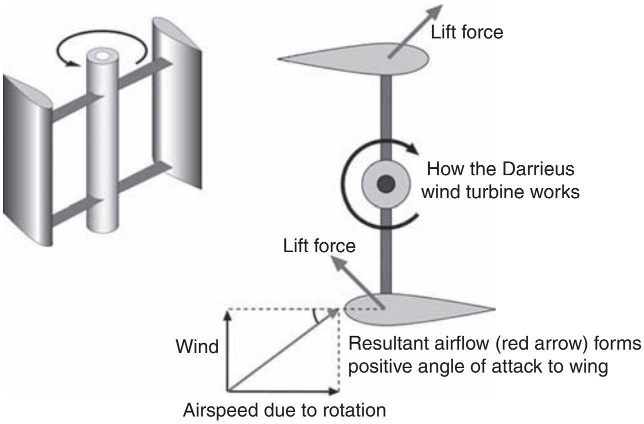
'Eggbeater' designs have also been much developed. Collectively known as **Darrieus turbines**, the earliest versions used simple fixed pitch blades arcing out from a central shaft, and were relatively efficient but were subject to large variations in torque and consequent stresses on the central tower. Other drawbacks were the need for assisted starting – sometimes by a small coupled Savonius turbine – and the loads on the central bearing produced by the downforce from the guy wires used to stabilise the tower.

Later developments took two main routes to improve the basic design. More fixed pitch blades were added, often in a helical arrangement, to minimise torque fluctuations and aid self-starting. A good example is the British **quietrevolution QR5** design. The basic model has three tapered S-shaped blades, a direct drive permanent magnet generator and measures 5 m high by 3.1 m diameter. Unable to self-start, the QR5 senses wind speed via an anemometer and the control system passes a current through the generator to start the turbine moving when wind speed reaches a predetermined value. In a typical urban situation, mounted either on a mast at least 9 m high or 3 m above a building roof the QR5 is claimed to generate at least 10,000 kWh a year in suitable locations.

An original approach to VAWT design – the 2007 version of the TMA unit (Reproduced with permission from TMA Wind)

An alternative approach sees the blades made straight and vertical, mounted at the end of radial arms, and often endowed with variable pitch. This latter feature enables self-starting, and produces a relatively flat torque curve as well as helping speed limitation in very high winds. Some, like the Italian **Ropatec** range, have their generators between their fixed pitch vertical blades and can be 'stacked' one above the other as needed.

An interesting variation on the Darrieus principle is the **Windstar** from the US. Basically a variable pitch vertical blade design with the tower supported by an external steel



Principles of the Darrieus turbine (Reproduced with permission from Graham UK)

framework, the Windstar is said to work best when installed in linear arrays of three or more, with the blades passing within 600 mm of each other. Dubbed **linear array vortex turbine systems**, the claimed advantage is a massive boost to the efficiency of the internal turbines at wind speeds below 20 m/sec. Current versions on offer are 15 m high and up to 23 m in diameter, and are seen as ideal partners to large HAWTs in wind farms, operating in the turbulent air beneath the HAWTS.

VAWTs can be mounted on towers, as shown by this 4 blade, 6 kW Solwind unit (Reproduced with permission from Alvesta)

Darrieus type VAWTs may also be mast mounted, as in the case of the **Solwind Four Winds** unit from New Zealand. Four or six fixed pitch blades drive a low-level generator via a right angle gearbox and vertical shaft. Self-starting is said to occur at wind speeds in excess of 1.5 m/sec, outputs on standard versions reach 9 kW. Solwind VAWTs became available in Europe in 2007 from Alvesta, and versions yielding up to 100 kW are under development.

VAWTs are becoming an increasingly attractive option for both **building mounted wind turbines** (**BMWT**) and **building integrated wind turbines** (**BIWT**). In some cases multi-bladed Darrieus turbines are actually mounted horizontally on rooftops, to minimise the forces transferred to the building structure. The Dutch led the way with the **WindWall**; a more recent development due to come onto the market in 2007 is the **520 H Aeroturbine** from Chicago-based **Aerotecture**. The company's first product was the vertical axis 510 V Aeroturbine, which features a translucent helical Savonius rotor fabricated from Lexan (polycarbonate) coupled with a small Darrieus turbine. Standing 3 m high, the 510 V is claimed to generate around 1 kW in 50 km/hour winds. Two 510 Vs mounted horizontally back to back make up the 520 H. In this form the turbine needs to be aligned with the prevailing wind. TMA turbines (see above) can also be mounted horizontally on rooftops.

Aerotecture's 520H Aeroturbine is one recent example of a VAWT turned on its side to better integrate with the building (Reproduced with permission from Kurt Holtz, Lucid Dreams Productions)

When located on the corners or sides of buildings, VAWTs can be visually much less obtrusive than HAWTs on rooftops, and more resistant to the inevitable turbulence in urban locations. Vibration can still be a problem, however, especially in retrofit situations.

Retrofitted rooftop-mounted small urban HAWTs have an unhappy history. Problems with vibration and turbulence are widespread, and overall performance has regularly fallen far short of optimistic manufacturers' predictions. Mounting the HAWT on a rooftop tower or mast helps to reduce the turbulence problem, although such an installation could fail to find favour with the planning authorities. It can also feed significant structural loads into the building. There is also concern about the health and safety implications of a blade failure, seen as much more likely in the highly turbulent urban environment. Some small HAWT manufacturers have tackled these problems head on by developing designs like the **Swift**, where the blade tips are linked by a circular rim, and the **Combined Augmented Technology Turbine**, where the power producing rotor is surrounded by a short duct and sits behind a free rotor which is claimed to 'process' rapidly veering and turbulent air before it hits the main rotor. Another approach is to use gears at the hub to turn a vertical shaft inside the tower, which then drives a generator at the base of the tower. This is claimed to increase reliability and minimise stresses at the rotor hub.

If space permits, the usual advice is to site the turbine as far away from any obstruction as possible – this obviously includes the building it is supplying. A set-off distance at least ten times the height of the obstruction is recommended. The fact that trees could gain significantly in height during the turbine's lifetime should not be forgotten. Long set-offs lead to energy losses in transmission from the turbine to the building, or heavier gauge cabling might have to be specified, adding to the expense. The only alternative way of maximising turbine efficiency is to mount it on a tower at least 10 m higher than the height of any obstructions closer than the ideal minimum distance. Experience with HAWTs, however, indicates that towers taller than three times the rotor diameter are rarely economic.

Mast mounting away from the building is usually a better solution than HAWTs on rooftops (Reproduced with permission from Proven Energy)

There will be few sites where such generosity of space is available, although schools with playing fields and shopping complexes with large surface level car-parks might be exceptions. Even on the urban fringes it might well be the case that some form of building-integrated turbine is the most effective option – and the easiest to get past local conservation groups and planning authorities. BIWTs are relatively recent developments, and many have yet to progress beyond the concept or prototype stage, although such experience as is available suggests that this could be a very useful option for building designers.

One of the simplest and least obtrusive is the **ducted wind turbine** design developed by the University of Strathclyde. A rotor is mounted on a vertical axis inside a duct curved through 90°. The inlet to the duct is mounted on the face of the building while the outlet is on the roof; the vertical shaft passes through the wall of the duct to drive a generator below. Orientation is obviously critical, and it may be that turbines have to be installed on more than one face of the building to yield worthwhile power.

A much bolder approach is to design the whole building around the wind generator. One of the most dramatic concepts is the **WEB Concentrator**, in which two aerodynamically shaped tall buildings are linked by large ducted HAWTs. A smaller-scale experimental version with a single rotor proved to be remarkably insensitive to wind direction and to perform better than expected at low wind speeds. Development continues, but obviously such an extreme building would be relatively expensive to construct.

More practical perhaps are the various concepts developed by Altechnica of the UK – collectively dubbed **Aeolian Planar Concentrator** devices. These use wing-like aerofoils to accelerate wind speed through both HAWTs and VAWTs, which can be free standing or mounted above the roof. Integrating them with the building proper is an exciting alternative. The simplest version is the **Aeolian Roof**. In new build the main roof can curve upward towards the centre, where a row of relatively small turbines, either HAWTs or VAWTs, are topped by a horizontal planar concentrator. This has a flat upper surface, which can support solar PV arrays. A similar, if less effective installation can be fitted to an existing pitched roof, and protective grilles or screens can be specified if there is a perceived risk to health and safety. These will reduce the energy yield, but the basic system is said to be remarkably tolerant of oblique winds, making orientation not so critical. Another alternative is to install a similar array arranged vertically at the corners of tall buildings.

Wind turbines can generate both alternating and direct current. Early large HAWTs and VAWTs invariably used gearboxes at the hub to speed up the input from the relatively slow rotation of the blades to one that suited the generators available. HAWTs in the 50 m diameter class are now available with highly efficient low speed direct drive generators, cutting capital and maintenance costs, and most wind turbine manufacturers are looking seriously at this option. Small HAWTs have almost always used direct drive generators to produce DC power, a legacy of their early role as battery chargers. For most purposes what is needed is AC power at grid frequency and voltage. One simple approach, used in most early wind farms, is to govern the speed of the turbine within very close limits so that a simple, cheap induction generator produces AC power at a frequency very close to grid frequency. This severely reduces the turbine's ability to extract power from a wide range of wind speeds. Later generation large turbines use more sophisticated AC or DC generators and control systems to supply precisely regulated current at prescribed frequency and voltages. There is some loss of energy in the regulation process, but this is more than compensated for by the greater range of operating speeds possible.

In the early days of wind generated electricity there was a regrettable tendency to rate turbines by the potential output of the generator itself. This could be completely misleading. The power produced by a turbine is determined almost entirely by the mass of air that can pass through its blades. This is a function of the **swept area**, which in HAWTs is the area of the circle described by the blades. Thus, for convenience HAWTs are usually classified by blade diameter, which is then linked to potential output.

Table 5.1 Typical relationship between HAWT rotor diameter and output

Diameter (m)	Output (kW)
9	15
15	50
20	100
30	225
40	500
50	600

VAWTs are harder to classify, as each type has its own unique characteristics. The whole situation is complicated by the fact that there is no internationally recognised standard testing or classification system. Manufacturers rate their products at different wind speeds, anything from 10 m/sec to 15 m/sec or more. As the output from any particular wind turbine at any particular location is probably influenced more by its micro-siting than by its basic design, specifying an installation that will be likely to meet a project's needs is fraught with problems.

A number of factors have to be considered, of which the unit's **rated capacity** is only the starting point. The next most common figure usually quoted is the **predicted annual output** for any given average wind speed. Basing any site-specific calculations on national wind maps can result in subsequent disappointment, as actual average wind speed. Therefore, actual output achieved may be significantly different to that predicted from the wind maps, especially if local obstructions generate energy-sapping turbulence. For anything but the smallest and most token of wind turbine installations a proper wind speed survey is essential.

This could well reveal that the projected turbine will only develop something between 20 and 40% of its theoretical annual output – a figure derived by multiplying its rated capacity in kilowatts by the number of hours in the year. Smaller turbines operating in largely turbulent airflows will struggle to meet even these figures. These **annual capacity factors** are site specific – those quoted by manufacturers are at best averages and at worst highly optimistic. The table below details a list of typical test results on an HAWT.

Even if a 12-month survey of a particular site reveals excellent potential for wind power, the next step may turn out to be the most frustrating. Currently there is a massive gap in

Energy Production and Carbon Dioxide Savings from Iskra Wind's AT5-1 Turbine, based on Test Site Results after Inverter

Annual average wind speed; m/s (at hub height)	Annual average wind speed; mph	Expected Yield per turbine; MWH/year	CO_2 saving per year; Tonnes/year	Expected Yield per turbine; MWHr over 20 years	CO_2 saving per year; Tonnes over 20 years
3	6.72	1.84	1.05	36.8	20.90
3.5	7.84	3.13	1.78	62.6	35.56
4	8.96	4.75	2.70	95	53.96
4.5	10.08	6.64	3.77	132.8	75.43
5	11.20	8.74	4.96	174.8	99.29
5.5	12.32	10.94	6.21	218.8	124.28
6	13.44	13.15	7.47	263	149.38
6.5	14.56	15.31	8.70	306.2	173.92
7	15.68	17.35	9.85	347	197.10
7.5	16.80	19.24	10.93	384.8	218.57
8	17.92	20.93	11.89	418.6	237.76
8.5	19.04	22.41	12.73	448.2	254.58

*Conversion factor: 0.568 kg CO_2/kWh for grid electricity – see UK Building Regulations L2A, para 22. Reproduced courtesy of Iskra UK.

Field test results post-inverter for a HAWT (Reproduced with permission from Iskra UK)

wind turbine availability. Units up to 20 kW are common, and a number of manufacturers offer the larger wind farm turbines in capacities from 225 kW to 5,000 kW.Demand in the intermediate size range has historically been low, and the number of manufacturers supplying suitable turbines is also low, while costs could be correspondingly high. The problem comes when the analysis for a particular project throws up an answer that falls into the size gap. For example, a typical modern energy efficient office development may consume up to 200 kilowatt-hours of electricity a year per square metre of floor area. To supply say 20% of that from wind energy implies an installation with an annual output equivalent to 40 kW hours per square metre. Assuming a generous capacity factor of 30% means that a relatively modest office development of 1,000 m^2 needs a turbine with a theoretical annual output of more than 130,000 kW hours. Meeting this demand would require thirteen 5 m high VAWTs such as the QR5, three or four HAWTs with 9 m diameter blades, for example, or possibly two 15 m diameter HAWTs on 30 m high towers. A 20 m HAWT would seem to be the simplest answer. The units described would probably be rated as 15 kW, 50 kW and 100 kW, respectively. Larger developments would need larger capacity, and the choice is limited.

Where the site is suitable and the planning authorities complacent, the best answer for the medium-sized project for the moment at least might well be a secondhand 225 kW

HAWT from one of the early wind farms. Wind farm operators are constantly upgrading their installations to take advantage of the improving performance and economics of ever larger HAWTs, and the earlier units are available at reasonable prices with at least ten years of potential trouble-free service left in them. By the time they need replacing more appropriate turbines might be on the market. A 225 kW machine is likely to have a 30 m diameter rotor and be mounted on a 35–50 m high tower.

Objections to such an installation will typically be based on visual intrusion, noise, flicker and danger to bird life. The latter now seems to be exaggerated, although controversy continues, and the danger to bats seems to be greater than expected. VAWTs are said to be safer in this respect, as the birds and bats usually perceive them as a more solid obstacle. Older HAWTs are noisier than the current generation of large wind farm turbines, but most fears about noise pollution have so far turned out to be unfounded. The flickering shadows from the revolving blades of an HAWT are also annoying to some people.

Development of building integrated wind turbines continues (Reproduced with permission from Kurt Holtz, Lucid Dreams Productions)

Small- and medium-scale wind power has so far failed to realise its theoretical potential. Many pioneering entrepreneurs have tried to develop the technology to the point at which it is a realistic option for every building developer. Some are beginning to succeed. Wind power on its own will never be the ideal solution; coupled with other technologies, especially an efficient energy store, it is definitely worth considering for more than a symbolic contribution to a greener future.

This page intentionally left blank

6 Small-scale hydropower

In many ways hydropower is the ideal alternative energy source. Its delivery is much more reliable, consistent and predictable than wind or solar energy. Modern turbines can extract up to 90% of the kinetic and potential energy in the water that passes through them – although an overall efficiency of 70% is more typical for small installations. More power is usually available during the wet winter months than in the summer, a supply profile that more closely matches normal demand. Unlike some other alternative energy technologies, hydropower installations generate many times more energy than is needed to build and run them; as much as 200 times more, it is claimed. Small hydropower installations are usually unobtrusive, quiet, emission free, and have little environmental impact.

Currently, around 20% of the electricity used across the world comes from hydropower. Some installations are very large – the largest, in South America, has an installed capacity of 12,600 MW. Most are much smaller, producing little more than 5 kW. Definitions vary, but **small hydropower** installations are usually considered to have a generation capacity below 10 MW. In some countries this dividing line is as low as 3 MW. **Mini hydropower** definitions also vary. Usually the upper limit is 1 MW; below 300 kW lies the category dubbed **micro hydro**. One other important distinction is also made: large hydropower installations use dams to create a high head of water above the turbines. The vast majority of hydropower installations, however, are **run of river**, i.e. no dams or significant water storage are involved (although weirs often are); water is taken straight from the river above the turbine and discharged back into it below.

Waterwheels have been used to extract energy from water for at least two millennia. For most of that time the energy abstracted was converted into mechanical energy – the wheels drove millstones, trip hammers and bellows in forges, looms, cranes, fulling hammers. By the end of the nineteenth century, the latest designs were achieving better than 60% efficiency. However, as generators of electricity, waterwheels leave a lot to be desired. In most potential locations maximum capacity will rarely exceed 5 kW, but even if this is acceptable, the low rotational speed of the wheel means that a gearbox is needed to increase this to the levels at which electrical generators are effective. Nevertheless, on the smaller scale a waterwheel might well be an appropriate solution, and can also make an

Watermills, like this Belgian example, were always a more predictable alternative to windmills (Reproduced with permission from Pierre 79)

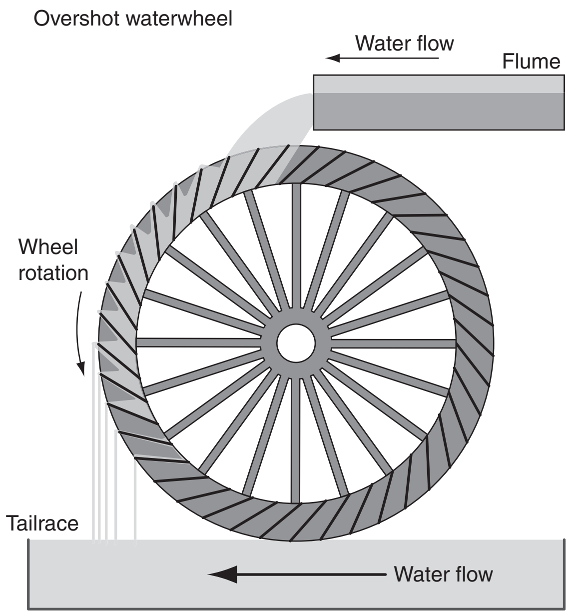
aesthetic contribution to many projects. In use, waterwheels are simple to control, long-lived, and relatively cheap to make. A number of companies in the UK and US now offer modern steel waterwheels using off the shelf gearboxes and generators, which are said to be effective solutions on many projects, especially in the Third World (see Chapter 19).

Many of the earliest watermills used vertical axis wheels. A stream of fast-flowing water drove paddles mounted on a vertical shaft, which typically was connected directly to the upper of a pair of millstones. These mis-named **Norse wheels** appeared all over the world and continued in use for many generations, but were always limited in power and low in efficiency. Horizontal axis wheels could be made much larger, but needed a mechanism for converting their horizontal rotation into vertical rotation before they could be used to mill grain or crush olives – the Romans were the first to use cast bronze gearwheels to achieve this goal. Roman engineers also developed large installations of up to 16 wheels stacked up a hillside so that the water emerging from the tailrace of a higher wheel flowed straight onto the wheel below.

Choice of wheel type is largely a function of the head of water available at the site. The oldest, simplest and least efficient type is the **undershot wheel**, which utilises the kinetic energy of the water flowing beneath it, and can work with almost no head at all. Flat paddles are used, output is low and efficiency is 30% at most. If water levels drop in the summer the blades of an undershot wheel can be left dangling in mid-air. This disadvantage could be overcome by mounting the wheel on floating pontoons or between boats – these were often moored immediately downstream of multi-arch bridges, to take advantage of the increase in water speed as the river rushed between the bridge piers. A much later development is the **Poncelet wheel**, where the paddles are curved and the water is diverted into a pipe system and forced out as a jet that strikes the wheel at its base. This variant on the basic undershot concept can more than double the efficiency, but it requires a higher head of water than the simple undershot design.

Zuppinger undershot wheels manufactured by **Hydrowatt** of Germany have seen something of a renaissance. To be pedantic, these are not classic undershot wheels, being designed to work with heads of 0.5 m to 1.5 m. Installed wheels have ranged up to 7.5 m in diameter, producing 45 kW at an estimated efficiency of 65%. These levels of efficiency are achieved by utilising as much as possible of what potential energy there is in the water flow: the flume closely follows the curve of the wheel downwards to the tailrace and fits closely around the wheel profile. Blades are curved and inclined 'backwards', minimising energy losses.

For heads of up to 3 m, the **breast shot wheel** was the popular choice. Water entered the wheel close to, or slightly above, its axis and was captured by bucket-like paddles. Potential as well as kinetic energy was available as a result. The wheel rotated in the same direction as the water in the tailrace, eliminating any energy-sapping counter rotation against the flow by the empty paddles.



Overshot waterwheel schematic

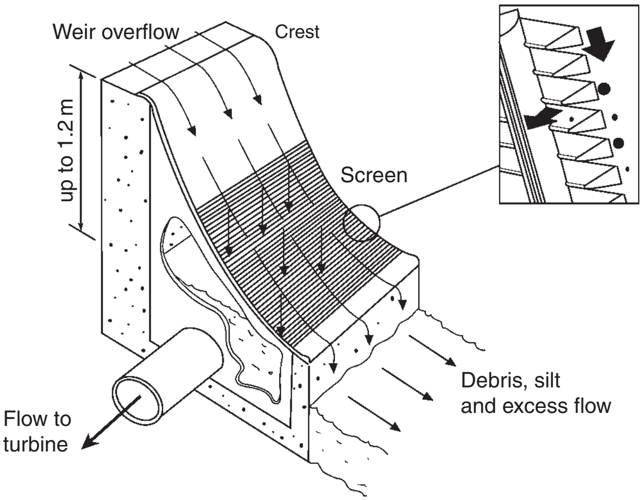
This was a problem with the classic **overshot wheel** design, which otherwise was the most effective choice for higher head situations. Normally water enters the bucket type paddles just past the highest point of the wheel, rotating it in the direction of the incoming flow. After rotating through 100° or so the paddles empty and begin to turn against the flow in the tailrace. This problem can be eliminated and the efficiency of the wheel significantly enhanced by converting it into a **backshot** design – also known as a **pitchback** wheel. Water enters the paddles before the highest point, rotating the wheel in the opposite direction to the incoming flow. Water leaving the paddles flows in the same direction that the paddles are rotating, adding some kinetic energy to the potential energy already extracted by the wheel. It is claimed that a modern steel backshot wheel is more efficient than most available microturbines, and needs a much simpler supply and tailrace configuration (see below).

At their peak in the eighteenth and nineteenth centuries there were hundreds of thousands of waterwheels in operation across the world. Few are left and even fewer are still being used for their original purpose – but their ancillary works often remain. Weirs, mill leats and sluices tend to be long-lived and relatively simple to refurbish. Taking advantage of such existing infrastructure can be economically very effective. It can also be much easier to obtain permission from the relevant authorities to re-open a defunct site than to construct new infrastructure. It is currently estimated that there are around 20,000 former watermills in the UK alone that could be upgraded to modern standards without great difficulty.

This Austrian example is typical of the existing weirs that could be utilised for small hydro (Reproduced with permission from European Small Hydro Association/KO)

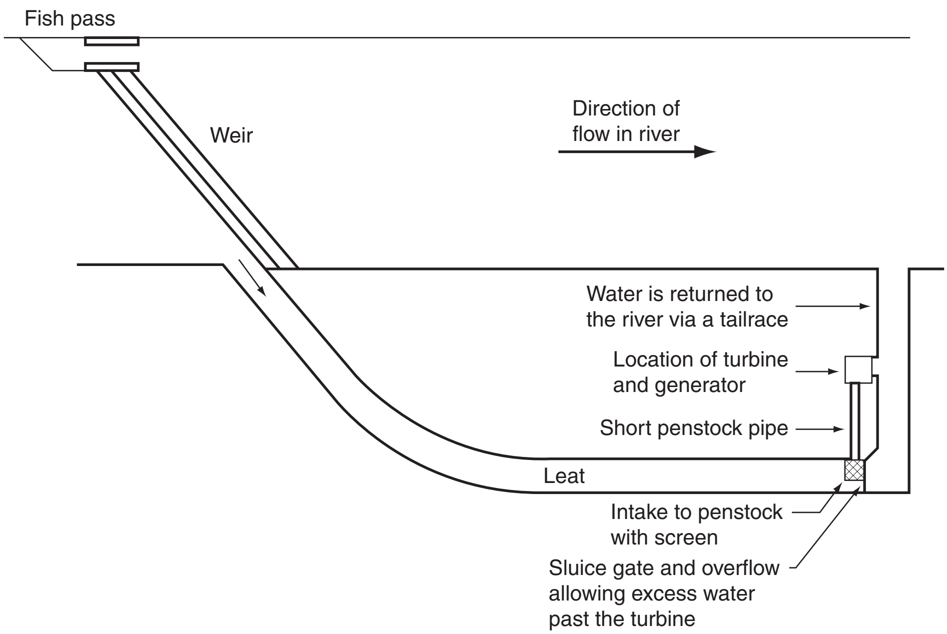
All run of river hydropower installations, ancient or modern, have certain components in common. There is usually a weir across the river, to ensure that the water level is always higher than the intake for the water heading off to the wheel or turbine. This intake is usually protected by a screen or **trashrack**, to stop fish and debris entering the system. (One of the advantages of the overshot waterwheel is that it is very tolerant of foreign objects in the water flow, and therefore needs a less elaborate trashrack.) If the water then enters a **leat**, or small canal (also known as a **headrace or lade**), this screen could be located just before the **forebay**, a tank where sediment is allowed to settle out. From the forebay the water flows into the **penstock**, a pipe that takes it down to the powerhouse, and then into a **tailrac**e which discharges it back into the river.

Sometimes there is no leat, and the water passes straight from the river into the forebay and the penstock. Sometimes the leat stretches right to the powerhouse – this is usually the case on most former waterwheel sites. Leats need spillways and sluices to control water levels. An alternative where the weir creates a reasonable difference in water level



Trashracks and inlet screens like this Coanda design are recommended (Reproduced with permission from Dulas Ltd)

above and below is the barrage option. Here the turbines are installed almost immediately downstream of the weir, usually without forebay and only a minimal penstock. As no water is abstracted from the river proper there are fewer regulatory hurdles to be surmounted. This type of installation is now being tried in the outflows from both water and sewage treatment plants, with considerable success.



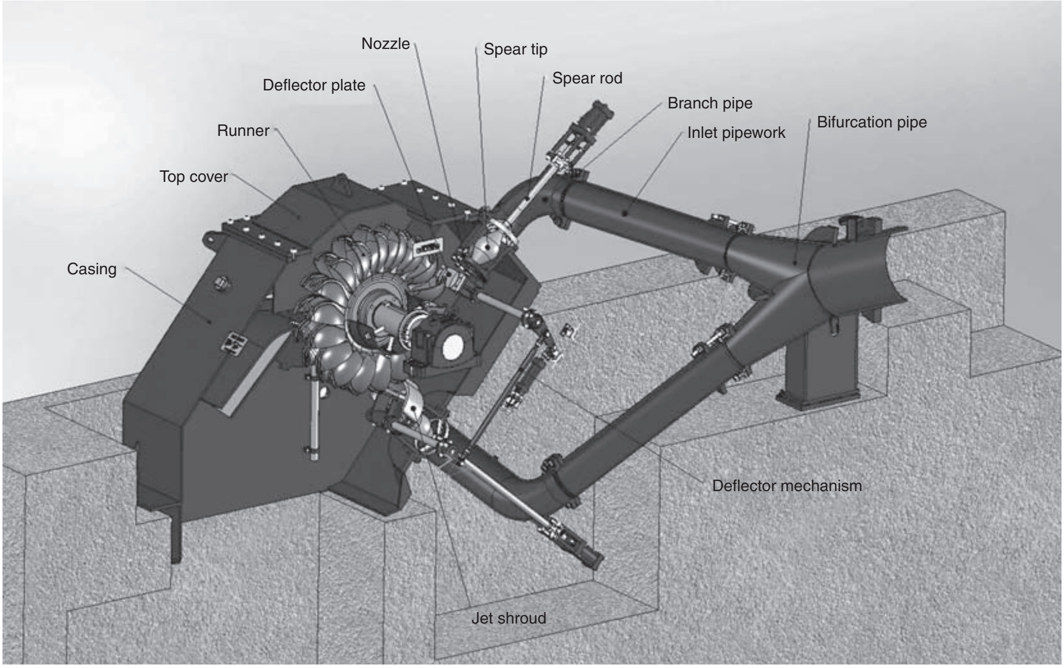
A simple layout without a forebay can be used where silt is not a problem

The most important factor in any installation, however, is the head, the vertical distance between the intake and the wheel or turbine. **Gross head** is the actual distance; **net head** is the effective head at the turbine intake, which will normally be less than the gross head due to losses to friction in the penstock.

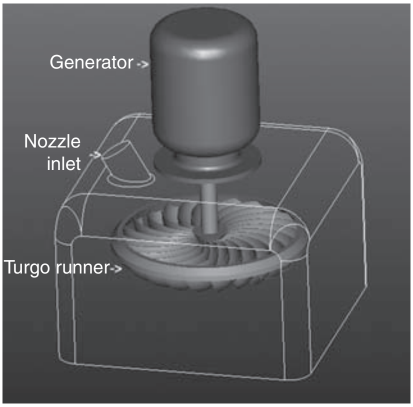
High head hydropower installations are usually classified as those with heads above 50 m, **medium head** would be between 10 and 50 m, and **low head** would be below 10 m. Most former waterwheel sites will have heads of 5 m or less, although overshot or backshot wheels over 20 m in diameter were built. There is a limited choice of turbine types which can function with such low heads, but there are commercially available units that can extract useful power from heads as low as 2 m, provided there is enough water passing through them.

Almost as important as head, therefore, is flow. The key value is the **available flow**; that proportion which can be abstracted from the river to drive the turbine. This value will normally vary throughout the year, so the most critical information is contained in the **flow duration curve**, from which the potential output and **capacity factor** of the installation can be calculated. Typically, the capacity factor for a mini hydropower installation is greater than 50%, significantly higher than wind or solar power.

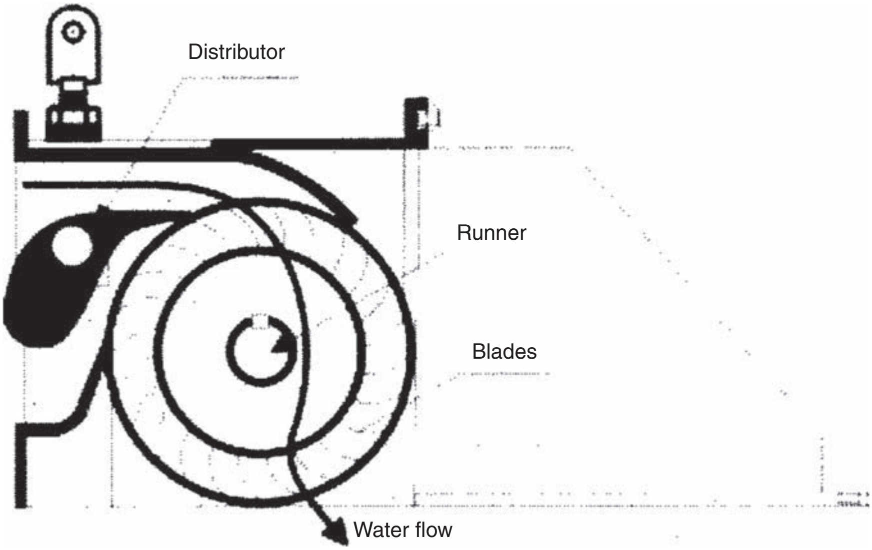
All turbines fall into one of two categories. **Impulse turbines** depend on the potential energy of the water being converted into the kinetic energy of a high velocity jet of water. The turbine runs in air and is rotated by the jet striking its blades or buckets. In the classic **Pelton** design the jet is aligned with the plane of the turbine wheel – or **runner**, in the **Turgo**



Pelton turbine schematic (Reproduced with permission from Gilbert Gilkes & Gordon Ltd)

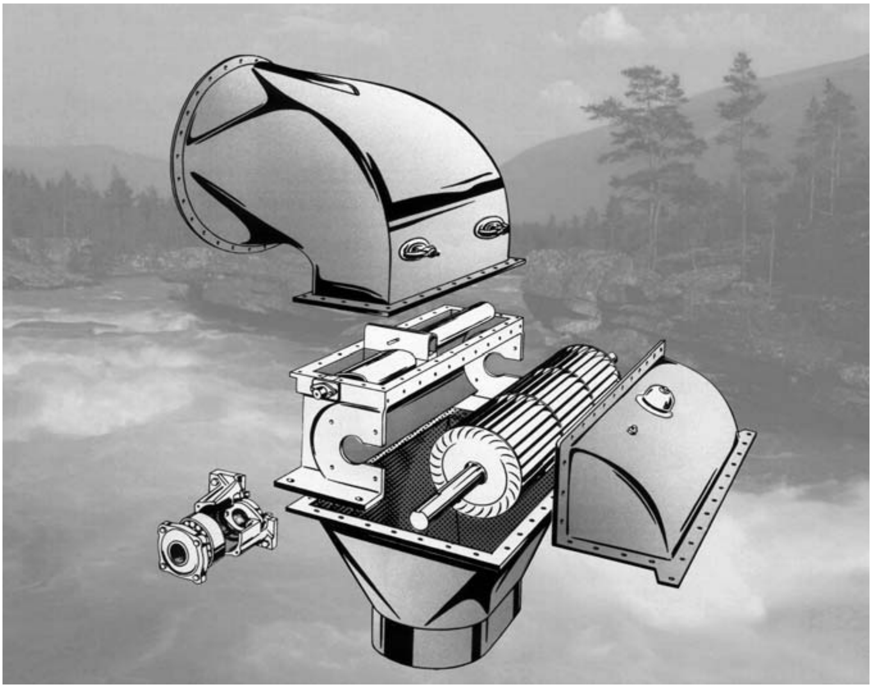


Principle of the Turgo turbine



Principle of a Banki crossflow turbine (Reproduced with permission from European Small Hydropower Association)

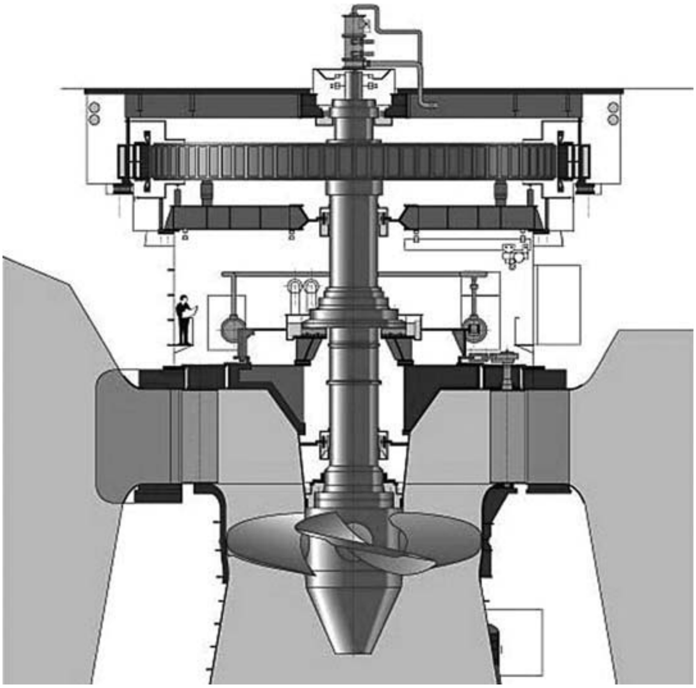
variant the jet is angled, reducing the effect of water splashing back from the runner and affecting the incoming jet. **Crossflow turbines** – also known as **Michell-Banki** or **Ossberger** turbines – have horizontal axis drum shaped runners, and act rather like a sophisticated overshot waterwheel. A rectangular nozzle directs the flow across the curved blades mounted around the rim. Water enters at the top of the wheel and passes through the blades again as it leaves. Crossflow turbines are relatively simple and cheap to construct and easy to maintain.



Exploded view of a crossflow turbine (Reproduced with permission from Ossberger GmbH & Co)

Reaction turbines are normally more expensive than impulse turbines because their runners are usually enclosed in pressure casings. Runner blades are carefully profiled to extract kinetic and potential energy from the water. Water pressure falls back to atmospheric as it flows through the runner and out through the obligatory draft tube, which reduces water velocity and lowers pressure across the runner. The first true reaction turbine was the **Fourneyron**, invented in 1827, a vertical axis outward flow design using blades curved in only one direction. It was something of a sensation at the time, as it could operate at more than 2,000 rpm and achieve 80% efficiency. In 1895, Fourneyron turbines were used to tap the energy of Niagara Falls, its high rotational speed making electricity generation much simpler.

Inward flow reaction turbines are inherently more efficient than outward flow designs, and from the late nineteenth century onwards the Fourneyron design was superseded by the **Francis turbine**, first invented in 1849, and still the most common turbine used worldwide. Water flows tangentially into the runner through a series of adjustable guide vanes and out along the runner axis. Early installations were open **flume** – the runner with its guide vanes and draft tube were simply immersed in the supply channel, leat or headrace, with the draft tube turning through 90° to discharge at a lower level. Later a spiral casing was added, which helped accelerate the flow into the runner. Later still came various forms of **propeller turbines**, which, as the name suggests, work like ships' propellers in reverse. Smaller versions generally have fixed pitch blades: on larger installations the **Kaplan** variant is usually a better choice. This has variable pitch blades, enabling it to work efficiently over a wider range of heads and flows.



Cross-section of a large Kaplan turbine (Reproduced with permission from Voith-Siemens)

Recently there has been considerable interest in and research into the concept of using readily available water pumps in reverse to generate power rather than consume it. The attraction is the significant potential cost savings. Turbines are virtually hand built in small numbers, pumps are mass-produced, and are generally rugged and reliable. Calculating the potential performance of a **pump as turbine** is far from straightforward, however, and some types are basically unsuitable. Pump as turbine installations have demonstrated efficiencies as high as 90% when used with high heads.

Measuring the gross head at a particular site is relatively simple, and this helps in a preliminary assessment of the likely optimum type of turbine. Potential suppliers would need more information than this, of which the key item is the **flow duration curve** (**FDC**). Obtaining a reliable flow duration curve for a particular intake location takes time. Ideally, measurements of flow are taken over a period of at least three years. A reasonably reliable curve can be derived from national gauging stations or from hydrological records, although these days allowance has to be made for the likely effects of global warming on rainfall patterns. A flat FDC is the optimum, indicating a largely spring-fed river with low risk of flooding. The authority responsible for the catchment will determine the volume of water that can be diverted into the hydropower installation. It will demand that a certain minimum **compensation flow** is maintained through the river at all times, to minimise the environmental impact. On low head run of river schemes the head will tend to vary with river level as the changes in level at head and tail of the scheme are never exactly in phase.

Typically the design flow for the site will be the mean river flow averaged over several years. Peak power in kilowatts can be estimated as 7 × design flow in cubic metres per sec × head in metres. Energy output will be a function of the capacity factor, which in turn will depend largely on the size and type of the turbine selected. In essence, the choice is between a larger installation which can handle high flows but will be working at less than full capacity for much of the year; and a smaller, less expensive unit which will be working harder for longer but will generate less electricity overall. The first will have a lower capacity factor and a lower rate of return on the original capital investment, but will be less stressed, last longer and probably be cheaper to maintain.

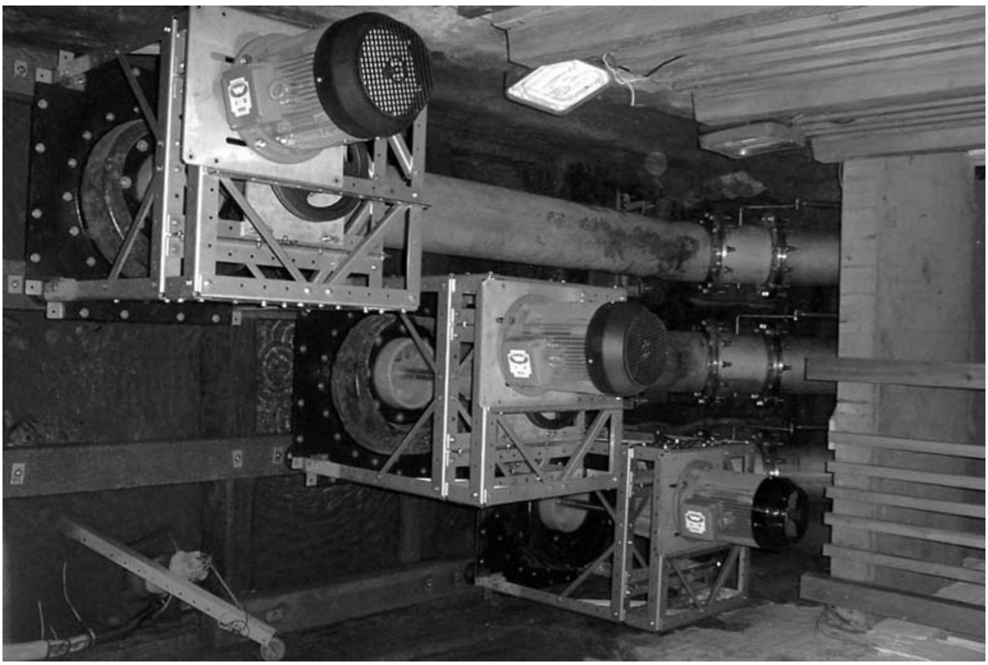
Another important factor is how well the turbine copes with low flow conditions. Pelton and Kaplan turbines retain high efficiencies when running well below design flow, cross-flow and Francis turbines lose efficiency sharply below 50% of design flow, fixed pitch propeller turbines need to operate above 80% of design flow. There are several possible ways of mitigating this problem. One of the most effective is to use multiple turbines, so that the flow can be directed away from some to keep the remainder running at high efficiency. (This approach also simplifies maintenance, as individual turbines can be taken off line without interrupting power generation.) The drop off of efficiency with flow on cross-flow turbines can be minimised by concentrating what flow is available onto a smaller section of the perimeter. On Kaplan turbines the runner blade pitch can be adjusted to suit. The flow duration curve should indicate how much of a problem low flow is likely to be, so that the appropriate installation can be selected.

Turbine speed was traditionally controlled by complex mechanical governors that opened and closed sluices and gate valves to vary the flow of water into the turbine. However, these are not very practical for smaller installations. Luckily, a more convenient modern alternative now exists. **Electronic load controllers** (**ELC**) effectively add an artificial load as needed to maintain total load on the turbine at its design level. This artificial load produces surplus electricity, which can be used for any number of purposes.

Generators also have optimum revolutions per minute (rpm), typically around 1,500. Some turbine types are relatively slow running, particularly in low head installations, so some form of 'gearing-up' is needed between turbine and generator. This is one reason why faster running propeller-type turbines have taken over from Francis turbines at the smaller end of the market. Generally, single-phase alternating current is produced by installations below 20 kW. Above this, three phase generation is the norm. Until recently, turbine speed had to be closely controlled to maintain the frequency of the supply at the desired level. However, turbines fitted with direct drive permanent magnet synchronous generators and **electronic power conditioning**, which allows them to operate over a much wider speed/flow range, are now available.

Using pumps as turbines (see above) leads logically to the use of **motors as generators**. Induction motors can be run above their rated speed to generate both single-phase and three phase current. Such off the shelf units can be significantly cheaper and still produce highly effective results. Integral gearing means they can be successfully coupled with modern waterwheel designs, such as the **Pedley Wheel**, which is claimed to be capable of producing up to 20 kW from a 6 m diameter wheel (see Chapter 19).

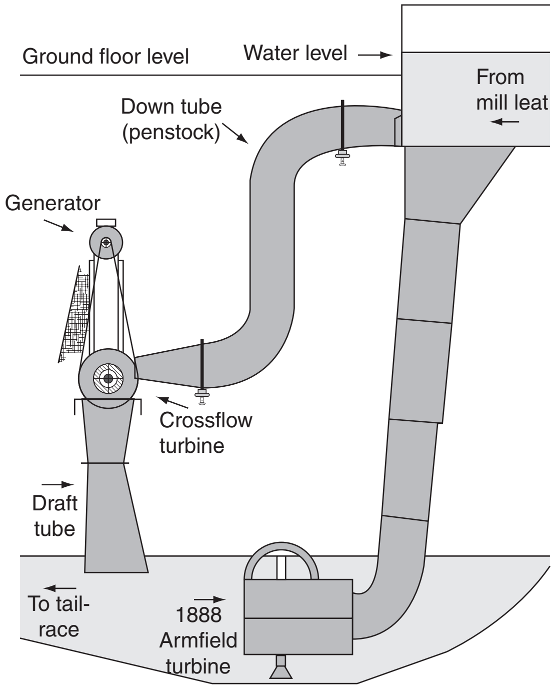
Hydropower is a mature technology and there is a wide choice of equipment suppliers. Development continues, however, with an increasing use of polymers to produce both runners and pressure casings. Modular construction is becoming the norm, and there is an increasing emphasis on rapid installation and minimal maintenance. Minimal visual impact is also a priority. Almost any desired output is readily available, from **picohydro** units with outputs of less than 1 kW upwards; and there is a wide choice of turbines with ratings of 10 kW to 50 kW. Many of these are specifically designed for low head situations where the risk of flooding should not be ignored, and are proofed and protected against prolonged immersion.



Three recently installed 1.47 kW crossflow turbines at the Crabble Corn Mill in Kent, England, produce 27 MWh annually (Reproduced with permission from Hydro Generation Ltd)

Assuming a capacity factor of 50%, a typical small office building consuming 200,000 kWh per annum would need a 45–50 kW turbine to supply 100% of its power. Reaction turbine units are available that can produce this sort of power from a 5 m head and a flow rate of around 1500 l/s (litres per second) – alternatively, five similar units could provide the same output from a head as low as 2 m and flow of 5000 l/s. Even with only 200 l/s and a head of 2 m a single reaction turbine could produce more than 2 kW, which might be best employed to power a water, ground or air source heat pump (see Chapter 12).

Grid connection, if available, is still worth considering even when there is plenty of hydropower potential. Intakes can become blocked, turbines can break down, the powerhouse could be flooded. There are other benefits, as detailed in Chapter 1. In either case, hydropower will always be a serious option for those projects where the opportunity exists.



At Gant's Mill in Somerset, England, whose history dates back nearly 1,000 years, a new Ossberger crossflow turbine generates 32 MWh every year (Reproduced with permission from Hydro Generation Ltd)

7 Biomass heating

For many millennia, the main source of energy was biomass, complex hydrocarbons produced by living organisms. Heat came from wood, charcoal, peat, bamboo, animal dung and bones, burnt in open fires and primitive kilns and furnaces. Natural oils, waxes and tallows gave light. Oils were pressed from seeds or nuts or rendered from whale or seal blubber, waxes were plundered from beehives or extracted from berries; tallow came from the carcases of cattle. The Romans had a very effective form of 'central heating' fuelled by biomass. Even today – several centuries after fossil fuels began to be widely exploited – much of the third world still relies on firewood for heating and cooking. This dependence has had adverse environmental effects, particularly in Africa, but as the search for alternatives to fossil fuels intensifies, the potential of some types of biomass has been recognised.

Firewood from local forests is still a major energy source for the Third World

In practice, biomass comes in two forms. Waste materials such as worn timber pallets, paper, forestry and sawmill residues can be processed into chipped, shredded or granulated form for convenience of handling. (In the US, forestry residues are often known **as hog fuel or hog mass**.) Food processing by-products such as nutshells, cereal straw and crushed sugarcane (bagasse) have high calorific values. The production of beer, wine, spirits, cheese and other dairy products generates large volumes of energy-rich organic wastes. Other biodegradable wastes with a high organic content – pelleted sewage sludge, agricultural and slaughterhouse waste and the like – yield useful amounts of energy when burnt, although there might be concerns about odours and emissions. Or crops can be grown purely as fuel.

Hemp yields oil and fibre as well as fuel

Ideally, these will be plants that flourish on marginal land otherwise unsuitable for modern agriculture, and require the minimal amounts of fertiliser and pesticides. Coppiced willow and poplar, perennial grasses such as miscanthus hybrids and switchgrass, hemp and sugarcane have all been tried, and several are now readily available. Hemp and miscanthus seem to be particularly promising. Hemp also yields valuable fibre and seeds; the residue left after the plants are 'retted' to release the fibres can easily be pelletised. Miscanthus has the advantage that it needs little or no drying after spring harvesting before processing into pellets or bales. It also has a low mineral content (see below).

Miscanthus needs little drying and has a low mineral content (Reproduced with permission from Miya)

Biomass crops are sometimes marketed as being 'carbon-neutral', i.e. the carbon released when they are burned is the same carbon that was taken up during their growth, so the net effect on the atmosphere is neutral. This is not exactly true: their cultivation requires significant amounts of fossil fuels, as does the manufacture of any artificial fertiliser or pesticide used, and the final processing and transportation to the point of use. However, their overall environmental impact is usually much better than the fossil fuels they replace – especially if they are used locally. And burning material that might otherwise be allowed to rot down in landfill and produce methane, an even more potent greenhouse gas than carbon dioxide, is obviously a good idea.

'**Localism**' is the essence of biomass energy. In reality there is little point in switching to biomass generation if the fossil fuel consumed during the production, processing and transportation of the biomass is greater than the fossil fuel that the biomass replaces. There can be a case for subsidising the transportation of biomass over long distances in the short-term to build up a customer base that would attract potential local biomass producers to enter the market, but unless local supplies eventually become available in the medium- to long-term the choice of biomass generation would be short-sighted.

Biomass fuels are usually processed only to improve their ease of handling, unlike **biofuels**, which are biomass crops processed to convert them into more energy dense solid, liquid or gaseous hydrocarbons such as charcoal, producer gas, biodiesel and bioethanol – although the term biofuel is now being used mainly for liquid fuels derived from plant matter and intended as a replacement for liquid fossil fuels (see Chapter 11).

Ease of handling is one of the attractions of using cereals like maize and oat as fuels. Oat in particular is attracting a lot of interest, as at the time of writing (2007), there is a marked surplus of oats in Europe. Its main attraction for farmers is that it can be grown further north than most cereals and requires less herbicide. But, because it lacks gluten and hence is unusable for breadmaking on its own, oat is less in demand than wheat, maize, rice or even barley. There is an obvious ethical issue in burning produce that could feed the starving, but there are cultural and environmental issues to be considered as well. Cereal production is usually heavily subsidised, associated fossil fuel consumption is high, and the vagaries of world cereal markets and government subsidies can make cereal supplies uncertain.

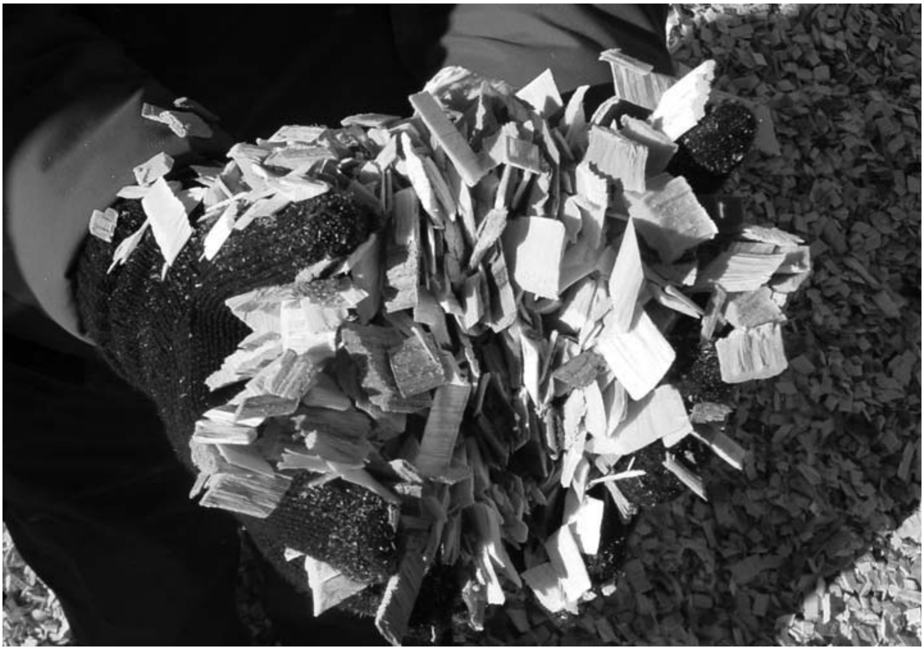
Oats are normally available with a consistent moisture content, usually around 15%. Moisture content is a critical factor in all biomass fuels. There are two ways of calculating this: **moisture content wet basis** (**MCWB**) and **moisture content dry basis** (**MCDB**). It is very important to know which figure is being quoted. One tonne of biomass with a 60% mcwb will have little more than half the energy content of one tonne at a 60% mcdb, although it is the mcwb figure that is usually quoted.

High moisture content biomass poses a number of problems. For the same calorific value transport costs will be higher. In store, various biochemical processes can take place, health-threatening mould spores can be released, and spontaneous combustion is always a risk (see below). During combustion there can be excessive emissions of carbon monoxide and unburnt hydrocarbons. Very low moisture content is not entirely desirable, however. Dust will always be a problem, and can represent both a fire and explosion hazard.

Moisture content also directly affects the calorific value or **heating value** of the biomass; it is the gross calorific value or heating value that is normally quoted. Unless the biomass is burnt in a condensing boiler (which recovers much of the heat in the water vapour emitted), the relevant figure is the net calorific value (which is the gross calorific value minus the heat of vaporisation of the water content).

Typical ranges for gross calorific value of biomass are from 15–20 GJ/tonne (gigajoules per tonne). This compares to 15–30 GJ/tonne for coal and 45 GJ/tonne for diesel fuel. Ash and sulphur content is usually much lower than with fossil fuels, and the ash can be re-used as a soil conditioner in many cases. However, bulk density – and hence energy density – is much lower than fossil fuels. Various densification processes such as chipping, shredding and pelletising have been used to improve this figure, but storage volumes will normally be significantly larger than with fossil fuels.

Alkali levels in the biomass must also be considered. High alkali levels can lead to serious problems with slag deposits in the boiler tubes. High mineral levels can also be undesirable, as the resulting ash may pose a disposal problem. Another key decision is on the pre-drying of the biomass before it enters the boiler. Some biomass will be available pre-dryed, either passively, by long-term exposure to the air, or by the application of heat – **active drying**. Or it can be dried actively or passively after delivery. There are practical limits to what can be achieved by **passive drying**. Green wood, even when chipped, can rarely be air dried below 30% or so, higher than most boiler installations prefer. Dry chipped or shredded waste kiln-dried or recycled timber is sometimes blended with green wood chips to reduce the overall moisture content. Active drying can reduce moisture contents to the optimum – at a price. However, reducing moisture content before the biomass is burnt increases flame temperature and improves the efficiency of the combustion process. Overall efficiency can be significantly greater, smoke is reduced and there is a lower risk of flue corrosion problems.



Moisture content of woodchips is critical (Reproduced with permission from Biomass Energy Centre)

Some biomass combustion systems are specifically designed to handle high moisture content biomass. Typically these utilise some of the heat of combustion to dry the fuel as it approaches the combustion zone. Some small biomass boilers come with built-in storage, in which some pre-drying occurs. Otherwise the options are purchasing biomass with a suitable guaranteed maximum moisture content – usually around 15% mcwb – installing an active drying system on site, or providing suitable storage facilities in which air drying can take place.

In an industrial situation, where waste process heat or steam is available, active drying could be a very cost-effective option. The choice is between conventional rotary driers using hot air or flue gases, flash dryers that use high velocity hot air, and systems using superheated steam. Flash dryers and **superheated steam dryers** (**SSD**) only work with small particles; single pass rotary dryers can handle larger or more variable material. There is a lower risk of fire or explosion with SSDs.

An increasingly popular treatment for biomass is a combination of SSDs and low temperature **pyrolisation** or **torrefaction** (see Chapter 11), sometimes known as **airless drying**. This produces a denser, more consistent solid material with a low moisture content and high resistance to dusting.

Airless drying can produce a very stable fuel
(Reproduced with permission from Airless Systems Ltd)

Passive drying is not without its risks. Large volumes of wet biomass will tend to compost, and high temperatures will develop at the centre, high enough in some cases for fire to be initiated. The usual advice is that woodchips should not be heaped up more than 10 m high for this reason. The biomass has to be exposed to the air as much as possible while being protected from the elements. Some materials have poor permeability and will need to be turned and mixed regularly. Apart from fire, the main danger is the growth of moulds within the store.

With woody biomass, an option to chipping and drying is '**ultrasonic wave reduction technology**' as typified by the American **KDS Micronex** system. This uses high-powered ultrasonics to simultaneously disintegrate the wood and vaporise the moisture content. The end product is a fine wood dust dry enough to go straight into the combustion process.

Biomass is available for delivery in a number of forms by a variety of transport systems. Bagged pellets come in sizes from 15–25 kg, or in 1 m^3 bags. Tipper trailers or trucks are the most common form of bulk delivery. Inland waterway delivery offers a low carbon alternative to road transport. However, consideration must be given to how bulk biomass is to be offloaded from barges, as this is far from straightforward. It is also important to minimise handling, especially of wood pellets. Excessive handling can lead to the formation of wood dust in unacceptable quantities.

Dry storage is one of the key factors in successful biomass generation. Some boiler manufacturers offer package deals with prefabricated storage and handling facilities. Existing silo capacity has been successfully utilised, and shipping containers have been adapted for storage purposes. On the larger scale, a purpose-built facility is usually the best answer, although a lot depends on the biomass chosen. Good ventilation and drainage are critical. This is particularly the case when a below ground storage hopper is preferred as the most space efficient solution where the biomass arrives in bulk in tipper trucks and trailers. Large stocks will need to be turned over and mixed regularly, to aerate the material and minimise variations in moisture content, but not too often (see above).

Storing and handling bulk woodchips is relatively straightforward, provided sensible precautions are taken (Reproduced with permission from Biomass Energy Centre)

Care must also be taken in selecting the most appropriate method for transferring the biomass from storage into its final destination. Screw auger feeds are popular for granular

Large volumes of damp woodchip can pose the risk of spontaneous combustion (Reproduced with permission from Biomass Energy Centre) materials such as chips and pellets; front loaders or bucket grabs may be the best solution for shredded waste timber or coppice wood. Gravity feed is less energy intensive and is often preferred for smaller installations. Pelleted materials in particular must be handled with care. There is always the risk of disintegration through friction and impact, especially if the moisture content has changed significantly while in store. Too much dust can jam the feed system, and lead to combustion problems.

Biomass can be burnt to produce either hot air or hot water. It can be combined with other technologies to form a cogeneration or trigeneration facility (see Chapter 14). Traditionally most of the heat from the biomass was used to generate steam, which drove turbines that drove electricity generators. Surplus heat was used for space heating/cooling, often on a district basis. This was only effective on the larger scale. A recent development replaces the turbines with a Stirling engine, best described as an external combustion piston engine (see Chapter 14). Such installations can be independent of national energy grids.

A wide range of boilers and combustion units are available, in sizes from a few kilowatts upwards. Most require electricity to function. All biomass combustion installations will be significantly larger than the equivalent fossil fuel installation, due to the lower energy density of biomass.

Space heating and hot water at the Nant y Arian Visitors Centre in Wales is provided by a 35 kW woodchip-fuelled boiler (Reproduced with permission from Dulas Ltd)

Boiler/combustion unit choice should be largely influenced by the type of biomass available. For example, some units will struggle to handle grain, which has a tendency to smother the flames as it enters the burner. Burners that can cope with grain often need to be started with pellets. Biomass installations generally need more supervision and expert intervention than fossil fuel installations, mainly because the fuel is more variable. On the other hand, most biomass boilers/combustion units can handle a wide variety of biomass fuels, allowing flexibility in operation and substitution of biomass sources as availability and prices fluctuate.

Biomass combustion technology is well established and a wide range of units is available (Reproduced with permission from Wood Energy Ltd)

One recent development, which falls somewhere between straightforward combustion and gasification (see Chapter 11), is the UK **Bioflame** system. Gasification and combustion take place in close sequence at atmospheric pressure, and the hot exhaust gases then go to a steam generator that normally drives a steam turbine, although other options are available. A wide range of different biomass sources can be exploited. Current Bioflame installations are relatively large, producing 2–3.5 MW of electricity, and are usually part of a cogeneration or district heating scheme.

The disposal of ash from biomass combustion has to be considered from the outset. Luckily, both fly ash (ash precipitated from the flue gases) and bottom ash usually contain significant levels of calcium, potassium and phosphorus, and hence can be recycled back to the soil to improve fertility and soil texture. Some ashes may have high levels of heavy metals, usually cadmium, and these will need special disposal. Willow is a known cadmium concentrator so willow ash must be monitored carefully. Municipal waste ash is also usually unsuitable as a soil improver. Some fly ashes contain significant carbon, and can be recycled back into the burners. There have been a number of projects to develop economic end uses for ashes unsuitable for soil improvement, such as replacing natural aggregates in low grade concrete products and the like.

Growing interest in the production of biofuels could lead to competition for biomass resources. This in turn could force up prices, eroding what should be biomass's inherent advantage over most fossil fuels. Against that, the increasing demand for biomass as a whole will persuade many industries and local authorities to look closely at their waste streams and assess their potential for energy production. More biomass options are the likely result, more localisation the logical outcome.

8 Passive cooling options

As the climate warms, the demand for environmental cooling will inevitably increase. It would increase anyway: in developed countries the acceptable 'comfort zone' inside buildings is becoming narrower. Occupants are less and less willing to modify their clothing and habits in response to seasonal changes. Fifty years ago clerical staff thought nothing of wearing woollen underwear to the office, where men would work in three-piece suits, collar and tie for most of the year. In the height of summer, windows would be thrown open and jackets removed, but only the young and irresponsible would roll their shirtsleeves above the elbow. These days, winter and summer alike, office workers expect their environment to be maintained above 20°C and below 25°C – and also demand air conditioning in cars and public transport as a necessity rather than a luxury.

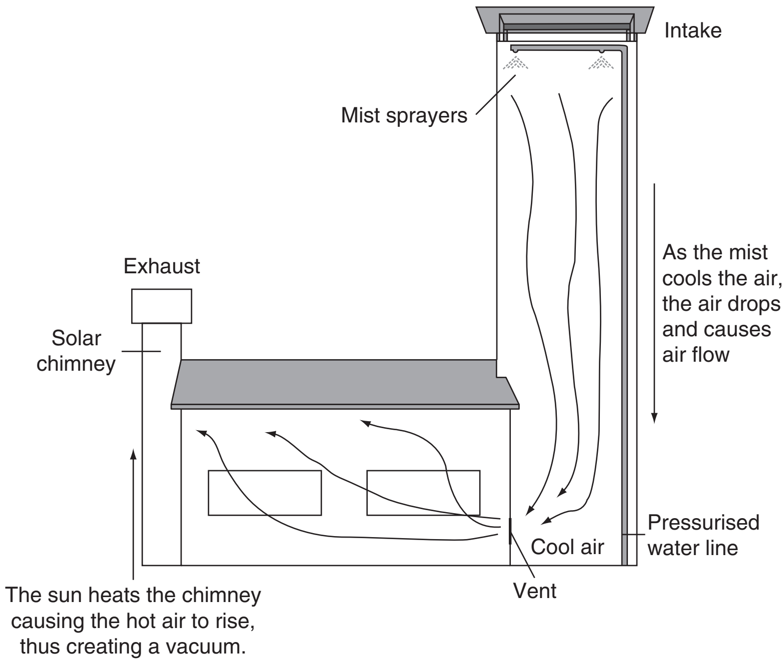
The elderly in higher latitudes were once seen as under threat from hyperthermia in winter, and thousands died every year in cold, damp, poorly insulated homes. Now summers offer no respite. Every prolonged heat wave sees deaths among the elderly hit new peaks. Unfortunately, while a number of well-established technologies exist for topping up internal temperatures with alternative energy in winter, alternative cooling technologies are less well known in temperate regions, where prolonged spells of hot weather have hitherto been a welcome novelty. Closer to the Equator, however, in areas like the southern United States and Australia, several cooling alternatives to conventional air conditioning have been developed which could be used at higher latitudes, particularly where ambient humidity levels in summer are relatively low. These techniques may not be capable of controlling internal temperatures and humidity levels as closely as traditional refrigerative air conditioning; but where the building occupants are prepared to accept greater variability they can offer very cost-effective solutions.

Passive cooling techniques have been around for millennia. Mediaeval builders in North Africa and the Middle East constructed houses and palaces with heavy floors, high ceilings, thick walls and roofs and minimal or non-existent glazing on the south side. Public buildings were often approached through a hierarchy of comfort zones: from full sunlight the visitor first entered an area shaded by vegetation, then progressed into a courtyard, shaded by more trees and cooled even further by fountains or pools. The final destination would be an internal space with low light levels and a tile or stone floor. Air moved through the building driven by differences in temperature and humidity, or by deliberately induced variations in air pressure between the interior and the outside world.

Passive cooling techniques can be incorporated into high technology buildings (Reproduced with permission from Mott Macdonald)

The simplest technique takes advantage of the **stack effect**. Warmer air is less dense than colder, and therefore rises above it. Air inside the building will be warmed by the bodies of the occupants, by lighting and any electrically powered equipment, and by solar gain in the building fabric. If the warmer air is allowed to escape from a vent at roof level, cooler air can be admitted at ground level to replace it. A more developed use of the stack effect is the **solar chimney**, basically an exterior vertical duct open at the top and with vents connecting it to the building interior. Located on the sunny side of the building, a solar chimney absorbs heat from the sun and transfers it to the air inside. The heated air rises, pulling in air from inside the building to replace it. This air will normally enter the interior of the building from the courtyard or a shaded area outside, although there are several other options. Internal barriers to air movement have to be minimised, either by an open plan design or by adequate internal venting between rooms and corridors. And there are practical limitations as to the size and geometry of the space that can be adequately vented by the stack effect or a solar chimney on its own.

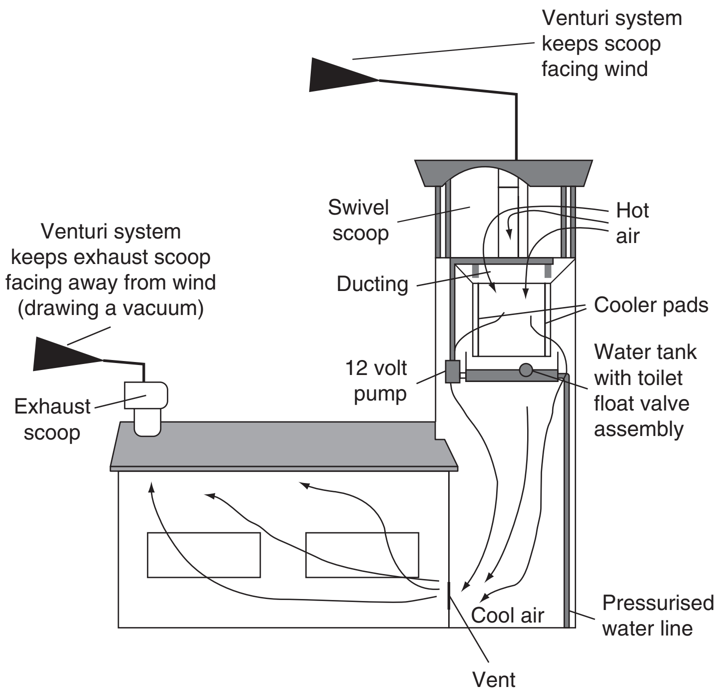
Large public buildings right up until the nineteenth century not only had much greater thermal mass than most of their modern equivalents, but were often built with a network of ducts below their ground floor slabs which were filled with ice in summer, ice cut from lakes and ponds in the winter and stored in insulated ice houses until needed. Natural convection and/or a solar chimney were used to draw air over the ice and into the public spaces. This would hardly be an economic solution today, but other early techniques are more promising. One is to use the suction effect of the solar chimney to draw air down through a **cool tower** at the opposite extremity of the building.



Basic cool tower design

Cool towers have their roots in antiquity as well. They resembled solar chimneys but were filled with porous water jars which cooled the air as water evaporated from them. The cool, dense, humid air sank down into the building, pulling in warmer, dryer air from the top of the tower. Early modern equivalents used pressurised mains water to spray a fine mist down from the top of the tower, which had to be relatively tall to be effective. Variations on this system – also known as **passive downdraught evaporative cooling** – have been used on a number of more recent multi-storey buildings. More common are cool towers that use special fibre pads kept moist by a header tank arrangement, although most installations also use a small electric pump (discussed in Chapter 13). Solar chimneys have also been found to be less efficient at promoting the essential airflow than rooftop exhaust venturis coupled with an air scoop or **windcatcher** at the top of the cool tower. Naturally, cool towers and other **evaporative cooling systems** only work well where ambient humidity levels are low, and are dependent on an unrestricted water supply. Cool towers prefer rainwater, as a high dissolved mineral content in the water can soon clog the system.

Decorative fountains located close to the inlet of a ventilation system can also contribute to building comfort. Evaporative **cooling ponds** can be very effective if properly designed, either located adjacent to the building close to the intake point for the cooling air, or even on a flat roof. A strong loadbearing structure is needed for rooftop ponds, but if the structure is reinforced concrete it can act as an effective thermal mass heat sink. In its simplest form the pond – usually between 300 and 150 mm deep – is encouraged to lose heat by evaporation at night, cooling down the slab significantly. During the day the pond is protected against solar gain by floating insulated covers. Other versions use permanent shading to minimise



Advanced cool tower design

solar gain, allowing the pond to function during the day as well, although this obviously consumes more water. In all cases a good airflow across the surface of the water is needed to accelerate the evaporation process; so care must be taken in detailing the surroundings to take advantage of the prevailing winds. Trees close by can not only block wind flows but also radiate heat back to the pond, compromising its efficiency. Sometimes a fan or fans are the only answer, and are also useful during calm periods.

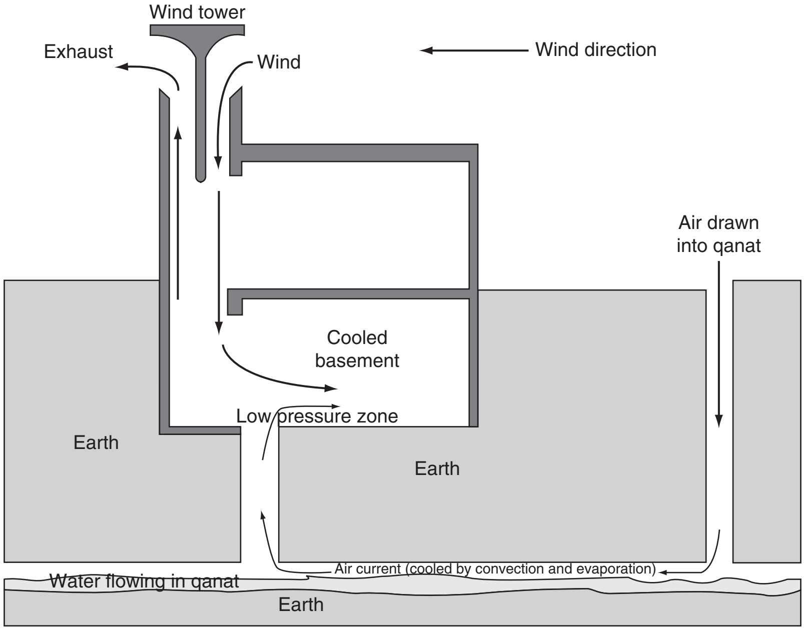
Air ducts or channels can be incorporated in the slab to encourage internal air circulation: water can circulate to floor slabs below by thermosyphonic action through cast in pipe networks. Some designs position a cooling pond on top of a water wall (see Chapter 3). Evaporative cooling can be very cost-effective – provided there is a suitable and reliable water supply – and more sophisticated active systems have been used successfully on large projects (see Chapter 13). Care must be taken to minimise the risks of legionella disease (legionellosis), see Chapter 2, and those of condensation within the building interior.

Windcatchers (**badghirs**) and **wind towers** have been a feature of Middle Eastern architecture for many centuries. Both operate on the same principle – that air will flow into an opening facing into the wind because it will be at a higher pressure than the air inside, but will be extracted from an opening facing away from it, due to the lower air pressure downwind of any obstruction. In its most basic form a windcatcher is no more than a uni-directional fabric or sheet metal scoop that can be rotated into alignment with the wind, to either suck air out of a building or conduct fresh air into it. A bi-directional windcatcher can perform both roles at the same time. Most developed versions are multi-directional and static: square shaped in plan with openings on each vertical face and adjustable vents or

Unidirectional windcatchers can be striking architectural features (Reproduced with permission from Arup – Mike Rainbow)

dampers. Cool night-time air is captured and exchanged for warm; the heavy structure of the traditional building is cooled down ready for the day. Extractive windcatchers were also used to draw in cool, humid air from underground water channels below the buildings – qanats.

Windcatchers, like this Iranian example, have been around for centuries (Reproduced with permission from Fabienkahn)



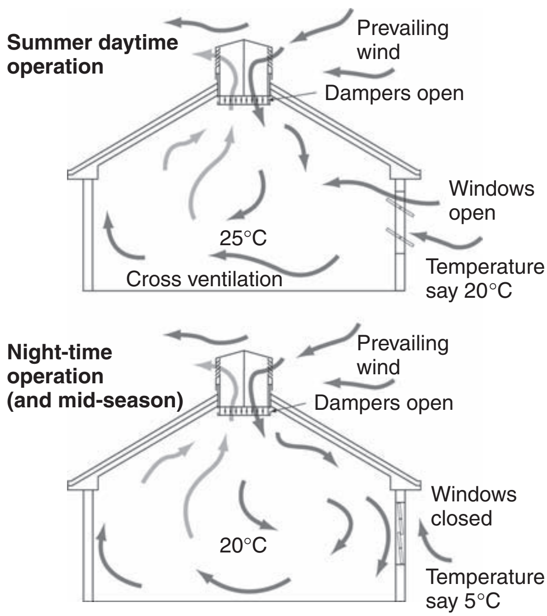
The ultimate in mediaeval passive cooling – windcatchers and qanats

Modern multi-directional windcatchers are a well-developed option (Reproduced with permission from Monodraught)

Windcatchers have an advantage over solar towers because they can operate just as efficiently at night. Even in windless conditions ventilation will continue, driven by the stack effect. Modern variants use temperature- and time-sensitive electrically operated dampers to control flow in and out of the building (discussed further in Chapter 13). All such systems depend on consistent airflow across the building – trees or other buildings close by can seriously compromise their efficiency. The same limitation applies to wind-driven extractive fans, of which several types are on the market. Perhaps the most sophisticated of these is the award-winning **VAWTEX** design developed by Arup, Zimbabwe, and now in use on a number of major buildings in Europe as well as Africa. VAWTEX uses a twin blade Darrieus-type vertical axis wind turbine for power with a central spiral Savonius turbine to ensure self-starting (see Chapter 5), stands 3 m high, self starts when wind speed exceeds 1 m/sec and was first used as part of a passive heating/cooling system based on underground thermal stores (see Chapter 15).

VAWTEX wind-powered extraction units (Reproduced with permission from Arup – Mike Rainbow)

Night-time cooling of the building fabric works best where there is a large diurnal temperature range. Ideally, night-time temperatures should be below 20°C. There should also be some form of thermal store in the system: most commonly this is a heavy concrete floor slab or slabs, but basement level rock bins or gravel beds have also been utilised. **Phase change materials** (see Chapter 15) can also be used to increase the thermal storage capacity of traditional construction. Simply opening windows wide after ambient temperatures fall can be enough to make a significant contribution to occupant comfort the next day. Cool night air removes the heat stored up during the day, lowering the temperature of the thermal store ready for the next day. Again, in some circumstances there may be the risk of condensation on the surfaces of the thermal store.

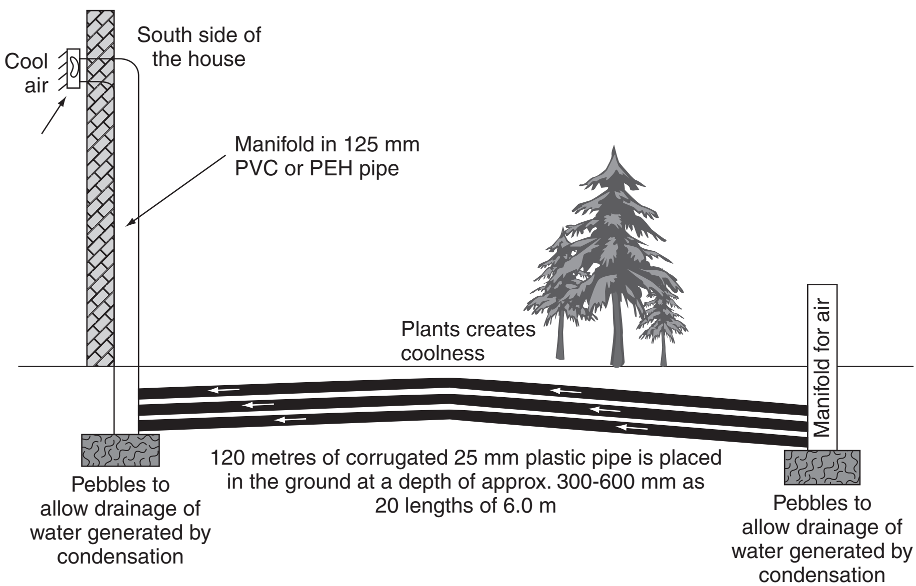


Modern windcatchers in action (Reproduced with permission from Monodraught)

Opening windows may be an undesirable option for reasons of security or noise pollution, so windcatchers or other forms of venting may be preferred. It is important that the cool incoming air is maintained in close contact with the thermal store. Exposed soffits on concrete floor slabs are the norm, coffered or sinusoidal profiles are usually adopted to maximise heat transfer area. Some active cooling systems go further (see Chapter 13), with internal ducts in the slab or other measures to promote effective heat transfer.

An alternative approach is the totally passive US **Skytherm** system, which uses plastic water-filled bags resting on a corrugated structural steel roof deck, and removable insulated covers. This bears a superficial relationship to rooftop cooling ponds (see above) but no evaporation takes place. The water bags act only as a thermal store. With the insulated covers in place during the day, the water absorbs heat from the occupied space below and stores it until night falls. Then the covers are removed, and the bags radiate heat into the night sky. The cooling effect is most obvious in areas where clear night skies are the norm. Generally, most installations have been on the domestic scale and have relied on manual removal and replacement of the insulated covers.

Solar chimneys, windcatchers and wind-powered extractive fans can be used to draw outside air into the ground floor or basement of a building through **earth tubes**, also known as **ground coupled heat exchangers** – usually thin walled metal or plastic pipes buried at least 2 m deep around the building, although standard concrete drainage pipes have also been used successfully. In summer, at that depth soil temperatures are significantly lower than ambient air temperature, so the system yields cool air throughout the day and night as long as stale, warm air is leaving the building at higher levels. In areas with high ambient humidity levels condensation inside the tubes would be inevitable, so most designs set the tubes at a downward slope towards the building and direct any condensate into a basement level drain. Provision for regular cleaning and sterilisation of the tubes would have to be made. Intakes at ground level would have to be rugged and regularly maintained.



A commercially available earth cooling tube installation (Reproduced with permission from SolarVenti)

Two-stage passive cooling has also been tried. During the day, air flows first through a night-time cooled thermal store, usually either earth tubes, rock bins or a gravel bed, and then into a cool tower. When night falls the water is turned off. A windcatcher or solar chimney drives air movement. Most two-stage systems use fans to drive the circulation and powered evaporative coolers (see Chapter 13).

Whatever the overall level of technology adopted, passive cooling techniques will always be worthy of consideration. Architectural freedom need not be compromised; structural efficiency should not be affected. On large or particularly complex projects passive cooling may be inadequate on its own. But as part of an overall environmental management package, passive cooling can make an important contribution towards lower energy demand.

Passive cooling solutions can be the most cost-effective (Reproduced with permission from Monodraught)

9 Active solar water heating

As described in Chapter 2, passive solar water heating systems have the merits of simplicity and are usually reliable. These benefits, however, come at a price. The systems are inflexible in that they need the hot water storage or heat exchanger to be positioned above the solar collectors, and they are difficult to integrate with other forms of alternative energy technologies.

Water-based active solar water heating systems use pumps to circulate the heat collection fluid between solar collector and thermal store. This gives much greater flexibility in the location of thermal stores and heat exchangers, and in the integration with other alternative energy technologies. In higher latitudes, for example, the most cost-effective use of solar collectors in a particular location could be achieved by using them to preheat the feed water to a boiler burning biomass (see Chapter 11); and, as the electrical power consumption of the pumps is relatively small, this can often be supplied by solar photovoltaics.

Several manufacturers supply so-called '**zero-carbon**' integrated solar water/solar PV systems for the domestic market. However, generally these still depend on back-up electric immersion heaters or gas-fired boilers for when hot water demand exceeds solar supply.

With pumped systems it is possible to position the solar collectors in the most convenient location, which is often the roof of the building. Indeed, systems exist in which the entire south-facing slope of a roof is effectively one giant solar collector, with integrated solar hot water panels and PV panels, and often roof windows as well, all forming part of the building envelope and replacing conventional tiles or cladding. Collectors can also be integrated into the façade (see below).

Variable speed pumps add extra sophistication, especially to direct systems using potable water straight from the storage tank (see Chapter 2). Often powered by solar PV panels, the pumps run slower on cold mornings in winter, when the demand for domestic hot water is at its peak. The potable water will spend longer in the collectors, absorbing more of the available energy and reaching a higher temperature than it would if it flowed through at a fixed compromise rate. This hotter water then can be added to the top of the tank, where it will float on the cooler, denser water below – a process known as stratification – and be readily available for use. Bright summer sunlight speeds the pump up, so that the water spends less time in the collectors and is less likely to reach dangerously high temperatures.

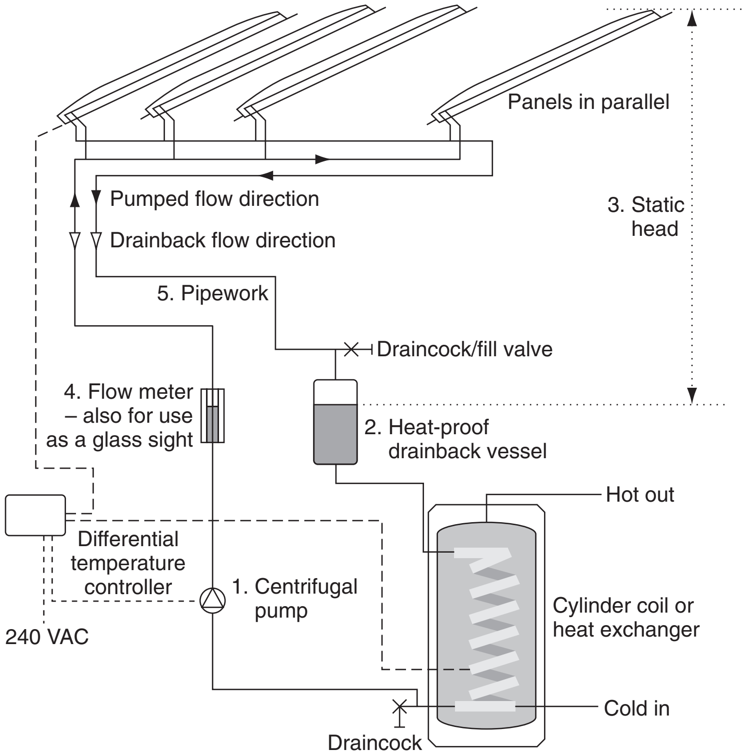
Low flow systems are offered for indirect domestic installations. These use microbore copper piping to carry the heat transfer fluid through the collectors and back into the heat exchanger. Advantages claimed include a much-reduced loss of heat from the primary loop – up to 50% – and a significantly reduced power demand for the circulating pump, typically 3 W as against 50 W or more in a conventional domestic installation. This makes it easier to power by integrated solar PV cells. Temperature rise in the heat transfer fluid as it passes through the collectors is said to be much higher – 30°C as against 3°C – but obviously the quantity of heat transferred to the storage tank will not be significantly greater, as the volume of heat transfer fluid will be smaller.

All active solar water heating systems use a more or less sophisticated electronic controller. In its simplest form the controller simply monitors the temperature difference between the fluid in the solar collectors and the water in the thermal store/storage tank, and switches the pump on when the former is a predetermined value higher than the latter. More sophisticated controllers will be programmed to deal with the risks of freezing temperatures or the problems of high stagnation temperatures in the collectors on sunny summer days, when available solar energy is at its peak but hot water demand is low (see Chapter 2). On larger installations this control function will almost certainly be integrated into a more complex building environmental management system.

Active solar water heating systems adopt a number of ways of dealing with high stagnation temperatures. The most simple and reliable is the **drainback** system, most commonly used on indirect installations with distilled water in the primary loop. When the temperature in the thermal store reaches its safe limit the controller will shut the pump down, allowing the circulating fluid to drain back into either a separate, insulated tank or the thermal store itself, to be replaced by air. This drainback principle can also be used to protect the system during sub-zero temperatures, although in areas where prolonged frosts are increasingly rare, burst-proof polymer piping could be a more reliable option. Drainback systems also depend on the collectors being far enough above the thermal store for drain back to occur reliably, but they do eliminate the need for expensive heat transfer fluids with antifreeze – distilled water is often used instead.

Stagnation temperatures in closed loop indirect systems without drainback can be as high as 200°C above ambient. This can raise the pressure within the primary loop to dangerously high levels. Such systems are normally protected by safety valves, set to release when pressures reach either 3 or 6 bar, and expansion tanks. Dependence on safety valves implies enhanced maintenance costs. Drainback systems, which typically operate at around 0.5 bar, would seem to be inherently safer, anywhere the collectors can be positioned well above the drainback tank.

Some active direct solar water heating systems actually reverse the flow during cold weather, sending a small quantity of warm potable water through the collectors to prevent them freezing. However reliable such recirculating systems might be, there is an inevitable loss of energy during recirculation; so overall efficiency is compromised. However, systems now coming onto the market that use flexible stainless steel tubing surrounded by high-density foam insulation within an expandable aluminium outer casing, in conjunction



Typical large-scale drainback indirect solar water heating system

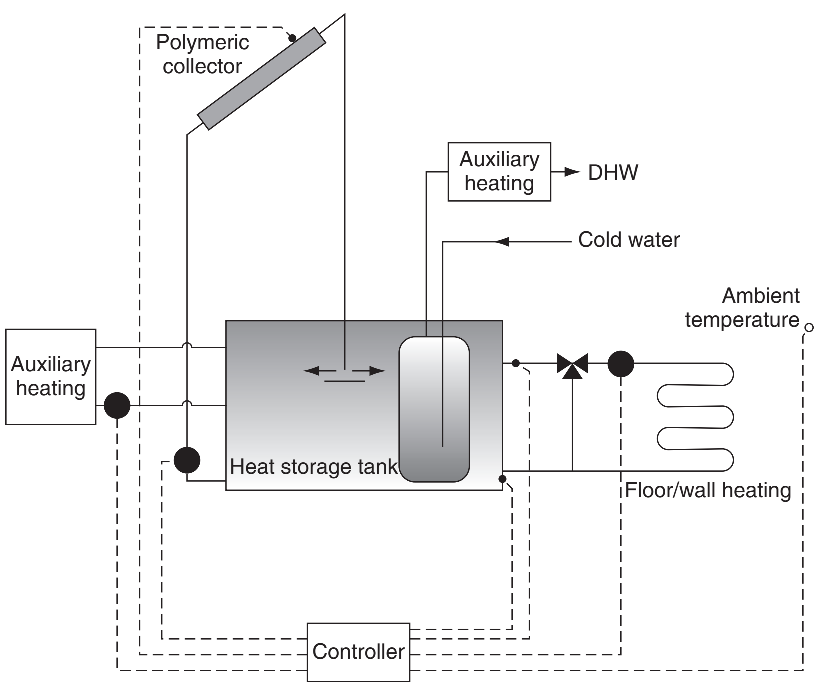
with hot water recirculation to protect the collectors, would seem to offer an attractive combination of ruggedness and low-maintenance costs – the reduced heat losses through the insulated pipework is said to more than make up for the small amounts of heat needed to keep the collectors frost free.

Well-insulated pipework and warm water recirculation is a new alternative to antifreeze in solar water heating installations (Reproduced with permission from Powertech Solar)

Involuntary recirculation can also occur on cold nights in closed loop indirect systems. As the heat transfer fluid in the collectors cools, its density increases. Gravity will tend to generate a reverse thermosyphonic flow back through the inactive pump into the bottom of the thermal store, with lower density hot water from the top of the store flowing into the collectors. Overnight much of the hot water in the store can be cooled down to levels at which the back-up heating system will have to kick in to ensure adequate hot water supplies in the morning. This waste of energy can be prevented simply, by the installation of one or more one-way spring-loaded check valves in the primary loop.

Another cold weather option for active direct systems is **draindown**. A thermostatic valve, typically set at 38°C, opens as ambient temperatures drop towards freezing, allowing the water in the collectors and exposed pipework to drain away. The problem is that in areas where frosts are relatively uncommon, the valve only operates intermittently, and if it should fail to open the water in the collectors could freeze and damage them beyond repair.

Developed in Sweden by Solarnor is a new concept in active solar water heating in which the heat transfer fluid is the water that circulates through the space heating system – either wall radiators or underfloor heating. The heated water flows first into a large thermal store that entirely surrounds a DHW tank. Some form of back-up heating is needed to ensure that both the space heating and DHW is at acceptable temperatures at all times (see Chapter 2).



Combined space heating and DHW is possible in this integrated system

Some form of easily monitored **flow indicators** are now recommended for all solar water heating installations. These soon pick up any problems, such as obstructions in the pipe network, pump failures, and leaks, and can prevent serious damage to the system. Such indicators add little to the overall capital cost. Research has also shown that the parasitic costs of the electricity used by the system should not be ignored. In one of the few exhaustive side by side tests of active solar water heating systems ever carried out – by the Energy Monitoring Company on behalf of the UK government's Department of Trade and Industry in 2001 – the parasitic costs varied enormously, with the system using solar PV panels to drive the pumps showing up best.

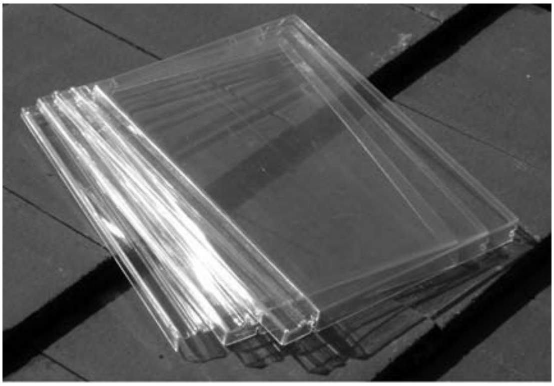
Eight commercially available domestic scale systems were set up side by side and exposed to identical solar conditions in Bedfordshire, north of London. The temperature and volume of hot water produced by each system was measured and recorded for six months. Various types of flat plate and evacuated tube collectors were involved; all but one system used conventional circulation pumps driven by mains electricity. A short power cut occurred during the trials, which caused two systems to boil, resulting in component damage. Extrapolated annual hot water production ranged from 928 kWh to 1340 kWh, extrapolated parasitic energy consumption lay between zero and 108 kWh. Evacuated tube collectors were found to be most efficient, yielding around 500 kWh/m^2 per annum as opposed to the 400 kWh/m^2 per annum of the flat plate collectors. However, the evacuated tube collectors were generally smaller, so total energy production was of the same order.

Many commercially available systems have progressed significantly over the last few years, especially in the areas of dealing with high stagnation temperatures and different patterns of demand. The focus is still largely on the domestic market; however, a number of major manufacturers can now offer sophisticated systems for larger buildings.

In order to maximise solar gain and hence supply a greater fraction of the hot water demand, including space heating, proportionally larger solar collectors are sometimes used. This could well lead to stagnation occurring more frequently in non-drawback installations. On larger projects solar gain in the collectors could be controlled by variable shading (see Chapter 2) or by the use of active collectors (see below) that can be aligned away from direct sunlight when required.

Combining the solar collectors with the building envelope, in the form of **solar slates**, **solar tiles**, **solar roofing** or **roof-integrated** and **façade-integrated** collectors can produce both cost-effective and aesthetically acceptable solutions. Solar slates and solar tiles replace their conventional equivalents on conventional pitched roofs of traditional construction. Definitions vary according to manufacturer, but solar slates are usually made of toughened glass, solar tiles of polycarbonate. They allow sunlight to pass through the roof and strike black-absorber plates fixed below, between the roofing battens. These absorbers are connected into a conventional active solar water heating system. Local planning authorities are said to look more favourably on this form of collector than on conventional panels. Thermal storage capacity must be carefully matched to the potential energy capture of the roof if high stagnation temperatures are to be avoided, or a drainback system adopted.

Toughened glass solar slates can replace an entire south-facing roof (Reproduced with permission from Solex Energy Ltd)



Translucent polycarbonate solar tiles are another option (Reproduced with permission from Solex Energy Ltd)

Replacing the entire south-facing roof of a low-rise office or factory building with high-efficiency evacuated tube collectors would normally not be cost-effective, as peak energy capture would almost inevitably be higher than the building's thermal storage could cope with. Replace expensive evacuated tube collectors with simple unglazed collectors over the entire roof area, and the equations become more attractive. Both polymeric and stainless steel solar roofing is available and, while the heat capture efficiency is significantly lower, this is compensated for by the lower unit cost, allowing it to be used economically over a much larger area. This type of collector is usually lighter, easier to install and much more rugged than conventional solar water heating panels. Aesthetically it is much less obtrusive, and a range of colour finishes is available. Stainless steel systems can also be curved for a more dramatic effect. A drainback system is probably the most practical in such applications.

Unglazed extruded polymer collectors first made their mark in the outdoor domestic swimming pool sector in the USA. The pool's standard circulation pump is used to circulate

Unglazed stainless steel flat plate collectors can be curved for architectural effect (Reproduced with permission from Energy Solaire)

the pool water through the collectors, raising water temperatures to little more than 25°C. High stagnation temperatures are unlikely, given the relatively large heat storage capacity of the pool, and outdoor pools are normally drained down and covered during the winter in higher latitudes. For such applications the low capital cost and general ruggedness of the simple collectors more than outweighs their lower heat capture efficiency. Larger, public swimming pool complexes and leisure centres also need large volumes of relatively low temperature solar heated water – for which solar roofing could be an attractive option – but they also need smaller volumes of higher temperature water for showers, space heating and so on. This could well be supplied by other low or zero carbon technologies, or a relatively small array of high-efficiency evacuated tube collectors could operate independently of the pool collectors to feed a separate hot water system.

Solarnor of Norway now offers polymeric flat plate collectors glazed with twin wall polycarbonate, although these do have an aluminium perimeter frame. Absorber plates are triple wall sheets of polyphenylene oxide/polystyrene copolymer. Low weight is one of the advantages claimed: filled with water, the imposed load from the collectors is only 8 kg/m^2. Unit cost is also low, and such collectors are being used increasingly to supply both DHW and underfloor space heating (see Chapter 10).

In winter at higher latitudes the low elevation of the sun minimises the difference in heat collection potential between inclined and vertical collectors. Architectural or planning considerations may also make inclined roof-mounted collectors less desirable. In such circumstances façade-integrated collectors may be the preferred solution. A growing range of systems is now available in Europe, in a range of colours and surface textures. Unglazed metal or polymeric collectors may replace conventional cladding. Absorbers can be positioned behind sections of visually conventional glazing. Buildings can be designed with their south-facing elevations sloped back to maximise the solar collection efficiency. The insulation that backs self-contained solar water heating panels is effectively replaced by the conventional wall insulation.

Façade cladding may be replaced by unglazed stainless steel or polymeric collectors in higher latitudes (Reproduced with permission from Energy Solaire)

Roof-integrated and façade-integrated solar collectors will effectively minimise passive solar gain all the year round. This is an obvious benefit during the summer, reducing cooling needs, but might be seen as a drawback during winter. Using solar heated water directly or indirectly for space heating (see Chapter 10) is probably more effective overall than relying on the passive solar gain of the building fabric, especially if the building is of reasonably conventional design.

The orientation of passive solar collectors is inevitably a compromise. Even when the collectors can be set up so that they face directly towards the Equator – which is not always the case – their angle of inclination is never ideal. In summer the most effective inclination can be calculated as latitude minus 15°, in winter latitude plus 15°, a 30° variation. Normal practice is to choose an inclination between these values. The obvious setting, for DHW heating at least, is the angle of latitude. This will reduce the risk of high stagnation temperatures on sunny summer days, at the cost of reduced efficiency during the depths of winter, when water heating demand can peak.

One way round this is to increase the tilt to latitude plus 15°, another is to make the collectors 'active' in the sense that their inclination can be varied during the course of the year. Such collectors can also be tilted away from the sun to reduce solar gain and hence stagnation temperatures during peak solar gain periods. This naturally increases the capital and maintenance costs of the collectors: but if active collectors reduce the use of back-up fossil fuel-generated heating and replace other stagnation temperature mitigation measures they can be cost-effective. There are also potential savings to be had from the greater overall efficiency of active collectors, not least the smaller area needed for any given end use.

Some solar PV installations use PV powered solar tracking to maximise their power output (see Chapter 4), but simply substituting evacuated tube collectors for solar PV panels is unlikely to be straightforward. In lower latitudes there are some solar power stations which use active arrays of parabolic mirrors to focus the sun's rays on evacuated tube collectors and produce heat transfer fluid temperatures of up to 300°C. These track the sun from

Conventional flat plate collectors can also be used on façades (Reproduced courtesy of Solarnor) east to west to maximise solar gain, but are expensive to maintain, and are subject to significant wind loading and vandalism risks. Potential efficiency is high, however, and ground mounted arrays, in a secure compound, could be the answer for light industrial applications.

This type of collector has been used to power large-scale solar cooling systems (see Chapter 13), although cooling systems that work well with the latest generation of evacuated tube collectors are under development. So-called **passive trackers** are now becoming available for solar PV installations and might be cost-effective for solar water heating. These use the solar-induced expansion of a low boiling point compressed gas fluid (the same principle used in glasshouse ventilation actuators) to keep the panels pointing at the sun, and viscous dampers to minimise wind shake.

Even on an installation where the collectors are basically passive and set to a compromise inclination, similar self-powered actuators could be used to tilt the collector array away from the sun when temperatures in the fluid approach undesirable levels. This could be a simpler option than similarly powered shading: the actuators, developed for the horticultural sector, are relatively cheap and reliable.

The simplest way of determining true south at any particular location is to record the alignment of shadows cast at solar noon – which is midway between local sunrise and sunset. Local sunrise and sunset times can be obtained from a number of sources, but without them, a reasonable approximation can be obtained by recording the alignment of the shortest shadow.

A simpler way of increasing the efficiency of heat collection is to use evacuated tube collectors where the individual tubes are far enough apart to minimise mutual shading early and late in the day. Several proprietary designs are available. A recent development is the **optimised parabolic collector** – basically a series of evacuated tube collectors suspended above rows of modified parabolic reflectors. These are claimed to maximise solar capture early and late in the day, and during the winter months.

'Oversizing' the collectors may be necessary if they are shaded for part of the day by nearby features such as other buildings, trees or high ground, or if the orientation is significantly different from the ideal.

Problems with high stagnation temperatures and winter freezing disappear if air is used as the heat transfer medium (see Chapter 3). Solar air heating is mainly used for space heating, but the addition of a suitable heat exchanger can produce a combined space and DHW heating system. Various forms of solar roof or façade-integrated collectors are normally preferred to traditional TAPs (see Chapter 3), when this type of system is chosen. Most heat exchangers use the finned tank principle – a double skinned water storage tank with fins in the cavity over which the hot air is blown. Some integrated systems recover hot air from attic spaces and use this as supplementary heating for the DHW system.

Using air as the heat transfer medium will reduce the risk of legionellosis (see Chapter 2) but not eliminate it. Precautions must still be taken.

Used DHW from showers, baths etc. still contains useful energy. This is usually lost as the DHW goes to waste – and even when it is stored as 'grey water' for flushing toilets and garden irrigation, the energy it contains is usually no more than an undesirable factor, as it encourages bacterial growth in the storage tank. Installing a heat recovery system in the waste pipe or a heat pump in the grey water storage tank can be an attractive option. Recovered heat is transferred to the building's thermal store.

Thermal stores are central to the success of active solar water heating installations. With a large enough thermal store a very high proportion of a building's DHW needs can be met by solar power alone. The larger the thermal store the more efficient it becomes. On new-build projects with significant DHW and/or space heating demands, active solar water heating is almost always going to be a realistic option. The technology is well established, there are many competing systems on the market and there is adequate practical knowledge of operation and maintenance needs.

This page intentionally left blank

10 Active solar space heating

Adding pumps or fans to passive solar water or air heating systems can greatly increase their overall efficiency and sophistication, at the expense of greater capital and running costs and lower reliability. Active solar space heating systems can take full advantage of thermal store possibilities to significantly reduce the need for back-up space heating. More solar heat can be utilised for longer periods, and extremes of temperature can be mitigated more effectively.

Active solar water space heating is not yet a fully established technology, compared to solar-heated DHW. The first generation of solar water heating systems were usually retrofitted to individual dwellings, which normally had limited potential for really significant reduction of their space heating needs through upgraded insulation, etc. Practical considerations limited the size of the hot water storage that could be retrofitted, and hence the actual solar collector area used was relatively small; only a fraction of the roof area, for example. And for most installations the temperature of the water in the thermal store during cold weather was lower than that at which conventional radiators are efficient. In such situations it made perfect sense to use solar heating for DHW only – and even then a conventional back-up heater was invariably installed as well. Space heating relied on other technologies, from woodburning stoves to gas-fired boilers.

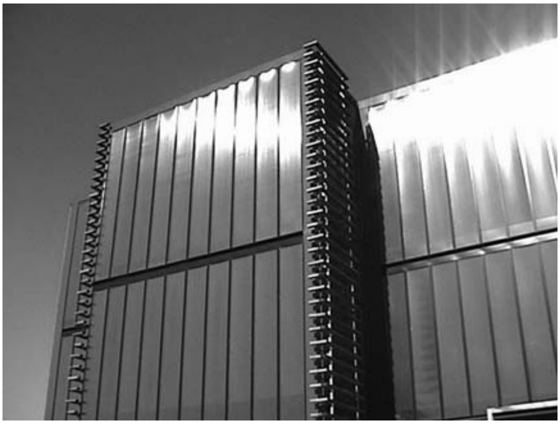
As low energy construction technology developed, however, the potential to use solar-heated water for space heating in new buildings increased. Improved solar collectors (see Chapter 9) and cost-effective large thermal stores (see Chapter 15) made it possible to utilise a much higher fraction of the sun's energy to heat water to higher temperatures. This increased energy availability could be used to either increase the proportion of DHW heated by solar gain to 100% right through the year or to provide a significant proportion of both DHW and space heating demand. Using lower temperature underfloor heating pipes rather than conventional wall-mounted radiators is also a practical option on new buildings.

Even with well-insulated buildings that make maximum use of passive solar gain, heating enough water to provide both DHW and space heating will require a significantly larger solar collector area. Planning and/or aesthetic considerations would normally dictate the choice of either some form of solar roof, solar slates or tiles or façade-integrated

Underfloor heating is suitable for the largest buildings (Reproduced with permission from Nu-Heat UK)

collectors when solar water space heating is to be provided. Where visual intrusion is not an issue, a roof-mounted array of conventional flat plate or evacuated tube collectors might be preferred. The closer to true south the collectors face the better; the usual advice is to tilt them to latitude plus 15° to maximise heat gain during winter.

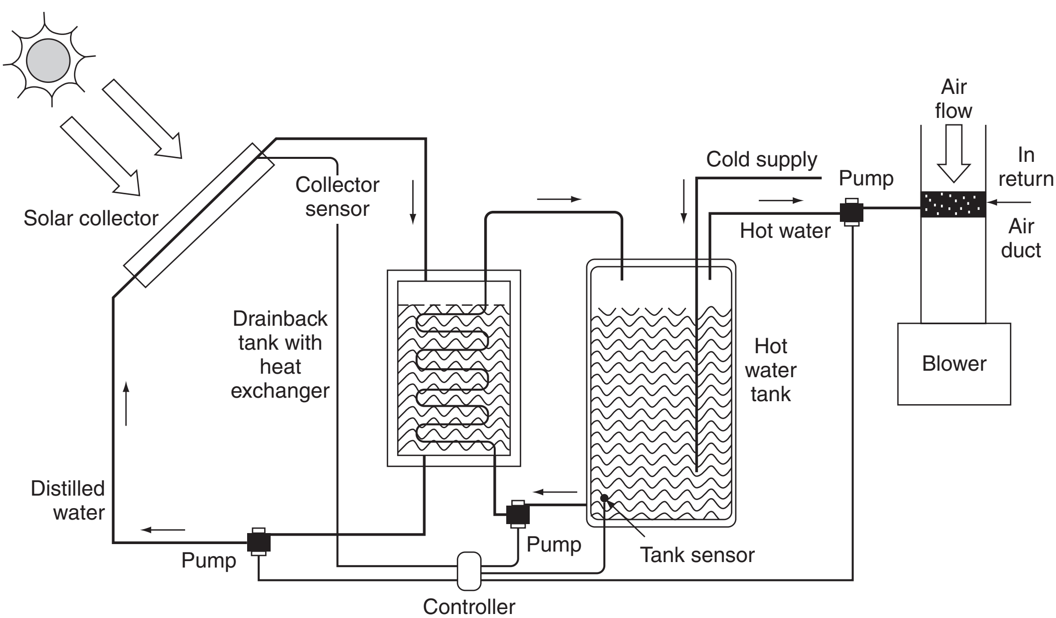
Tall buildings have a relatively small roof area and a high surface to volume ratio. In situations where current or future shading from adjacent buildings is judged to be no problem, **façade-integrated collectors** would be the obvious choice, and could almost certainly capture enough solar energy to provide a very high fraction of the hot water needed for both DHW and space heating. Tall buildings often have deep basements, where a large thermal store could be conveniently located.



Façade-integrated collectors could be the best choice for solar water heating on tall buildings (Reproduced courtesy of Solarnor)

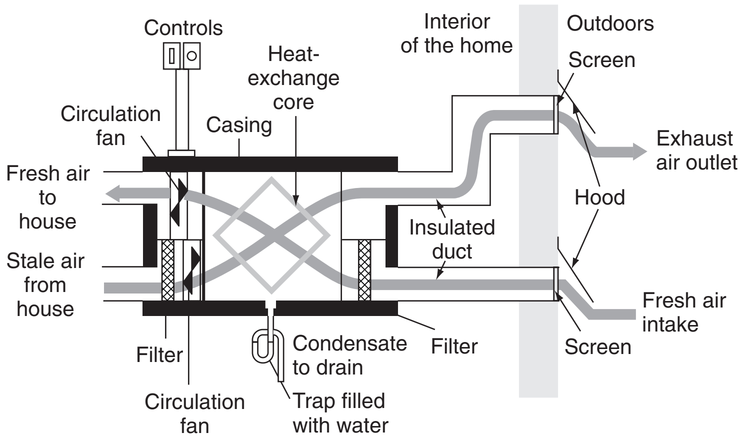
Active direct solar water systems (see Chapter 9) can be used for space heating. The heat transfer fluid circulates through the collectors, into an insulated thermal store, then through the radiators or underfloor heating network. A secondary loop allows back-up heating as needed. This system could be kept completely separate from the solar DHW heating system, or they could be integrated, with the DHW heated by some form of heat exchanger in the space heating storage tank. Some systems, often known as **solar combisystems**, take elaborate measures to promote stratification within a common thermal store. DHW is drawn off from the upper, hotter part of the tank; space heating uses the cooler water lower down. A completely separate space heating system has the advantage that the collectors can be drained down in summer.

However, active indirect systems are the normal choice. A heat transfer fluid carries energy from the collectors to a high temperature thermal store. DHW and space heating water pass through independent heat exchangers in the thermal store. Stratification is often utilised as well. Several pumps and a sophisticated electronic controller are needed, and most thermal stores will normally have to be positioned at ground or basement level because of their weight. At the time of writing, it is unlikely that a conventional thermal store large enough to provide more than 50% of both DHW and space heating needs throughout the year would be economic for an individual dwelling, even if space could be found for it. On the larger scale, however, the calculations could well be more positive. And there is the added bonus that all elements of such a system are well developed, and that a number of specialist manufacturers in Europe and North America can supply modular packages offering a choice of technologies, including warm air heating.



Solar space heating system using solar-heated water/air heat exchanger

Modern low energy buildings usually need constant ventilation to maintain internal air quality, as they are deliberately made as airtight as possible to prevent warm internal air leaking out through the building envelope. In terms of energy efficiency, however, allowing warm stale air to leave the building through a simple ventilator is no better than losing it through gaps around windows and doors. Some form of **heat recovery ventilation** (**HRV**) or **energy** (**or enthalpy**) **recovery ventilation** (**ERV**) is the obvious solution, and many proprietary systems are available. HRV technology is based on straightforward heat exchanger principles that extract heat from the outgoing stale air and transfer it to the incoming cold air. ERV units also transfer humidity from outgoing to incoming air, maintaining internal humidity at comfortable levels.



Principles of a heat recovery ventilator

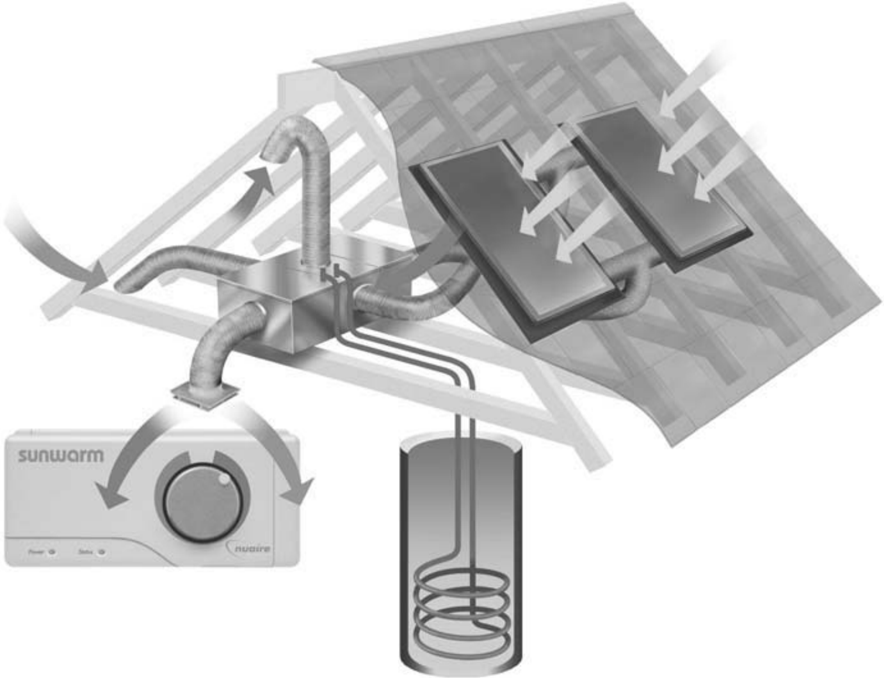
Air entering an HRV or ERV system must be above freezing point or there is a risk of ice forming. One way round this – used in Europe – is to draw the air first through **earth ducts**. These are smooth large diameter plastic or metal pipes buried at least 1 m below ground level, where temperatures rarely drop below 7°C. Such systems can also work 'in reverse' in summer, to pre-cool incoming air and reduce its humidity (see Chapter 8). Regular maintenance is required, especially for ERV units. Mains power is almost universally used.

Heat that would otherwise go to waste can be recovered from a number of sources. Domestic hot water often goes down the drain only a little cooler than when it left the thermal store. Passing it through a heat exchanger before it goes to waste is an obvious option. The recovered heat might be returned to the diurnal thermal store directly, or be used to preheat mains water entering the diurnal thermal store, or go to a seasonal thermal store outside the building.

There are some very simple ways of improving occupant comfort by recirculating warm air. One of the most basic just recirculates the warmer air from attics, with the intake immediately under the peak of the pitched roof. This air has normally been heated by a combination of solar gain and heat rising from the rooms below, and is normally no more than a supplement to another form of space heating system. Only effective where the loft insulation is immediately above the ceiling of the rooms below – and the underside of the roof proper is uninsulated – the system's efficiency can be increased by the installation of very simple collectors on the underside of the roof. This is particularly effective when the roof is dark-coloured; natural slate is a prime example.

A simple heat exchanger recovers useful energy from waste DHW

A further development is the **Nuaire Sunwarm** system, which adds roof-mounted TAPs (see Chapter 3). The hot air from the TAPs and the attic space is circulated through ducts for space heating and also provides DHW via a roof-mounted heat exchanger.



The Sunwarm warm air space heating system uses heat from TAPs and the attic, and can also provide DHW (Reproduced with permission from Nuaire)

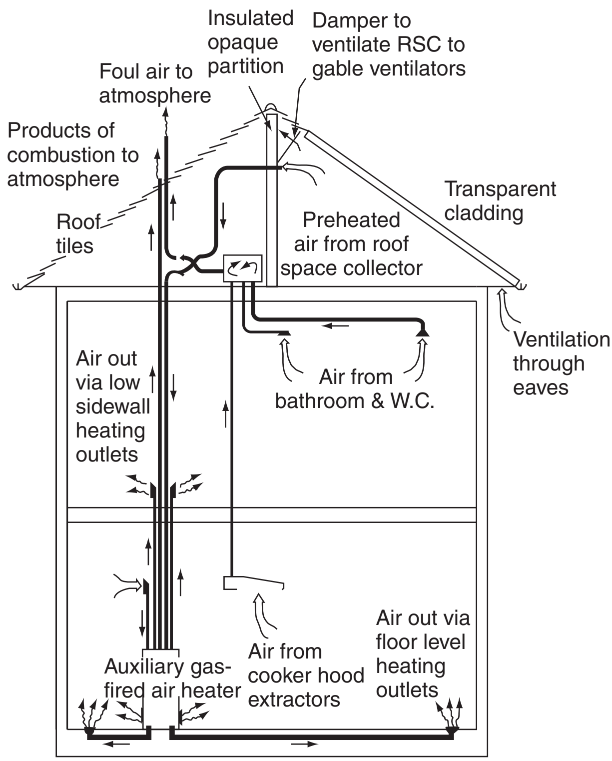
Sometimes this heated air is circulated through a gravel bed diurnal thermal store or a low temperature seasonal thermal store under the ground floor (see Chapter 15). Even simpler is a hot air recirculating system for occupied areas with no ceilings and roofs at high level – basically a high-efficiency fan is fitted below roof level to collect the rising hot air and blow it straight downwards at relatively high velocity, back to occupant level. Air below a well-insulated roof is typically 5°C warmer than at occupant level, so significant savings on space heating costs can be achieved.

Monodraught's Heat Harvester recirculates warm air from under the roof (Reproduced with permission from Monodraught)

Adding fans and ductwork to a basic **thermal** or **Trombe wall** (see Chapter 3) greatly increases its potential efficiency. Heated air can be distributed to all sections of the building

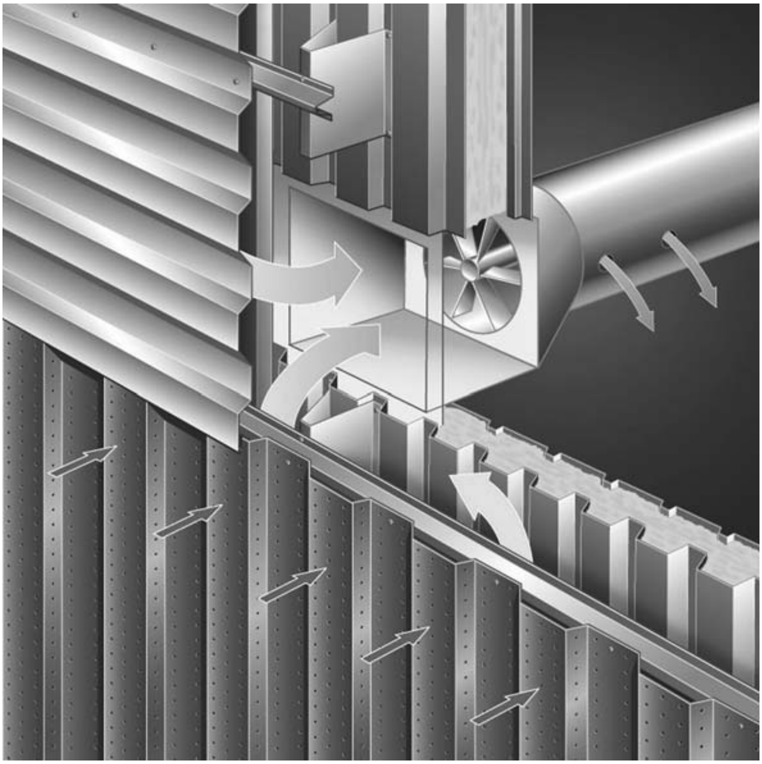
Thermosyphoning air panels offer a space heating solution for light industrial buildings (Reproduced with permission from SolarVenti) and discharged into the occupied areas at relatively low velocity through large vents, to maximise occupant comfort. Where traditional construction is preferred for dwellings, forcing air heated by a Trombe wall through the **crawlspac**e between the ceiling and the floor above converts the mass of the floor construction into a reasonably effective thermal store that will increase efficiency and prolong the comfort period.

Thermosyphoning air panels are often connected to the intake of a conventional air heater by means of ducts and fans. Another alternative is the **roof space solar energy collector**, which is essentially a pitched roof partially or fully glazed on its southern aspect. Heated air can either be distributed into the building directly or be fed to a warm air space heating system. This can be a very cost-effective option, as the preheating of the feed air can significantly reduce the energy consumption of the air heater, however it is fuelled.



Typical roof space solar energy collector space heating and ventilation system

On the larger scale, façade-integrated collectors consisting of plastic coated steel or aluminium cladding panels with around 2,500 minute perforations in every square metre are available in a wide range of colours. These, sometimes known as **transpired air collectors**, are normally mounted 100 mm away from the internal wall, and in their darker colour versions are said to be able to raise the temperature of the outside air entering the cavity through the perforations by more than 20°C. In the summer they act as a sunscreen, with the heated air discharged back to the atmosphere at roof level. Solar PV panels are often used to power the fans in this type of installation.



Transpired air collectors work well with solar PV powered fans (Reproduced with permission from CA Gro)

Simple thermal stores for solar air heating systems normally utilise gravel, and are not particularly efficient compared to water-based stores (see Chapter 15). However, in some applications – such as low-rise schools and offices – their basic simplicity and low capital and running costs can make them very attractive. The most common form is the gravel bed store, supplied by TAPs; an option that is, however, only open to new build projects. An insulated waterproof box immediately below a concrete ground floor slab is filled with clean, dry 'single size' gravel that contains little fine material that could obstruct airflow through the stones. Air from TAPs or other forms of solar air collectors is circulated through the gravel bed.

This type of installation has to be backed up by some other system of space heating, but it has the advantage of working quite efficiently with relatively low temperature air from the collectors as none of this enters the living space. The crawlspace under a suspended concrete or timber ground floor can also act as a thermal store; timber is a 50% more effective thermal store than gravel, and the ground itself can also make a significant contribution.

TAPs are available as a package with a fan driven by an integral solar PV panel. This form of space heating, particularly when combined with a rock bin or underfloor gravel bed, is much more common in the US than in Europe, for example, but is well worth considering for smaller projects. In many cases, the arguments in favour of solar-powered space heating are closely linked to the increased need for summertime cooling (see Chapter 13). Using the same solar collectors to power both heating and cooling will make a lot of sense on many projects.

Buildings with façades made up of transpired air collectors look little different to conventional structures (Reproduced with permission from CA Group)

This page intentionally left blank

11 Pyrolisation, gasification and anaerobic digestion

Even when a particular biomass material is suitable for straightforward burning as described in Chapter 7, this will not necessarily be the most efficient way of recovering the embodied energy of the biomass. Materials with naturally high moisture content in particular may well contain significant amounts of hydrocarbons and other organic materials; but drying them to a state in which they could be fed directly into a boiler is rarely either practical or economic. However, alternative methodologies are available, some of which have been around a very long time. These can transform basic biomass into more convenient fuels with a greater energy density that can burn cleaner and at a significantly higher temperature.

Wood straight from the forest is a poor quality fuel

For example, as a fuel, wood from the forest leaves a lot to be desired; timber from most species of tree needs to air-dry for a considerable period before burning, otherwise excessive smoke is produced. The moisture in the wood limits the maximum flame temperature that can be attained. Tarry residues from oils and resins in the wood clog up chimneys and flues. In the search for a better fuel, sometime in the distant past people learned how to convert tree wood into charcoal, which burned hotter and gave off much less smoke. The process of charcoal burning, crude as it originally was, was the first systematic use of what we now call **pyrolisation.**

In essence, pyrolisation occurs when organic material is heated in the absence of air. Gases and liquids are driven off to leave a purified char behind. The production of charcoal originally involved the slow combustion of part of the wood in a large pile sealed with clay or turf. Some air is needed for the process to work, but air supply is carefully restricted to the absolute minimum. Charcoal is the only end product; however, if wood is heated in a sealed container, it will yield charcoal, **tar**, wood spirit (**methanol**), turpentine, pyroligneous acid – also known as wood vinegar – and **wood gas**, an inflammable gas containing hydrogen and carbon monoxide, which can be used as fuel for the heating process. This process is also known as **destructive distillation**, and played a major role in industry for many centuries. The tar was essential to the shipping industry as a preservative coating, turpentine was a valuable solvent, wood vinegar could be refined into acetic acid and the production of steel and gunpowder depended on large quantities of charcoal. However, increasing demand caused massive deforestation, especially in Central Europe, and increasing scarcity stimulated a swing to coke and coal tar – also produced by the pyrolisation process.

Most biomass materials can be pyrolised in the absence of oxygen. All will yield similar combinations of **char**, liquids and gas – the gas is usually dubbed **syngas,** and is used as the basic fuel in most pyrolisation plants. The liquid is **bio-oil**, which can be used directly as a heating fuel, or can be processed into raw materials for pharmaceuticals or petrochemicals. Chars can also be burnt, or used as a soil conditioner and fertiliser, locking up significant amounts of carbon in the process.

Fast pyrolysis technology has been developed in the Netherlands by the **Biomass Technology Group.** At the heart of the process is the **rotating cone reactor**. Fine particles of biomass and hot sand are introduced at the bottom of the cone, and pyrolysis occurs as the reactor rotates at 300 rpm, spinning the biomass upwards. Bio-oil is the main product: the heat required comes from the separate combustion of the char produced.

A more energy efficient alternative is **torrefaction**. This is effectively pyrolisation at a lower temperature than that normally used for charcoal making, and the process can cope with a wider variety of feedstock types and moisture contents. The solid end product, sometimes known as **biocoal**, is more predictable, less prone to dusting and is effectively resistant to reabsorption of moisture when stored. It can be burned directly, or used to produce pellet fuels and barbeque briquettes, and has shown good results as a gasifier fuel (see below). An integrated process in which **airless drying** with superheated steam prepares the biomass for the high temperature stage is also available. The steam comes from the biomass itself, the heating from the gas driven off in the torrefaction process. Moisture content of the 'smokeless' solid end product is 3%, original mass is reduced by around 30% but 90% of the initial calorific value is retained.

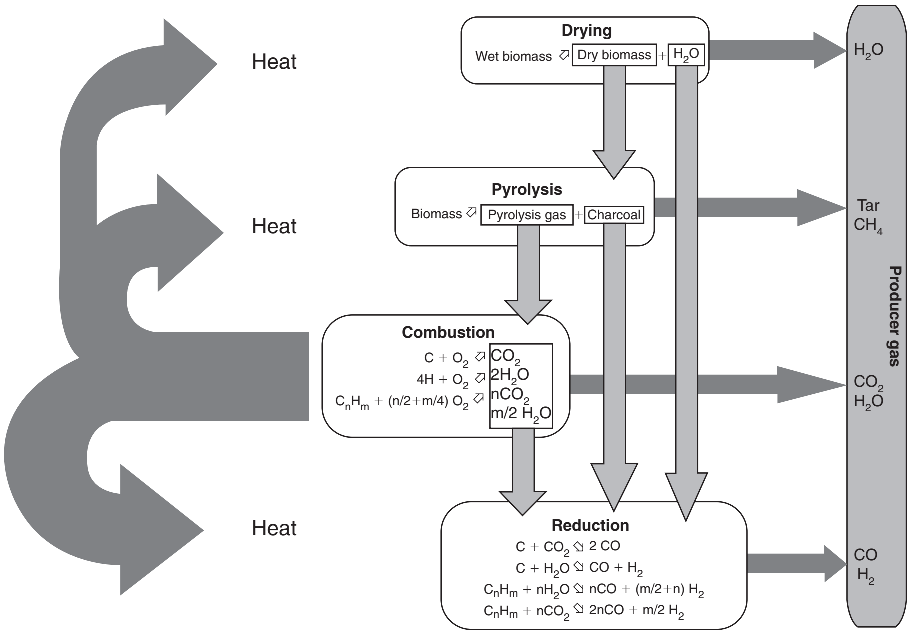
In the nineteenth century it was discovered that by admitting limited amounts of air and/ or steam to the pyrolisation chamber the volume and energy content of the gas produced

A rotating cone pyrolisation reactor (Reproduced with permission from Biomass Technology Group)

was significantly increased. A three-stage process is involved. Straightforward pyrolisation occurs first, releasing volatile liquids and gases and leaving char behind. Then combustion begins, as the volatile products (and some of the char) react with the oxygen in the air, raising the temperature and producing carbon monoxide and carbon dioxide. Finally, the char reacts with the carbon dioxide and steam – which can come from the moisture content of the biomass – to yield more carbon monoxide and hydrogen. The end product – usually known as **producer gas** – will have lesser or greater percentages of contaminants such as tars, alkalis, sulphur, ammonia, chlorine, and particulates, and may well need to be cleansed before further use.

At the beginning of the twentieth century wood or producer gas was a widely used alternative to town gas, which came from the gasification of coal. Petroleum shortages during both World Wars boosted the demand for gas as an alternative if less effective fuel for motor vehicles. Un-pressurised gaseous fuels have a much lower energy density than liquid fuels, so the near 1 million vehicles around the world that were converted to run on gas were immediately recognisable, thanks to the large inflated gas bags on their roofs. Cheaper fossil fuels in the 1950s and 1960s largely killed off interest in gasification, only for it to be revived by the 1973 oil crisis.

The terms 'producer gas' and 'wood gas' are often interchangeable, reflecting the reality that most non-coal gasification traditionally used either wood or charcoal as the raw material. Charcoal was the simplest option, as its gasification yielded the minimum of ash,



Schematic of the biomass gasification process (Reproduced with permission from Biomass Technology Group)

tars and other unwanted contaminants, but this was a low efficiency process. Charcoal production wasted at least 50% of the energy in the wood. These days, most modern gasification plants now use some form of wood, either recycled, wastes from forestry or arboriculture, or specially grown (see Chapter 7). An initial drying stage is usually included in the gasification process, unless torrefied wood or biocoal are used.

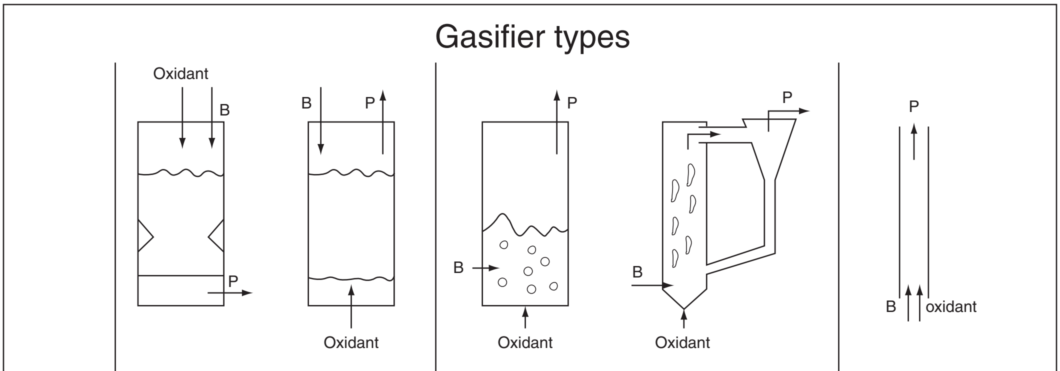
Gasification of wood is reckoned to yield around 2.5 m^3 of producer gas for every 1 kg of wood consumed – this gas will have nearly 70% of the calorific value of the original wood. Other types of biomass can be gasified and performance is similar, but experience is still limited and results are mixed. There is often a useful by-product in the form of a char that can be processed into briquettes that can replace firewood for cooking – or be used as a soil improver.

A number of manufacturers worldwide now offer a range of gasification plants. The most popular and longest established variant is the **updraft gasifier**, also known as the **counter current fixed bed** and, confusingly, **the counter current moving bed gasifier**. Biomass enters the reactor at the top, steam, oxygen and/or air is blown in at the bottom below a grate. The biomass falls down against the upward flow of the gases until it reaches the grate at the bottom. During this transit the biomass is progressively dried, pyrolised, chemically reduced and finally combusted.

For the process to work the biomass has to have significant mechanical strength and be non-caking, so that it can form a permeable bed of red hot char through which the incoming gases can flow freely. Throughput is low, thermal efficiency is high – but so is the tar content of the gas, as gas exit temperature is relatively low and condensation of volatiles is inevitable. Slag production is low. Most updraft gasifiers operate at atmospheric pressure. One interesting variation inserts a gas combustor above the gasifier, which burns the hot producer gas as it leaves. The flue gas is then piped directly to the heater head of a Stirling engine, best described as an external combustion piston engine (see Chapter 14). This in turn drives an electrical generator.

A more efficient alternative, especially in smaller sizes, is the **downdraft**, or **co-current**, **fixed bed** (**moving bed**) **gasifier**. As the name suggests, the air flows in the same direction as the movement of the biomass, which still enters from the top. Producer gas is drawn off from the bottom. Downdraft gasifiers tend to be significantly taller than the updraft alternative, and are unable to cope with very variable biomass or small particle sizes. Against this, the gas will leave at a much higher temperature, reducing the tar content, and thermal efficiency is on a par with the updraft design.

Fluidised bed gasifiers are generally much more tolerant to variations in the biomass supply, at the cost of greater complexity. The biomass is suspended in high-pressure air blasted up through a sand bed. Mixing is vigorous, with all stages of gas production taking place simultaneously. Tar content of the gas is intermediate between updraft and downdraft gasifiers, and the process is somewhat more difficult to control.

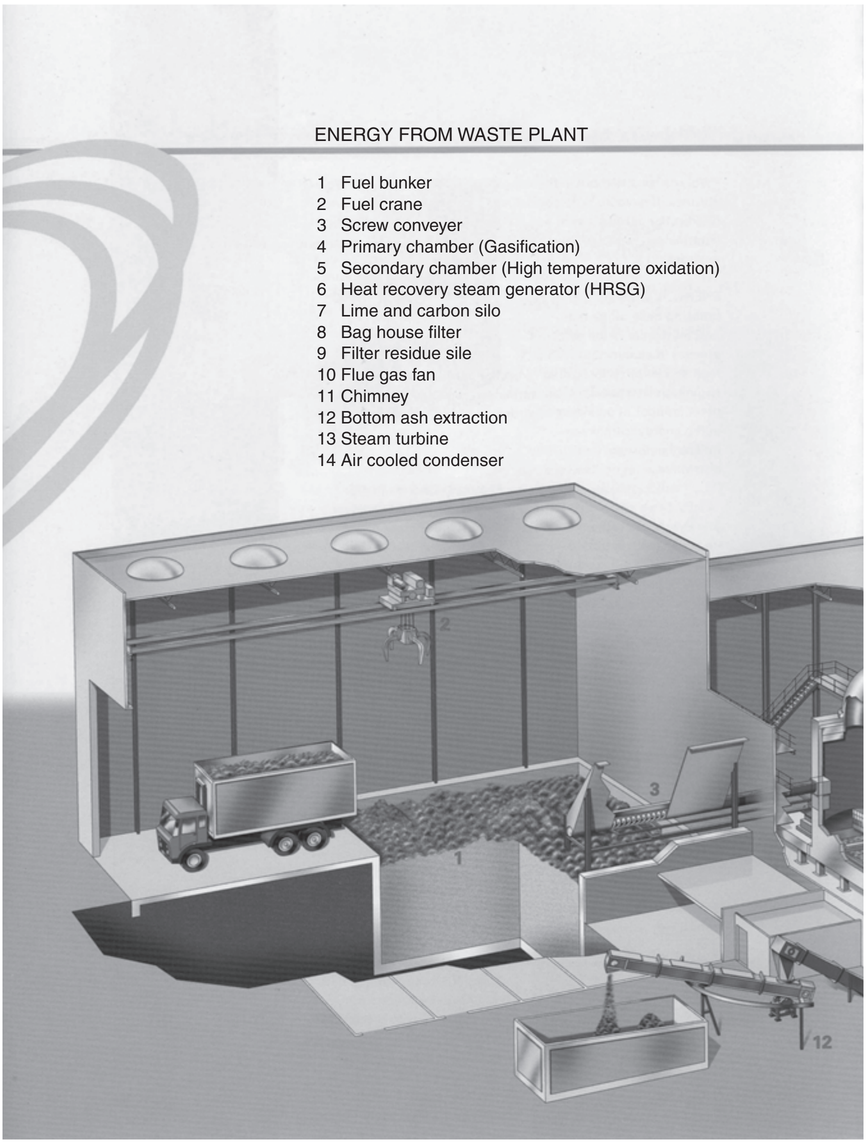


	Moving beds		Fluid beds		Entrained beds
	Co-current	Counter current	Dense	Circulating	
T°C	700–1200	700–900	<900	<900	~1500
Tars	Low	Very high	Intermediate	Intermediate	Absent
Control	Easy	Very easy	Intermediate	Intermediate	Very complex
Scale	<5 MW_t	<20 M_t	10< MW_t< 100	20< MW_t< ?	>100 MW_t
Feedstock	Very critical	Critical	Less critical	Less critical	Very fine particles

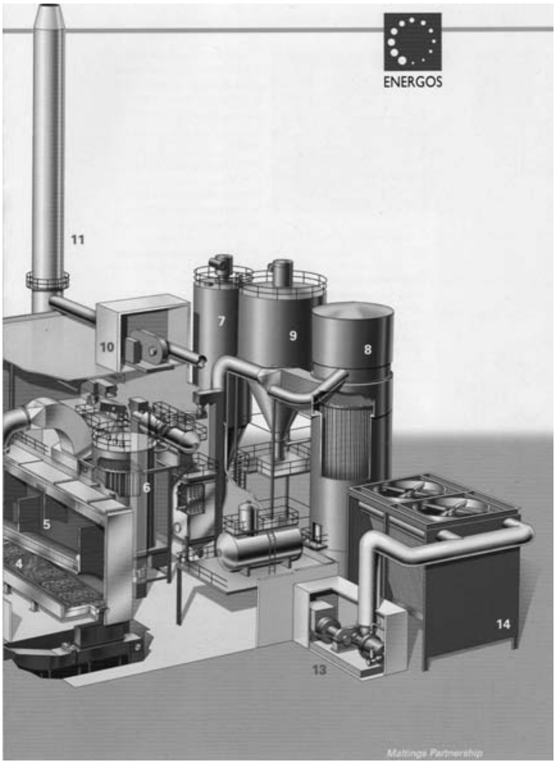
Biomass gasifiers (Reproduced with permission from Biomass Technology Group)

Gasifiers using air as the **oxidant**, or **gasification agent**, and operating at atmospheric pressure yield gas with a significant nitrogen content, which lowers its calorific value. Typically, producer gases from this type of installation will have a calorific value in the range 2.5–8.0 MJ/Nm^3. Much higher calorific values – up to 20 MJ/Nm^3 – can be obtained by using oxygen instead of air, and/or operating the gasifier at high pressure, up to 16 bar. This obviously increases the complexity of the process by several orders of magnitude. Gasification equipment is still comparatively expensive, and small-scale gasifiers are unlikely to be economic unless the biomass supply is effectively free.

Raw producer gas may be burnt in furnaces and boilers without further treatment, and this is perhaps the best route where the biomass/gasifier combination used yields gas with a high tar content. The heat produced can be utilised for a wide range of purposes.



Generating energy from biogas is now an established technology (Reproduced with permission from Ener-G, www.energ.co.uk)



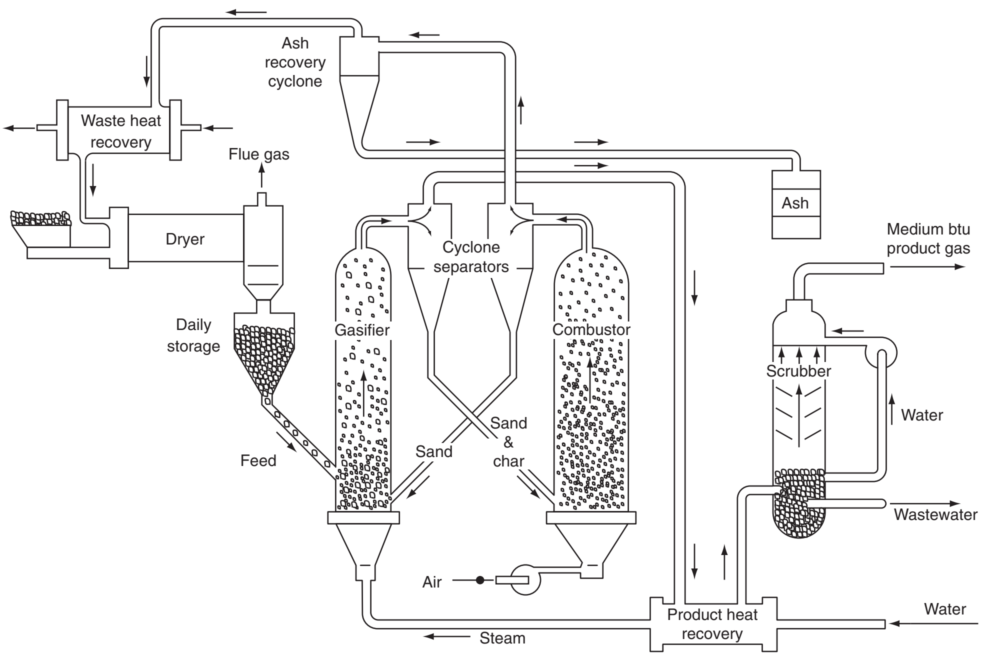
Continued

Normally the raw gas will be cooled before storage/use, to increase its energy density. Electricity generation using producer gas is said to be around 20% more efficient than generation based on the direct combustion of biomass. The concept of using producer gas to fuel a cogeneration (combined heat and power) plant has been attracting a lot of attention, as this promises overall thermal efficiencies of more than 80%, as compared to direct combustion's 60%. On the smaller-scale, this usually involves converting the chemical energy of the producer gas into electrical energy by using it as fuel in some form of internal combustion engine, which then drives an electricity generator (see Chapter 14). The problem is that most internal combustion engines demand a very clean gas to function effectively, so that tars in particular must be removed before the gas is acceptable.

This has proved to be the Achilles' heel of many pioneering gasification installations used for cogeneration. Moisture content of the gas is fairly easy to control; if the preliminary drying stage takes the initial moisture content of the biomass to below 20%, the moisture content of the gas leaving the system is usually acceptable. Dust is normally removed through a combination of filters. The tars or condensates are a much bigger challenge, and work continues on the development of a reliable, cost-effective and energy efficient tar removal system.

In the USA there has been significant progress in using plasma torches to raise the temperature within a classic downdraft fixed (moving) bed gasifier to 1,250°C; this 'cracks' the tars and other volatiles, reducing them to hydrogen and carbon monoxide. Any inorganic material in the biomass is vitrified; all the carbon is converted to gas, leaving no char. Other systems use a combination of high temperatures and oxygen injection to achieve the same effect. Although oxygen minimises the nitrogen content of the gas – and hence enhances its calorific value – the technology is more complex and expensive and still not fully developed.

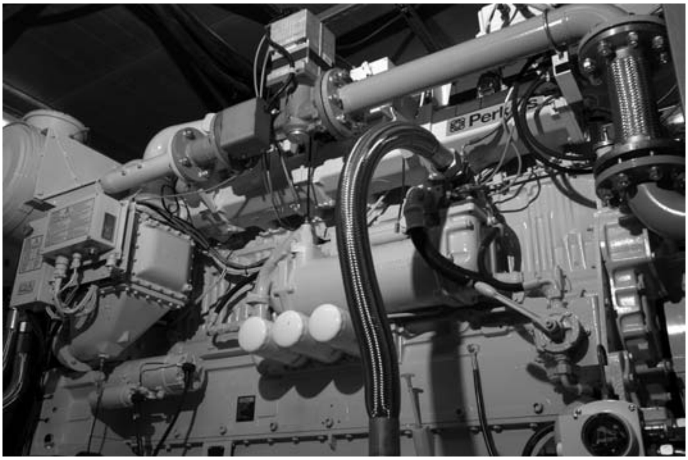
An alternative approach is adopted in the **Batelle/FERCO** process. No oxygen is used. Instead there are two, physically separate, reactors. Dried biomass passes first into an updraft gasifier, then the residual char passes into a second combustor, where it is burned to provide the heat for the gasification process. Heat transfer between the two reactors is accomplished by circulating sand, and throughput is said to be much higher than in other systems.



The Batelle process has a high throughput

Conventional spark ignition internal combustion piston engines, i.e. the type of engine that is mass produced, cheap, reliable and rugged, can easily be converted to run on clean producer gas. Power output drops significantly – by up to 50% – thanks to the lower calorific value of the producer gas compared to petroleum products. Producer gas can also co-fuel the even more rugged and reliable compression ignition internal combustion piston engine – better known as a Diesel engine. To ensure effective ignition, only 80% or less of the diesel fuel can be replaced by producer gas, but this, and the more appropriate lower speed of diesel engines, means that overall power drops only by about 15 to 30%. Carbon monoxide emissions can be a problem, however.

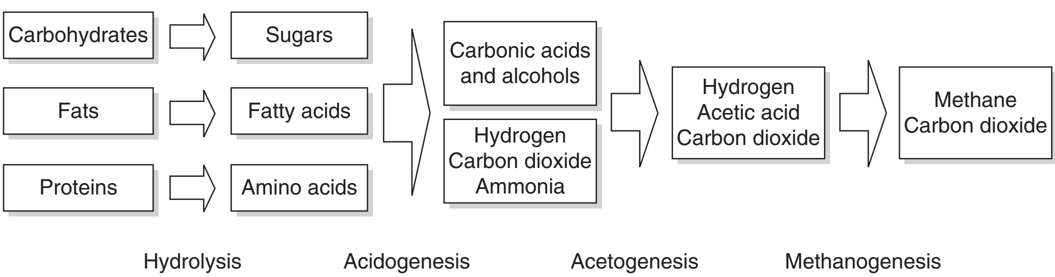
Despite their lower efficiencies, piston engines are popular because of their low capital cost, ease of maintenance and availability of spares. On larger installations gas turbines are the norm. Potential efficiencies are significantly higher, but so are capital and maintenance costs. Microturbines operating at up to 100,0000 rpm and producing between 25 and



Spark ignition internal combustion piston engines running on biogas are widely available (Reproduced with permission from Ener-G, www.energ.co.uk)

500 kW are a promising development. And for combined heat and power – cogeneration – and similar installations, the optimum choice may well be a modern version of the venerable Stirling engine (see Chapter 14).

The **anaerobic digestion** of biomass produces a much cleaner gas. Usually known as **biogas**, this is a mixture primarily of **methane** and carbon dioxide, with nitrogen content below 10%. There are no tars or other volatiles; however, some types of biomass will yield biogas with significant **siloxane** content. Siloxanes are organosilicon compounds (and when burnt release silicon), which can form abrasive deposits within internal combustion engines fuelled with siloxane-contaminated biogas. Even Stirling engines can be affected, as the deposits build up in and around the heat exchanger and are very difficult to remove.



Anaerobic digestion schematic

Siloxanes are usually found only in sewage. Anaerobic digestion has been used for many years to treat sewage sludge and animal waste, especially in the form of slurries. In many cases it yields not only biogas but also valuable by-products such as soil improvers and fertilisers – although the levels of heavy metals and pesticides have to be monitored closely. It is a basically simple process that can work on the smallest and the largest scales and needs no external power supply. Biomass with moisture contents in excess of 75% can be effectively processed. In recent years other types of waste have been tried or at least experimented with, mainly materials, such as the waste from food processing and beer and spirit production, which have moisture contents too high to make them economic for other forms of use. Energy crops such as ryegrass are also used, either on their own or as a boost to low carbon content wastes. In practice, there are two distinct types: wastes and energy crops which have negligible contents of such undesirables as heavy metals, and unsorted wastes, where the levels of contaminants are such that the residues left after digestion have no practical value and will need further treatment.

A potentially useful by-product is anaerobic digestate (Reproduced with permission from Alex Marshall, Clarke Energy Ltd)

Many different species of bacteria are needed for anaerobic digestion. They gradually break down the complex organic molecules in the biomass, first into simple sugars and amino and fatty acids, then into the simpler molecules of ammonia, carbon dioxide and hydrogen sulphide. Further digestion yields hydrogen and acetic acid. Finally, **methanogenesis** occurs, methane and water and carbon dioxide is produced. All of these reactions take place in a sealed container in the absence of air. In the most common type of digester, only limited additional heat is needed, and **mesophilic bacteria** perform the digestion. The optimum operating temperature is around 40°C, but digestion will occur over the range 20–45°C. Simple batch type digesters are sealed for up to 30 days. Biogas production peaks in the middle of this period, gradually declining as the reactive materials are exhausted. Up to 60% of the biomass will be converted to biogas.

Most modern anaerobic digesters use a continuous process with regular mixing of the biomass, which results in a much more consistent production of biogas. Even so, the biomass will spend up to 18 days actually inside the digester. Mesophilic digestion will not kill all of the pathogens that might be present in the biomass; so there is often a preliminary pasteurisation stage where the biomass is heated to at least 70°C for an hour or so. Biogas burners normally supply the heat for pasteurisation and digestion. Apart from the biogas, the process also yields a slurry known as **digestate**, which can be separated into a fibrous, compost-like material with a significant calorific value and a nutrient-rich liquid, both of which are potentially valuable products in their own right – provided the biomass used was relatively clean. Otherwise the solid residues will have to go to landfill and the liquid will need further treatment.

Thermophilic bacteria operating at 50°C or more can digest biomass much quicker, but the process is less stable and requires more added energy. In hotter climates very small batch mesophilic digesters fed with animal and human wastes have proved to be very successful without any added heat at all. There are believed to be more than 2 million such digesters in India alone, attached to individual households and supplying low calorific value gas for lighting and cooking.

Biogas can also be used directly for space heating and cooling, or as fuel for a cogeneration plant (see Chapter 14). Produced by modern digesters, its calorific value is around 20 MJ/m^3. Anaerobic digestion will not be an attractive option for many projects despite the quality of the gas it yields. The economics of very small plants are unlikely to be attractive. In urban locations particularly, all biomass technologies may run into local objections based on the need for frequent deliveries and, in the case of anaerobic digestion, the inevitable concern about unwelcome odours.

However, for the right projects (such as industrial parks) where cheap clean biomass is available locally and space for storage and processing can be found, the conversion of biomass into a combustible gas is one of the greenest options currently available. It is an option that will become increasingly practical as technology improves.

This anaerobic digestion unit in Shropshire, England, produces more than 1,600 MWh annually from 5,000 t of food waste and grass cuttings (Reproduced with permission from Greenfinch Ltd)

This page intentionally left blank

12 Air, ground, and water source energy

Heat is not the same thing as temperature. The water in a stream or well, the soil a few metres below ground level, even the ambient air, might be significantly cooler than the desirable temperature for domestic hot water or space heating use – but they still contain heat energy. If the heat from a large volume of lower temperature water, soil or air can be extracted then transferred to a much smaller volume of water or air, the temperature of the receiving water or air will be raised, even if it started out warmer than the source. One device that can achieve this desirable end is the rather misleadingly named **heat pump**, a technology that has attracted a lot of attention and development over recent years.

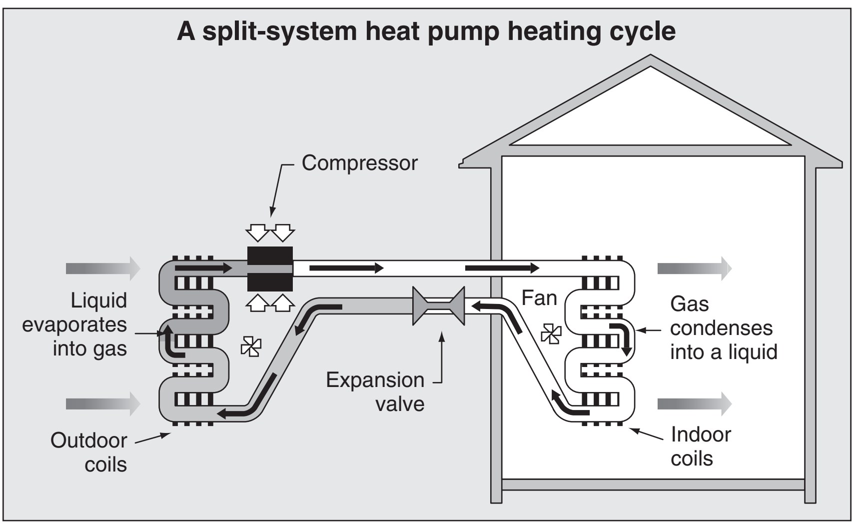
In fact, heat pumps have been virtually ubiquitous in the developed world for many decades. Small heat pumps lurk behind refrigerators and freezers, extracting the heat from inside the heavily insulated cabinets and transferring it to the air in the room. They are quiet, reliable and unobtrusive. Efficiency is high. At first glance, a heat pump might appear to defy the laws of thermodynamics; indeed, to be a virtual perpetual motion machine. It is often claimed that a typical heat pump installation can produce 3 kW of space heating (or even more) from only 1 kW of energy input, giving it an 'efficiency of 300%' (or even more).

This is a misconception. What is happening is that the heat pump is using 1 kW of energy to transfer 3 kW of energy from the ground, water or air outside the building to the interior. In its most basic form, the energy in the outside source comes mainly from the sun. However, in more sophisticated installations the ground or the water might have been topped up with surplus heat from other processes (see Chapter 15). Unlike other solar energy systems, heat pumps drawing energy from the ground and water are not weather-dependent, and so work equally well night and day. Air source heat pumps obviously are more sensitive to the weather, but ambient temperatures fluctuate much less than sunlight.

Most heat pumps are based on the same **vapour compression cycle** used for refrigeration and air conditioning, and use a compressor driven by an electric motor. This type of heat pump is sometimes said to 'replace' the energy lost in the generation and transmission of electricity over national grids. Thus the 3 kW of heat transferred to the building by the 1kW of power consumed by the heat pump equates to the 3kW of energy – mainly chemical energy from fossil fuels – that is needed to ensure 1kW of electrical energy arrives at the point of use. The missing 2kW is dissipated as waste heat and transmission loss. From the consumer's point of view, a heat pump should cost only one-third or less to run than a basic electric resistance heating system.

For those wishing to minimise their dependency on fossil fuels, an increasingly popular alternative is the **absorption heat pump**. This runs on heat rather than electricity, has fewer moving parts and usually utilises a safer refrigerant than the vapour compression alternative. Heat can be supplied from a number of sources, of which the most energy efficient is normally waste heat from an industrial process. Solar-heated water can also be utilised, especially if it comes from evacuated tube collectors. Again, there is an apparent multiplication process. One unit of heat put into the heat pump will transfer around one and a half units of heat into the building's interior. This represents a **coefficient of performance** (**COP**) of 1.5, as against a vapour compression heat pump's COP of 3 to 4 or more, and may seem comparatively ineffective. However, the potential of an absorption heat pump to provide both heating and cooling from one heat source and – with a little help from solar PV panels to drive the essential fans and pumps – to be independent of energy grids, can make it an attractive solution for some projects.

The first generation of heat pumps designed for space heating and cooling used external air as the energy source. **Air source heat pumps** are relatively cheap and simple. They are particularly effective where winters are mild and long periods of freezing weather rare or unknown. In its simplest form, an air source heat pump consists of two air-to-refrigerant heat exchangers – one outside, one inside – an expansion valve, and a compressor. The outside heat exchanger acts as an evaporator in the heating mode, absorbing heat from the air into the refrigerant. This then flows into the internal heat exchanger where it condenses, releasing heat into the inside air. Ducts and fans then distribute the heated

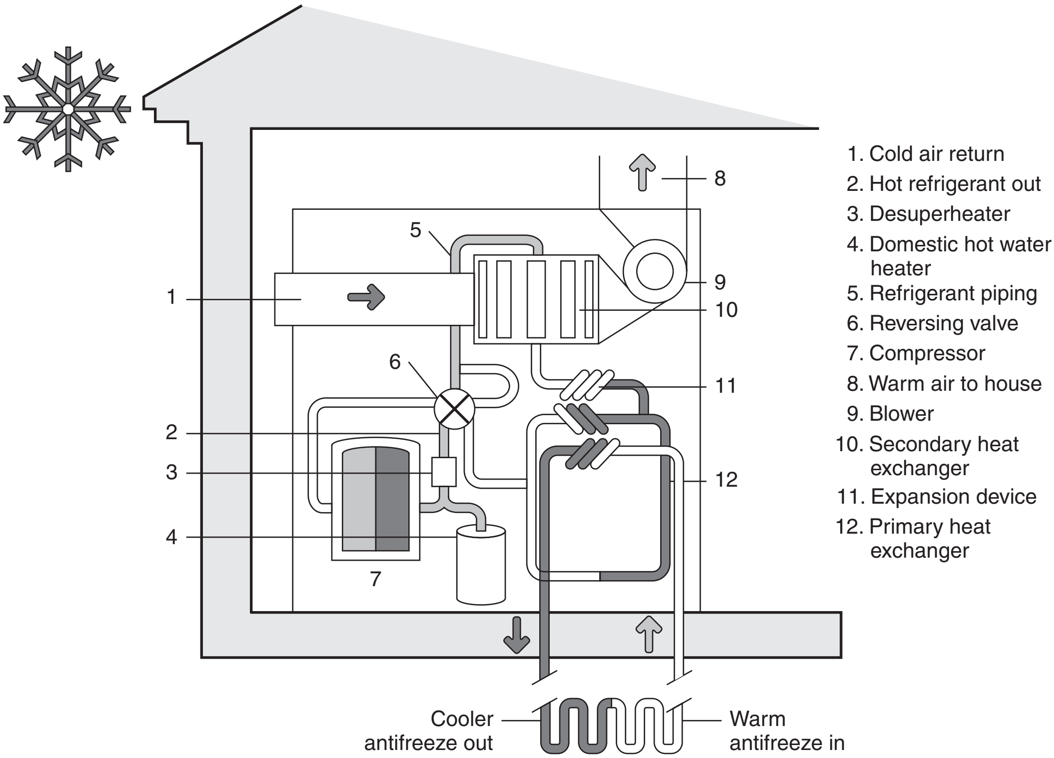


Water loop system using external heat pump air throughout the building. In effect, this is air conditioning in reverse (see Chapter 13), and in many installations the air source heat pump is expected to perform both functions. More versatile units can offer both space heating and domestic hot water via refrigerant to water heat exchangers. Many of these are packaged systems, and are installed entirely outside the building.

Drawbacks include aesthetics – the external elements can be visually obtrusive – compressor noise, and a high risk of the external coils icing up in cold weather. Defrosting is needed, a function normally performed by switching the heat pump into reverse. However, this cools the inside of the building while it occurs. Prolonged low ambient air temperatures can be a real problem. As the temperature falls the heat pump must do more work in order to move the same amount of heat into the building – which will be losing more heat anyway. Ultimately the pump will be using one unit of electricity for every unit of heat that it moves into the building, and will be highly stressed. To cope with such extremes, many small packaged air source heat pumps have back-up electrical resistance heaters built in.

Air source heat pumps are well developed and widely available (Reproduced with permission from Nu-Heat)

A much less obtrusive and reliable, if significantly more expensive, option is the **ground source heat pump**, also known as the **geothermal**, **geoexchange**, **ground-coupled**, **earth coupled** or **earth energy heat pump**. (Geothermal energy more properly refers to the tapping of the energy of hot rocks up to 10 km below the surface.) The ground used as an energy source in this application can be as little as 1 m below the surface where there is little ground freezing in winter. At such depths soil temperature will be influenced by solar gain, rainwater evaporation and atmospheric conditions. Experience suggests that as a rule of thumb, annual average shallow soil temperature can be taken as average annual air temperature. This will generally lie in the range of 7°C to 21°C, but will vary significantly between winter and summer. At greater depths – in excess of 10 m – soil temperature is

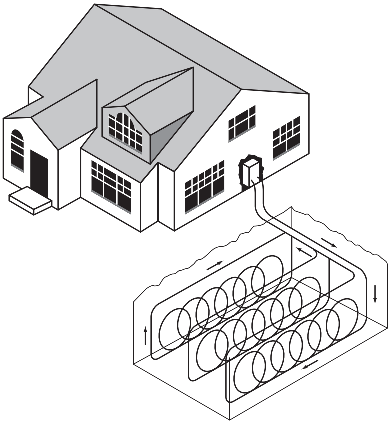


Typical ground source heat pump providing warm air space heating

much more constant, but again it can be assumed that it will be approximately the same as average annual air temperature.

How much energy can be extracted from the ground is a function of its thermal properties. Solid rock has much greater thermal conductivity than soil. Dry, loose soil has a significantly lower thermal conductivity than wet, compacted soil. Groundwater movement across the site can also increase the potential rate of heat transfer. Before any decisions on what type and performance of ground heat exchanger – or **ground loop** – will be needed for a particular project, a proper geotechnical survey is essential, including trial boreholes.

A trial borehole will enable the size of ground loop needed to be calculated. The final choice is between a horizontal or vertical design. Horizontal ground loops used to be the most common, especially for individual dwellings, and were significantly cheaper than the vertical alternative. They do depend on enough land being available, land where extensive trenching work is acceptable. Trenches have to be at least 1,200 mm deep and up to 600 mm wide. The ground loop itself was originally a single pipe, which ran out, and back again along the network of trenches. The so-called '**Slinky**' layout is quite popular. Shorter, deeper trenches are used, with the pipework installed in a series of overlapping vertical loops. This usually cuts installation costs – it can also make a horizontal ground loop a practical option when site space is limited.



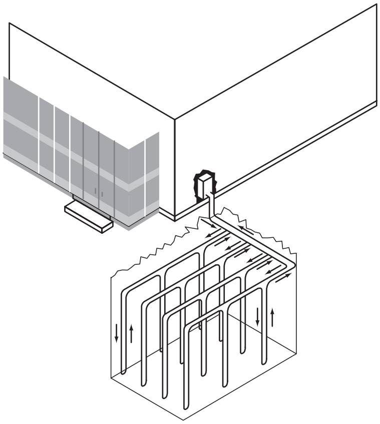
Horizontal closed loop system with vertical 'Slinky' layout

Horizontal closed loop system with horizontal 'Slinky' layout (Reproduced with permission from ICE Energy Heat Pumps)

A more recent development from Sweden is the '**compact collector**', basically 2 m × 2 m assemblies of eighteen 40 mm diameter high density polyethylene (HDPE) pipes that act like radiators in reverse. These can be installed horizontally or vertically, depending on which is the priority: minimising the depth of excavation or its extent.

Vertical ground loops used to be considered only for larger projects, or where there was no room for a horizontal ground loop, or where there was little soil above bedrock. It was usually a much more expensive alternative. However, recent advances in small-scale drilling technology make the vertical option competitive with horizontal designs, even on the domestic scale. As housing plots grow even smaller, this development is timely. It can also make ground source heat pumps a much more attractive retrofit option, as there is minimal disruption to mature gardens.

Horizontal 'Compact Collectors' from ICE Energy (Reproduced with permission from ICE Energy Heat Pumps)



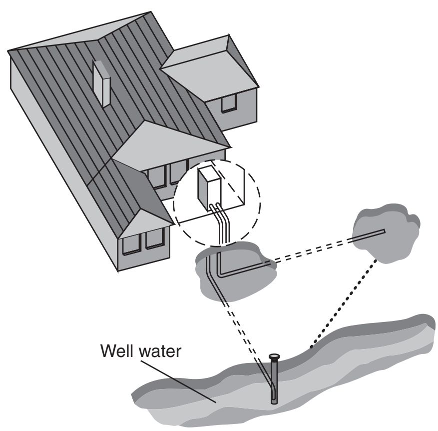
Vertical closed loop system

Another option being tried in Europe lies somewhere between straightforward solar water heating and ground energy capture. In its simplest form, a horizontal ground loop is installed a short distance below the surface of car-parks or access roads; these absorb solar energy quite effectively. Areas with dark surfacing are particularly suitable. A central car-park may also be a convenient location for an underground thermal store (see Chapter 15) from which warm water might be pumped back through the ground loop in winter to de-ice the car-park and access roads.

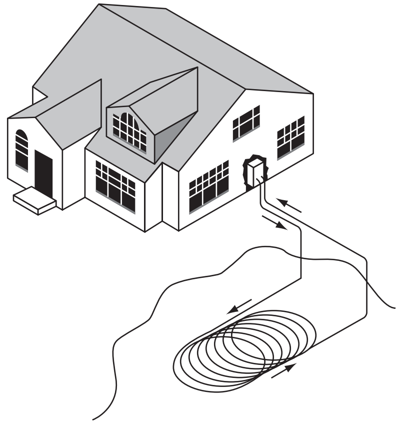
Most ground loops form part of a **closed loop indirect system**. A pump circulates a mixture of water and antifreeze though the loop then through a heat exchanger at the heat pump. High-density polyethylene tubing between 20 and 40 mm diameter is commonly used, with all joints heat fused. **Closed loop direct systems** dispense with the heat exchanger, and circulate the heat pump's refrigerant fluid through copper pipes in the ground. These are falling out of favour, largely due to planning authorities' reluctance to allow potentially toxic refrigerants to circulate close to aquifers. Trenches for horizontal ground loops are usually kept at least 3 m apart to avoid thermal interference. Multiple pipes within individual trenches should be separated by at least 300 mm. Pipes are normally laid on a sand bed and protected by at least 150 mm of sand before being carefully backfilled. Proper compaction is important.

Vertical ground loops typically will use boreholes up to 150 mm in diameter and 120 m deep, spaced 5 m apart. After the pipes are installed they are commonly backfilled with a high conductivity grout. Getting the size of the ground loop right is crucial – too large and capital costs could be uncompetitive; too small and the loop will not be able to collect enough energy to meet the building's needs. Perhaps the most difficult calculation, even with modern software, is the determination of exactly how much energy will be needed and when (see Chapter 16). In many cases the most economic installation will depend on other forms of back-up heating for peak demand, and this is usually supplied by natural gas or mains electricity.

Much the same comments apply to **water source** energy installations. These are only possible when there is a suitable water source on or close to the site, or even below it. Lakes, ponds, rivers and streams, flooded quarries and even old wells can be used, as can the right type and depth of aquifer or flooded mine workings. The earliest form of water source energy installations used an **open loop design**. Water was pumped directly from the source, through a heat exchanger on the heat pump, and either discharged into a convenient stream or river or pumped back into the source again. Usually, systems that return the water back to the source are reversible; heat is dumped into the source during the warmer months, some of which will be recovered during the cold weather (see Chapter 15). Problems with biological growth inside the pipe networks, corrosion and planning limitations make closed loop systems more popular these days. These usually consist of the same heat fused HDPE pipework as used in ground source installations, which has to be installed deep enough to avoid any risk of freezing.



Open system using well water

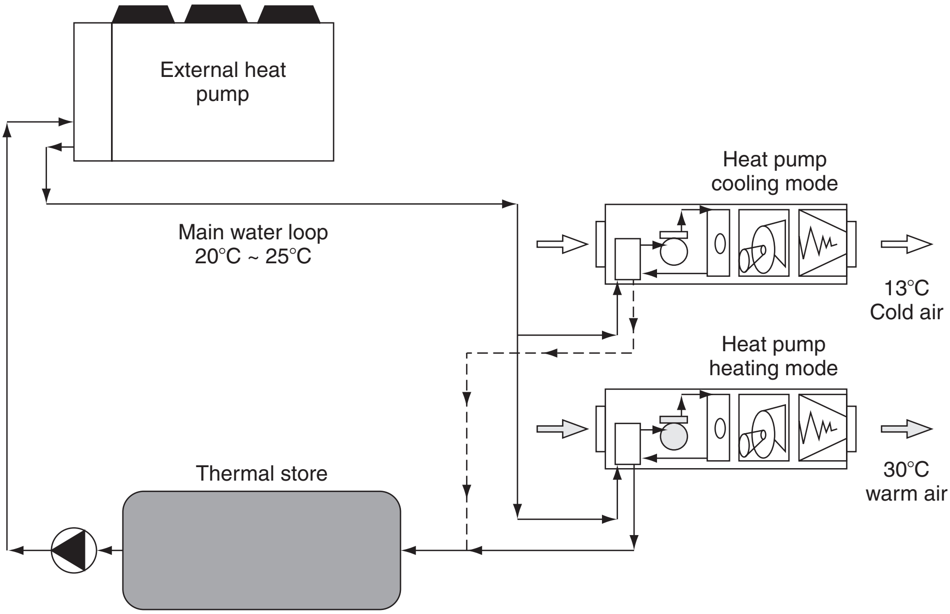


Closed loop system in ponds

Confusion can be caused by the misuse of the term 'water source heat pump systems' for installations; which is more correctly described as **water loop heat pump systems**. These are alternatives to conventional heating and air-conditioning systems for larger buildings. They use water to air heat pumps in each zone connected to a separate pipe loop which usually passes through both a cooling tower and some type of boiler. Together the boiler and the cooling tower maintain the water in the loop at a temperature somewhere between 15°C and 30°C as the heat pumps heat or cool the air in the individual zones. Where there is a mixed use building, such as retail/residential, there is often a simultaneous need for heating and cooling in different zones, so the loop will need little energy input or cooling as the heat is transferred from one zone to another.

In some cases the heat pumps on the northern side of a building could be drawing heat from the water loop at the same time as the units on the sunny southern side are adding heat to it. Although such a system can use simpler, cheaper heat pumps as they have to operate over a much smaller range of temperatures, there are the usual caveats regarding the risks of legionella in the cooling tower. And in most cases the overall energy demand is greater than with other forms of heat pump system. Running costs can be significantly reduced, of course, if the heat in the loop can be supplied by renewable energy. Domestic scale water loop heat pump systems are available in the US. One variant of the system uses an external air source heat pump to both heat and cool the water in the loop.

Water source energy systems gain efficiency if the water is used as a thermal store, effectively cooled down in winter ready for the summer and vice versa. Other forms of heat pump systems can benefit significantly from the inclusion of a more conventional thermal store or **buffer tank** in the circuit. At the very least, this allows the heat pump to operate mainly on off-peak electricity; heating or cooling the tank cheaply in advance of peak demand. It also makes heat pump systems powered by solar or wind energy more practical. Coupled to an air source system, the thermal store provides the heat to defrost the external heat exchanger when necessary, eliminating the unpopular routine of putting the pump into reverse to achieve the same effect (see above). It can also store the heat collected by the **desuperheater**, a secondary refrigerant to water heat exchanger that can be



Typical air source heat pump in action

installed at the compressor outlet, and which normally yields about 10% of the total heat pump capacity.

The real benefit of a desuperheater, however, is that it has an output temperature of up to 70°C, which is very suitable for DHW. Maximum output occurs during the summer months, and will usually be almost negligible at some times of the year. Heat pumps are not otherwise normally capable of producing hot water above 55°C. This is only barely adequate for DHW, and many commercially available heat pumps use supplementary electrical resistance heaters to boost the temperature to a more useful 65°C. This also eliminates the theoretical risk represented by legionella bacteria (see Chapter 2). Regular 'pasteurisation' – heating the water to more than 60°C to kill the bacteria – is required by the regulatory authorities in most developed countries. In the absence of a desuperheater, this can be achieved with an immersion heater in the storage tank running on off-peak electricity if no renewable energy source is available.

Another potential problem is that conventional space heating radiators are only efficient at temperatures between 60°C and 90°C. For space heating, especially on new build projects, **hydronic underfloor radiant heating** is the sensible choice, as it will work efficiently with water temperatures no higher than 30°C to 45°C. **Hydronic wall radiant heating** is another possibility. (Hydronic = water based rather than electric.) These could be described as large low temperature versions of conventional radiators, operating at 35°C or less, and warming occupants through direct radiation rather than indirectly by convection currents in the internal air. Radiant ceiling panels are another option.

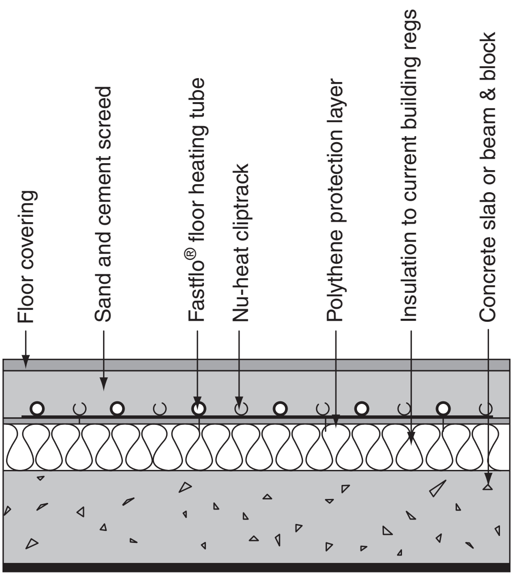
Radiant energy was utilised for centuries by the Romans, whose villas and bathhouses were heated by underfloor ducts known as **hypocausts** which connected into vertical flues in the walls. Slaves kept wood fires burning at the entrance to the hypocaust, and the hot gases were sucked along under the floors and up through the flues, creating a much more comfortable internal environment than the open hearths used by the Barbarians at the time. In Korea it was not just the rich who enjoyed the benefits of underfloor heating. Houses with **ondol** – literally warm stone – floors had their kitchens positioned about 1 m below the rest of the house. Heat and smoke generated by the kitchen stove flowed under the main rooms and out through a conventional chimney at the far end of the house. The famous American architect Frank Lloyd Wright is said to have invented hydronic underfloor heating after experiencing an ondol floor in Japan in the early 1900s. Using hot water rather than hot combustion gases eliminates one of the weaknesses of both the hypocaust and the ondol floor – the constant risk of carbon monoxide poisoning.

Roman underfloor heating was more sophisticated than the Korean equivalent shown below (Reproduced with permission from Akajune)

But Korean houses were the inspiration for more modern housing

An example of a modern Korean home

First generation hydronic underfloor heating systems used copper pipes cast into concrete floors, and had a mixed record. Leaks were common, and difficult and expensive to repair. These days fusion welded high technology polymer piping is used, and the pipes may be cast into the structural floor proper, cast into a screed on top of insulation supported by the ground floor slab, or hung between the joists below a timber floor. Leaks are rare, and the extra space and safety achieved by the removal of hot wall-mounted radiators from the rooms above can easily justify the retrofitting of such a system. Underfloor



Typical underfloor heating arrangement (Reproduced with permission from Nu-Heat, UK) heating in general usually needs a less sophisticated electronic controller than a radiator-based system, simply because it involves much greater thermal masses and, therefore, much slower changes in temperature.

DHW supplies can become more reliable if a so-called **triple function** system is specified. This uses a dedicated second internal refrigerant to water heat exchanger to supply heat to the DHW tank/thermal store. To make economic sense when running entirely on electricity from national grids, heat pump installations are normally sized to produce less than 100% of the building's DHW and space heating and cooling needs, although the ideal percentage is unique to each location and each project and is very dependent on current and projected energy prices. When renewable energy is involved the equation can look very different.

Heat pump performance continues to improve, with vapour compression pump COPs now topping four for the inherently more efficient ground source variant. The latest versions are quiet, reliable and compact, and prices are increasingly competitive as more manufacturers enter the market. Serious consideration should be given to heat pumps for almost every building project – especially in combination with other technologies (see Chapter 16).

13 Active cooling options

Passive cooling systems, like passive space heating systems, have many attractive features, not least simplicity, cost and reliability. They also have serious limitations. Windcatchers, solar chimneys and the stack effect on their own can never ensure that stale warm air is always extracted from every nook and cranny of every building and that cool fresh air always replaces it at a rate which significantly improves occupant comfort. Larger buildings with complex floor plans that depend entirely on unforced natural circulation have a mixed record in practice. Odours can be a problem. Occupant expectations can be higher than the building design can satisfy. Where there is a high density of occupation and a multiplicity of heat-generating office equipment the case for active cooling could be unanswerable.

However, this does not mean that traditional air conditioning is the only alternative. Buildings can be cooled very effectively without resorting to conventional refrigeration technology or ozone layer-depleting chemicals. Even small energy inputs can make a significant difference to occupant comfort. Windcatchers with remotely operated vents and dampers are much more efficient when used for night-time cooling; for example, cool towers work better with a pump to keep the cooling pads consistently moist (see Chapter 8). A 'zero carbon' option is simply to add fans to the basic passive system, fans that can be effectively powered by solar PV or other forms of alternative zero carbon energy, such as mini hydro or wind turbines.

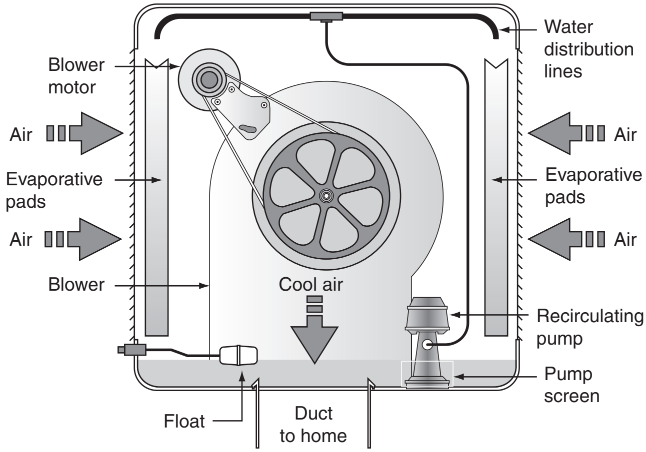
Relatively small fans can radically improve air circulation when used as a supplement or a back-up to natural extraction via a windcatcher or solar chimney. Forced circulation usually needs smaller ducts and vents, extraction and cooling can be targeted to high priority areas. Evaporative cooling can be accomplished in a much smaller installation than a cool tower. Even when mains electricity has to be used to power the fans, alternative active cooling systems will usually consume significantly less energy than traditional air conditioning. At the very least, alternative cooling technologies can be used to significantly reduce the need for conventional air conditioning, minimising both capital and running costs.

Night-time cooling can be accomplished more effectively if mechanical ventilation is chosen. There will be no need to open windows at night, reducing the otherwise inevitable security and noise pollution risks, and cooling airflows can be directed more precisely at

Solar PV-powered fan-boosted windcatchers (Reproduced with permission from Monodraught)

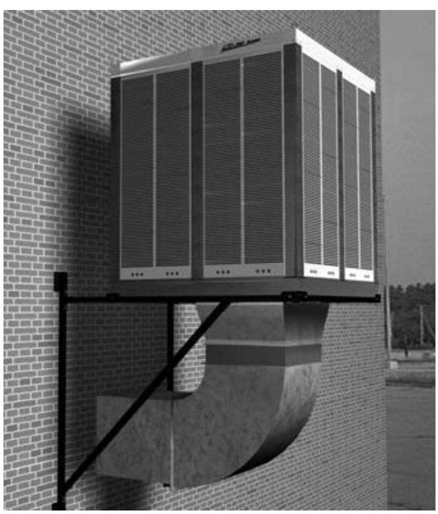
the selected thermal store. Exposed concrete soffits will no longer be strictly necessary. Cool air can be circulated easily through ducts in precast concrete floors, or directed above false ceiling panels to cool the soffits of conventional floors, which are usually much cheaper to construct. In the UK-developed **CoolDeck** system the air is persuaded to flow through a narrow gap between the soffit and a steel duct plate bonded to it. Turbulent flow is deliberately produced to enhance the heat transfer rate – CoolDeck is claimed to be up to 100% more efficient at cooling the slab than straightforward ventilation, and its performance can be enhanced even further by the inclusion of suitable phase change materials within the ducts (see Chapter 15). Most active night-time cooling systems to date have been powered by mains electricity, as solar PV is obviously no use at night. Care must be taken to avoid overcooling the thermal store; otherwise daytime condensation is a real risk. And there can be no fine control of temperature or humidity with such a system.

Forced circulation can make **closed loop earth tubes** an attractive option. These are a form of **ground-coupled heat exchanger** (see Chapter 15). Internal air is blown or sucked in to and out of large diameter smooth plastic or metal tubes buried at least 2m below ground level close to the building, where soil temperatures are well below ambient air temperatures during summer months. Both ends of the tubes connect to the building; no outside air enters the system. Open loop earth tubes, where outside air flows through the tubes before entering the building, is another option, but require rugged external ground level air intakes which need regular maintenance, and can suffer from condensation and mould growth (see Chapter 8). A closed loop system recirculates internal air, and generally cools it further than an open loop system can, but it does nothing for air quality. On the other hand, simply venting stale air to atmosphere when it is still cooler than ambient is a waste of energy.



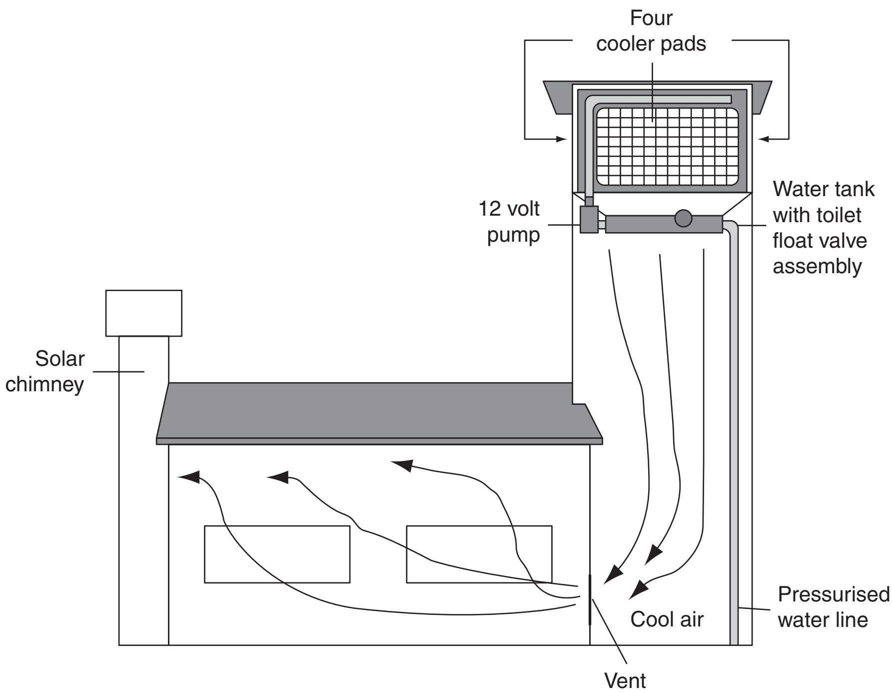
Principles of a swamp cooler

Fan-driven **evaporative coolers**, also known as **desert coolers** or **swamp coolers**, work on the same principle as cool towers, but are much more compact. External air is drawn through wetted fibre pads, causing the moisture to evaporate and take up heat from the air. The air gains humidity and loses heat, a desirable outcome in many environments. All evaporative cooling systems suffer from the same limitations: they work best when ambient humidity is low and they require an abundant and reliable supply of high quality



Commercial size evaporative cooler (Reproduced with permission from JS Humidifiers) water. Some swamp coolers are small and efficient enough to be powered economically by solar PV panels, and units with integral PV panels are available for mounting on the exterior walls of buildings. These can be a very effective solution in hot dry climates, as the PV panel will provide most power when the sun is hottest.

Despite its name, all forms of **passive downdraught evaporative cooling** (**PDEC**) work better with some forms of energy input, either in the form of pumps, fans or remotely controlled vents and dampers. Swamp coolers, sprinklers or sprays cool and humidify incoming air at high level, either in a separate **cool tower** or at roof level in one or more atria. This denser air then sinks to ground level, displacing lighter, warmer air as it does so. The cooled air can be directed into intermediate floors on the way. Perimeter vents allow the warm air to escape. All over the world a number of PDEC installations have demonstrated the concept's efficacy and practicality, and the system is said to be popular with building occupants.



The most common cool tower design

Sometimes the extra humidity produced by direct evaporative cooling can be undesirable. The alternative is an **indirect evaporative cooling system**, in which the air that is cooled by evaporation passes through a heat exchanger and, in turn, cools the air that actually enters the building. An indirect system can also form the first stage of a **two-stage evaporative cooling system**, feeding pre-cooled air at ambient humidity into a direct evaporative stage. Evaporative systems have the advantage that their effectiveness increases as ambient temperatures rise – and in most climates humidity generally reduces on the hottest days, another bonus. Direct comparisons with conventional air conditioning are slightly unfair as air conditioning works in humid climates as well and has an inherent dehumidification effect. However, it is suggested that a well-designed evaporative cooling system in the right location will cost much less than half the cost of refrigerated air conditioning to install, and demand less than 25% of the energy to run.

Other active evaporative cooling systems have been tried. One system designed for residential buildings is based on the use of a metal pitched roof. During the night, water is sprinkled on the side opposite the direction of the prevailing winds and flows down to the gutter. Fans draw the air from inside the attic space and distribute it through the building. For non-residential buildings where daytime cooling is more important a flat roof is normally used. Water is cooled by spraying and then captured in roof top drains, stored, then circulated through pipes cast into floor slabs.

Spray cooling usually works best when the water supply is pressurised well above mains pressure, so that the water can be forced through nozzles that produce as small a droplet size as possible. The finer the spray or mist, the more energy is absorbed in the evaporation process – and the lower the water consumption needed for a specific reduction in temperature. At 15% relative humidity a well-designed evaporative cooling system could reduce the temperature of ambient air entering the building by around 50% – e.g. 40°C to 21°C. Even with ambient air at 50% relative humidity the potential reduction is worthwhile; 32°C to 24°C, for example.

Soft potable mains water is usually preferred for evaporative cooling systems, as water from other sources could contain high levels of dissolved salts that would precipitate out and eventually clog up the system. Unfortunately, the periods of highest demand from evaporative cooling systems can inevitably coincide with periods of low rainfall and mains water shortages. Many of the areas of highest demand will have naturally hard mains water supplies. Grey water is not a realistic alternative, and collecting enough rainwater to feed evaporative coolers throughout the summer is likely to be impractical. Suitable water might be available on site from boreholes or artesian wells, but even if the water is too hard or official permission to extract it not forthcoming, water from deep aquifers can still be used for cooling if it is recirculated back into the ground after use.

Aquifer cooling is usually accomplished via a dual-purpose **aquifer thermal energy store** (**ATES**) (see Chapter 15). When ground conditions are suitable, cold water from an aquifer below the building is circulated through one or more heat exchangers, where it cools incoming ventilation air and/or water in a closed loop, which can then be circulated through some form of cooling element inside the building. Typically, the aquifer water might leave the ground at 7°C and have its temperature raised to 15°C in the heat exchanger before being pumped back down to the aquifer at least 100 m away from where it was extracted. In winter the system is reversed and used for space heating. An ATES is ineffective as a thermal store where there is significant water movement along the aquifer: it would still function as a source of cold water, however. Ground water that is particularly brackish or otherwise aggressive has to be handled with care, but has been used successfully, usually by circulating it in largely plastic pipe networks. Experience to date suggests that where the right ground conditions exist, aquifer cooling can be remarkably efficient and cost-effective (see Chapter 18).

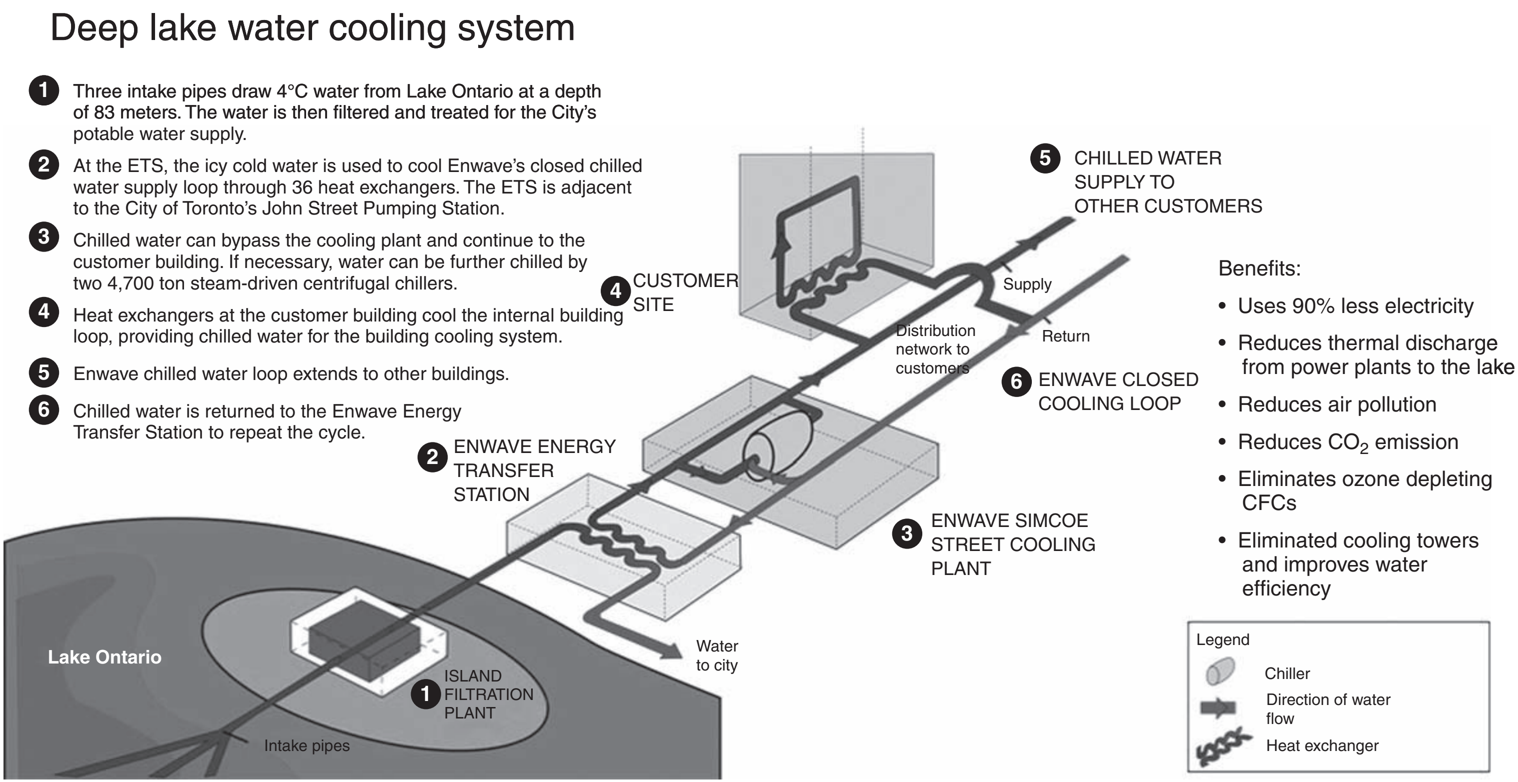
At some locations cooling water may be available from other sources, such as deep ponds, lakes or even the sea. The source must be deep enough for the bottom water to stay cool right through the summer. In deep lakes thermal stratification begins to take place as spring advances into summer. Below 15 m or more the water temperature can be 20°C below the surface layers, where water temperature varies little with depth due to the mixing effects of wind and convection. A shallow layer with a steep temperature gradient separates the warmer and colder waters. This is known as the **thermocline** or **metalimnion**, and cooling water intakes are normally sited to be below all normal levels of the thermocline to assure reliable supplies. Flooded quarries are often deep enough and sheltered enough to develop a stable and predictable thermocline, and disused underground mine workings often contain water at a constant low temperature.

A recent example is the Enwave Energy Corporation's use of water at 4°C from a depth of 83 m in Lake Ontario, Canada, to cool buildings in downtown Toronto. The water is filtered and processed and eventually passes to the city's potable water supply. On the way it flows through heat exchangers in an 'energy transfer station', the key element in the Deep Lake Water Cooling System.

Summertime thermoclines can establish themselves in the sea as well, but there is no guarantee this will occur at any specific location. In deeper seas there will be a permanent thermocline, which can be as deep as 1,000 m or as shallow as 50 m. Sea bottom temperatures above the permanent thermocline and close to shore will vary widely from location to location, depending mainly on depth, tidal range and exposure. However, in higher latitudes, even the seas at shallower depths take a long time to warm up. Water below 20 m or so, which may be only 2°C in May, could remain below the 10°C mark until late September. These temperatures are perfectly acceptable as the basis of a space cooling system, so buildings close to sea water deeper than 20 m have a very economic cooling option available. Points to consider include the need for corrosion resistance in the system and the prevention of organic growth internally – this is perhaps best accomplished by cathodic protection. A debris screen must protect the intake itself.

Wherever the cool external water comes from, it will normally be passed through a heat exchanger where it will take up heat from either air or water before being returned to the source. The cooled air or water can be utilised in a number of ways. Water is often passed through a second heat exchanger to cool the building's ventilation air. Less energy is needed if the cool water is circulated through a **radiant cooling system**, which ideally utilises the ceiling as the cooling element. Cooling pipes can be incorporated into ceiling panels, hidden behind false ceilings or cast into the slab above. Of the heat removed from the room below, up to 50% will be lost by radiation and the rest by convection. This type of system can operate at cooling water temperatures as high as 15°C: indeed, temperatures much lower than this should be avoided, because of the risk of condensation.

Chilled beams are another option. Basically a mirror image of a space heating radiator, chilled beams are air to water heat exchangers mounted at ceiling level. They come in many designs, and these days often manifest themselves as **multi-service chilled beams**: units which can incorporate lighting, fire suppression sprinklers and even public address systems alongside the heat exchangers. Again, the water circulating through the chilled beams is at relatively moderate temperatures. Both radiant cooling and chilled beams



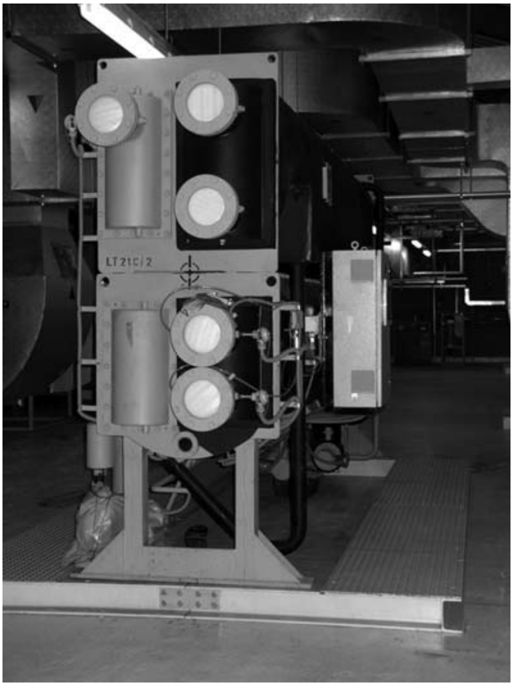
Toronto takes advantage of permanently cold water below the thermocline in Lake Ontario (Reproduced with permission from Enwave Energy Corporation)

Once famous for the energy saving gold coating to its glazing – more than $1 million worth of gold was used – Toronto's Royal Bank Plaza is now cooled via the waters of Lake Ontario

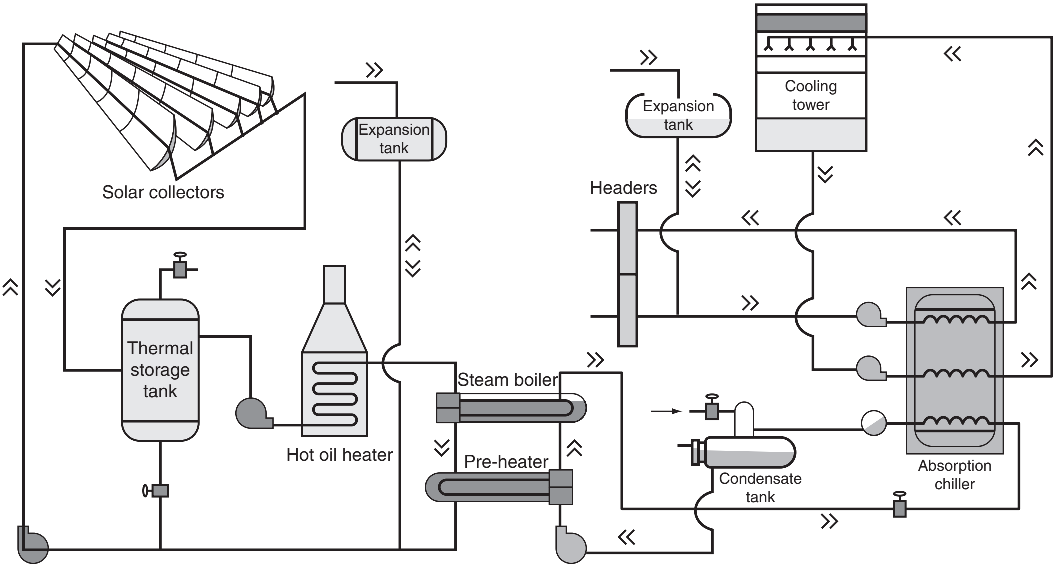
are said to be more comfortable for building occupants than traditional air conditioning, although there will be no dehumidification of the internal air.

In buildings where cooling loads are high and alternative options are limited, some form of **refrigeration technology** may have to be considered, to meet part or all of the cooling needs. Two different approaches are currently used**:** mechanical **vapour compression** and heat driven **absorption**. The first is based around an electrically powered compressor and a heat transfer fluid that these days is a safer form of **chlorofluorocarbon** (**CFC**) than the original Freon patented in 1928. Freon and its close relatives are now banned because of the damage they cause to the ozone layer. Other, safer, forms of CFC are now used, but still the potential for ozone depletion exists. Compressive chillers could be powered by electricity from mini hydro, for example, or even from a photovoltaic array, but it is still questionable that a PV-powered compressive chiller is a realistic option.

Absorption chillers are a different matter. They can utilise heat from solar panels, waste heat from industrial processes, or the heat generated as electricity is produced in a trigeneration installation (see Chapter 14). Solar-heated water has to be at temperatures typically between 80°C and 120°C, which normally imply the use of either high performance

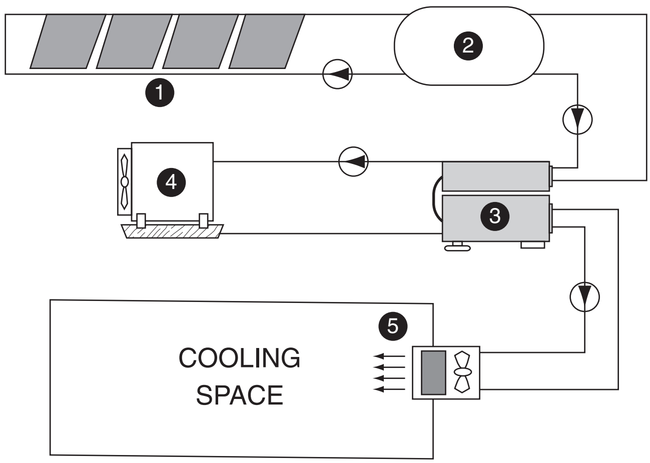


Absorption chillers are well developed and widely available (Reproduced with permission from Ener-G, www.energ.co.uk)



A large-scale solar cooling installation using parabolic trough collectors

evacuated tube collectors or **concentrating collectors** (see Chapter 9). Some more modern versions are said to be capable of operating at significantly lower temperatures compatible with cheaper collectors. Absorption chillers use water as the heat transfer fluid and ammonia or non-toxic lithium bromide solution as an absorbent. Water evaporates in a low pressure chamber, causing the temperature to fall to around 7°C. More water flows through a heat exchanger inside the evaporator, is cooled, and is pumped to another heat exchanger where it cools the air entering the building. The water vapour passes to an absorber, where it is taken up by the ammonia or lithium bromide and the heat released in the absorption process is exchanged with cooling water, which then circulates through a cooling tower.



1. Evacuated tube solar collectors
2. Thermal store
3. Absorption chiller
4. Cooling tower
5. Air to water heat exchanger

Absorption coolers can also be powered by high-performance evacuated tube collectors

Absorbent leaving the absorber is dilute and needs to be concentrated again before it can be re-used. Solar-heated water is used to drive off the water in the absorbent as vapour; the freshly concentrated absorber is returned to the absorber while the water vapour passes to a condenser and then back to the evaporation chamber. Gas-heated water is often used as a back-up for when solar power is inadequate. Using surplus heat from a cogeneration installation for cooling to achieve trigeneration of electricity, heat and 'coolth' can be very effective as, unless a seasonal thermal store is available, disposing of surplus heat from CHP units during the summer can be a real headache and may even limit the amount of electricity that can be generated (see Chapter 14). Waste heat from industrial processes is another option, as is the use of solar PV power to drive the essential pumps.

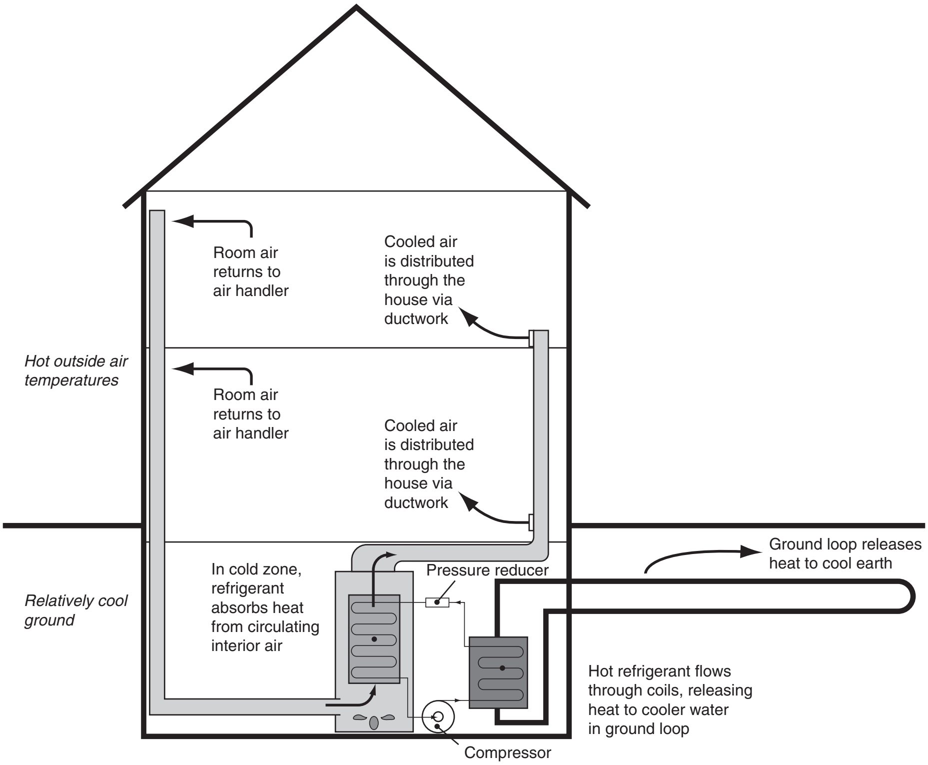
A **single-stage absorption chiller** as described above is relatively inefficient in terms of energy conversion, but when the energy is heat which would otherwise go to waste the overall package can be very attractive; especially as the incoming air is dehumidified as well. A **two-stage absorption chiller** re-uses some of the heat normally lost to the cooling tower and is significantly more efficient, although capital costs are inevitably higher. It normally needs water or steam at temperatures of up to 300°C to be really effective, which actually rules out solar power, as temperatures like these can only be achieved by **tracking parabolic trough collectors** in lower latitudes.

The latest generation of **desiccant chillers** are able to operate with either solar-heated water or air, and are said to be compatible with solar tiles and other forms of building envelope integrated solar collectors. Earlier designs were based on a simple process. Incoming air is dehumidified by a solid desiccant such as silica gel then cooled in a heat exchanger by the cooler outgoing air. This fresh, dry, pre-cooled air then passes through a direct evaporative cooler before entering the building. Heat absorbed by the outgoing air is used to regenerate the desiccant, which is usually mounted on a wheel that rotates through both the incoming and outgoing air streams. This regeneration needs extra heat, which can be supplied by renewables or back-up gas heating. Installations like this were commonly used to feed precooled air into a conventional mechanical vapour compression air conditioning system: the combined installations are said to be more cost-effective than stand-alone conventional air conditioning.

Developments like the US-developed **NovelAire** system offer a more integrated option. In it a proportionally larger volume of ambient air is dehumidified and then split into two streams. One passes through a direct evaporative cooler then is used to cool the second air stream before being exhausted back to atmosphere. The second stream is cooled without any increase in humidity, and then passes through a second direct evaporative cooler where final temperature and humidity levels can be determined. Solar and/or recovered heat backed up by gas heating is used to regenerate the desiccant; waste heat can be transferred to the main diurnal thermal store for domestic hot water heating or to a seasonal thermal store (see Chapter 15). Solar-heated air is the simplest option for desiccant regeneration in practice, and the most efficient, as no heat exchanger would be needed as it would with solar-heated water.

A number of other ways to utilise the sun's energy to cool buildings are under development. Most have the same basic advantage: solar air or water heating arrays are sized to perform well in spring and autumn, so that in the summer there is excess energy available. This could be diverted into a seasonal thermal store – or it can drive the cooling system. Peak demand will match peak output. Adding some form of 'coolth' store, which could be anything from a rock bin to a store based on phase change materials, will extend the cooling period into the night. Gas is the obvious back-up energy source.

Heat pumps (see Chapter 12) are also becoming popular as a space heating technology – but heat pumps are essentially reversible. In principle, a heat pump is a device that uses energy to move heat from one location to another. Thus in the space heating mode of most heat pump installations heat is extracted from the air, from the ground or from a convenient water source, and transferred into the interior of the building. The source may be at low temperature, but the heat pump will concentrate the heat collected into a much smaller mass of air or water, raising its temperature to useful levels. Switching the heat pump into reverse will cool the air inside the building and transfer the heat into the outside air, the ground, or the water source, from whence some of it may be recovered in colder weather. Heat pumps are inherently less efficient as space coolers than as space heaters unless the heat removed from inside the building is transferred to a thermal store for later use.



Heat pumps can be run in reverse to provide summertime cooling (Reproduced with permission from Geothermal Heat Pump Consortium Inc.)

One practical problem is that it is difficult to balance both heating and cooling needs with one heat pump, as the heat from the compressor motor and any internal fans adds to the heat transferred from the outside source when the pump is used for space heating. When used for cooling, the pump has to transfer both the heat from the building and the heat from the motor and fans. Add to this the fact that many modern buildings, especially offices, have a significantly greater cooling demand than heating, and in practice a heat pump sized for heating might well be capable of dealing with only half the building's cooling needs. Another problem is that if the space heating is based on underfloor pipe networks, reversing the system and cooling the floor slab may cause condensation to form. One way round this is to install an additional small air source heat pump, usually in the loft or above a suspended ceiling, whose sole function is to extract heat from internal air. This heat could then be transferred to the ground loop of a ground source heat pump installation or the water source for a water source heat pump and stored for winter use.

Heat pumps, of course, depend on electrical power. A typical dual-function heat pump installation for a medium-sized building may require up to 100 kW. This would imply either a solar PV array of close to 1,000 m^2, a horizontal axis wind turbine with a diameter approaching 30 m, or a sizeable mini hydro installation, if alternative energy is to be used. Other routes include the use of various forms of biomass to generate the necessary electricity (see Chapters 7 and 11). Alternatively, an **absorption heat pump** might be specified. This works on much the same principles as the absorption chiller described above, deriving its power from any heat source available. Its drawback is that it is not yet a fully developed technology, and that it suffers from the same sizing problem as all other dual-function heat pumps.

Using intermittent energy supplies from wind turbines and the like is rarely the ideal solution for cooling purposes, especially where the building has limited thermal mass. The alternative is to use the heat pump to cool a thermal store when energy supplies are available. A heat exchanger within the thermal store supplies the actual cooling function within the building.

For most building projects in the foreseeable future the provision of space cooling will be a major priority. Conventional air conditioning will continue to have some role to play, but that role will have to become much less important if the energy consumption of buildings is to fall significantly. Luckily, the technology exists for this change to happen without major disruption to current lifestyles or architectural fashion.

This page intentionally left blank

14 Cogeneration, trigeneration and beyond

Generating the electricity that the modern world depends on by burning hydrocarbons can be a very inefficient process. This is particularly the case where the electricity is generated in large power stations then transmitted long distances to the consumer. National electricity grids may be very convenient, for producer and consumer alike, but as little as one-third of the chemical energy in the fuels burned actually arrives in the form of electrical power. This applies to both fossil fuels and renewable biomass. Some of the energy is lost in the transmission lines, but most is dumped into the atmosphere or convenient waterways in the form of waste heat. When power stations were smaller and located much closer to, or actually right in, the centre of urban areas it was common practice

Hot water from London's Battersea Power Station was stored in this 'accumulator' – a large thermal store – on the other side of the Thames and used to heat houses in Pimlico (Reproduced with permission from Fin Fahey) to use the hot cooling water to heat nearby buildings; in the case of the landmark Battersea power station in London, the hot water was actually pumped under the Thames to Pimlico on the far bank. This practice gradually died out as power stations were banished to remote country areas because they needed to be larger and larger in the search of greater efficiency and cost effectiveness. These **district heating** schemes, as they were first known, never completely died out, however, and there is now growing interest in the concept and its more recent variants.

Using one combustion process to generate both hot water and electricity is known as either **combined heat and power** (**CHP**) or **cogeneration**. Cogeneration is perhaps the most appropriate appellation, as it fits neatly with the use of the term **trigeneration** for installations where the heat generated also powers an absorption cooler (see Chapter 13). Some medium-sized trigeneration installations also produce steam, and the term **quadgeneration** is coming into use for these. Any form of hydrocarbon fuel could in theory be used, but for the small- to medium-sized installation the most common are biomass, natural gas, syngas, biogas and producer gas (see Chapters 7 and 11); although biofuels such as rapeseed oil are an alternative. Basic biomass is burnt in a furnace, and the heat produced is used to generate electricity either by raising steam to power either a reciprocating steam engine or steam turbines or perhaps to directly heat a Stirling engine (see below).

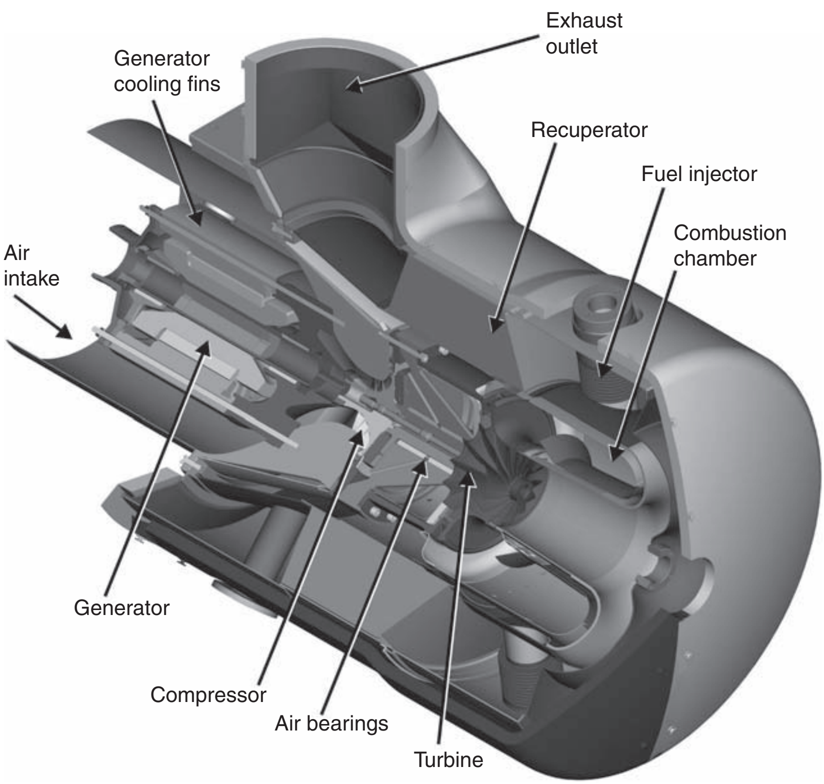
Cogeneration on the larger scale is well established – this Danish plant burns more than 60,000 t of straw a year, and produces 8.3 MW of electricity and 20.8 MW of heat

Gas can also be used to raise steam, but in small- to medium-sized installations of less than 1 MW the most convenient options are to use it to provide heat for a Stirling engine or as fuel for some form of **internal combustion** (**IC**) engine. The final choice depends mainly on the cleanliness and calorific value of the gas to be used (see Chapter 11).

Historically, the first IC piston engines were large low-speed stationary units fuelled by town or wood gas, and used to provide electric and hydraulic power for factories and other industrial facilities. Engines powered by petroleum products came later, but these are now often adapted to run on various forms of gas from biomass. The advantages of this approach include low capital cost and proven reliability, but recovering waste heat from their cooling systems and exhaust gases is far from straightforward.

There are also a number of manufacturers who offer purpose built IC **gas piston engines**, usually turbocharged, designed to run on a wide range of gases and able to function efficiently even when the calorific value of the gas is relatively low. Usually these are specifically intended for cogeneration applications, so heat recovery is simpler and more reliable. A typical example is the modular **SenerTec DACHs** range, which starts with units producing 5.5 kW of electricity and 12.5 kW of heat.

Microturbines able to generate between 5 kW and 1 MW have undergone extensive research and development. The introduction of reliable foil bearings, a simpler form of air bearing which allows the turbine to operate at more than 100,000 rpm without lubrication, has transformed their economics. Waste heat is almost entirely confined to the exhaust, simplifying heat recovery, and noise levels are low. A number of manufacturers now offer packaged cogeneration microturbine units designed to run on natural gas. Syngas and producer gas would normally have to be carefully cleaned of tars and other condensates before they could be considered as fuels for microturbines, but good quality biogas with low levels of siloxanes would be acceptable (see Chapter 11). The US **Capstone Turbine Corporation**, for example, currently offers microturbine units with integral generators producing between 30 and 65 kW, which can run on either natural gas or good quality biogas.



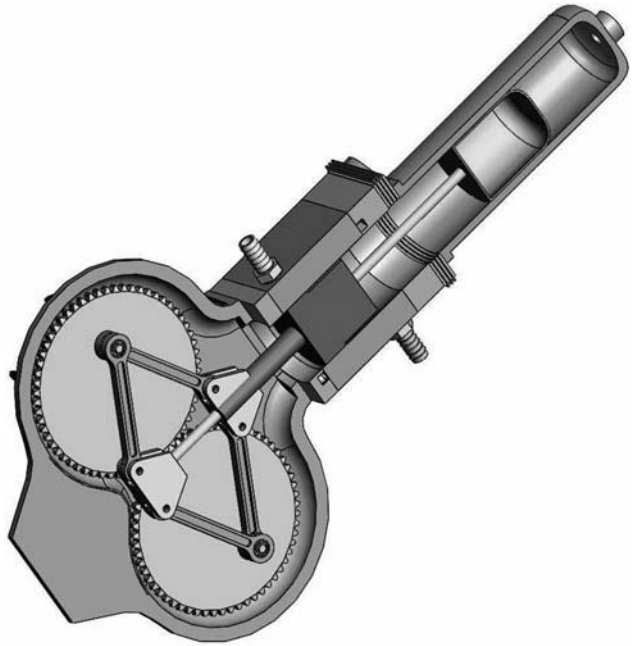
This Capstone MicroTurbine® C65 engine cutaway has foil bearings that allow it to operate at 100,000 rpm (Reproduced with permission from Capstone MicroTurbines®)

Capstone C65 MicroTurbine® Integraded Combined Heat and Power units ranging from 30–65 kW (Reproduced with permission from Capstone MicroTurbines®)

Ever since it was invented in the early nineteenth century, the **Stirling engine** has fascinated and beguiled generations of engineers and technologists. Effectively an external combustion piston engine, its apparent simplicity and quiet operation are in stark contrast to the complexities and noise of the internal combustion engine. There are very good reasons, however, why the Stirling engine has, until now, been very much the poor relation of the ubiquitous internal combustion engine, not least that it is very hard to vary its operating speed. The main reason in practice is that the technology of the nineteenth and most of the twentieth century was simply not up to the task of manufacturing a Stirling engine that could develop anything like its theoretical efficiency – as much as 80%.

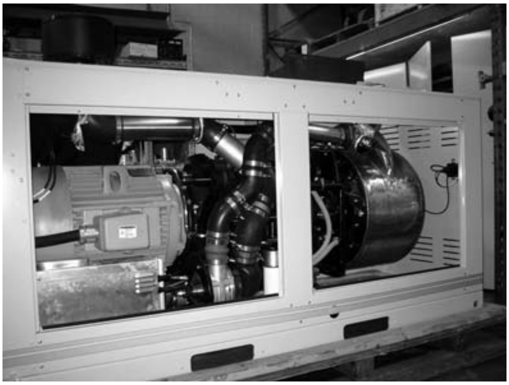
In principle, a Stirling engine extracts energy from an external heat source and uses it to heat a working fluid inside. This causes expansion, which drives a piston connected to a crank. The working fluid is then cooled, causing it to contract. A second piston then transfers the working fluid back to the hot section of the engine, ready for the cycle to begin again. There are several potential configurations, notably the **Alpha**, **Beta** and **Gamma Stirling** designs, each with their particular advantages and disadvantages. Originally the working fluid was air, but efficiency was low. The ideal fluid is hydrogen gas, which puts high demands on sealing technology as it has the unwelcome ability to leak out through solid metal. These days helium is the usual choice.

Heat exchangers are key to the concept. The larger the difference in temperature between the hot fluid and the cooled fluid the more power the engine will produce, although it will work with remarkably small differences. Thus the heat exchangers must be highly efficient, resistant to corrosion and easy to maintain. Usually this means that the cooling fluid has to be circulated through proportionally large radiators, another factor reducing the attractiveness of Stirling engines as automotive prime movers. Increasing internal pressures also increase the power at the cost of greater loads on the seals, thicker cylinder walls and so on.



A rhombic drive Beta type Stirling engine (Reproduced with permission from Togo)

Used as stationary engines in a cogeneration or trigeneration installation these drawbacks are more than outweighed by the benefits. Continuous combustion produces fewer unwanted emissions than the intermittent combustion of the IC piston engine.



This Stirling engine generator set by STM Power produces 55 kW and can run on biofuels and biogas (Reproduced with permission from Wtshymanski)

Proportionally greater weight and size for the same power output is less relevant, as is the need for a protracted warm-up before it starts to generate power. Constant speed operation is perfectly acceptable in practice. Recovery of waste heat is simpler.

In theory, a Stirling engine can be run in reverse to produce cold air or chilled water. **Stirling cryocoolers**, which produce very low temperatures, are commercially available in a range of sizes. A cogeneration installation could be upgraded by arranging for electric power to drive the generator in reverse as a motor – the power could come from the national grid or alternative energy sources such as wind or solar PV. This may be more practical in the smaller sizes than the use of surplus heat to power effective but complex absorption coolers.

Modern versions of the traditional reciprocating steam engine also have much to offer in the right applications. More than 150 years of development has produced units which have few of the practical disadvantages of their forbears, most notably that they rarely explode. They are more efficient than steam turbines below the 1MW power threshold, and perform well at part load. When biomass is used to raise steam its naturally variable calorific value results in variable steam output and parameters, which turbines struggle to cope with. Reciprocating steam engines are much more tolerant. Traditionally, maintenance costs were higher, despite the lower operating speeds, pressures and temperatures, and noise and vibration levels were worse. More modern designs offer much improved performance.

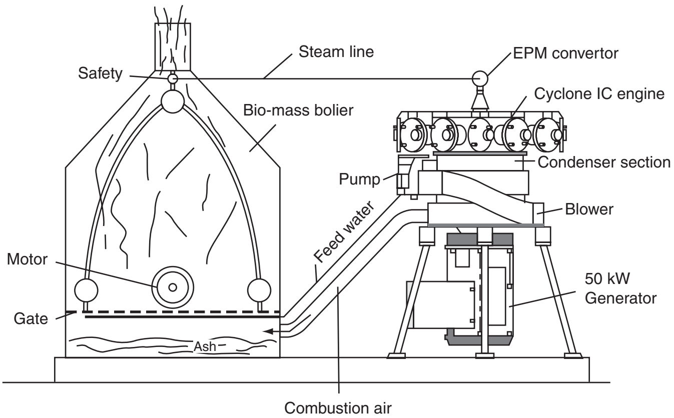
The Swedish **Ranator** system, for example, features compact and efficient steam generators – which can have catalytic coatings to further reduce emissions – and 'buffers', thermal stores on both the steam supply and the condenser which smooth out variations in load and speed. Great attention is paid to seals and piston rings, to eliminate the traditional loss of lubricant into the steam, producing a so-called **oil-free design**. Efficiency is said to approach 35%, double that of a traditional design.

Smooth, high-efficiency oil-free operation is also offered by rotary steam engines such as the Canadian **Quasiturbine** and the German '**Steam Cell**'. These are sometimes known as **screw-type steam engines**, thanks to their resemblance to modern screw air compressors. Modular oil-free reciprocating steam engines are also available from **Spilling** of Germany with outputs ranging from 25–1,500kW.

Another oil-free engine concept is **the heat regenerative cyclone engine**, currently (2007) in the final stages of development by Florida-based **Cyclone Power Technologies**. Claimed to offer all the theoretical advantages of the Stirling engine without the practical drawbacks, the cyclone engine features a cyclonic combustion chamber in which the fuel/air mixture is spun to promote complete combustion. The working fluid is supercritical de-ionised water, power is extracted via a multi-cylinder radial engine, and the inclusion of heat exchangers and regenerators boosts thermal efficiency up to Diesel engine values. A wide range of fuels can be used, including natural gas, biogas, bio-oils, and even powdered coal. A **Waste Heat Engine** variant is also under development. This utilises the hot gases from internal combustion engine exhausts or gas turbines, or solar heat. It can also be intimately linked to a biomass boiler.

Reciprocating steam engines and steam turbines both operate in accordance with the thermodynamic Rankine cycle, first described in the nineteenth century. For use in turbines

The radial cylinder arrangement of the Cyclone Waste Heat Engine (Reproduced with permission from Cyclone Power Technologies Inc.)



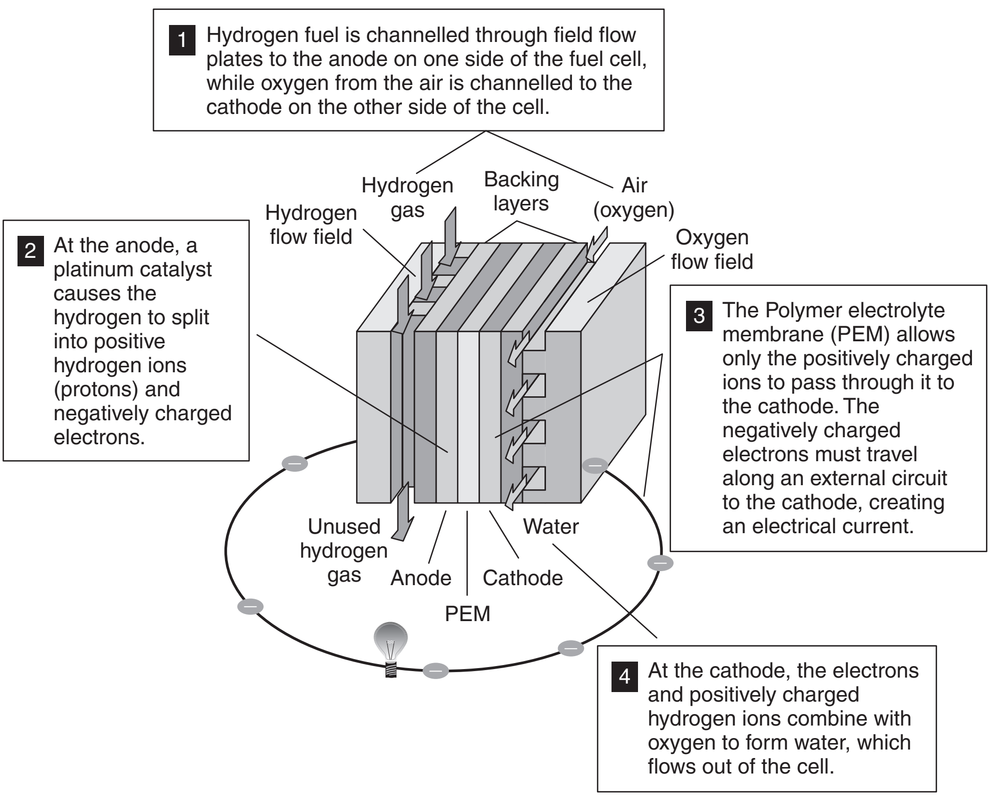
Schematic of the Cyclone Waste Heat Engine powered by biomass combustion (Reproduced with permission from Cyclone Power Technologies Inc.)

the steam must be **superheated** – heated to well above 100°C – so that when it is expanded in the turbine there is little or no condensation, which would erode the turbine blades. An attractive alternative, especially for smaller installations, is to replace water with some organic compound such as liquid refrigerants, ammonia or silicon oil. Turbines powered by such fluids are said to be operating on the **organic Rankine Cycle** (**ORC**). There are many potential benefits. Superheating is not essential: in fact ORC installations can operate on waste heat at no more than 70°C. Due to the greater density of the organic fluid the size of the installation will be proportionally smaller. The unit is a closed loop system, so maintenance is simple and it can operate automatically and unsupervised. ORC units are often installed downstream of a large gas engine to recover energy from the gas engine's exhaust – this is particularly useful where the demands on a gas engine cogeneration or trigeneration installation are primarily electrical (see below.)

On the downside, lower operating pressures restrict efficiency, the technology is relatively expensive, and some of the working fluids are both potentially toxic and inflammable. A number of manufacturers offer ORC units in a range of sizes.

In strictly mechanical terms, the simplest way of converting the chemical energy of a hydrogen-rich gas into electrical power is to pass it through some form of **fuel cell**. This is an electrochemical device in which the gas is reacted with air or oxygen to produce water/steam and electricity – effectively electrolysis in reverse. Many different forms of the fuel cell have been tried since the first practical example was demonstrated in 1959, but most require virtually pure hydrogen as fuel. Some types can use less pure fuels such as natural gas, biogas or producer gas, and are therefore particularly suitable for cogeneration. Of these there are three types currently available, although others are in the final stages of development.

All fuel cells contain anodes and cathodes separated by an electrolyte. In most forms the hydrogen in the fuel is split into protons and electrons at the anode, which may incorporate a catalyst. The positively charged protons can pass through the electrolyte to reach the cathode, but the negatively charged electrons have to flow through an external circuit to meet up with the protons at the cathode. There, both react with the available oxygen to form water. It is the flow of electrons through the external circuit that generates the



All fuel cells work on similar principles, although this type demands pure hydrogen power. Sometimes it is the oxygen that is broken down to electrons and protons: in both cases the electrical output is low voltage direct current, and individual cells are stacked together to produce a useful voltage.

Types of fuel cell differ basically in the materials used for anode, cathode and electrolyte. The longest established type capable of working on less than pure hydrogen is the **phosphoric acid fuel cell** (**PAFC**), which uses liquid phosphoric acid as the electrolyte and platinum coated carbon paper electrodes. Operating temperature is between 150°C and 200°C, but because phosphoric acid solidifies at 40°C start up is difficult and PAFCs are only really suitable for continuous operation. The cost of platinum is another drawback, as are its projected long-term shortages.

A **solid oxide fuel cell** (**SOFC**) differs from most other types of fuel cell in that it is made up entirely from solid-state materials, usually ceramics. Operating at temperatures up to 1,000°C, SOFCs have no need of expensive catalysts and can accept a wide range of gaseous fuels, up to and including paint fumes – provided all sulphur compounds are removed first. This latter step is becoming easier as new sorbent technologies based on rare earth oxides come on stream. SOFCs can be flat sandwiches or concentric tubes: tubular SOFCs are easier to seal but have slightly lower performance. The biggest drawback of current SOFCs is the long start-up period needed to minimise thermal shock to the system. Research continues to develop lower operating temperatures – which will reduce material costs – and to shorten start-up times.

High operating temperatures are the distinctive feature of **molten carbonate fuel cells** (**MCFC**). The electrolyte is a mixture of carbonate salts – usually potassium and lithium carbonate – suspended in a porous, insulating and chemically inert ceramic matrix. Anodes are powdered nickel/chromium alloy; cathodes are porous nickel oxide doped with lithium. Operating temperature is around 650°C, and for the reaction to work carbon dioxide must be present at the cathode. This is usually recycled from the exhaust gases. MCFCs are currently the most efficient type of fuel cell available, but durability is still lower than other types. The German company **MTU CFC Solutions GmbH** is currently offering the **HotModule MCFC**, which, when fuelled by natural gas, produces 245 kW of electrical power and 180 kW of heat. It can also accept biogas, producer gas and similar hydrogen-containing products of pyrolisation and gasification (see Chapter 11).

The exhaust, mainly steam at around 400°C, can be used for both space and water heating and cooling and the generation of more electricity via steam turbines, Stirling engines or ORC units. Although most fuel cells have to incorporate start-up heaters, the reactions once initiated are exothermic, and useful heat can be recovered for cogeneration or trigeneration purposes.

At first sight, therefore, a cogeneration or trigeneration installation can seem like the ideal solution for many projects, especially if the fuel used comes from renewable sources. Under optimum conditions this type of installation can recover 90% of the energy in the fuel and put it to use. But there is one key drawback, an Achilles' heel that in some circumstances can render the whole concept impractical. The production of heat and electrical power are inextricably linked. If more power is needed, then more heat will be automatically produced – and vice versa. In all types of building there will be times when the demand for heat and power are out of sync, and there will be surpluses or shortfalls of one or the other.

Surplus heat could be diverted to a thermal store (see Chapter 15) and used to make up shortfalls at other times. At worst it could be vented to atmosphere. A surplus of electricity is harder to deal with. Electrical energy stores tend to be expensive and complicated. One option is to use the surplus electricity to generate heat that goes to a thermal store, and in the near future **unitised regenerative fuel cells** might be a practical option, (see Chapter 15), but the preferred solution for many cogeneration and trigeneration installations is to sell surplus power back to the national grid.

On the domestic scale, the Honda-developed **ECO-WILL** microcogeneration unit is now in widespread use in both Japan and the US. Based on a natural gas or propane fuelled specially developed single cylinder IC engine, the unit produces 3 kW of thermal energy and 1 kW of electricity – and, at 44dB (A), is no noisier than a conventional air conditioner. Its relatively modest heat output minimises summertime surpluses but a back-up furnace or boiler is needed for the depths of winter in most locations. Electrical output is also modest, meaning the household will often need top-up power from the grid. Any surplus can hopefully be sold back to the main electricity supplier.

Natural gas fuelled CHP, like this 15 kW installation from EC Power, is a well-developed technology (Reproduced with permission from EC Power)

It is unlikely that any building project would deliberately shun the benefits of back-up grid connection (see Chapter 1). The use of net-metering to allow the building owner to be paid for the surplus electricity exported to the grid and to set those payments against the cost of taking power from the grid to make up shortfalls or keep the building functioning during any outages of the building's own generation facility is attractive in its evident simplicity. In practice, this may turn out to be a complicated and frustrating exercise, and anyone contemplating cogeneration and the like is advised to discover the local electricity supplier's attitude towards distributed generation and net-metering at an early stage in the project's development.

This page intentionally left blank

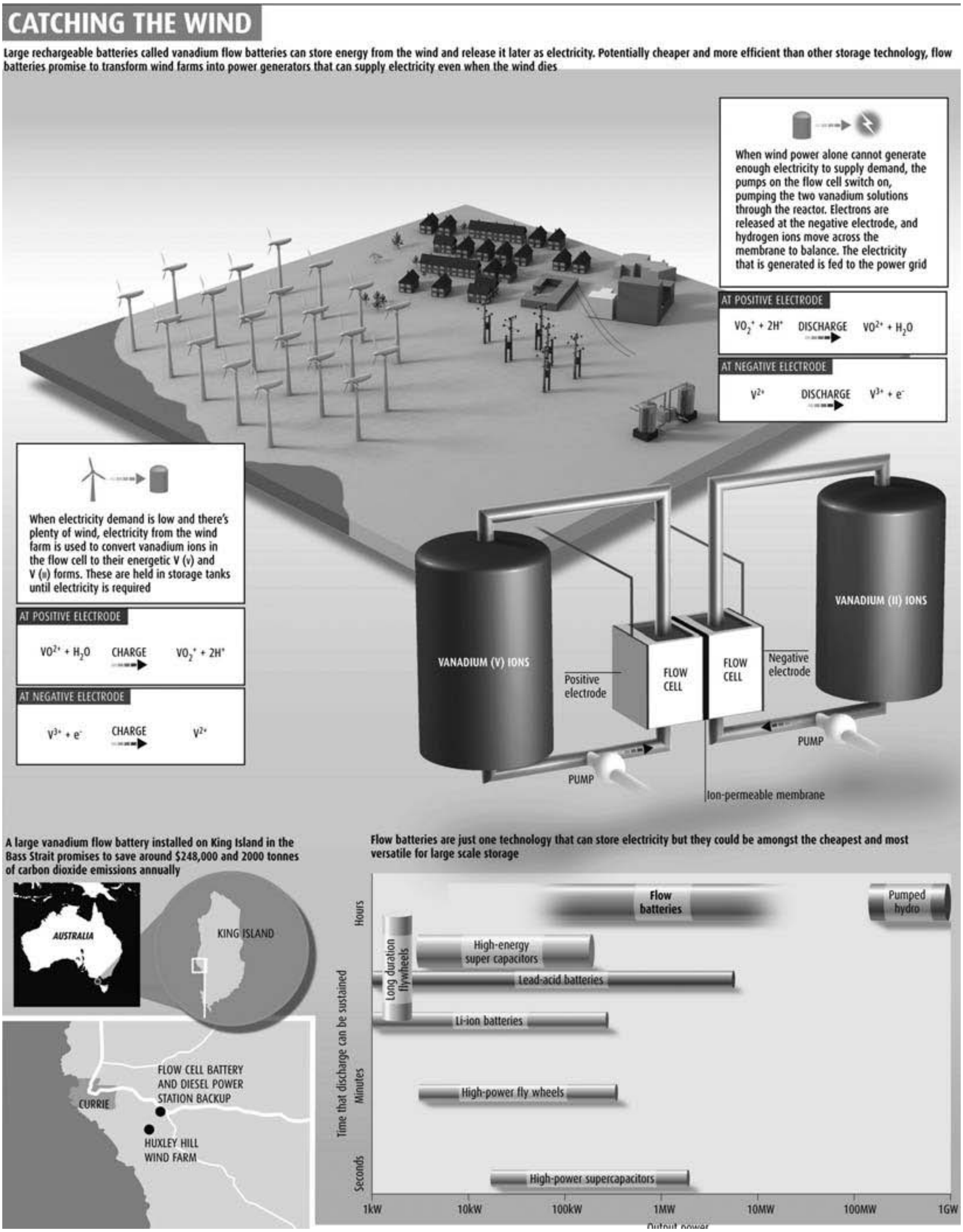
15 Energy stores

Most alternative energy sources are inherently variable and unpredictable. Solar and wind power are the worst offenders in this respect, while being in many ways the most convenient and cost-effective. Technologies based on wind and solar power, therefore, have to cope with a widely fluctuating energy input that rarely matches demand for more than short periods. A practical alternative energy system must be able to smooth out any mismatches that occur without an overdependence on back-up supplies from national energy grids. The only practical way of doing this is to store surplus alternative energy for use when input falls short of demand.

Surplus electricity from wind turbines, solar PV panels and mini hydro is normally best 'stored' on the national grid, via **net metering**, if it is available (see Chapter 1). Buildings not connected to the grid normally have either large conventional batteries or standby fossil-fuelled generators for when supplies from the alternative energy source are inadequate. Purpose-designed **deep cycle** or **deep drawdown** batteries are essential, of the type often used for forklift trucks. Automotive starter batteries are not suitable. Current battery installations mostly use lead/acid technology, and have a limited lifespan.

Alternatives under development include the **sodium-sulphur battery**, which has a high energy density and efficiency of charge/discharge and is manufactured from inexpensive, non-toxic materials. Unfortunately, it operates at temperatures of up to 350°C, and sodium is highly corrosive and reacts violently with water. Another high-performance option is the **molten salt battery**. This needs a temperature of up to 700°C to function properly, with obvious safety issues. Several companies have announced progress with lower temperature high-density batteries utilising non-toxic materials, but none are (at the time of writing) on the market.

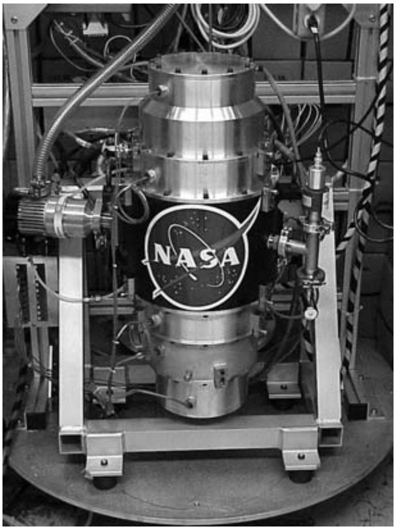
A promising development is the **flow battery**, which uses liquid electrolyte. This is stored in two separate tanks outside a flow cell, which contains two chambers separated by a thin membrane. One chamber contains a positive electrode, the other a negative electrode. When surplus electricity is available the two electrolytes are pumped separately through the flow cell, where each acquires a different electric charge, and returned to their storage tanks; if the energy supply drops below demand, the electrolytes are recycled through



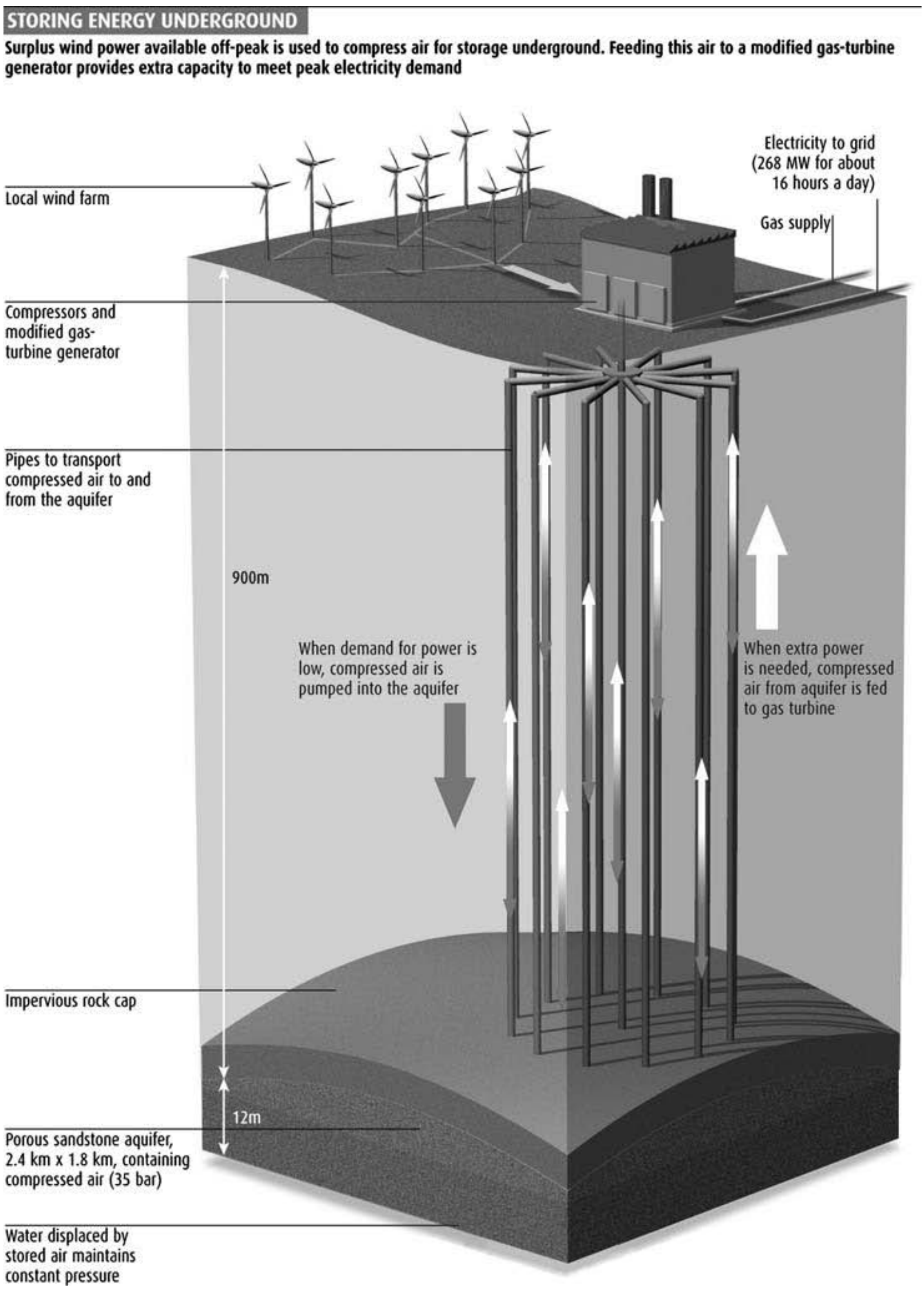
Flow batteries are a promising development (Reproduced with permission from New Scientist Magazine) the flow cell, where they give up their stored energy as hydrogen ions move through the membrane to balance electrons released at the negative electrode. Two variants have been tested, one based on **vanadium sulphate**, one using **zinc bromide**.

Developed in Australia, vanadium flow batteries are said to have a much longer potential operating life than lead/acid or other conventional battery types, and to be much easier to scale up for larger installations. Two installations of more than 200 kW have already been completed on wind farms in Japan and Tasmania and one that is designed to produce 1.5 MW for up to eight hours planned to go into operation on the Sorne Hill wind farm in Ireland at the end of 2007.

On the larger scale, and where site topology allows, **pumped storage** might be feasible. Surplus electricity is used to power a pump that moves water from a lower to a higher reservoir. When a shortfall occurs, the system goes into reverse, with water from the upper reservoir flowing back through the pump, which then acts as a generator. Other options becoming available include **superconducting magnetic energy storage**, which has the quickest response time of any electrical energy store. Units capable of producing 10 MW for two hours are now available, and are said to be very reliable as there are almost no moving parts. Also available are **flywheel energy storage units**. These typically will utilise advance carbon composite rotors mounted on magnetic bearings that can operate at more than 50,000 rpm inside a vacuum chamber. Energy efficiency, defined as the ratio between energy input and output, can top 90%, and storage capacity available ranges from 3 kWH to 130 kWH. The Australian Powercorp has installed a number of its 1 MW Powerstore units to back up both wind and hydropower installations. Early experiments with flywheel energy storage were dogged by problems with flywheel explosions, which could only be mitigated with rugged containment vessels. Even with modern composite rotors many users prefer to embed the systems in the ground for safety reasons.



A NASA-developed flywheel energy storage



Compressed air energy storage may be the answer for some projects (Reproduced with permission from New Scientist Magazine)

On the larger scale, and where site geology is favourable, **compressed air energy storage** (**CAES**) may be a realistic option. This uses surplus energy to compress air up to 35 bar or more and pump it into underground voids such as worked out salt mines and aquifers capped with impervious rock. Energy can be recovered via a gas turbine with a bypassed compressor stage – the high pressure air from the store passes directly to the combustion chambers. Between a half and two thirds of the power generated by a gas turbine is needed to power the compressor stage, so bypassing it allows the unit to generate up to three times as much power from the same quantity of fuel.

Regenerative fuel cells are another possibility. Basically an electrochemical device that directly converts the chemical energy of oxygen and hydrogen-rich gases or liquid hydrocarbons into electrical power and water, a fuel cell can also be considered as something that reverses the well-known electrolysis process, which uses electrical energy to break down water into hydrogen and oxygen. Combining both functions produces the **regenerative fuel cell** (**RFC**), also sometimes known as the **reversible fuel cell**. Some types of fuel cells operate at very high temperatures (see Chapter 14). However, the RFCs now becoming commercially available are based on the **proton exchange membrane fuel cell** (**PEMFC**), which has an operating temperature of around 200°C or less.

The first generation of RFCs were developed in the US and aimed at aerospace and defence applications, although there is still considerable interest in their use as prime movers in road transport. Energy density is approximately ten times higher than that of conventional lead-acid batteries. Some early versions separated the functions of electrolysis and power generation. These days, it is more usual for both functions to be combined in one cell, consequently known as a **unitised regenerative fuel cell** (**URFC**). Later developments include the substitution of metal hydrides for the traditional noble metal catalysts in the hydrogen electrodes.

This would appear to have the potential to slash cell prices and eliminate the need for separate storage of the hydrogen gas produced by electrolysis. Technological benefits should include almost instantaneous start up and excellent performance in low ambient temperatures. The leading developer is the **Ovonic Fuel Cell Company** of Michigan, which claims that when they come on the market, metal hydride URFCs will be slightly cheaper than conventional batteries in terms of initial cost and much cheaper over the long-term.

An alternative and much simpler strategy on the smaller scale is to use surplus electrical energy to generate heat, which is then stored. A straightforward immersion heater is one alternative, or a ground, water or air source heat pump might be preferred. Some of the surplus electricity could be used to power anti-legionella systems (see Chapter 2), drive irrigation pumps and perform other tasks that do not require regular operation.

Storing surplus heat is somewhat more straightforward. Thermal store technology is developing rapidly, and there are now four basic subdivisions. The main distinction is between **diurnal storage**, which absorbs heat during the daylight hours and releases it at night, and **seasonal storage**, in which summertime heat is saved to maintain supplies during the winter. In practice, on larger projects where the main input comes from solar energy, it may be preferable to go for an intermediate thermal store, which can provide enough heat for several days. A further distinction is between **low temperature** and **high temperature** storage. Low temperature storage normally involves heating a large mass – often the ground near to or below the building – to a relatively low temperature, usually below 40°C.

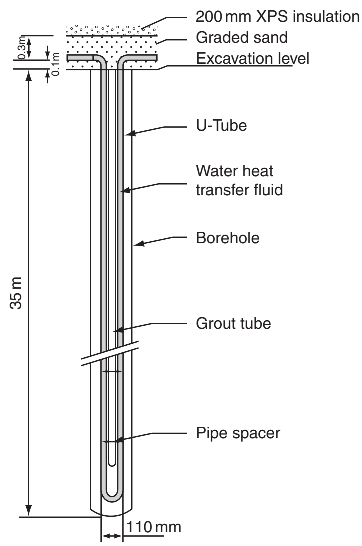
Early prototypes of **zero energy** or **autonomous** buildings used the earth below, around (and sometimes above) the building as a low temperature seasonal thermal store, relying on passive heat transfer to transmit passive solar gain through the walls and floor (and sometimes the roof) into the earth during the summer. A waterproof membrane curtain extends out from the building to stop rain penetration into the storage area. Keeping the moisture content of the earth used for storage relatively low minimises energy losses to the surroundings.

More sophisticated designs relied on solar collectors to heat either air or water, which was then ducted or piped into the ground. The earth reached a higher temperature than with a completely passive system, so the area that needed to be protected by a waterproof curtain was smaller. Heat movement back into the building in winter was still often down to uncontrolled conduction through the ground floor slab, but temperatures within the building were generally better controlled in both summer and winter than with the totally passive system. More control could be achieved in air ducted designs, which used either a fan or a solar chimney to draw air back through the underground ducts in winter.

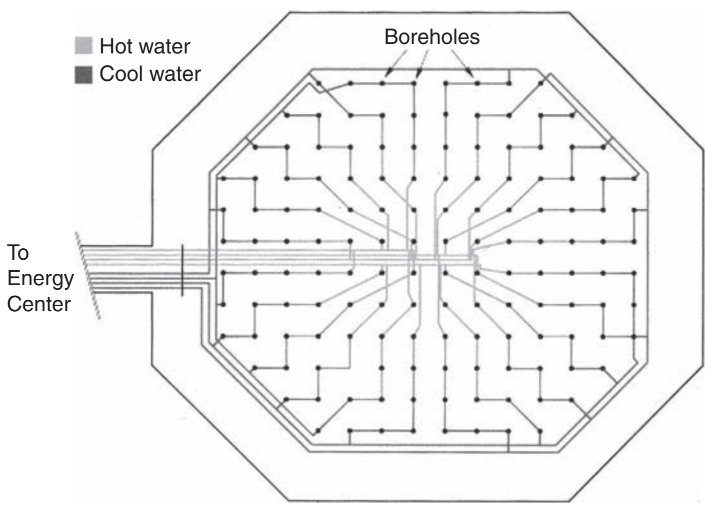
Larger, more sophisticated forms of low temperature seasonal **underground thermal energy storage** (**UTES**) have been used successfully to supply housing developments, offices, schools and factories with sizeable fractions of their annual demand for both DHW and space heating. There are three basic types: **aquifer thermal energy storage (ATES)**, **borehole thermal energy storage** (**BTES**), and the least common, **cavern thermal energy storage** (**CTES**). ATES systems can only be used when ground conditions allow – specifically, there must be at least one aquifer at a convenient depth that will yield adequate groundwater supplies. There must be very little lateral water movement as well. Most systems installed to date use cold groundwater pumped up from a water bearing strata a convenient distance below the surface, heated in solar collectors and pumped back down another borehole some distance away. The cold water may also be used for space cooling purposes before it passes through the solar collectors (see Chapter 13).

In winter the flow is reversed although in some installations, a heat pump is used to abstract heat from the fairly low temperature store and concentrate it in the building's DHW and space heating systems (see Chapter 12). An aquifer with a high rate of groundwater flow is only suitable for summertime cooling, although there is at least one installation, the Reichstag building in Berlin, that uses two aquifers at different levels, one for heating, one for cooling.

If no aquifer is present below the site, BTES might be the answer, especially in impervious soils and rocks with high specific heat. Boreholes up to 200 mm diameter and 200 m deep are usually positioned 5 to 8 m apart in a hexagonal pattern to minimise heat loss. U-pipes or more sophisticated forms of heat exchanger are installed in the boreholes and are often bentonite grouted after installation to maximise heat transfer to the surrounding substrate. A heat transfer fluid, typically water containing glycol antifreeze, circulates through the boreholes and solar collectors in the summer, and usually transports heat collected from the cooling system as well. In winter the stored heat in the ground is drawn off for DHW and space heating, either directly or via a heat pump.



Schematic of a typical borehole in the BTES at Drake Landing Solar Community (diagram provided courtesy of Natural Resources Canada)



Layout of the Drake Landing Solar Community BTES (diagram provided courtesy of Natural Resources Canada)

A variation of BTES is **ducts in soil**, also known as **earth tubes** or **ground coupled heat exchangers**. These are usually a horizontal installation of pipes and/or ducts at relatively shallow depth. This has the advantage of tapping into the natural solar gain of the ground, and overlaps in operation with ground source energy systems (see Chapter 12). Using a relatively high mass of soil heated to relatively low temperature means that a heat pump is normally needed to obtain DHW and space heating at acceptable temperatures. Against this can be set the opportunity to use less sophisticated solar collectors, which may be more durable and vandal-proof, and hence cheaper overall. Constructing a CTES can be expensive. The best strata are stable, impervious igneous or hard sedimentary rock with low thermal conductivity and potential for leaching. A configuration with low surface to volume ratio is essential; even then at least 10% of the energy stored in the water inside the cavern will be lost, and it will take at least 12 months for energy flows to stabilise.

Low temperature **seasonal pit storage** is more popular, and its performance is easier to predict. Many forms have been tried, with varying degrees of sophistication, and development work continues. At its simplest, a thermal storage pit consists of an excavation lined with a suitably rugged insulation material and waterproofed by a heavy duty waterproof membrane. In some examples this is then filled with plain water, but such a tank would need either a loadbearing cover slab or perhaps a floating cover, which would involve long-term maintenance issues. An alternative is to use either gravel/water or gravel/sand/water storage. The latter design positions the heat transfer pipes in layers of sand between layers of gravel to protect them from damage. A loadbearing cover slab is not needed, as the cover is supported by the mineral fill. Unit storage capacity is somewhat less, but it costs little extra to enlarge the pit to compensate. Some installations have a history of leakage problems. There is also the potential problem of legionella disease, and local regulations might demand the periodic sterilisation of the store to kill any legionella bacteria that might be breeding. Against that, legionella disease is unlikely to spread from a covered store with no significant water movement.

Double the physical dimensions of a storage tank and its surface area will increase by a factor of four. Its volume, however, will increase eightfold. Thus the larger the tank the more efficient it will be at storing heat, as the area through which heat can escape by conduction through the insulation will be proportionally lower. Large water thermal stores have been successfully used for seasonal storage on a number of projects, operating at temperatures of 40°C or less to minimise heat loss even further. These usually take the form of heavily insulated underground concrete tanks, either in the basement in the case of a single large building or located centrally amongst a number of smaller buildings or homes. Heat input can be either through an indirect solar water heating system or a solar-heated air supply passing through heat exchangers. Energy for DHW and space heating is most conveniently extracted by passing water through another series of heat exchangers, or by the use of a heat pump.

Capital cost is higher than most other forms of low temperature seasonal storage, but the greater efficiency of thermal water stores can make concrete tank stores attractive, especially if they are constructed at the same time as the rest of the building. There are problems associated with the construction of insulated watertight concrete that can push up both capital and running costs. Waterproof lightweight concrete, which has a significantly lower thermal conductivity, is now a practical proposition, and might be preferred to more traditional forms of construction. Again, attention must be paid to the legionella potential.

Almost all UTES installations require a **buffer tank** between the thermal store proper and the DHW and space heating/cooling circuits. This damps down the inevitable short-term variations between demand and supply temperatures. No buffer tank is needed in one **hybrid low temperature thermal storage** system which combines both pit and borehole storage. A central underground concrete water tank insulated only on its top surface is surrounded by a ring of boreholes fitted with heat exchangers. Heat transfer fluid from solar collectors and/or space cooling passes first through a heat exchanger in the central tank until the maximum operating temperature is reached, then into the boreholes. Heat lost through the walls and floor of the tank is largely retrieved by the boreholes when the system goes into reverse during the winter. The central tank acts as a buffer, and the elimination of insulation to walls and floor significantly reduces capital cost. In practice it can take up to three years for the system to stabilise and achieve its maximum efficiency.

Prototypes of this design have seen temperatures in the central store reach 90°C. Other high temperature UTES systems have also been trialled. These raise ground or water temperatures to 70°C or more, but have a mixed record in practice. There have been problems with clogging, scaling, corrosion and leaching, and most installations have struggled to reach their design performance. On the other hand, such high temperatures effectively eliminate the risk of legionella disease.

Another possible source of input into UTES of all types is waste heat from industrial processes, or from cogeneration or trigeneration installations (see Chapter 14). Industrial waste heat can be stored for DHW and space heating needs, or as a back-up supply should the industrial process suffer any interruption of primary heat supply. It could also be stored for use in spells of severe weather, to de-ice car-parks and access roads.

Rock bins and **rock beds**, also known as **gravel beds**, are popular low temperature diurnal thermal stores when used in conjunction with solar air heating (see Chapter 3). Both involve the use of single size clean dry high density gravel or crushed rock, usually of a 20 m or 40 mm nominal size, stored in insulated waterproof airtight containers. Recent research indicates that, where available, rocks of a 150 mm nominal size offer the best combination of heat storage and airflow. Although relatively cheap, simple and requiring little maintenance, rock bins and gravel beds can suffer problems with mould, mildew and insect infestations. Their biggest drawback is size – a rock bin can store only 30–40% as much heat as a water-based store of the same volume. Rock bins, which have a predominantly cubical design, are more effective than underfloor gravel beds due to their more advantageous surface/volume ratio and associated lower rate of heat loss. Normal practice, when space allows, is to construct a rock bin large enough to store enough heat to meet up to five days space heating demand.

High temperature diurnal thermal stores are usually just larger, more sophisticated versions of the ubiquitous domestic hot water cylinder. Water is stored in large prefabricated insulated tanks constructed from steel or glass fibre reinforced plastic. Sometimes insitu concrete is preferred. The main distinction is between vented and unvented stores: vented stores, operating at atmospheric pressure, can deviate from the obligatory cylindrical form of the pressurised unvented store and can be manufactured in more convenient shapes, such as cuboids. This can take up less floor space than the cylindrical form, at the cost of slightly greater conductive heat loss due to their greater surface to volume ratio.

Whatever the geometry, stratification is encouraged, heat is extracted for DHW and space heating via one or more heat exchangers: more effective stratification is said to be possible when external plate heat exchangers are fitted. Prefabricated tanks are easier

Rock bins using large aggregate have proved very effective (Reproduced with permission from Arup – Mike Rainbow)

to plumb into the pipe networks than the *in situ* concrete alternative. Against that must be set the practical limitations on the size of prefabricated tanks set by site logistics.

A more advanced and less space hungry alternative currently coming onto the market is thermal storage utilising **phase change materials** (**PCM**). The most convenient change of phase is that from liquid to solid and back again, although solid to solid PCMs exist and liquid to gas PCMs have been investigated. Below the critical phase change temperature liquid to solid PCMs behave like any other solid: temperature rises in proportion to the heat input.

At the phase change temperature, however, the solid PCM melts, absorbing large amounts of energy as latent heat without any significant temperature rise. As heat supply increases, the PCM behaves like any other liquid store. As heat is extracted and the temperature falls, however, the liquid will solidify again at the critical temperature, releasing its stored latent heat. There are a number of materials such as salt hydrides, fatty acids and esters, and paraffins such as octadecane, which change phase in the convenient 20°C to 30°C range. In practice, most of these only work efficiently when the operating temperature range is relatively small, less than 20°C, which makes them suitable for many alternative energy applications.

Some PCMs are available in microcapsulated form. These are basically minute spheres of PCM coated with an inert polymer, which have been incorporated into traditional building materials such as fibreboard, plasterboard and floor tiles. As a typical PCM can store up to more than 10 times as much thermal energy as masonry or reinforced concrete, this has the effect of significantly increasing the building's thermal mass without a corresponding increase in structural weight. **Thermal** and **Trombe walls** (see Chapter 3) could be made much slimmer and lighter.

A PCM high temperature diurnal thermal storage tank could be only one-fifth of the volume of the equivalent water-based storage, or even less. Or five times or more energy can be stored in the same volume. Most commercial PCM products on the market are aimed at the cooling sector (see Chapter 13). However, a number of suppliers offer custom-made PCM-based thermal stores, usually involving PCMs packed in corrosion-proof metal shallow metal cassettes or stainless steel spheres, typically 100 mm in diameter. These are housed in insulated tanks through which water is circulated as the heat transfer medium. As these tanks can operate at relatively high pressures and temperatures they are particularly suitable for storing waste process heat. PCM-based thermal stores could also utilise air as the heat transfer fluid.

Larger-scale installations utilising several different technologies could well use two distinct types of thermal store, e.g. a UTES which is topped up with a mixture of heat recovered from cooling systems and DHW, and a high temperature diurnal store fed by solar water heaters, which is backed up by a heat pump in the UTES.

Without an effective energy storage system most microgeneration technologies will be neither practical nor economic. Luckily, there is a wide range of practical options available. Whatever the nature of the project and the peculiarities of the site, it should not be difficult to come up with an effective solution that will make the numbers look attractive.

This page intentionally left blank

16 Combining technologies

Meeting a significant percentage of a building's energy needs with microgeneration is usually best accomplished with a mixture of compatible technologies. Even a low technology approach might, at the very least, involve windcatchers, passive solar air and DHW heating and a rock bin thermal store. Over-complexity is a perceptible risk with a higher technology approach; nevertheless, phase change materials, ground source heat pumps, advanced active solar water heating, several forms of solar photovoltaic technology and cogeneration are all well-developed, proven options with readily available hardware. Medium-scale wind is promising, biomass can be a very practical choice when and where the right sort of biomass is available at the right price; and in any location fortunate to have a suitable stream or river close by, a small hydro can be the most effective option of all. As technologies develop, more options will become available, and microgeneration will become more than an ethical choice. However, selecting the most effective combination for a particular project is not straightforward.

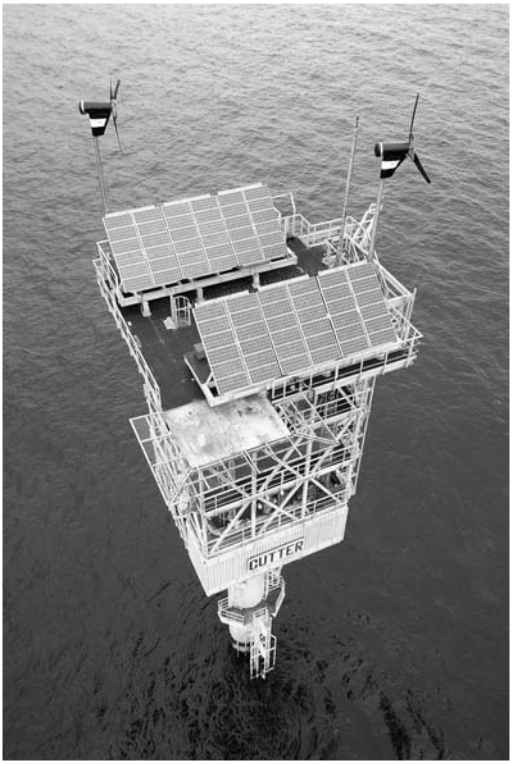
Initially, a thorough assessment of a site's potential is essential. Key questions would be:

- Will it be possible to orientate the building to maximise the area of any solar water heating or PV panels while simultaneously minimising unwanted solar gain?
- Is there room on the site outside the projected building's footprint for the more space-hungry types of microgeneration options (for example, storage and processing of biomass, ground mounted wind turbines, earth tubes, underground thermal stores)?

Site topology is important; a marked cross-fall can make passive solar water/space heating a realistic possibility, a site in a depression is unlikely to be a good location for a wind turbine. Similar limitations apply to a site surrounded by rugged terrain, trees, or tall buildings.

Data on the ground conditions below the site is also important for more than foundation design: the presence or absence of aquifers or flooded mine workings will influence decisions on space cooling; the depth to rock head will affect any choice of ground loops for ground source heating; the type and conductivity of the soil would determine the size of any such ground loop.

There may be potential assets just outside the site's boundaries, such as deep water that can provide cost-effective cooling, or an energy-rich river or stream that could be used for both water source heating and cooling and electricity generation. There may even be an old watermill site nearby that could be revived, or a water or sewage treatment plant whose outflow could also be harnessed to generate electricity. A search should always be made for local sources of biomass. Some local authorities would welcome the opportunity to dispose of horticultural waste and out-of-date food from supermarkets other than to landfill; local food and drink producers may even pay for their hydrocarbon-rich waste to be taken away. Dependence on processed biomass – such as wood pellets – should be avoided unless a local source is both available and long-term.



Wind turbines and solar PV are an effective combination on this offshore installation (Reproduced by permission from Eagle Power)

No decisions on wind power should be made without a proper survey of the actual wind resource at the site. This takes time, preferably at least 12 months. A reliable estimate of both average wind speed and prevailing wind direction is also important if natural ventilation is to be contemplated. Solar resource should be checked over for at least six months, to monitor the effects of any seasonal shading from local features, including trees, buildings, hills and mountains. A similar survey of hydropower potential is also desirable when a prospective site is available. Aquifer and ground temperatures could also be monitored, to further refine any relevant calculations. And it is always a good idea not to take potable mains water supplies for granted. Evaporative forms of cooling should never be adopted without a cheap and reliable supply of mains water being available.

There should also be a thorough investigation to ascertain the attitude of the local electricity supplier towards microgeneration and grid connection (see Chapter 1) and whatever national and local financial incentives might be available. Grants and subsidies should never be relied upon to justify the long-term economics of a microgeneration package; nevertheless, they can make a project initially much more attractive. There is, however, a danger that government funding, rightly or wrongly, might overemphasise one particular technology – such as solar PV in Germany – distorting any analysis of the options for a particular project.

As mentioned in Chapter 1, the next and crucial stage, the calculation of a building's energy needs, is a complex exercise. Demand varies constantly throughout each 24 hours and throughout the seasons, and is likely to vary unpredictably over the building's design life as climate change kicks in. It should be remembered that global warming does not mean that all areas will become uniformly warmer. Climate change could mean milder, wetter winters and hotter, dryer summers; it could also produce localised cooling as ocean currents change their patterns. Early indications are that weather will become more extreme. For example, building designers may well have to rethink their assumptions on wind and snow loadings and make provision for heat waves longer and hotter than anything experienced in the last 100 years. Unseasonable flash flooding can threaten building services, even in areas traditionally immune to flooding.

Heat emitted by lighting, cooking, computers, and so on, is an important factor in the overall energy flow patterns within a building. There are countervailing trends here. Consumers, if surveyed, will claim to be demanding ever more efficient appliances, but are actually purchasing more, larger and more energy intensive items such as large flat-screen digital TVs, games consoles, whirlpool baths, power showers, hot tubs and domestic air conditioning. Office equipment continues to proliferate; the paperless office is even further over the horizon, colour printers are becoming the norm, vending machines and water coolers are standard items. On the other hand, low energy **light emitting diodes** (**LEDs**) might soon become standard fitments now that true white LEDs are available at realistic prices. Predicting what contribution waste heat from lighting and appliances will make to the building's space heating and cooling loads over the medium- to long-term is a chancy business.

Nevertheless, such predictions have to be made, and increasingly sophisticated tools are becoming available to enable at least the short-term picture to be clarified. Advanced software is available that can allow for energy flows in to and out of the building under a wide range of conditions. Some programs can check solar gain and wind potential against local weather records, although local wind data is usually not accurate enough to give really reliable results for wind turbines, where micrositing is so important (see Chapter 5). Allowance for climate change is more difficult: one option is to run the model for a location significantly warmer than the actual location and calculate the 'future-proofing' premium that this would involve. Thanks largely to a number of 'House of the Future' projects in different countries, more data is becoming available to validate the models. It is now possible to make reasonably accurate estimates of seasonal energy demands on most projects, and then to look at how some of this demand can be met by microgeneration.

It should always be remembered that there is no virtuous target, no ethical minimum percentage which separates a true low carbon building from a cynically greenwashed project. The target percentage of overall annual demand to be met by microgeneration might, for very good reasons, vary between 10 and 90% on individual projects – (100% if one includes fossil-fuelled back-up generators in the microgeneration equation). Much depends on the site, on the primary function of the building, and on the availability of grants and subsidies at the time of planning. For every project there will be a realistic optimum percentage beyond which the law of diminishing returns will set in.

This optimum will also be affected by the aspirations of the building's owners/tenants. Currently, the most common motive to go down the microgeneration road is probably the desire to insulate against instabilities in fossil fuel supply: to minimise the impact of potentially soaring prices and to cover for politically driven interruptions in supply. Maintaining at least some function when national energy grids are down could be a prime imperative for some.

Others might wish to be seen to be making an ethical commitment. This might be reflected in a preference for the high visibility of a wind turbine, for example, even when a wind turbine in practice may not be the most cost-effective solution in that particular location. In such cases, the wind turbine would have to be backed up by a less visible but more appropriate technology. Those clients who are really serious about achieving a low carbon footprint may also insist on materials with low embodied energy being used, which will restrict the use of some types of solar photovoltaic cells, for example. A far-sighted client may also wish consideration be given to the environmental implications of the eventual demolition of the building – some materials may pose a serious disposal/ recycling problem.

Most solar thermal equipment includes a high proportion of easily recyclable materials such as steel, copper, aluminium and glass. Polymer content is growing as metal prices soar – but so is polymer recycling capability. Similar comments apply to wind and hydro power. Fuel cells, PV arrays and most forms of battery are more problematical. More complex technologies – biomass gasification, anaerobic digestion, cogeneration and tri-generation – are relatively easy to dismantle and have a high content of material that could be recycled.

Every effort should be made to reduce overall energy needs before considering the specifics of microgeneration. High levels of insulation and the control of airflow into and out of the interior should be a feature of every modern building. Passive technologies should be evaluated at an early stage. Even the most aggressively advanced technology building can take advantage of passive solar gain: passive solar air heating can be integrated into advanced cladding systems, atria can function as effective solar chimneys. Windcatchers or windscoops can be striking architectural features. Well-sited pools and fountains can produce a more benign internal environment in more ways than one. Where there is significant cross-fall on the site, low-level solar collectors can function passively, a reliable and cost-effective water-heating option whose only significant drawback might be the potential risk from vandalism.

This roof features solar PV, windcatchers and lightpipes (Reproduced with permission from Monodraught)

Moving up the complexity ladder one step might involve the use of motorised dampers to control natural ventilation, or solar PV-powered pumps or fans to drive water or air through solar collectors. Another upward step would take the designer to technologies such as evaporative cooling, water and/or air heating powered by biomass combustion, mini hydropower, wind and solar PV. Those seeking the ultimate solution would be considering biomass gasification or anaerobic digestion, trigeneration, unitised regenerative fuel cells and the like. On most major projects, however, a mixture of technologies from the simplest to the most complex will usually be the answer.

Where space permits, a separate 'powerhouse' for microgeneration has the advantage of imposing no architectural restrictions on the project proper. Vertical axis wind turbine manufacturer TMA (see Chapter 5) envisages the support structure for its turbine housing not just a generator and control equipment but also a biomass fuelled generator to act as standby. Similar principles could be achieved with other types of wind turbine. Concentrating solar thermal and tracking solar PV arrays are probably best located at ground level in most cases, and biomass gasification and anaerobic digestion would be difficult to include within the footprint of most buildings.

When a best estimate of the building's energy demands is available, the first topic to be addressed is usually the energy storage that can be provided. Most commonly the energy to be stored is heat; electrical energy is usually best 'stored' on the local grid, although

'Powerhouses' need not be boring, as this installation at the ARC building in Hull demonstrates (Reproduced with permission from Solarcentury.com)

realistic alternatives are now coming on stream (see Chapter 15). The bigger the thermal store, the higher the proportion of the building's needs for space and DHW heating that can be met by alternative energy supplies. Ideally, surplus heat produced/collected in the warmer months is stored for use in winter. Seasonal thermal stores using water have to be relatively large; for example, for a typical dwelling to meet virtually all its annual space heating and DHW needs from solar water heating, the store would have to be at least 10 m^3, implying a cubical tank more than 2.15 m on a side and weighing over 10 t. Hardly practical for a single dwelling – although the use of phase change materials would make the dimensions more realistic – but a central seasonal thermal store serving a number of dwellings would normally look much more attractive (see Chapter 18).

Large (capacity) thermal stores can be fed by a number of secondary sources, including heat recovered from attics, outgoing air and grey water, cooling air from PV panels, and the heat generated by speed controllers on wind and water turbines. Cogeneration is often only practical when a large thermal store is available. The ratio between heat and electric power production is fixed, so that at times when electricity demand is such that a surplus of heat is produced, this surplus can be transferred to the thermal store. And where there is no mutually beneficial relationship between the building owner and the local electricity supplier, surplus electricity can be converted to heat and stored as well. On larger projects it may well be that the ideal thermal store solution might be a combination of low temperature seasonal and high temperature diurnal stores, perhaps involving **PCM**.

PCMs can also be used to add virtual thermal mass to lightweight structures, opening up a number of heating and cooling strategies that would otherwise be unavailable. Conventional thermal mass in the form of concrete or structural steel can also be the right solution, especially where long span structures are preferred.

Some microgeneration technologies are obviously very compatible. Solar heating and solar PV are a near perfect fit, with the PV arrays providing the current when most needed to power the pumps and fans of an air- or water-based solar-heating system. A true solar roof or active cladding would incorporate both solar collectors and PV arrays, in a ratio determined by the relative energy needs of the building, or the desire for the PV arrays to provide enough back-up power to keep key IT elements functioning when local electricity grids go down. Both active cladding and solar roofs are now well-developed technologies that can provide energy as well as successfully keeping the weather out.

Where power is needed during the night hours a well-sited wind turbine is more appropriate than solar PV. Even then the power supply will be intermittent. Intermittency is a potential problem with many forms of renewable energy even if generous energy stores are provided. This is more likely to be a serious problem with electrical power, where long-term energy storage is still not a well-developed technology. If a reliable source of power other than that derived from fossil fuels is a priority, then the realistic options are cogeneration using some form of biomass or biomass derived gas, or mini hydro.

Mini hydro is demonstrably green, especially if a former watermill site is rejuvenated. Biomass can pose some complex ethical questions. The most convenient forms, such as pelletised waste wood and grains, will often have travelled considerable distances before use, and some will have required heavy dosages of agrochemicals. Biomass crops could usurp land previously devoted to food production. Efforts to maintain the current highly

Several technologies were combined at the ill-fated Earth Centre, Doncaster, England (Reproduced with permission from Powertech Solar Ltd) mechanised and personally mobile Western lifestyle by substituting biofuels produced from sugarcane and corn for liquid fossil fuels are already putting pressure on basic food prices. Even carbon-rich waste, which is currently a disposal problem rather than an asset, could soon become desirable. A commitment to biomass-based technologies should only be made in the knowledge that continuity and availability of supply can never be totally guaranteed.

A super-insulated high thermal mass design was chosen for the Brocks Hill Environment Centre near Leicester, England. Solar PV, flat plate collectors and a 29 kW wind turbine supply energy (Reproduced with permission from Henderson-Scott Architects)

A commitment to minimise the energy required to cool the building and its occupants carries less risk. Over the longer term, for many buildings the cooling demand will be the most energy intensive. Luckily, several alternative and reasonably well-developed options which can reduce or even eliminate the need for traditional refrigerative technology exist. Even with relatively small energy inputs, natural cooling based on wind scoops and windcatchers and aided by sophisticated powered dampers can supply much of the space cooling needs of the most complex buildings (see Chapter 17). Many developers will still prefer to have the reassurance of refrigerative air conditioning; but passive and low energy active cooling techniques can significantly reduce the size, cost and energy consumption of the air-conditioning system.

It also makes sense to use solar power or air, ground or water source energy or waste, or recovered heat to preheat the feed water into a boiler; even if the main energy source is biomass. This will normally be via a heat exchanger in a high temperature thermal store. Preheating can allow the size of the water heating installation to be significantly reduced, with a beneficial knock-on effect on the size of any biomass drying and storing facilities.

As a general principle, the objective should always be that as little heat as possible should be allowed to go to waste. A cost benefit analysis is always going to be central to the process of determining just how far this quest should go. Heat or energy recovery ventilation is usually cost-effective where space heating and cooling and DHW are top priorities – such as for residential accommodation, hotels, hospitals and the like – but is harder to justify on economic grounds alone for buildings with low night-time occupancy. The same comment is even truer for heat recovery from grey water. A lot also depends on the sophistication and effectiveness of the building management system, and on how easily the occupants can override it.

Occupant behaviour is a key factor in electricity conservation as well. There have been several cases where it is alleged that pioneering high technology low-carbon buildings have failed to meet their original targets, partly because their occupants behaved in unexpected ways. For example, they switched lights back on after the building management system switched them off, or opened windows to increase perceived comfort levels inside, or brought in fan heaters to warm up rooms that had stood empty for some time in winter. And, even with the best intentions, people are going to leave equipment on standby for long periods unless there is a positive programme of regular checks – or until equipment manufacturers put limits on how long their products can be left idly consuming energy, most of which will only put extra loads on the cooling system.

Such limits will probably require government intervention on an international scale. Government legislation, particularly through local building codes and regulations, is also going to have an unpredictable effect on project design. A rapid upgrading of standards in response to particularly dramatic events can lead to recently completed buildings designed to older codes becoming less attractive to potential tenants – the furore over means of escape from tall buildings post 9/11 is a good example of that phenomenon.

Good intentions and a willingness to explore the possibilities offered by microgeneration technologies may not always be enough. Local planning authorities have to be compliant, or at least co-operative, neighbours and local amenity organisations may have to be placated. In November 2007 plans were announced for a £20 million package of technologies designed to dramatically reduce the carbon footprint of London's landmark Houses of Parliament, a grossly inefficient Victorian mock-Gothic edifice on the left bank of the River Thames. Some of the proposals were uncontroversial: a natural gas-fuelled trigeneration plant in the basement, aquifer cooling, rainwater harvesting and partial secondary double-glazing. Other proposals brought the inevitable howls of protest from conservation and heritage bodies. Fifty 'tidal' turbines in the restricted river zone next to the building with small vertical axis wind turbines mounted above them were bad enough, it was said, but what really triggered the outrage was the proposed 1.65 MW, 35 m high horizontal axis wind turbine sited in Victoria Gardens, a small park on the riverbank next to Parliament. Given its central urban location, such a turbine would be little more than a very visible symbol of the government's commitment to the battle against climate change, one that could backfire badly if it spent most of its life motionless. The proposed small vertical wind turbines above the tidal turbines are unlikely to fare much better.

True low-carbon buildings with massively reduced energy demands will become the norm in a very few years. Today's designers now have the tools to get ahead of the game. A range of reliable technologies is available, which may be combined to produce the right result for a particular project. No great leap of faith is required.

17 Manchester Civil Justice Centre

A unique combination of natural ventilation and daylighting coupled with the use of aquifer water cooling helps cut energy costs by more than 20% for this landmark public building.

Described as a 'fourteen-storey filing cabinet', the £110 million, 35,212 m^2 (gross) Manchester Civil Justice Centre is the largest court building to be developed in the UK

Cantilevered courtrooms are a distinctive feature of the Manchester Civil Justice Centre (Reproduced with permission from Mott MacDonald) since 1892. Its designers were set very strict briefs on the internal environments of its 47 courtrooms, requirements that sometimes took precedence over the sustainability of the project. Internal temperatures had to be maintained between 21°C and 24°C at all times, with the maximum possible use of natural daylight. However, the unique layout of the building, with its vertical stacking of courts, corridors and meeting rooms, created unique opportunities for environmental and engineering designers Mott MacDonald.

Originally the target was to achieve a 'very good' BREEAM* rating, but this was later uprated to 'excellent' at the instigation of the end tenant, Her Majesty's Courts Service and the developer Allied London Properties. A final rating of 'excellent' was achieved.

Several possible microgeneration options were considered. For instance, a wind turbine mounted on the roof of or integrated with a 100 m high building standing well above its neighbours can be very effective. However, Mott MacDonald could find no suitable units available. Cogeneration was ruled out on the grounds that the heating load in the building was relatively small. Site investigations, however, revealed that below the building, at a depth of 100 m, there was an aquifer holding water at a temperature of 12°C with obvious space cooling potential.

Tests confirmed that water quality was excellent. This came as no surprise, as a world famous brewery nearby draws its supplies from the same aquifer. Mott MacDonald's preferred solution would have been to abstract cooling water directly from the aquifer and reinject the used water some distance away after use. Unfortunately, a fault in the underlying sandstone would have allowed the water to circulate too freely, warming up the area around the extraction point. A closed loop indirect system would have needed a lot more boreholes, and would have achieved temperatures no lower than 14°C.

The third option was to take advantage of the proximity of the navigable River Irwell and discharge the used water into that. After two years of negotiations with the Environment Agency, a licence to abstract 40 l/sec from two 300 mm diameter boreholes was granted along with approval for discharge into the River Irwell. The Environment Agency insisted on a third borehole to monitor water levels and temperatures.

Abstracted water performs two distinct functions:

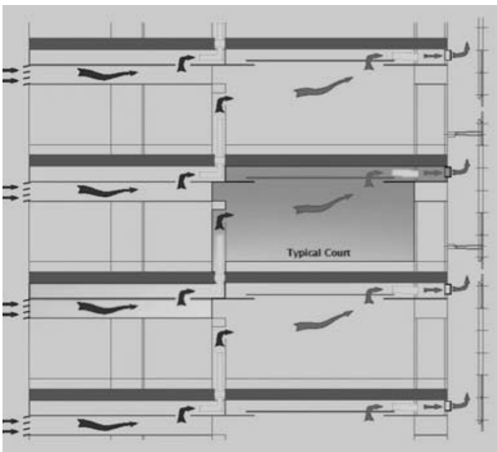
1. Cooling of the dramatic ten-storey atrium is down to an underfloor network of 20 mm diameter medium density polyethylene (MDPE) pipework, cast into the floor screed, containing water, which passes through a plate type heat exchanger where it is cooled by the aquifer water.
2. At peak load conditions localised areas on concourses used for waiting areas have underfloor displacement cooling provided.

Late afternoon solar gain through the west-facing glazed atrium could have been a major cooling load: Mott MacDonald's solution was to provide active ventilation to the double skinned glazed façade with a 900 mm central cavity. In winter the cavity is closed off and the façade acts as a thermal buffer; in summer, dampers at top and bottom of the

* BREEAM is the UK Building Environmental Assessment scheme developed by the Building Research Establishment and launched in 1990. There are four possible ratings, apart from failure: 'pass', 'good', 'very good' or 'excellent'.

cavity open at 18°C, creating a solar chimney which draws air in from the outside and discharges it into atmosphere. At the same time, the aquifer water is used to reduce the size, cost and energy consumption of a conventional vapour compression chiller installation.

This feeds an underfloor **variable air volume** (**VAV**) system, which comes into operation when the natural ventilation provided fails to maintain the internal temperatures of the various sized courtrooms (between 60 m^2 and 180 m^2) below 24°C. Floor to floor heights vary, being 4.4 m on levels 2 to 4 and 5.6 m on levels 5 to 10. Ceiling height in the courtrooms on levels 2 to 4 are 3.0 m high and on levels 5 to 10 they are a stately 4.5 m, compared to a more conventional 3.0 m in adjacent consultation rooms. Such a large height difference creates substantial voids above the lower height rooms, voids that have been utilised to provide both ventilation and natural daylighting.



How fresh air circulates through the courtrooms (Reproduced with permission from Mott MacDonald)

Orientation of the tall narrow building is crucial here. Its long sides face east and west, with the west façade lying athwart the prevailing winds. Ten 7 m × 1.2 m and eight 7 m × 0.8 m wind scoops trap the wind and direct it into horizontal ducts running along the building's centreline above the consultation rooms. Acoustically lined spurs connect the ducts to vents mid-way up on the inner walls of the courtrooms, which are all located on the east side of the building. High-level vents on the outer eastern court walls above the judges' corridors allow stale air to escape, via an energy recovery ventilation system based on air-to-air enthalpy wheels in winter or by discharging to atmosphere through dampers in the eastern façade in summer, negating the need to run the extract air fans.

Sequential motorised dampers at inlets and exhausts control airflow through the ducts. Inlet dampers close at less than 14°C and more than 21°C; if the temperature within the courtroom falls below 21°C, air warmed by high-efficiency gas-fired boilers with heat recovery in the flues is supplied by the air handling units. Above 24°C the chilled water air handling units supply air to the spaces. Mott MacDonald calculates that the supply of pre-cooled

Cooling air intakes are blended into the façade (Reproduced with permission from Mott MacDonald)

water from the aquifer increases the COP of the chillers from 5.2 to 6.0, effectively a 15% boost. No chances are being taken: if there are long-term problems with the aquifer supply, then an extra chiller could be installed on a spare chiller platform in the plant room, and there is space on the roof for conventional cooling towers; condensing water pipework will have been installed within the building core for future connection if it was required.

The main horizontal ventilation ducts also act as giant lightpipes. Inner top and bottom surfaces are painted white, sides are glazed. Light from the atrium bounces through the ducts into the courtrooms, which also benefit from clerestory windows above the outer judges' corridors. At dusk, low energy dimmable lighting takes over.

According to Mott MacDonald's calculations, the total package of energy saving measures, both active and passive, will cut energy demand by 20% over a conventional equivalent. This represents a potential short-term saving of £73,000 a year. More importantly, the planet will benefit from an annual reduction in CO_2 emissions of no less than 540,000 kg.

Client and end user: Her Majesty's Courts Service
Developer: Allied London Properties
Architect: Denton Corker Marshall
Structural engineer: Mott MacDonald
Environmental and building services engineer: Mott MacDonald
Design and build contractor: Bovis Lend Lease

18 Drake Landing Solar Community

Situated in Okotoks, Alberta, Canada at a latitude of 51°N, the Drake Landing Solar Community (DLSC) is claimed to be the first major use of high temperature seasonal borehole thermal energy storage in North America.

The energy comes from an active indirect solar water heating system using flat plate solar collectors which harvest enough energy to provide 90% of the annual space heating and 60% of DHW needs for the 52 individual dwellings on the site, even throughout long winters where temperatures can plummet to −33°C. The project was conceived by Natural Resources Canada, a Canadian federal government department, as a show-case environmentally friendly residential community, and carried out in partnership with local developers, equipment suppliers, local authorities and other government departments.

Solar energy for space heating is captured by an array of 798 collectors totalling 2,293 m^2 mounted on the detached garages. The community is more than 1,000 m above sea level, but peak summertime temperatures average more than 20°C, so the collectors, facing due South at an angle of 45°, can generate 1.5 MW of heat energy on a typical summer's day. (The tilt angle is latitude −6°, showing a slight bias towards summertime efficiency.) Solar energy is transferred to a glycol solution, which passes down to an underground pipe network and thence to a heat exchanger inside a high temperature **short-term thermal store** (**STTS**) in the project's 'Energy Centre'.

Two unpressurised 120 m^3 epoxy lined cylindrical steel water tanks form the STTS. Internal baffles encourage stratification. The Energy Centre also houses most of the pumps and controls. When, as is frequently the case during the summer, the temperature in the STTS exceeds that in the BTES, pumps cut in, and hot water from the STTS is circulated through the boreholes. In summer the collectors heat up the STTS about twice as fast as the BTES can absorb heat from the SSTS, so the BTES pump has to run most of the night to maintain a balance.

There are 144, 150 mm diameter boreholes 35 m deep at 2.25 m centres arranged in a hexagonal pattern 35 m in diameter. Each contains a single 25 mm diameter cross linked polyethylene (PEX) U-tube grouted with a high conductivity mix of 9% ordinary Portland cement, 9% Portland Blast Furnace cement, 32% fine silica sand and 50% water. Above

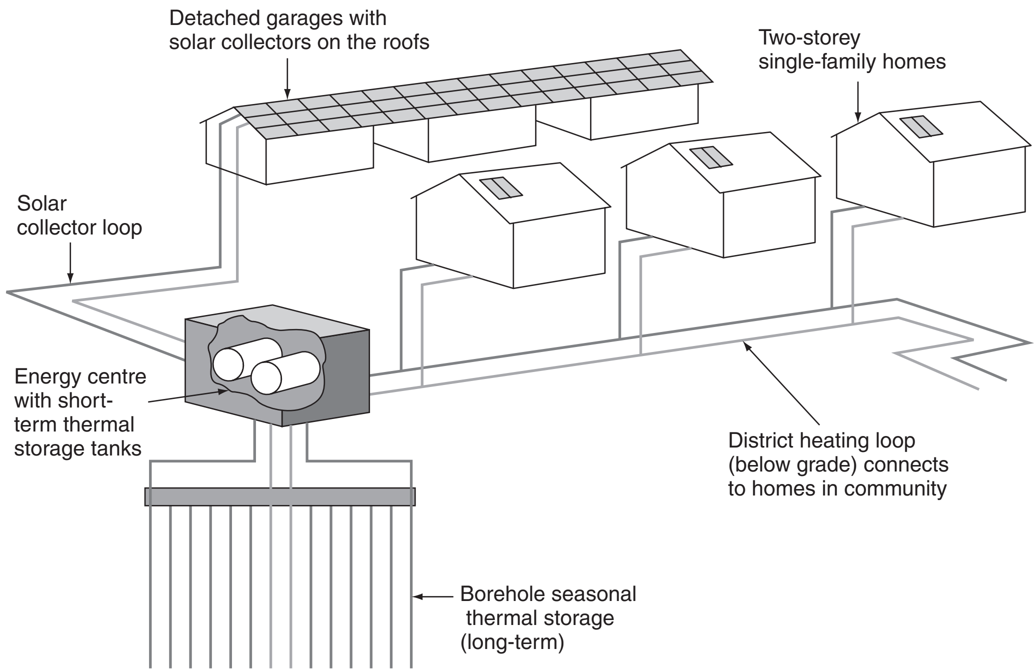
Solar energy is captured by flat plate collectors on garage roofs (Photo provided courtesy of Natural Resources Canada)

them, layers of sand and insulation are protected by a waterproof membrane, topped by clay and landscaping. The store is made up of 24 strings of six boreholes in series, divided into four circuits and distributed through four quadrants so that the loss of any single string or circuit will have minimal impact on storage capacity. By the end of a typical summer, temperature in the earth surrounding the boreholes is expected to top 80°C.

A power cut on a sunny summer's day could cause serious problems with overheating of the glycol loop. To insure against this possibility, a 3.6 kW solar PV array is mounted on the roof of the Energy Centre, backed up by a 27 kWH battery bank and inverters inside the control room. This set-up provides enough power to run the primary collector loop pumps; during normal operation the power from the array supplements mains supplies and keeps the batteries fully charged.

During winter nights when the glycol is not circulating, parts of the loop can cool down to below freezing. When the collectors start operating on a sunny winter's day, the glycol solution is diverted through a bypass loop until its temperature is greater than the water at the top of the STTS to protect the glycol to water heat exchanger in the STTS from freezing.

In winter, whenever the temperature in the STTS is lower than the BTES, water again circulates to transfer heat from the BTES to the STTS and thence via a heat



The Drake Landing network (Diagram provided courtesy of Natural Resources Canada)

exchanger to the district heating loop. This supplies heated water at 50°C or less on demand to individual houses – space heating is accomplished by a specially designed low temperature air handler unit in the basement, inside which the hot water passes through a water to air heat exchanger. Warmed air is distributed through the house via internal ductwork.

If the stored water temperature is insufficient to meet the current heating load, natural gas-fired boilers raise the temperature of the district loop as required. Two independent solar collectors on each house roof supply DHW, backed up with a high-efficiency gas-fired water heater. The Canadian low-flow solar DHW system is designed to provide about 60% of the annual hot water load.

Currently, space heating and DHW in a typical newly built Canadian home consumes around 125 GJ of natural gas each year, with 80% used for space heating, and 20% for DHW. Another 30 GJ is needed for lighting, appliances and the like. This all produces around 7 t of greenhouses gases each year. The target is to reduce the use of natural gas at Drake Landing by nearly 94 GJ on space heating and 17 GJ on water heating. Overall, this represents a saving on each of the 52 houses in the DLSC of at least 5 t of greenhouse gases annually, a reduction of more than 70%.

A significant contribution to these savings comes from the design of the houses themselves, which feature upgraded insulation, high-performance windows and heat recovery ventilation.

Solar energy began to flow into the BTES in June 2007, but it was estimated it would take at least three years to fully charge it and reach 80°C by the end of each summer. Construction of the 52 homes is complete, and all homeowners had moved in by September 2007. Early performance results indicate that the solar energy system is performing as expected and that the 90% solar fraction will be achieved by year 5.

Houses on the development are popular with residents (Photo provided courtesy of Natural Resources Canada)

Project leader: Sustainable Buildings and Communities Group, CANMET Energy Technology Centre, Natural Resources Canada
Solar and heating system designer: Enermodal Engineering
Home builder: Sterling Homes
Energy centre building and system construction: Hurst Construction Management
Thermal storage design: IFTech International.

19 The Stornoway Waterwheel

A modern version of the classic overshot waterwheel is at the centre of an imaginative restoration project in the Outer Hebrides.

Back in the early nineteenth century, the subsistence economy of western Scottish islands like Lewis was based on a plethora of small vertical axis or 'Norse' waterwheels. These powered the grindstones that ground the barley and oatmeal which formed the staple diet of the locals – wheat was unsuited to the infertile, acid soils and cool, damp climate of the Hebridean islands, and potatoes had not yet arrived. Change was in the air, however. Britain's Industrial Revolution was taking off, agricultural production on the mainland had taken great strides, and local landowners were keen to modernise.

In those days Lewis was owned by the Mackenzies, who built three modern horizontal axis watermills on the island in the years up to 1816. The 250 local Norse mills were eventually closed or destroyed in the pursuit of more efficient production (and greater profits). One of the new watermills was actually in the grounds of Seaforth Lodge itself, the home of the Mackenzies. The site was known as Willowglen, the water came from the River Glen. What was initially dubbed the Stornoway Mill later became known as Latta's Mill after the death of John Latta in an accident there in 1834 − or possibly because the Latta family operated the mill for more than 20 years.

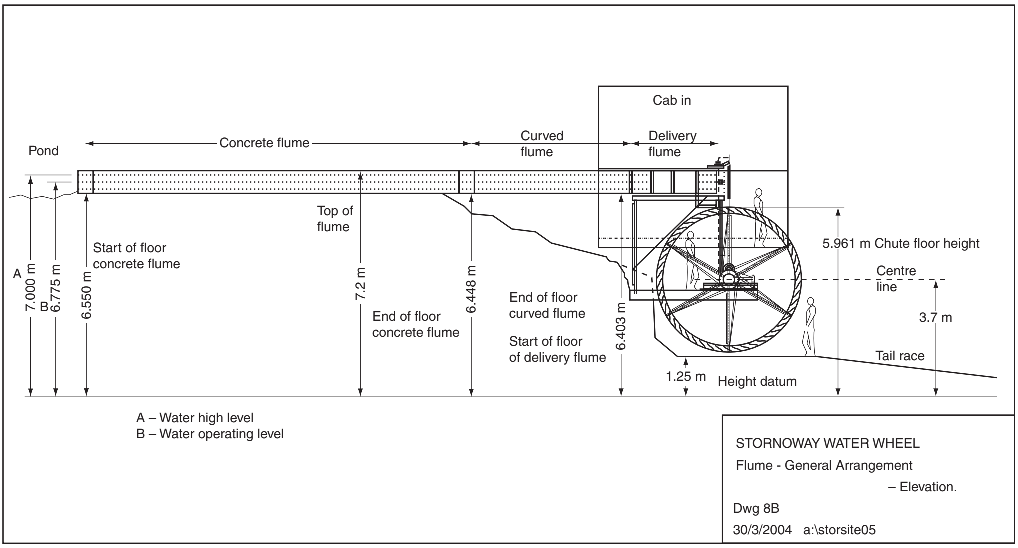
In 1844 the Mackenzies sold Lewis and Seaforth Lodge to James Matheson, one of the founders of the world famous Jardine Matheson trading company of Hong Kong. The wealth that Matheson amassed from the China trade funded major improvement works throughout Lewis, including nearly 250 km of roads and a peat distillery which produced paraffin for lighting, sheep dip, marine anti-fouling, roofing pitch and candlewax. He also demolished Seaforth Lodge and a nearby whisky distillery, then built Lews Castle on the site and even laid out extensive grounds surrounding it.

After more than 70 years of operation, Latta's Mill burnt down in February 1890 and was never rebuilt. By the end of the twentieth century, all that remained to mark its passing was the overgrown mill lade and mill-pond, and the stonework that once housed the overshot wheel itself. The Category 'A' listed Lews Castle had also fallen on harder times: since it was gifted to the local community in 1923 by the last owner, Lord Leverhulme, it has served variously as a wartime naval hospital and the first home for Lews Castle College. Major structural defects were discovered at the end of the 1980s, and by the turn of the century it was unoccupied.

This decline mirrored a similar decline in Stornoway itself. In 2000, however, a major regeneration effort by several agencies began. In the Burgh itself the Stornoway Amenity Trust undertook a number of projects that began to revitalise the built environment, and transform the ambience of public spaces. The Stornoway Trust built a new visitor centre on the site of the old whisky distillery in the Castle grounds, which had suffered from years of neglect. Both trusts then combined their resources in 2003. The joint objective was to restore the Castle grounds, and the bold decision was taken to install a modern water-wheel in the sad remains of Latta's Mill. This would be no cosmetic exercise; the wheel would generate electricity – which would light the Castle grounds.

The Stornoway Waterwheel revives a 19th Century mill site (Reproduced with permission from Tony Robson Consultant)

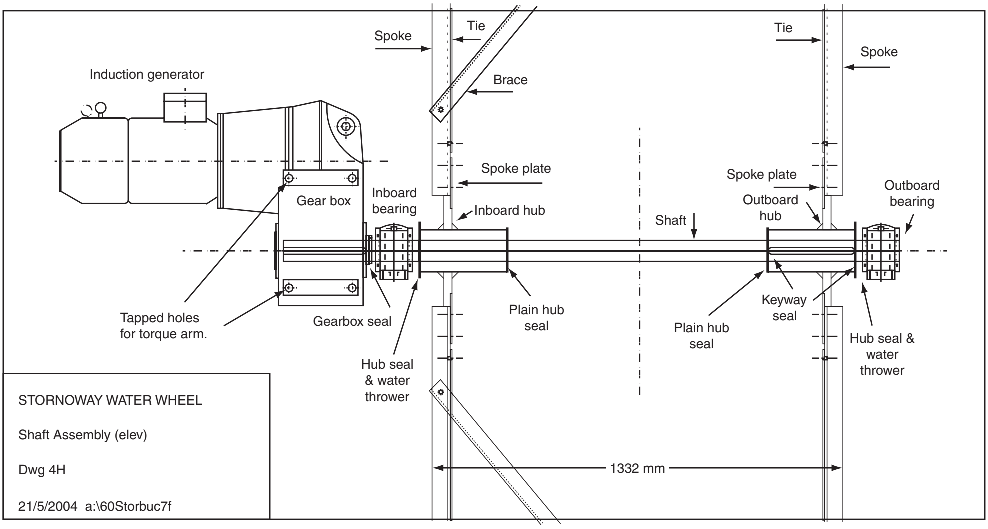
Design and project management of the project was undertaken by local civil engineer Tony Robson on behalf of the Amenity Trust. Advice and assistance on the detail design of the wheel itself came from the Pedley Waterwheel Trust. The first overshot Pedley waterwheel was installed at Pedley Wood in Cheshire in 1991, and was intended to demonstrate that with modern technology the low speed traditional waterwheel could be used effectively to generate low cost mains voltage and frequency AC power. After six years the original 2.4 m diameter wooden wheel was replaced by a modern steel version running on self-aligning roller bearings and coupled directly to a readily available modern integral geared induction motor running 'in reverse'. The gearing increased the wheel's 12 revolutions per minute to a much more useful 1,600. Between 1997 and 2005 a number of Pedley waterwheels with outputs of up to 5 kW were installed in low head installations in Sri Lanka.



General arrangement (Reproduced with permission from Tony Robson Consultant)

At the Willowglen site the available head was 8.5 m, maximum flow was 150 l/s. Wheel size was limited to a diameter of 4.5 m and a width of 650 mm by the configuration of the existing stonework. It was calculated that such a wheel could generate up to 4 kW, enough for the intended end use. To supply water to the wheel some 340 m of the lade had to be cleaned out and relined and a v-notch weir constructed in the river, which is used by salmon and seatrout so a mesh fish screen is also needed. Gradient in the lade was 1:200. The mill pool was dug out and put back into service and a 50 × 25 mm mesh trashrack installed between it and the wheel. (Overshot wheels cope better with trash than most hydropower alternatives.) A short tailrace takes the water 20 m back into the river.

Most of the time, the wheel will generate surplus power. This surplus power is fed to the local grid. (Control of the supply is down to an induction generator controller supplied by Nottingham-based Sustainable Control Systems.) As the water begins to flow, this ensures



Adapting a readily available geared induction motor is the key to the wheel's efficiency (Reproduced with permission from Tony Robson Consultant)

The visitor centre and waterwheel during construction (Reproduced with permission from Tony Robson consultant) that the power from the wheel matches the grid in terms of frequency, voltage and phase before the 'soft connection' to the grid is made. Control is via a motorised sluice immediately before the wheel, which allows small variations in the wheel's speed to be made to maintain synchronisation. Should the local grid suddenly go down, there would be the risk of the wheel accelerating to dangerous speeds as the load comes off and before the sluices can reduce the flow enough. In such a case 'ballast heaters' absorb the power that would have gone to the grid and convert it to heat which is dissipated to atmosphere.

Fabrication of the wheel from 6 mm galvanised sheet steel was undertaken by a local blacksmith. Construction began in early 2005 and the visitor centre and the waterwheel were officially opened in October 2005. There are plans afoot to refurbish Lews Castle itself as a mixed-use development comprising a new home for the Museum nan Eilean and a high quality hotel with function suites.

According to the Pedley Waterwheel Trust, a modern waterwheel like the one in Stornoway should extract more than 80% of the energy in the water. Gearbox efficiency is 97%, generator efficiency 90%. 'Water to wire' efficiency, therefore, is approximately 65%, which few turbines could match at such low heads and flow rates.

Client: Stornoway Trust in partnership with Stornoway Amenity Trust
Designer: Tony Robson Consultant assisted by Pedley Wheel Trust and SCS
Contractor: Bardon Hebrides
Millwheel fabricator: I. M. Murray Engineering

This page intentionally left blank

20 Manchester College of Art and Technology

Active rainscreen cladding made up of solar photovoltaic cells is a prominent feature on this award-winning development.

For generations of Manchester citizens the imposing Victorian public baths at Harpurhey were a local landmark. The Grade II listed structure finally closed in 2001 after serious structural defects were discovered and judged to be uneconomic to repair. In 2004, however, work began on an imaginative redevelopment of the site, aimed at providing new facilities for the Manchester College of Art and Technology (MANCAT). Part of the original building has been retained, with the potential for an alternative reuse. A new three-storey 5,000 m^2 building alongside provides a home for the North Manchester Sixth Form College and North City Public Library; one that uses the latest microgeneration and energy saving techniques to minimise its carbon footprint.

From the outside the most distinctive feature of the £7.1 million building is the blue wall of polycrystalline silicon photovoltaic cells that dominates the southern façade. A total of 482 SHARP 80 W modules are used, backed up by a further 238 SHARP 165 W modules mounted unobtrusively on the extension's flat roof. Together these total some 720 m^2, which can generate a maximum of 76 kW, and which are capable of producing more than 43,000 kWh annually – a saving of at least 18,000 kg of CO_2.

Such a large array might seem hard to justify economically. However, a high quality building façade would have been specified in this particular location anyway. Integrating the cladding and electricity generation functions into one component makes the case for solar PV even more persuasive. Advantage is also taken of the heat-generating properties of the PV array, which has to be cooled to keep it operating at maximum efficiency. A 200 mm void between the cladding and the main wall of the building is intended to create an effective solar chimney, with air drawn in across internal spaces and out through louvres in the wall behind the cladding gaining heat from rear of the cells and rising up to roof level vents. This void also serves to reduce solar gain within the building during the summer months.

Solar gain through the west-facing atrium glazing is managed by an array of three cylindrical windcatchers above the main entrance, which boast mechanical dampers controlled by the building management system. In the warmer months these windcatchers

MANCAT at night (Reproduced with permission from Solarcentury.com)

Solar cladding replaces more conventional alternatives (Reproduced with permission from Solarcentury.com) draw cool night air into the building through courtyard windows; air that is circulated over the exposed soffits of the concrete floor slabs, cooling them ready for the following day. Thanks to this use of the building's thermal mass, no conventional air conditioning is considered necessary.

Insitu normal density concrete was the preferred option for the building's structural frame. Floor slabs 300 mm thick span between exposed columns at 6,750 m centres. This high thermal mass is boosted by block-and-plaster internal partitions and coupled with unusually high levels of insulation. High-performance structural glazing with a typical U-value of 2.2 W/m^2K forms much of the Library Block's external skin. External cavity walls feature a 100 mm rendered normal density concrete block outer skin, a 162.5 mm cavity with full fill mineral wool insulation, and an inner skin of 140 mm plastered normal density block. This yields a U-value of only 0.22 W/m^2K. Beneath the single ply membrane roof there is cut to falls mineral wool insulation, and U-value is 0.25 W/m^2K. Air-tightness is 5.4 $m^3/hr/m^2$, as against the 10 $m^3/hr/m^2$ demanded by current regulatory requirements.

An indirect active solar thermal water heating system is used to supplement domestic hot water supplies. Solar heat from a roof-mounted array of evacuated tube collectors feeds a 350 l thermal store. A high-efficiency gas-fired condensing boiler is the main source of hot water, which is also used for space heating.

Rotex supplied the unusual German-developed heating system. Underfloor heating is used on all floors of the Library Block, based around a double skinned cross linked polyethylene (P-EX) pipe, with the inner surface of the outer skin ribbed to maintain a constant insulating air space between the skins. Water flowing through the pipe's core can therefore enter the system at a significantly higher temperature than with conventional underfloor heating systems, eliminating any need to blend in cold water to reduce the initial heating circuit temperature to safe levels. The network is supported on polymer 'system plates' and cast into the floor screed.

Although underfloor heating is very compatible with the water temperatures generally produced by microgeneration technologies such as heat pumps and solar heating, its safe

Roof-mounted modules supplement the PV façade
(Reproduced with permission from Solarcentury.com)

operating temperatures are normally well below that of the optimum operating temperature of modern boilers. With this system, however, the same temperature water also feeds conventional wall-mounted radiators in the Teaching Block.

Room has been found on the site for a large underground rainwater storage tank, which is used for cistern flushing. A very popular feature in the atrium is a panel that monitors the performance of the PV arrays. Readouts display the current output, the total output since the building opened in March 2006 − and how many years that total output would light an average three-bedroomed semi-detached house. This figure has now passed the 100-year milestone. The UK Department of Trade and Industry provided some of the funding for the PV installation, as part of its programme of demonstration projects.

Client: Manchester College of Art and Technology
Architect: Walker Simpson Architects
Structural engineer: Arup
Building services engineer: Operon
Solar PV supplier: solarcentury
Main contractor: Eric Wright Construction

21 Holiday Home at Rock, North Cornwall

High thermal mass, the control of solar gain and water heating by a combination of solar and ground source energy are featured on this new build project in south-west England.

By English standards Radoon, a two-storey house overlooking the estuary of the River Camel in Cornwall, is a large dwelling, with six double bedrooms in its 323 m^2 of floor area. The original Radoon was built in the 1920s using concrete blocks made with sand from the local beach. By the turn of the century the concrete was crumbling and demolition was the only option. London-based ECD Architects were tasked with the design of a replacement, and came up with an 'upside down' concept, with living accommodation above the bedrooms and superb views across the estuary and surrounding countryside. Sustainability was also central to the concept, and a number of approaches were combined to reach the best solution.

Masonry construction to provide high thermal mass was the key decision. Outer walls are made up of an outer skin of externally rendered 100 mm thick 'Thermalite' (lightweight autoclaved aerated concrete block) and an inner skin of 140 mm thick high strength Thermalite 7 N block. Inside the 140 mm cavity is 90 mm of Celotex polyisocyanurate (PIR) foam insulation. Overall U-value is just 0.2 Wm^2K, well below current regulatory requirements.

First floor construction is also comparatively massive, being a combination of 150 mm deep precast 'inverted T' concrete beams at 450 mm centres infilled with standard dense concrete blocks. Curved steel beams support the zinc-clad roof. Insulation here is 300 mm mineral wool, which produces a U-value of 0.15 Wm^2K.

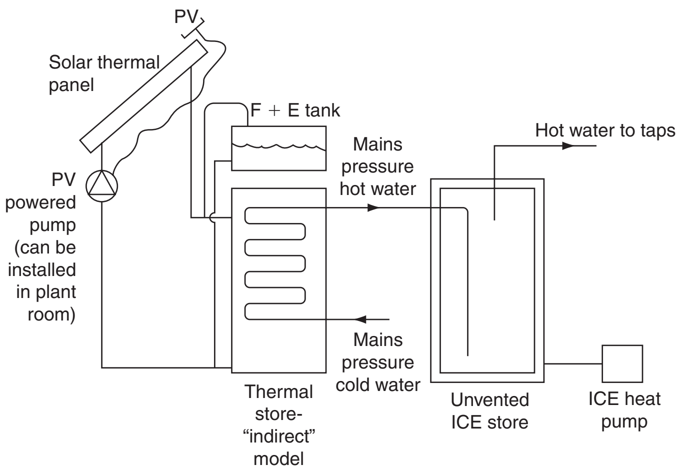
Roof design is critical. With the site sloping up towards the north and the best views lying to the south, most windows face the sun for most of the day. Solar gain through the large south-facing living area windows in particular could be a problem in summer – and a bonus in winter. The answer is to extend the roof some 1.8 m out from the building line to act as a summer sunshade. A similar function is performed by the balcony, which runs across the entire south-facing façade and shades the bedrooms below. Summer cooling can be boosted by high-level vents over the stairwell, which takes advantage of the stack effect.

An 'upside-down' layout and high thermal mass shape the architecture of this holiday home (Reproduced with permission from Clive Boursnell)

Cornwall is noted for its equable climate, which could be even milder as global warming really makes itself felt; already olive groves are being planted in the county. Even in the depths of winter the demand for space heating will be significantly less than in the rest of the UK, especially with such high degrees of insulation. However, solar energy absorbed by the building fabric from the low winter sun via the high-performance windows should be a major contributor to occupant comfort. There is still the chance, however, of chilly winter mornings following days when the sun has failed to shine, or even long periods of inclement weather. For quick warm-up there is a wood-burning stove – although the oil-burning Aga cooker should also make a significant contribution to space heating (when used). For longer periods there is low temperature underfloor heating supplied mainly by a ground source heat pump.

To reduce the extent and depth of the excavations needed to install an appropriate ground loop for the system, Swedish-developed 'compact collectors' from Oxfordshire-based ICE Energy Heat Pumps are used, installed horizontally at a depth of 1.5 m in the sandy ground. Heat extracted from the ground is stored in the 160 l capacity outer shell of an ICE-supplied unvented thermal store, which is wrapped around a 300 l inner tank used to supply both DHW and space heating. Heat pump coefficient of performance is 4.0; maximum temperature inside the thermal store 51°C, and the space heating is designed to maintain internal temperature at 20°C.

Before entering the main thermal store, mains water passes first through a heat exchanger in a booster thermal store supplied by a solar water heating installation. This is an unusual system, which has won several awards for innovation for its manufacturer Solartwin of the UK. All pipework outside the thermal store is flexible microbore silicon rubber tubing that is unaffected by freezing temperatures, so no antifreeze is needed. A small solar photovoltaic array drives the circulation pump. This circulates the water through the flat plate collectors as long as the sun is shining: there is no temperature control, and it is claimed that the system is immune to the normal risk of dangerously high stagnation temperatures. In optimum conditions it is calculated that the solar collectors will raise the temperature of the water entering the main thermal store to 40°C.



The heating system integrates ground source and solar energy (Reproduced with permission from ECD Architects)

Although the original house drew its water supplies from a well on the site this is now capped off. Rainwater is now harvested from the roof and stored in a 3,0001 tank located below ground at the rear of the building. From there it is pumped to a header tank and used to flush toilets. It is estimated that this reduces mains water consumption by 25%.

Construction began in October 2005 and was completed in August the following year. Building cost was £500,000.

Client: Claire Lloyd and Tessa Chamberlain
Architect: ECD Architects

This page intentionally left blank

Index

00025