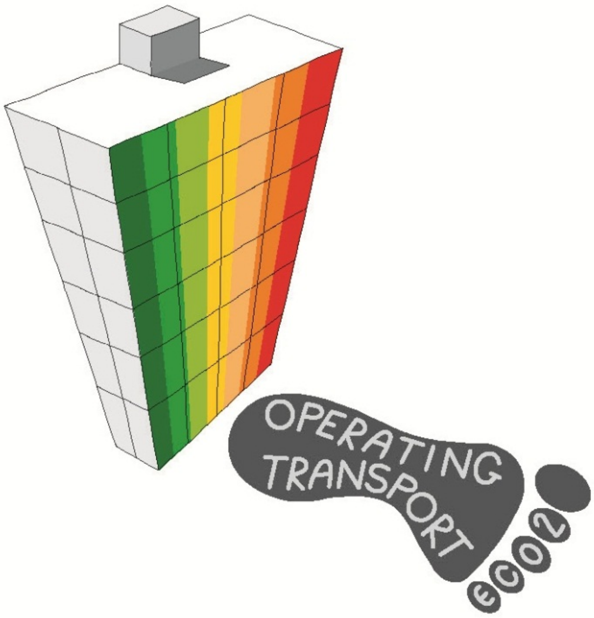
WHAT COLOUR is YOUR BUILDING?

Measuring and reducing the energy and carbon footprint of buildings

David H. Clark



Appendix I

Renewable energy data

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Appendix I: Renewable energy data

The use of solar energy has not been opened up because the oil industry does not own the sun.

Ralph Nader, American political activist.

Contents

This appendix provides information and calculations to support Chapter 7 (Renewable energy).

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I1. SOLAR

I1.1 Solar energy resource

Solar irradiation is the amount of radiant energy emitted by the sun that falls on 1 m^2 of the earth's surface. It is measured in W/m^2 but is often expressed in kWh/m^2 per annum. The higher the value, the more energy produced by photovoltaics (PV) and solar thermal. Figure I.1 gives a good indication of where the world's solar energy resource lies. Figure I.2 shows the solar irradiation in Europe (note that the colour scales used in the two maps are different).

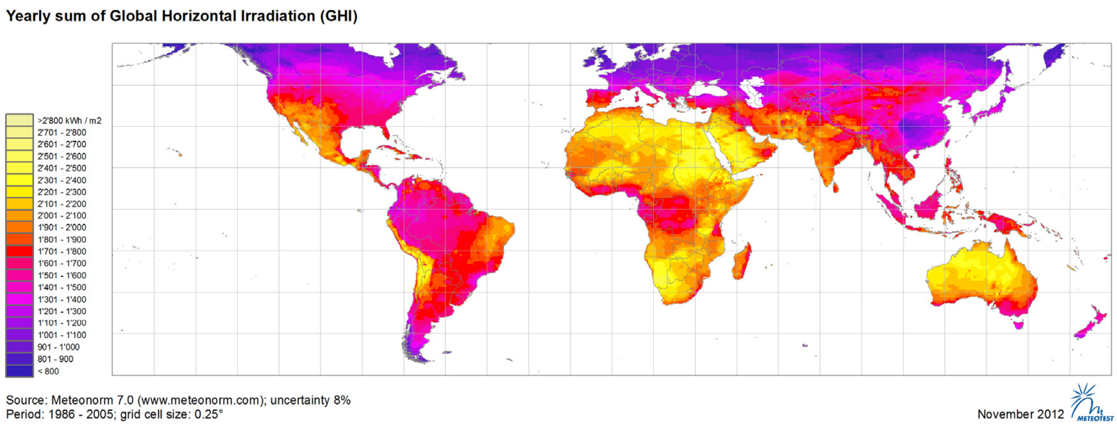


Fig I.1 **Global solar irradiation (kWh/m^2) on a horizontal surface (source: © Meteotest; based on www.meteonorm.com)**

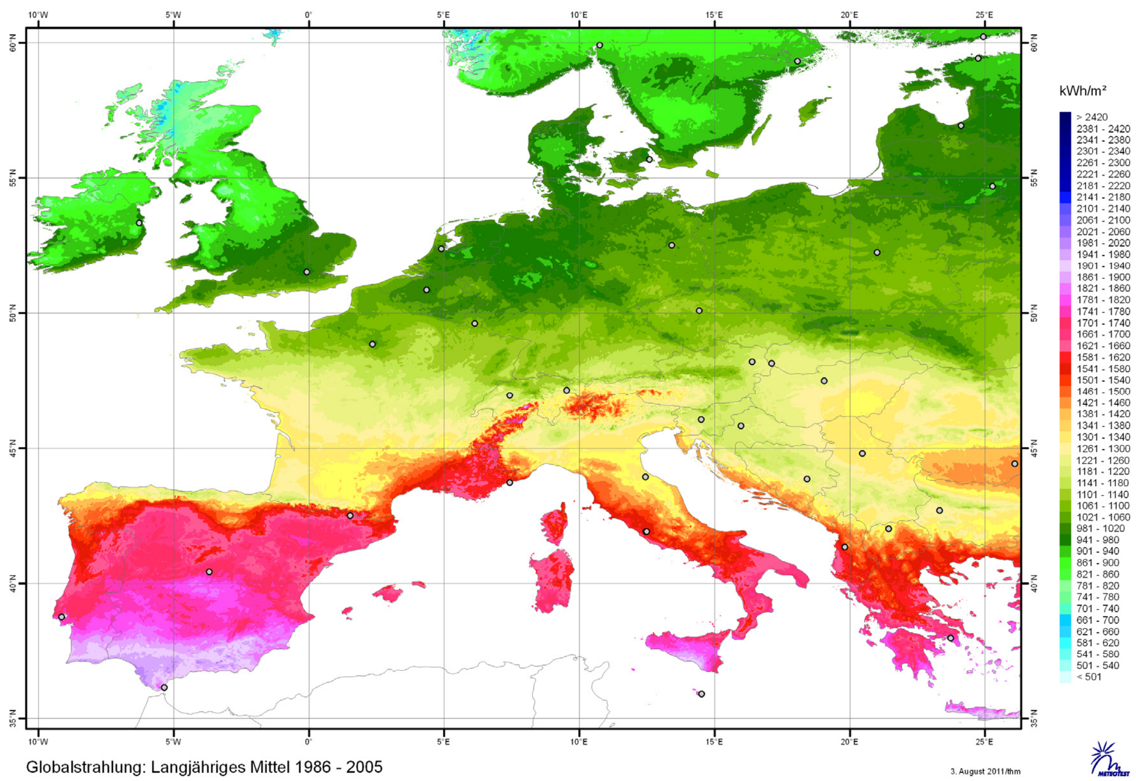


Fig I.2 **Global solar irradiation in Europe (long-term mean 1986 – 2005) on a horizontal surface (source: © Meteotest; based on www.meteonorm.com)**

Table I.1 provides a summary of the annual solar irradiation in a selection of countries in Europe.[1] The angle of optimum tilt for photovoltaic panels is also shown.

	Annual solar irradiation (kWh/m^2)				Optimum tilt for PV	Range of optimum tilt (5% to 95%)
	Horizontal (ave)	Optimum (ave)	Variation in optimum tilt (5%)	Variation in optimum tilt (95%)		
Spain	1,586	1,819	-319	146	34°	32° to 36°
Italy	1,448	1,664	-255	292	35°	32° to 37°
Romania	1,328	1,534	-111	67	36°	33° to 37°
France	1,248	1,437	-291	356	35°	33° to 37°
Germany	1,014	1,157	-70	107	35°	34° to 37°
Netherlands	976	1,115	-30	32	35°	34° to 36°
Denmark	967	1,129	-21	30	38°	37° to 38°
Ireland	948	1,092	-42	56	37°	36° to 37°
United Kingdom	943	1,090	-75	112	37°	36° to 39°
Sweden	871	1,079	-24	63	44°	37° to 47°

Table I.1 **Annual solar irradiation for a selection of European countries (source: PVGIS © European Communities, 2001-2012)**

I1.2 The importance of orientation and tilt

Maximum solar collection on a panel occurs when the sun's rays strike perpendicular to the collector surface. The best orientation is due south in the northern hemisphere and due north in the southern hemisphere. The sun at noon is lower in winter than in summer and so the optimum tilt depends on whether you want to maximise heat collection in the winter (for solar thermal systems) or to maximise average solar energy annually (for electricity generation from photovoltaics).

CIBSE have produced monthly solar irradiation data for three cities in the UK at different orientations and tilts.[2] A summary of this annualised data for south-facing panels and vertical panels (wall cladding) is shown in Table I.2, with maximum values shown in bold.

Sometimes it is not possible to obtain the optimum orientation and tilt due to the layout of the building, roof pitch and so on. Contour plots of the irradiation data (expressed as a percentage of the maximum) help to illustrate the relative importance of orientation and tilt at a particular location – refer to Figure I.3. For photovoltaic panels, orientation is generally more critical than tilt.

Annual solar irradiation (kWh/m²)									
		South facing				Vertical panels			
	Horiz	30°	45°	60°	Vertical	W	SW	SE	E
London	1002	**1141**	1137	1078	820	654	807	731	568
Manchester	982	**1113**	1105	1047	794	577	731	753	598
Edinburgh	884	1024	**1030**	984	766	531	690	717	555
Increase (or decrease) in energy compared to horizontal									
London		14%	13%	8%	-18%	-35%	-19%	-27%	-43%
Manchester		13%	13%	7%	-19%	-41%	-26%	-23%	-39%
Edinburgh		16%	16%	11%	-13%	-40%	-22%	-19%	-37%

Table I.2 Annual solar irradiation for different orientation and tilt in three UK cities (source: CIBSE Guide A)

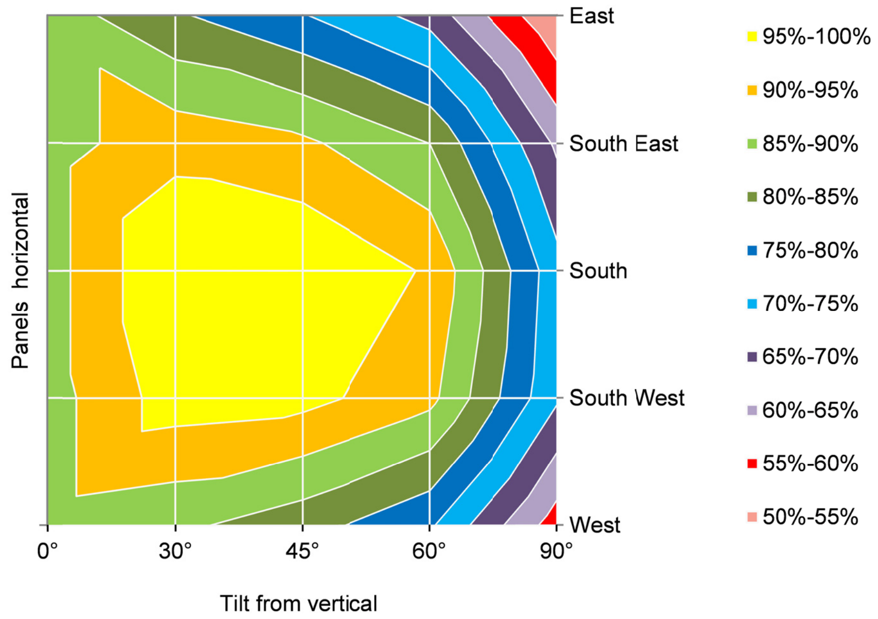


Fig I.3 Solar outputs for different orientations and tilts in London expressed as a percentage of the solar irradiation of 1141kWh/m² at 30° (adapted from data in CIBSE Guide A)

I1.3 What is the optimum tilt?

Solar thermal panels should be orientated towards the winter sun angle to generate as much heat energy as possible in winter. This allows the system to be sized to collect heat more evenly throughout the year. Table I.3 shows that the daily irradiation in the winter months in London is highest at a tilt of 60°. At flatter angles (30 to 45°), more solar energy will be captured over the whole year– but much of this will occur in the summer months and some may be rejected if it exceeds the demand for hot water energy. With photovoltaic panels, the angle should be set to maximise annual solar energy (because excess electricity can be exported to the grid) and so the optimum angle will be flatter.

	Days	Daily irradiation on inclined planes (Wh/m²)				
		0°	30°	45°	60°	90°
Jan	31	683	1111	1247	**1317**	1243
Feb	28	1332	1899	2051	**2099**	1869
Mar	31	2235	2738	**2808**	2743	2233
Apr	30	3611	**4027**	3963	3714	2725
May	31	4647	**4777**	4547	4109	2774
Jun	30	**5064**	5026	4708	4189	2731
Jul	31	4928	**4980**	4700	4213	2784
Aug	31	4310	**4682**	4554	4209	2975
Sep	30	2843	3386	**3425**	3300	2588
Oct	31	1746	2450	2628	**2668**	2331
Nov	30	908	1443	1609	**1689**	1574
Dec	31	534	932	1066	**1141**	1101
Annual total (kWh/m²)		**1002**	**1141**	**1137**	**1078**	**820**
			PV (30°–45°)		SHW (60°)	

Table I.3 **Daily solar irradiation (Wh/m²) each month in London for south-facing surfaces at different tilts (source: CIBSE Guide A)**

The following (very crude) rules of thumb can be used to give an indication of tilt for solar energy feasibility evaluations:

- Solar hot water panel tilt: Latitude + 10°
- PV panel tilt: (Latitude x 0.75)°

Table I.4 shows these rules applied to various cities. Always use local design guidance if available.

Location	Latitude	PV tilt	SHW tilt
Edinburgh	56.0 N	42°	66°
Manchester	53.5 N	40°	63°
London	51.5 N	39°	61°
Bucharest	44.4 N	33°	54°
Madrid	40.4 N	30°	50°
Shanghai	31.2 N	23°	41°
Dubai	25.2 N	19°	35°
Hong Kong	22.3 N	17°	32°
Singapore	1.4 N	1°	10°
Cape Town	34.0 S	25°	44°
Sydney	33.9 S	25°	44°
Melbourne	37.8 S	28°	48°

Table I.4 **Indicative panel tilts for various cities using the rules of thumb**

I1.4 Avoiding overshadowing on PV panels

If PV panels are placed on a flat roof, they must be spaced so that there is minimal overshadowing of the panels behind by the front panels. As a rough guide, the panels should be spaced to avoid overshadowing on the winter solstice between 10am and 2pm. The winter solstice angle[3] at midday in London is 15°.

Figure I.4 shows that it is often better to place panels close to a horizontal position than at the optimum solar tilt (35 to 40°) to maximise the area of panels on a flat roof in London. This is because spacing panels to reduce overshadowing reduces the area of panel that can be installed. A 10° angle is more practical than a totally flat position as it allows ventilation to the back of the panel (as PV panels heat up, their output decreases) and minimises water pooling on the panels (which would result in dirt accumulating more quickly).

Table I.5 summarises the spacing of panels for different tilts in London, and also shows:

- The ratio of installed panel area to roof area.
- The solar energy collected by the panels per square metre of roof area.

On a flat roof, laying the panels at 10° allows more energy to be collected from the available roof area than if panels are inclined at optimum solar angles between 35 and 40°. The flatter panels may receive 10% less solar irradiation per m^2, but a greater solar collection area is installed on the roof. Figure I.5 shows one of many proprietary systems available to install panels on existing flat roofs which provides air circulation behind the panels and doesn't require fixings through the waterproof membrane. However, if you have plenty of space to fit your panels (i.e. if panel numbers are limited by cost budget and not available roof space) then spread them out to optimise the tilt and so maximise the annual solar irradiation that they receive.

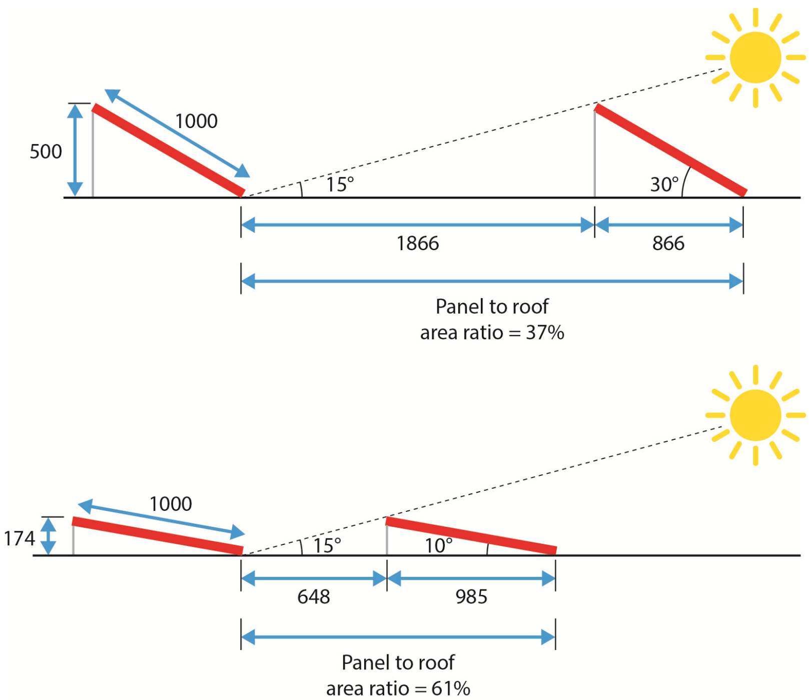


Fig I.4 Spacing of PV panels to avoid overshadowing on a flat roof in London

Tilt of panel	10°	30°	45°	60°	90°
Length of PV panel	1000	1000	1000	1000	1000
Plan length on roof	985	866	707	500	0
Height above roof	174	500	707	866	1000
Spacing between panels	648	1866	2639	3232	3732
Panel area to roof area ratio	**61%**	**37%**	**30%**	**27%**	**27%**
Solar irradiation in London (from Table I.3)	1002	1141	1137	1078	820
Solar energy collected per m^2 of roof (kWh/m^2)	**613**	**418**	**340**	**289**	**220**

Table I.5 **Panel to roof area ratio and solar energy collected for different panel tilts on a flat roof in London**

It is also important to apply the same principles to assess overshadowing from adjacent buildings and other objects, particularly trees (don't forget that they will have leaves in summer if doing a site inspection in winter). Even a small amount of shading on part of a PV array can dramatically reduce the electrical output. To prevent the output from the whole array being significantly reduced if just one part of one panel is in shade, make sure bypass diodes are installed and use multiple inverters on large arrays.

In a single string array (all panels linked together in series), the reduction in power can be equivalent to over 30 times the physical size of the shadow (i.e. if 1 m^2 of a 100 m^2 array is in shade then the output is equivalent to less than 70 m^2 of unshaded panels).[4]

Fig I.5 **PV laid on a flat roof. The system does not penetrate the waterproof membrane and also provides ventilation to the back of the panels. (Source: Solion)**

I1.5 Capital costs of PV systems

Table I.6 and Figure I.6 show the capital costs used in Chapter 7. These are based on typical prices for PV panels installed on flat roofs in the UK in 2012. The area of panels is based on 250 W monocrystalline PV panels with an efficiency of 15.5%. PV prices seem to defy inflation and costs per kW have been steadily decreasing year on year.

PV system size	£/kW	Area of PV panel (m^2)	£/m^2	no. of 250 W panels
1 KW	£3,000	6.5	£465	4
20 kW	£2,000	129	£310	80
100 kW	£1,500	650	£231	400
250 kW	£1,100	1,610	£171	1,000

Table I.6 **Indicative capital cost and panel area of PV systems in the UK in 2012**

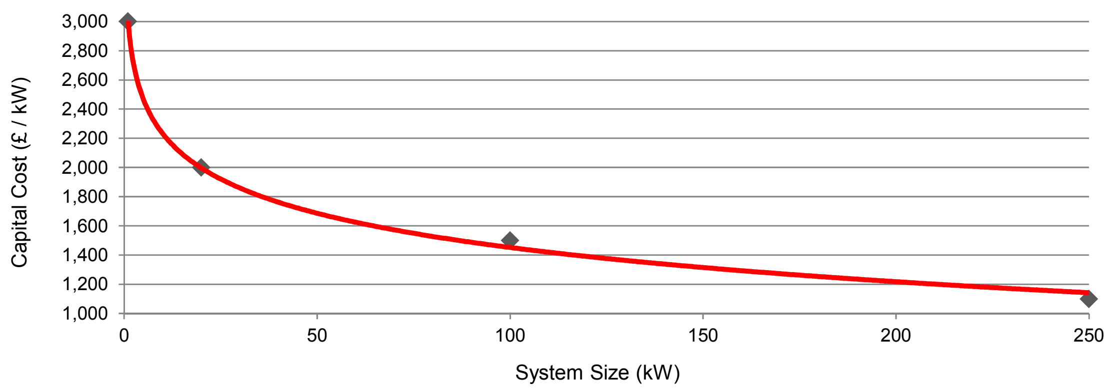


Fig I.6 **Indicative capital cost of PV systems in the UK in 2012**

I1.6 What is the most efficient solar system – thermal or PV?

If there is limited roof space, is it better to install solar thermal panels or photovoltaic panels? Table I.7 shows a quick comparison for a commercial building and suggests that solar thermal panels deliver the best CO_2e reduction per area of panel, however the total installed area is limited by the demand for domestic hot water in the building. Ignoring the influence of any government incentives for PV (e.g. feed-in tariffs) and solar thermal systems (e.g. renewable heat incentives), PV panels provide a more cost-effective solution for reducing CO_2e emissions in commercial office buildings. Domestic scale PV systems, with a cost around £2,500 per kW, have a payback similar to solar thermal.

	System efficiency	Tilt	Energy produced (kWh/m^2 of panel)	kgCO_2e/m^2 saving of panel	Annual cost saving (£/m^2)	Capital cost (£/m^2)	Payback	£/tCO_2e saved over 15 years
Photovoltaic	11.1%	35°	127	**76**	£12.7	£230	18	**£80**
Solar thermal	39%	60°	418	**93**	£16.3	£500	31	**£231**

Assumptions: electricity (0.6 kgCO_2e/kWh, 10p/kWh), gas for heating (0.2 kgCO_2e/kWh, 3.5p/kWh, 90% efficient boiler), discount rate of 5%, effects of energy tariff inflation and government incentives not included.

Table I.7 **CO_2e and energy cost comparison for PV and solar thermal panels on Building X**

I2. BIOMASS AND BIOFUELS

I2.1 How much energy is in wood?

The energy available from wood, the calorific value (kWh/kg), varies with moisture content. The moisture content is the proportion of water in wood and is measured on a 'wet basis' for fuel applications.

Moisture content (MC) = [(green weight – oven dry weight) / green weight] x 100

Oven dry timber with a moisture content of 0% has a calorific value of 5.28 kWh/kg – but wood fuel is typically not dried in an oven before burning. The calorific value for wood fuel is the calorific value of the dry timber contained in the fuel less the energy used to evaporate the water.[5] This is why you try to avoid putting wet logs onto a fire.

Calorific value = [5.28kWh/kg x (1 – MC)] – 0.679 x MC = 5.28 – 5.96 x MC

Table I.8 summarises typical moisture contents and calorific values of different woods and fuels.[6]

Type	Moisture content	Calorific value (kWh/kg)
Oven dry timber	0%	5.28
Wood pellet	8%	4.80
Recycled wood (ave)	20%	4.09
Wood chip	30%	3.49
Typical hardwood	45%	2.60
Sawdust	50%	2.30
Typical softwood	60%	1.70

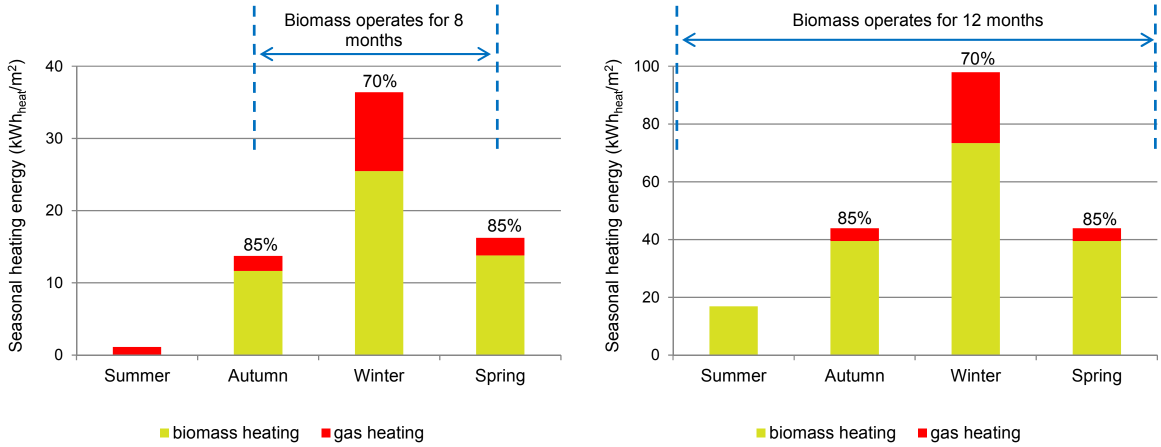
Table I.8 **Typical moisture content and calorific value of different wood fuels (source: Biomass Energy Centre)**

I2.2 Biomass boilers in Building X and Hotel Y

The example calculation below provides a quick method of determining the reduction in the buildings' CO_2e emissions from a wood pellet boiler. The calculation for wood chips is similar. The following assumptions apply:

- The biomass boiler has an average efficiency of 85%.
- The wood pellets have a calorific value of 4.8 kWh/kg.
- Additional heat, when required, is supplied from gas boilers with 90% efficiency.
- Wood pellet boilers are permitted under the local council's air quality standards.
- The biomass boilers will not operate when there is little demand for heat.

To determine the efficient operation of the boilers (and sizing of thermal storage/buffer tanks) to meet the fluctuating hourly heating demand requires more complex analysis. To keep the analysis simple, the energy supplied by the biomass boilers in Building X and Hotel Y is shown in Figure I.7.



Biomass total: 509,600 kWh_{heat} (75%)
Gas total: 165,400 kWh_{heat} (25%)

Biomass total: 1,692,600 kWh_{heat} (84%)
Gas total: 332,400 kWh_{heat} (16%)

Fig I.7 Contribution of biomass in Building X (left) and Hotel Y (right)

The energy contribution and CO_2e emissions are shown in Table I.9.

		Unit	Calculation	Building X			Hotel Y
				Biomass	Nat gas	TOTAL	TOTAL
(A)	Heat supplied	$kWh_{(heat)}$		509,600	165,400	675,000	2,025,000
(B)	Boiler efficiency			85%	90%		
(C)	Energy consumption	kWh	= A / B	599,529	183,778	783,307	2,360,627
(D)	Emissions factor	$kgCO_2e/KWh$		0.04	0.2		
(E)	CO_2e emissions	$kgCO_2e$	= C x D	23,981	36,756	60,737	153,518
(F)	CO_2e (base case)	$kgCO_2e$			150,000	150,000	450,000
(G)	Reduction in CO_2e	$kgCO_2e$	= F – E			89,263	296,482
(H)	Total CO_2e emissions (base case)	$kgCO_2e/m^2$				105	105
(I)	**Reduction in CO_2e**	**$kgCO_2e/m^2$**	**= G /10,000**			**8.9**	**29.6**
	% reduction in CO_2e					*8.5%*	*28%*

Table I.9 Calculation of biomass boiler CO_2e reduction in Building X and Hotel Y

Biomass boilers can reduce CO_2e emissions by one third in hotels but only by less than 10% in offices. This is because hotels have a high annual demand for heat (which is even higher if they have swimming pools) while offices have limited demand for heating and domestic hot water.

I2.3 Biomass is renewable – but is it low carbon?

The CO_2e emission factors used for biomass in this book are based on the factors published by the UK Government in 2012 and described in Appendix B. However, there is growing debate as to whether biomass can be considered to be low carbon. Biomass releases 0.35 kgCO_2e/kWh when burned which is higher than natural gas (0.2) and petrol (0.3). The assumption that biomass is low carbon is based on the reabsorption of CO_2 by growing replacement biomass fuel stock (e.g. trees). There can be a significant time lag between the felling of a tree for fuel and the years it's replacement takes to reabsorb the CO_2.[7]

In Appendix B, an unofficial 'CO_2 half-life' factor for biomass was proposed to promote debate about this time lag. The appendix also proposed factors to take the potential global warming contribution due to black carbon (soot) released during the combustion of biomass into account, with both typical and efficient flue filters. These factors are summarised in Table I.10.

Alternative factor	kgCO_2e/kWh	Comment
'CO_2 half-life' factor	0.19 – chips 0.21 - pellets	Includes 50% of the CO_2 released at the time of combustion
Black carbon	0.05 – efficient flue 0.15 – average flue	A rough estimate based on the global warming potential of soot released from the flue.

Table 1.10 Unofficial alternative CO_2e emission factors for biomass (source: Appendix B)

Table I.11 summarises the impact that these alternative CO_2e emission factors would have on the benefit of biomass boilers in Building X compared to a natural gas boiler solution.

There is clearly some debate to be had over whether biomass boilers can be considered a low carbon solution, and which CO_2e emission factors should be used in the evaluation of biomass systems. While the use of a 'CO_2 half-life' factor may be contentious (this very much depends on the feed stock used and the time it takes to reabsorb the CO_2 emitted), the issue of black carbon really needs to be looked at in more detail. The Intergovernmental Panel on Climate Change (IPCC) states that it is the third biggest contributor to global warming after CO_2 and methane, and recent studies suggest that it might even be second.[8]

	Biomass boiler	Natural gas boiler	Total	% heating CO_2e saving compared to natural gas boiler
Natural gas boiler only ($kgCO_2e/m^2$)	-	15	**15**	-
Energy consumption (kWh/m^2)	599,529	183,778	783,307	
Standard biomass factors				
Emission factor ($kgCO_2e/kWh$)	0.04	0.2		
$kgCO_2e/m^2$	2.4	3.7	**6.1**	60%
CO_2 half life				
Emission factor ($kgCO_2e/kWh$)	0.21	0.2		
$kgCO_2e/m^2$	12.6	3.7	**16.3**	-8%
Standard + black carbon (typical flue filter)				
Emission factor ($kgCO_2e/kWh$)	0.19	0.2		
$kgCO_2e/m^2$	11.4	3.7	**15.1**	0%
Standard + black carbon (efficient flue filter)				
Emission factor ($kgCO_2e/kWh$)	0.09	0.2		
$kgCO_2e/m^2$	5.4	3.7	**9.1**	40%
CO_2 half-life + black carbon (typical)				
Emission factor ($kgCO_2e/kWh$)	0.36	0.2		
$kgCO_2e/m^2$	21.6	3.7	**25.3**	-68%
CO_2 half-life + black carbon (efficient)				
Emission factor ($kgCO_2e/kWh$)	0.26	0.2		
$kgCO_2e/m^2$	15.6	3.7	**19.3**	-28%

Table I.11 The impact on CO_2e emissions due to potential 'CO_2 half-life' and black carbon emission factors in Building X

I2.4 Biomass storage and delivery requirements for Building X and Hotel Y

The volume of storage for biomass boilers depends on the heating demand, the type of fuel used, and the size of trucks and frequency of delivery. The calorific value and bulk density of typical wood chips and pellets are shown in Table I.12.

	Wood pellets	Wood chips
Calorific value (kWh/kg)	4.8	3.5
Bulk density (kg/m^3)	650	250

Table I.12 Calorific value and bulk density of wood chips and pellets

Table I.13 shows a simplified calculation and assumes that the peak weekly heating demand is 25% higher than the average winter weekly energy consumption.

		Unit	Calculation	Building X	Hotel Y
(A)	Winter heat energy	kWh_{heat}		364,100	978,800
(B)	% supplied by biomass			70%	75%
(C)	Biomass energy used in winter	kWh_{heat}	= A x B	254,870	734,100
(D)	Weekly energy in winter	kWh_{heat}	= C / 12	21,239	61,175
(E)	Peak winter heating (week)	kWh_{heat}	= D x 125%	26,549	76,469
(F)	Boiler efficiency			85%	
(G)	Peak winter week fuel energy	kWh	= E x F	31,234	89,963
(H)	Calorific value of pellets	kWh / kg		4.8	
(I)	Weight of pellets for peak week	kg	= G / H	6,507	18,742
(J)	Bulk density of pellets	kg / m^3		650	
(K)	**Volume of pellets for peak week**	**m^3**	**= I / J**	**10**	**29**
(L)	No. of heating days per week	days		5	7
(M)	Volume of pellets for peak day	m^3	= K / L	2	4
(N)	Wood pellet delivery truck load	tonnes		14 tonnes	
(O)	Volume of truck delivery	m^3	= N x 10^3 / J	22	
(P)	**Frequency of peak deliveries**	**days**	**= (O / K) x 7**	**15**	**5**

Table I.13 **Estimation of wood pellet storage and delivery requirements for Building X and Hotel Y**

Wood pellets can be delivered in partial loads, although it is usually cheaper to have full deliveries. For Building X, a full delivery (14 t) will last over two weeks during the peak winter heating period while deliveries every 5 days are required for Hotel Y. The biomass storage hopper/tank should typically have the capacity to take a full delivery load while having at least one week's storage in reserve to allow for issues with delivery and public holidays.

Assuming a full 14 t delivery in Building X, the storage volume would be 22 m^3 + 5 days x 2 m^3 = 32 m^3. This could be reduced to around 20 m^3 to save space but would require more frequent deliveries of partial loads, thereby increasing fuel costs. For Hotel Y, the storage volume would be 22 m^3 + 7 days x 4 m^3 = 50 m^3 which is 12 days' fuel supply.

A similar calculation for wood chips, assuming a truck delivery capacity of 40 m^3, is summarised in Table I.14.

		Building X	Hotel Y
Weight of wood chips	kg	8,900	25,700
Volume of wood chips	m^3	36	103
Frequency of deliveries	days	8	3
Storage volume	m^3	75	145

Table I.14 **Wood chip consumption and deliveries for heating in peak week**

I2.5 Simplified cost / benefit analysis for Building X and Hotel Y

The capital cost assumptions for a biomass boiler in Building X are shown in Table I.15. The capital cost for an 800 kW biomass boiler and associated plant and space in Hotel Y is assumed to be around £350,000.

Item	Cost	Assumptions
Biomass boiler (400 kW) plus thermal tanks, etc.	£200,000	A gas boiler back-up is typically provided so no capital to offset by replacing a gas boiler.
Plant room space (32 m^3 hopper thermal tanks, augers, etc.)	£45,000	Extra plant room area = 20 m^2 Fuel store = 5 m x 5 m = 25 m^2 Total plant room area = 45 m^2 £1,000/m^2 for plant space in commercial office buildings.
Total capital cost	**£245,000**	Additional compared to natural gas boilers.

Table I.15 Capital costs assumptions for biomass boiler in Building X

The energy costs for the biomass boilers in Building X are shown in Table I.16. A similar calculation for Hotel Y gives an increased energy cost of £25,780 (£2.6/m^2). This does not include the benefit of the UK's Renewable Heat Incentive (RHI) scheme.

	Biomass	Nat gas	Total	£/m^2
Fuel Tariff	£0.046	£0.035		
Fuel consumption (kWh)	599,529	183,778	783,307	
Energy cost	**£27,578**	**£6,432**	**£34,011**	**£3.4**
Base case energy cost		£26,250	£26,250	£2.6
Cost increase			**£7,761**	**£0.8**

Table I.16 Biomass boiler energy cost review for Building X

I2.7 Delivering biomass to buildings

Biomass is usually delivered to buildings by road. It is therefore important to understand the vehicle capacities, dimensions, turning circles and delivery method as this will have an impact on the design of the building to accommodate biomass. Wood pellets flow and can be easily pumped. Delivery is performed by tankers or trucks fitted with a blower – refer to Figure I.8. In city centres, where space is at a premium, wood pellets may be the only viable option, even though they have a higher fuel cost than wood chips.

Fig I.8 **Wood pellets being pumped into a building (photo: Forever Fuels)**

Wood chips cannot be easily pumped and so are usually delivered by either trucks tipping the contents into a hopper, or a roll-on/roll-off big bin system. This requires more space for both storage (the hopper must be large enough to take an entire delivery load) and vehicle access. In the UK most wood chips are delivered by tipper truck or tractor with a tipping trailer. Figure I.9 shows tractors with tipping trailers (15 – 20 m^3), which are usually the cheapest option but which cannot carry chips over long distances. Roll-on/roll-off bins are typically 35 m^3 and act as both delivery container and fuel feed hopper. Two bins are required if a continuous supply of wood chip is required (while the empty bin is being replaced).

Fig I.9 **Wood chips being delivered by trailer**
(photos: Econergy - a British Gas Company [left], Dick Bradford [right])

The largest capacity delivery systems are walking floor articulated trailers which can deliver 80+ m^3. These do not tip and so place restrictions on the hopper configuration. Figure 1.10 shows wood chips being delivered to a biomass district heating energy centre in Ry, Denmark.

Fig 1.10 Wood chip delivery to district heating plant by articulated lorry (photo: author)

SAFETY AND DESIGN ISSUES WITH BIOMASS BOILERS

Despite their widespread use in the UK, there are concerns regarding the safe and efficient design of biomass boiler systems. In an article in the CIBSE Journal dated December 2012, the following issues were raised:

- Since 2002, at least nine people have died in Europe following entry into inadequately ventilated wood pellet storage areas.
- Chimney heights and design are often inadequate to prevent flue gases from reaching explosive limits when the boiler is in 'slumber mode'.
- No back-up power to control biomass boiler (flue fans, pumps, controls) in the event of a power failure.
- Headers not designed to avoid interaction between water flows in the boiler (constant temperature and flow) and the heating circuits (variable temperatures and flows) leading to inefficient operation of the boiler.
- Use heat-load control (with flow/heat meters) in preference to simple temperature-based control.
- Not enough people skilled in the procurement of biomass boiler systems in the UK and more training required.

I2.8 Supplying Building X and Hotel Y with biomass

Table I.17 shows the area of short rotation coppice (SRC) willow plantation (shown in Figure 7.5 in Chapter 7) required to supply Building X and Hotel Y's annual biomass requirements.[9]

	Building X	Hotel Y
Biomass fuel consumption (MWh/annum)	600	1,990
Yield from SRC willow (MWh / hectare)	46	
Area of plantation required (hectares)	13 ha	43 ha
Area of plantation per m^2 of building GIA	*13m^2*	*43m^2*

Table I.17 Indicative area of SRC willow plantation to supply biomass to Building X and Hotel Y

The saving in CO_2 per hectare if the SRC willow fuel is converted into wood pellets (and used in biomass boilers to replace natural gas boilers for heating) is as follows:

- CO_2e emissions from wood pellets in biomass boiler = 46,000 kWh x 0.04 = 1,840 kgCO_2e / Ha
- Heat energy produced = 46,000 kWh x 85% = 39,100 kWh_{heat}
- CO_2e emissions from natural gas boilers = (39,100 / 90%) x 0.2 = 8,688 kgCO_2e / Ha
- CO_2e saving per hectare = 8,688 – 1,840 = 6,848 kgCO_2e / Ha *(6.8 tCO_2e / Ha)*

For comparison, preserving 1 Ha of Amazon rainforest prevents 642 tCO_2 being released.[10]

I3. HEAT PUMPS

I3.1 Heat pump efficiency – CoP, SCoP and temperature

The efficiency with which a heat pump converts electricity into heat is expressed as the Coefficient of Performance (CoP):

CoP = Heat output / Energy input

A CoP of 3 delivers 3 kWh of heat for every 1 kWh of electrical energy input. Manufacturers usually express the CoP for defined test conditions (in standard EN14511): for air to water heat pumps, the outside air is 7°C and the water supply is 45°C (returning at 40°C) – a temperature difference of 38°C.

The CoP varies with the temperature difference between the heat source and the heat output – the higher the difference, the lower the CoP. Figure I.11 shows a CoP curve for a generic heat pump – individual heat pumps will have their own curve which may be more efficient than the one shown. Once the temperature difference exceeds about 40°C then the CoP in the example heat pump drops below 3.

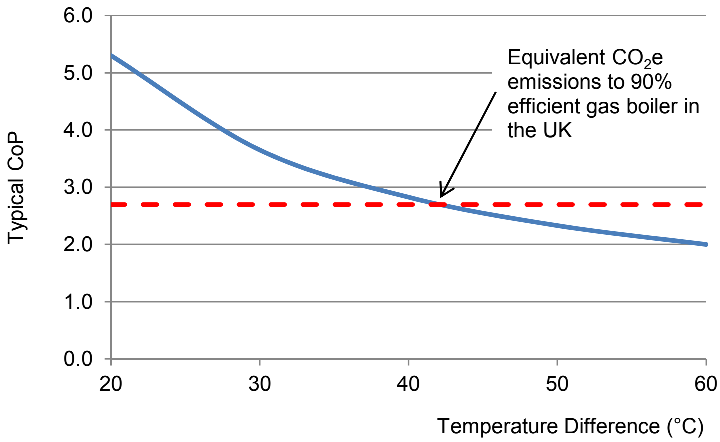


Fig I.11 Typical heat pump CoP curve for temperature difference between heat source (evaporator) and heat supply (condenser)

Maximising annual operating efficiency requires an understanding of the seasonal changes in heat source temperature and the heat supply temperatures – refer to Table I.18. All heat pumps work best with low temperature heating systems. For example, a ground source heat pump supplying under floor heating (30°C temp difference) might have a CoP of 3.7, while an air source heat pump providing domestic hot water (average 55°C temp difference) might have a CoP of 2.1.

Heat source	Typical UK design temperatures	
	Winter	Summer
Air	-5°C	30°C
Ground loop	10°C	14°C
Borehole	11°C	12°C
Aquifer	8°C	14°C
Surface water	0°C	18°C

Heat supply	Typical design temperatures
Under floor	35 to 45°C
Radiators / fan coils	50 to 80°C
Air handling unit	50 to 70°C
Domestic hot water	55 to 60°C

Table I.18 Summary of typical source and supply temperatures in the UK

From January 2013 onwards, the EU Energy Related Products Directive 2010/30/EU (Supplement No. 626/2011 dated 4 May 2011) requires that manufacturers label the energy efficiency of air conditioning systems below 12 kW using the Seasonal Coefficient of Performance (SCOP) for heating and the Seasonal Energy Efficiency Ratio (SEER) for cooling. This is a fundamental shift in measuring energy efficiency. As there is no correlation between COP and SCOP ratings all manufacturers have to recalculate their products' energy efficiency ratings.

The old COP measured performance at a fixed outdoor temperature of 7°C. The new SCOP calculates the average system performance at the variable temperatures experienced throughout the heating season in three different climate zones – refer to Figure I.12. The energy consumption in stand-by modes is also taken into account. This better reflects the real annual operating conditions of heat pumps.

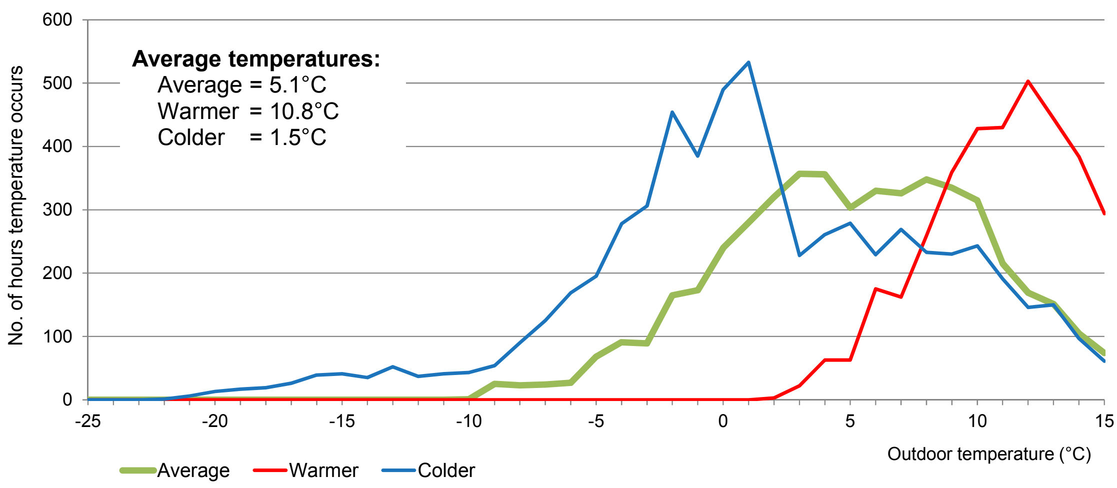


Fig I.12 European seasonal conditions for calculating heat pump SCOP in EU 626/2011

Equipment that was designed to have a peak CoP at 7°C may not score so highly when running at part heating loads. For example, in northern European climates heat pumps operate at peak load for less than 30% of the time. Minimum standards will tighten in 2014 and consultation is underway to extend the scheme to systems over 12 kW.

I3.2 Are heat pumps renewable?

There is no standard definition of when a heat pump is considered to be a source of renewable energy. The following standards/schemes have set different minimum CoPs, which may be updated in due course to use the SCoP:

- The European Union, under the community eco-label award scheme, considers heat pumps to be renewable when the design CoP, depending on the system type, is not less than 2.6 to 3.1.[11]
- The Renewable Heat Incentive in the UK requires that heat pumps have a minimum CoP of 2.9.
- The UK's Microgeneration Certification Scheme[12] requires heat pumps to have design CoPs not less than 3.0, as shown in Table I.19.

Heat source: Heat supply:	Air	Ground	Water
Air	3.0	3.2	3.5
Water	3.2	3.5	3.8

Table I.19 Minimum CoP for heat pumps under the UK Microgeneration Certification Scheme (MCS)

In the UK, the CoP must be at least 2.7 before heat pumps connected to grid electricity have lower emissions than a 90% efficient natural gas boiler. This will vary in countries with different grid electricity emissions factors, for example in Australia a CoP of 4.5 is required for a heat pump to have lower emissions than a natural gas boiler.

The output from a heat pump with a CoP of 3.0 is not delivering 100% renewable heat. The renewable energy component in this book is considered to be the difference in CO_2e emissions between the heat pump's energy input and the fossil fuel source that it is replacing. Heat pumps are only 100% renewable if the electricity powering them is also 100% renewable.

In situations where natural gas isn't available, heat pumps provide the lowest carbon and energy cost option, compared with other fossil fuel heating systems. Table I.20 summarises the CO_2e emissions and fuel costs for a heat pump with a CoP of 2.7 compared with other typical heating fuels to provide 100 kWh of heat.

	System efficiency	Fuel required (kWh)	Emissions factor ($kgCO_2e$/kWh)	**Emissions ($kgCO_2e$)**	Cost per kWh of fuel	Cost per 100kWh of heat
Heat pump	2.7	37	0.6	**22**	10.0 p	3.7 p
Natural gas	*90%*	*111*	*0.2*	**22**	*3.5 p*	*3.9 p*
Heating oil	90%	111	0.31	**34**	6.0 p	6.7 p
LPG	90%	111	0.26	**29**	7.6 p	8.4 p
Direct electric	0.98	102	0.6	**61**	10.0 p	10.2 p

Table I.20 Heat pump cost and CO_2e compared to other heating fuels

I3.3 CO_2e and cost-saving calculations for Building X and Hotel Y

Table I.21 shows the data used to produce Figure 7.9 in Chapter 7 and the energy cost savings in Building X and Hotel Y for different heat pump CoPs. The domestic hot water in the two buildings is assumed to be supplied by natural gas boilers.

BUILDING X						
Space heating energy $kWh_{(Heat)}/m^2$ =		63	Base heating energy cost (£/m²) =			£2.45
	Gas boiler	CoP of heat pump				
		1	2	3	4	5
Electricity (kWh/m²)	n/a	63	32	21	16	13
$kgCO_2e/m^2$	14.0	38	19	13	9	8
Reduction in CO_2e		-24	-5	1	5	6
Total $kgCO_2e/m^2$	**105**	**129**	**110**	**104**	**100**	**99**
% reduction		-23%	-5%	1%	4%	6%
Energy cost	£2.45	£6.30	£3.15	£2.10	£1.58	£1.26
Cost saving		-£3.85	-£0.70	£0.35	£0.88	£1.19
HOTEL Y						
Space heating energy $kWh_{(Heat)}/m^2$ =		135	Base heating energy cost (£/m²) =			£5.25
	Gas boiler	CoP of heat pump				
		1	2	3	4	5
Electricity (kWh/m²)	n/a	135	68	45	34	27
$kgCO_2e/m^2$	30.0	81	41	27	20	16
Reduction in CO_2e		-51	-11	3	10	14
Total $kgCO_2e/m^2$)	**105**	**156**	**116**	**102**	**95**	**91**
% reduction		-49%	-10%	3%	9%	13%
Energy cost	£5.25	£13.50	£6.75	£4.50	£3.38	£2.70
Cost saving		-£8.25	-£1.50	£0.75	£1.88	£2.55

Table I.21 CO_2e **and cost-saving calculations for heat pumps in Building X and Hotel Y**

GAS ABSORPTION HEAT PUMPS

Gas absorption heat pumps (GAHPs) use a gas burner to drive the refrigeration cycle, instead of an electric motor connected to a compressor. They typically have a gas utilisation efficiency of between 140 and 160% when external temperatures are 7°C and output flow temperature is 35°C.[13] Generating 100 kWh of heat using a 140% efficient GAHP at these temperatures requires 67 kWh of gas (13 $kgCO_2e$) at a cost of 23.5p. An air source electric heat pump with a CoP of 3.0 at the same temperatures requires 33 kWh of electricity (20 $kgCO_2e$) at a cost of 33p.

The use of GAHPs is likely to increase in the future, although as grid electricity decarbonises, their carbon advantage over electric heat pumps will reduce.

I3.4 Types of ground source systems

Heat can be sourced from the ground or large water bodies such as lakes, rivers and seas. There are two primary types of piping:

- Closed loop – water is pumped through pipes with heat transferred through the wall of the pipe.
- Open loop – water is pumped directly from the heat source (e.g. lake, aquifer).

Closed loop piping is used in horizontal or vertical configurations in the ground. Open loop systems are more efficient if a suitable body of water is available (e.g. an underground aquifer), but requires extraction and recharge licences. The three main types of pipe configuration used for ground source heat pumps are shown in Figure I.13.

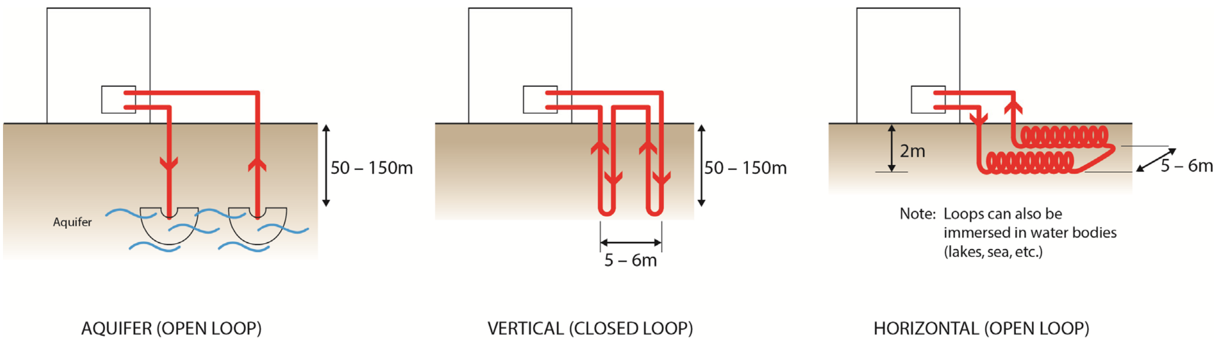


Fig 1.13 Main types of ground source heat pumps

I3.5 Aquifer systems (open loop)

These systems are typically used to provide cooling, with or without heating in the winter. The system typically has two wells, a 'hot well' and a 'cold well', which should be spaced at least 100 m apart. The ideal storage temperatures of the hot and cold wells are 21°C and 7°C respectively.

During winter, groundwater is discharged from the 'hot' well with energy recovered by a plate heat exchanger, and the heat pump raises the temperature for heating purposes. In summer, the function is reversed and cool water is extracted from the 'cold' well and used for cooling purposes. In order for the system to work efficiently there must be minimal net heat transfer to or from the ground over the course of a year, otherwise the system will fall out of balance.

Typically in London, the aquifer temperature is 14 to 15°C with injection (recharge) temperatures limited to 24°C. The main use of the aquifer is for heat rejection from cooling systems. Providing 1 kW of cooling with a temperature difference of 9°C requires 95 litres per hour.[14] A borehole with an extraction rate of 12 l/s can provide around 1600 kW of heat rejection. Aquifer-based open loop systems are usually designed to re-inject all water back into the aquifer. The groundwater must not be exposed to contamination as this may be used for drinking water elsewhere. There should also be no net addition or removal of groundwater from the aquifer. A successful open loop system requires a sufficient groundwater yield which is dictated by the hydrogeology of the aquifer underlying the site. The borehole depth will vary based on the geology and hydrogeology underlying the site.

An aquifer-based open loop system has some advantages over a closed loop system, one of which is the higher energy output, which results in a smaller number of boreholes being required at the site. However, there are a number of site and cost-related factors, as well as regulatory procedures, which need to be taken into consideration for an open loop system. These include:

- The cost of boreholes and field trials.
- The unpredictability of groundwater yield over a long time.
- Lengthy procedures for obtaining permits for groundwater extraction and consent for re-injection. The license conditions will depend on the presence of other licensed systems and wells in the vicinity.
- Changes in legislation could affect the operation of the system.
- Existence of geothermal ground heat systems or wells at neighbouring sites.

I3.5 Closed loop systems

Pipes are buried in the ground (horizontally or vertically), and water is circulated to exchange heat from the ground to the pipe (heating mode) or vice versa (cooling mode). The ground temperatures at a certain depth remain steady, without the influence of seasonal temperature change. In areas with freezing problems, anti-freeze solutions such as ethylene glycol, brine or alcohol are used to replace water in the pipes. These systems can present a groundwater pollution risk if there is leakage from the pipes.

The ground temperature profile is influenced by the air temperature, the depth and thermal conductivity of the ground, and heat transfer by flowing groundwater. The ground temperature near the surface generally matches the average air temperature – but with a lag of one to two months; it is lower than the air temperature in summer and higher than the air temperature in winter. At around 2 to 3 m depth, the variation in temperature becomes more stable, varying between 5 and 15 °C in the UK. At a depth of approximately 10 m, the ground temperature typically remains fairly constant with an average temperature of approximately 10 to 12°C year-round. An example seasonal ground profile is shown in Figure I.14.

The mean observed equilibrium temperature for the UK at a depth of 100 m depth is close to 12 ±1.6°C with a range of about 7 to 15°C. In addition, ground temperature generally increases about 3°C for every 100 m depth.

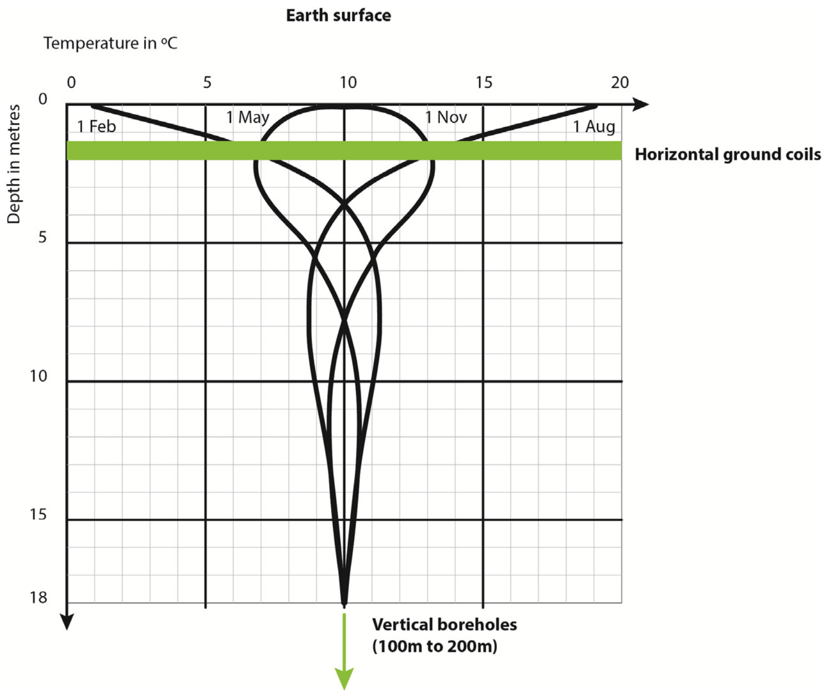


Fig I.14 Theoretical temperature distribution versus depth for a location with 10°C annual mean external temperature (adapted from BS EN 15450)

If the ground is used for heating only (i.e. heat extracted from the ground) then there can be a slight reduction in ground temperature over the first couple of years, depending on ground conditions. Provided the system (ground collector area) is not undersized then this should stabilise and not unduly affect the long-term seasonal performance.

If the system is used for heating and cooling (i.e. heat extracted in winter and then injected back in summer) then there should be little or no change to annual average ground temperature, assuming a balanced heat rejection and extraction rate.

I3.6 How much heat can be extracted from the ground?

The amount of heat that can be extracted each year depends on the operating period of the system and the type of ground. Table I.22 shows the values adopted for Building X and Hotel Y. These were taken from BS EN 15450, which provides maximum extraction rates for horizontal ground loops and closed loop boreholes.

	Building X	Hotel Y
BS EN 15450 hours per year category	*1800*	*2400*
Vertical boreholes	**W/m**	**W/m**
Clay	35 to 50	30 to 40
Limestone	55 to 70	45 to 60
Sandstone	65 to 80	55 to 65
Value assumed for calculations	50	40
Horizontal trenches	**W/m^2**	**W/m^2**
Dry, non-cohesive soil	10	8
Moist cohesive soil	20 to 30	16 to 24
Water saturated sand	40	32
Value assumed for calculations	20	16

Table I.22 Specific heat extraction rates for ground source heat pumps in Central Europe (source: BS EN 15450)

Boreholes

The design of borehole systems can be quite complex and optimising the design requires a detailed understanding of ground conditions and geothermal properties of the ground. A detailed geological and hydrogeological evaluation of the site, initially by a desk study followed by ground investigation, is usually essential to assess the viability of the most appropriate system for a building. Field evaluation of the proposed system, by drilling a geothermal borehole (which can be subsequently used in the final system) and testing by a specialist contractor, is required in order to obtain the design parameters before the final design can be undertaken.

Horizontal Trenches

There are lots of different configurations for laying pipes in trenches, although coils laid flat or in vertical trenches (300 mm wide) are the most common. Figure I.15 shows a typical vertical coil arrangement.

According to Baxi,[15] '*the formulae of 10 m of trench to provide 1 kW of delivered heat from the heat pump can be, more or less, uniformly applied across most of the UK.*' Assuming 50 m x 50 m of land area, this equates to 500 m of trench, providing 50 kW of delivered heat, or 20 W/m^2. Assuming a CoP of 4, the heat extracted is 20 x (1-1/4) = 15 W/m^2 which is consistent with the value in Table I.22 for 2,400 hours of heat per year.

Undersizing will cause the system to operate at a lower efficiency (and possibly freeze the ground), while oversizing is a waste of money. It is therefore recommended to undertake a geological survey prior to sizing a system.

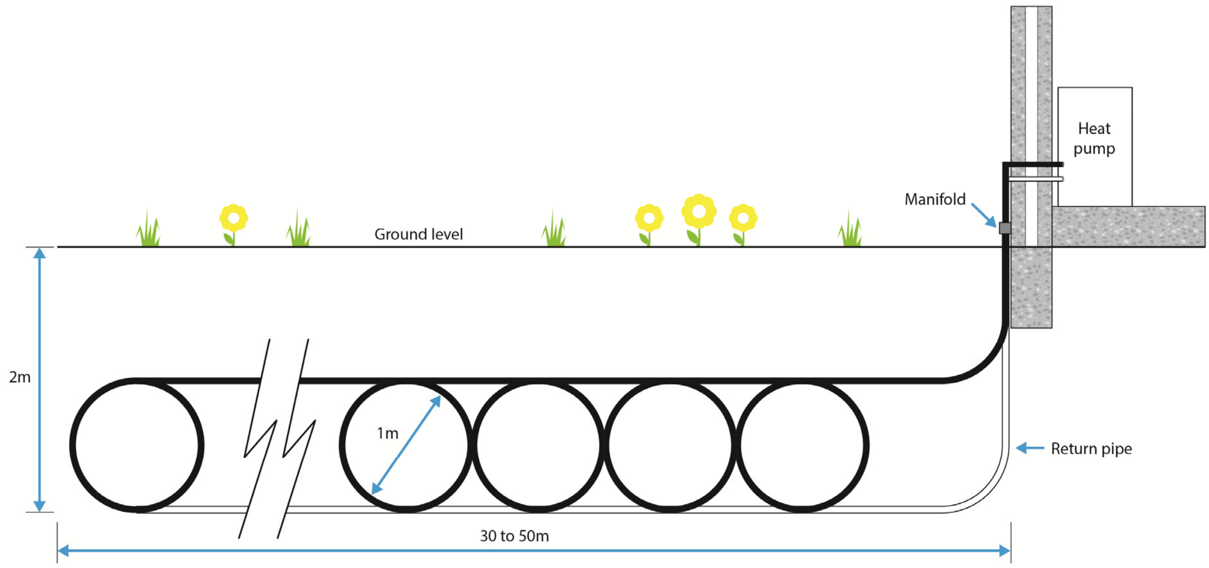


Fig I.15 **Typical installation of a 32 mm diameter black slinky pipe in a 300 mm wide trench spaced 5 m apart (source: adapted from Baxi)**

I3.7 Estimating the area of ground required for Building X and Hotel Y

Heating-only ground source heat pump (GSHP) systems typically have a CoP of between 3.8 and 4.2 if properly designed, installed, controlled and maintained.[16] In commercial buildings, cooling is also usually provided and the CoPs for a combined heating and cooling GSHP system are improved because the ground acts as a large thermal store – heat rejected by the ground in the summer is extracted in winter. The heating CoP of such systems can be up to 5.0, while the cooling CoP can be up to 6.0. For the comparison of renewable heating systems in Chapter 7, Building X and Hotel Y are assumed to have GSHPs providing heating only, and a CoP of 4 was assumed in the calculations.

The heat required from the ground is based on the heat pump capacity and the CoP. A heat pump with a CoP of 4 produces 4 kW of heat energy from 1 kW of electrical input with 3 kW of heat required to be extracted from the ground. This is represented by the equation:

$$\text{Heat required from ground} = \text{Heat pump capacity} \times (1 - 1/\text{CoP})$$

A preliminary estimate of the land area required for GSHPs to provide space heating in the two buildings is shown in Table I.23. The area of land required for 200 m long boreholes is greater than the footprint of the buildings. Unless a large area of land is adjacent to the buildings (unlikely in a city centre) or an aquifer with sufficient thermal capacity is accessible (and extraction licences are available) then ground source heat pumps will only be able to provide a proportion of the building's space heating requirement.

If no additional land is available then the boreholes would need to be contained within the site boundary. Ignoring the practicalities of incorporating 200 m deep boreholes with the foundations of a 10 storey building, the maximum number of boreholes that could be installed in a 1,000 m^2 footprint is 36. Table I.24 shows the maximum heat pump capacity these boreholes could support.

	Building X	Hotel Y
Heat pump capacity	800 kW	800 kW
Heat pump CoP (annual average)	4.0	4.0
Heat required from ground	600 kW	600 kW
Heating hours category	*1800 hours/year*	*2400 hours/year*
Vertical boreholes		
Heat extraction rate (Table I.22)	50 W/m	40 W/m
Length of borehole	12 km	15 km
Borehole depth	200 m	200 m
No. of boreholes	60	75
Dimensions of land (@ 6m spacing)	30 m x 72 m	30 m x 90 m
Land area required	2,160 m^2	2,700 m^2
Cost (@ £50 per m of borehole)	£600,000	£750,000
Horizontal trenches		
Heat extraction rate (Table I.22)	20 W/m^2	16 W/m^2
Land area required	30,000 m^2	37,500 m^2

Table I.23 Estimate of land area for GSHP in Building X and Hotel Y

	Building X	Hotel Y
Heat capacity of 200m borehole	10 kW	8 kW
No. of 200m boreholes	36	36
Heat capacity of boreholes	360 kW	288 kW
Heat pump CoP using boreholes	4	4
Maximum GSHP capacity	480 kW	385 kW
% of peak capacity	*60%*	*48%*

Table I.24 Maximum GSHP capacity for 36no. boreholes in Building X and Hotel Y

The shortfall in capacity from the ground would need to be provided by an air-based system. The heat pumps could be connected to a large air-cooled heat rejection unit on the roof operating in reverse to extract heat from the air, or separate ASHP and GSHP units could be provided. The controls of the air source and ground source system would need to be configured to optimise the overall system CoP, taking into account the fact that for most of the heating period, the system will not operate at the peak heating demand of 800 kW.

A very crude assessment of the combined system CoP is shown in Table I.25, which includes some assumptions regarding the percentage of annual heating energy that is supplied from the GSHP, with the remainder being met by the ASHP.

	Building X	Hotel Y
Ground source capacity	480 kW	385 kW
Assumed % of heat from GSHP	85%	70%
GSHP CoP	4	4
Air source capacity	320 kW	415 kW
Assumed % of heat from ASHP	15%	30%
ASHP CoP (operates on coldest days)	2.5	2.5
Average heat pump CoP	**3.8**	**3.6**

Table I.25 **Maximum GSHP capacity for 36no. boreholes in Building X and Hotel Y**

I3.8 Calculating the CO_2e and cost/benefit of heat pumps

If the cost of installing ASHPs is assumed to be cost-neutral compared to gas boilers then the cost for GSHPs is due to the boreholes. Table I.26 shows the CO_2e savings and capital and energy costs associated with ASHPs, GSHPs and a combination of the two.

	Building X			Hotel Y		
	ASHP	both	GSHP	ASHP	both	GSHP
Heat pump CoP (annual average)	2.8	3.8	4	2.8	3.6	4
kgCO_2e saving	5,000	40,526	45,500	10,714	75,000	97,500
kgCO_2e/m^2 saving	**0.5**	**4.1**	**4.6**	**1.1**	**7.5**	**9.8**
Energy cost saving	£2,000	£7,921	£8,750	£4,286	£15,000	£18,750
Length of boreholes (m)	0	7,200	12,000	0	7,200	12,000
Cost (@ £50 per m of borehole) [17]	£0	£360,000	£600,000	£0	£360,000	£600,000
Payback period (years)	0	45	69	0	24	32
Net Present Cost (15yrs @ 5%)	-	£260,800	£490,400	-	£172,100	£365,000
Cost per tCO_2e saved over 15yrs	**-**	**£429**	**£718**	**-**	**£153**	**£250**

Table I.26 **CO_2e and cost benefit of heat pumps in Building X and Hotel Y**

I3.9 The VRF heat pump conundrum

In Chapter 7, heat pumps were considered as an option to provide heating in a building. However, by pumping the refrigerant in reverse, they also provide cooling. They can potentially reduce emissions due to heating, but if they are also used for cooling, do they reduce or increase a building's overall carbon emissions?

Variable Refrigerant Flow (VRF) systems are a development of heat pump technology and allow multiple indoor delivery units to be connected to a single outdoor unit with multiple compressors. This allows units to provide heating or cooling in different zones to suit demand (e.g. heating to the perimeter and cooling to internal zones) and to pump heat from one zone where it is not needed, to another where it is, bypassing the external compressor units. Figure I.16 shows the configuration of an example 3-pipe system. 2-pipe systems, with larger zone control units, can also be used.

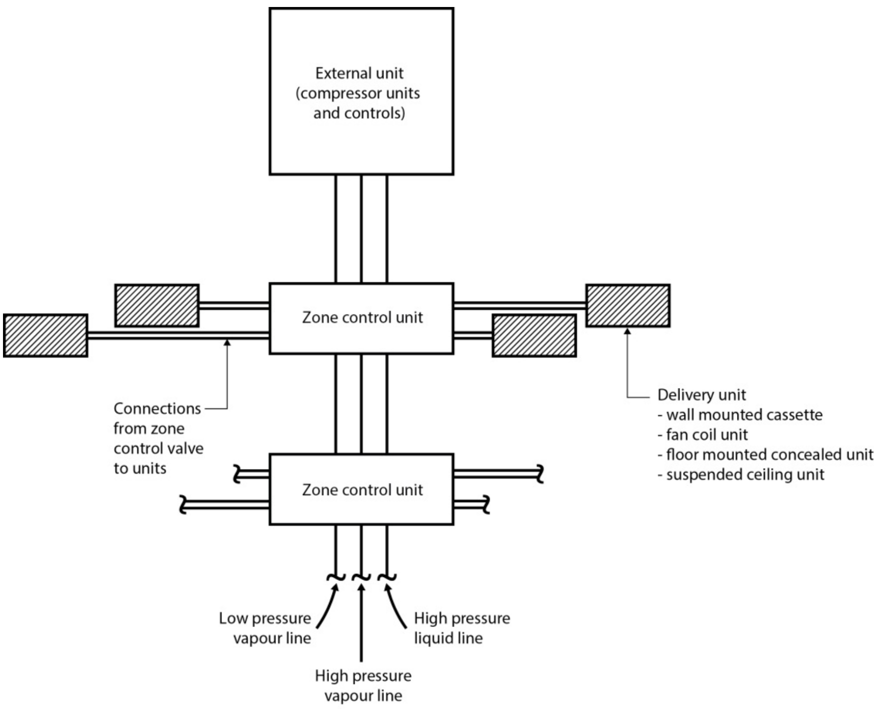


Fig I.16 Example 3-pipe VRF system arrangement

A CoP of 7 can potentially be achieved when 40% of indoor units require cooling and 60% require heating with an outdoor temperature of 7°C DB / 6°C WB and an indoor temperature of 20°C DB / 15°C WB.[18] In 100% cooling or 100% heating mode, the CoP at these temperatures is around 4.5, but reduces when the difference between outdoor and indoor temperature increases. This is why seasonal CoPs are essential, so that realistic operational efficiencies can be used in energy modelling and comparisons between systems.

VRF systems have become very popular in UK office buildings over the last few years for a number of reasons, including the following:

- They have a lower initial capital cost compared to heating hot water and chilled water systems (although the life cycle costs are not dissimilar as VRF systems often have an expected life of around 10 years, compared to 20+ years for central plant systems).
- In speculative offices, the VRF heating and cooling systems don't need to be installed until the tenancy fit-out, further reducing upfront costs to the developer.
- The heat pump can be connected directly to a tenant's metered electricity supply.

Since heat pumps can be classed as renewable energy systems then a VRF system is often considered to contribute to a building's renewable energy target at the planning stage. Is this right? Table I.27 shows an estimate of Building X's CO_2e emissions using a VRF system, with a CoP of 3 for heating and a seasonal energy efficiency ratio (SEER) of 3.75 for cooling, compared with a more traditional system (the gas boiler and electric chiller efficiencies of 90% and 5 respectively have been reduced by 5% to allow for heating and chilled water pumps).

	Gas boiler & electric chiller	VRF
Heating		
Annual heating demand (kWh_{heat}/m^2)	63	63
Efficiency of hot water system / heat pump	86%	3
Energy required (kWh/m^2)	74	21
Fuel source emissions ($kgCO_2e/kWh$)	0.2	0.6
$kgCO_2e/m^2$	**14.7**	**12.6**
Cooling		
Annual cooling demand ($kWh_{cooling}/m^2$)	100	100
Efficiency of chilled water system / heat pump	4.75	3.75
Energy required (kWh/m^2)	21	27
Fuel source emissions ($kgCO_2e/kWh$)	0.6	0.6
$kgCO_2e/m^2$	**12.6**	**16.0**
Total $kgCO_2e/m^2$ (space heating & cooling)	**27.4**	**28.6**

Table I.27 Indicative CO_2e emissions due to typical central plant versus a VRF system in Building X

In this hypothetical example, the overall CO_2e emissions of the VRF system are slightly higher. The VRF heating CO_2e emissions may be lower than gas boilers but the cooling component is not as efficient as a good quality chilled water system. When the two are added together, there is no net CO_2e benefit in using VRF compared to a traditional central plant system.

VRF is a perfectly valid system for providing heating and cooling in office buildings – but it does not necessarily produce less carbon than other efficient HVAC systems, and so shouldn't really be classed as a 'renewable.' The potential for refrigerant leaks is also increased (the building contains a network of refrigerant pipes), which could lead to further CO_2e emissions (refer to Appendix B) – but this is not usually considered when the carbon performance is assessed.

I4. WIND

I4.1 Wind speed data

Getting reliable wind speed data is crucial when determining the feasibility of wind turbines in a particular location. A number of countries have produced wind resource maps or databases which give an indication of likely wind speeds at different heights above ground (typically 10 m, 25 m, 50 m or 80 m). Using this data to estimate wind turbine outputs in urban areas without adjustment has led to unrealistic predictions in the past. This is because trees and buildings reduce wind speeds locally.[19]

For example, a wind trial on Ashenden House, a 10 storey building in London (refer to Table I.30 and I.31) measured the average wind speed in the period from June 2008 to 2009 as 3.65 m/s. This is much lower than the 6.1 m/s predicted by the old NOABL database, although better than the 2.6 m/s predicted by the Energy Savings Trust's Wind Speed Prediction Tool.[20]

As a very rough rule of thumb, in urban locations, reduce the average wind speed given on maps or databases (that haven't already made adjustments for urban locations) by 30 to 40% and then make further reductions if the turbine height is lower than the wind speed database height. Ideally, wind speed logging using a site anemometer should be undertaken to establish the likely wind resource on site (wind speeds and frequency of occurrence) before installing a wind turbine, although sometimes this isn't possible.

Most wind turbines require average wind speeds of at least 5 m/s to work effectively. The power in wind varies by the cube of the wind speed, which means the power in wind at 3.6 m/s is approximately five times less than wind at 6 m/s. Choosing a site with reliable wind speeds is critical for a successful wind turbine installation.

I4.2 Wind speeds in different units

Wind speeds can be expressed in different units. The conversion factors are shown in Table I.28. To put wind speeds into context, Table I.29 shows the Beaufort Scale.[21]

	m/s	mph	km/h	knots
1 m/s =	1	2.24	3.6	1.94
1 mph =	0.45	1	1.61	0.87
1 km/h =	0.28	0.62	1	0.54
1 knot =	0.51	1.15	1.85	1

Table I.28 Wind speed conversion factors

Beaufort wind scale	Mean wind speed				Limits of wind speed	Wind descriptive terms	
	m/s	mph	km/h	Knots	m/s		
0	0	0	0	0	0–0.2	Calm	Smoke rises vertically.
1	0.8	1.8	2.9	2	0.3–1.5	Light air	Smoke drift indicates wind direction, still wind vanes.
2	2.4	5.4	8.6	5	1.6–3.3	Light breeze	Wind felt on exposed skin. Leaves rustle, vanes begin to move.
3	4.3	9.6	15.5	9	3.4–5.4	Gentle breeze	Leaves and small twigs constantly moving, light flags extended.
4	6.7	15.0	24.1	13	5.5–7.9	Moderate breeze	Dust and loose paper raised. Small branches begin to move.
5	9.3	20.8	33.5	19	8.0–10.7	Fresh breeze	Branches of a moderate size move. Small trees in leaf begin to sway.
6	12.3	27.5	44.3	24	10.8–13.8	Strong breeze	Large branches in motion. Whistling heard in overhead wires. Umbrella use becomes difficult.
7	15.5	34.7	55.8	30	13.9–17.1	Near gale	Whole trees in motion. Effort needed to walk against the wind.
8	18.9	42.3	68.0	37	17.2–20.7	Gale	Some twigs broken from trees. Cars veer on road. Progress on foot is seriously impeded.
9	22.6	50.6	81.4	44	20.8–24.4	Severe gale	Some branches break off trees, and some small trees blow over. Construction/temporary signs and barricades blow over.
10	26.4	59.1	95.0	52	24.5–28.4	Storm	Trees are broken off or uprooted, saplings bent and deformed. Some roofs are damaged.
11	30.5	68.2	109.8	60	28.5–32.6	Violent storm	Widespread damage to vegetation. Many roofing surfaces are damaged.
12	-	-	-	-	32.7+	Hurricane	Very widespread damage to vegetation. Some windows may break and buildings damaged. Debris may be hurled about.

Table I.29 The Beaufort wind scale

I4.3 How much electricity do wind turbines on buildings generate?

A number of studies on the output of building mounted turbines, mainly systems less than 6 kW, were undertaken in the UK in 2008 and 2009.[22] The results are summarised in Table I.30. The capacity factor is the ratio of electricity generated in a year compared to the maximum possible output from a wind turbine.

$$\text{Capacity Factor} = \frac{\text{annual electricity generated (kWh)}}{\text{turbine capacity (kW)} \times 365 \text{ days} \times 24 \text{ hours}}$$

Wind trial	Year of study	Type of turbines	Average capacity factor	No. of turbines in study	Measured average wind speed
Warwick wind trials	2008	Building mounted (400 W to 1.5 kW) on various types of building	4.2% *	26	**
Ashenden House, London	2008	6 kW horizontal turbine on 11 storey building in central London	8%	1	3.8 m/s
	2009	6 kW vertical turbine on the same building didn't work properly	0%	1	3.6 m/s
Energy Saving Trust study	2009	Building mounted – urban (400 W to 1.5 kW)	<3% ***	57	< 4 m/s
		Pole mounted – rural (600 W to 6 kW)	19%		> 5 m/s

* This excludes time when the turbines were switched off or broken. The actual capacity factor, including downtime, was less than 1%.

** Average wind speed not stated but 16 of 26 sites had average annual wind speeds over 40% lower than estimated using the UK's NOABL database.

*** In some cases, the inverters consumed more energy than the wind turbines generated.

Table I.30 Summary of various wind trials in the UK in 2008 and 2009

All of these trials found that building-mounted wind turbines in urban locations generally did not achieve the design predictions using wind speed databases and manufacturers' turbine power curves. There are two primary reasons for this:

- The wind speeds near buildings in urban environments are usually much less than the wind speeds used in the analysis – most wind speed databases do not consider the impact of local obstructions.
- Wind turbine power curves from manufacturers can sometimes be overly optimistic.

I4.5 Examples of wind turbines on buildings

Table I.31 provides three examples of wind turbines on buildings.[23] In the absence of published measured energy output, the reader is left to decide if the predicted outputs and capacity factors for buildings 2 and 3 are likely to be realistic.

	1	2	3
Type	Horizontal axis	Vertical axis	Building integrated
			
Location	Ashenden House, London	Marine Building, Hobart	Strata SE1, London
Year installed	2008	2010	2011
Height of building	11 storeys	10 storeys	42 storeys (140m)
Height of turbines above upper roof level	9 m	< 2 m	n/a
Installed capacity	6 kWe	48 KWe *(4 x 12KWe)*	57 kWe *(3 x 19kWe)*
Diameter	5.5 m	5 m (5 m high)	9 m
Annual output	4,200 kWh *(measured)*	120,000 kWh *(predicted)*	50,000 kWh *(predicted)*
Capital cost	£40,000	not known	£1.5 million
Simple payback estimate *	95 years	not known	300 years
Predicted capacity factor	**15 to 17%**	**28%**	**10%**
Measured capacity factor	**8%**	**not available**	**not available**
Comments	Undertaken as a trial with extensive monitoring. A vertical axis 6 KW turbine installed in the same location 12 months later (costing £50,000) consumed more power than it generated.	Within a couple of weeks of installation in July 2010 two of the turbines were damaged by wind. The turbines were back in operation by late 2011.	Concerns have been raised about noise from the turbines affecting residents in the top (most expensive) apartments, with suggestions being made that they might need to be turned off at night.
Photo credit:	*Brian Dunlop*	*Michael Bedelph*	*Stephen Maddocks*

* Simple payback calculated by author based on 10p/kWh for electricity using annual output.

Table I.31 Examples of wind turbines on buildings

I4.4 Estimating wind turbine output on Building X

Table 7.12 in Chapter 7 is based on a series of assumptions regarding spacing of turbines and capacity factors. Assuming a minimum spacing of 5x diameter spacing means that four 6 kW VAWT and four 6 kW HAWT can fit on the roof (spaced 25 m apart). It is only possible to fit two 9 m diameter building-integrated turbines (option 3) on Building X.

To determine the potential electricity generation, a capacity factor needs to be assumed. Building X is located in central London and so the likely average wind speed at the top of the building will be between 3 and 4 m/s.

A capacity factor of 8% is assumed for the horizontal wind turbine as it is almost identical to the Ashenden House wind trial – refer to Table I.31. There is some doubt, from various wind trials, that the vertical axis turbines will actually work in this location, but an 8% capacity factor has (very generously) been adopted for the calculation. However, obtaining a written guarantee from the supplier of the suitability of using a wind turbine in a particular location is essential prior to an order being placed.

The building-integrated turbines option cannot rotate to catch wind from all directions, so assuming that the turbines are set up to capture the prevailing winds, a capacity factor of 5% has been assumed. This is half the predicted capacity factor for the Strata building in Table I.31, but Building X's turbines are not 140 m above ground level.

I4.5 Estimating wind turbine outputs using a wind turbine power calculator for turbines on Building X and rural location

The capacity factor approach was used in Chapter 7 to provide a rough estimate of the potential electricity generated by a wind turbine. A more accurate estimate of annual electricity from a specific wind turbine requires a calculation involving the wind speed distribution at the particular site (the number of hours each wind speed occurs during the year) and the turbine power curve (how much electricity is generated at each wind speed). Various software packages are available to do this.

Wind speeds at a site vary throughout the year, from dead calm to gale force. In most areas, strong winds are rare while moderate winds can be quite common. The variation in wind speed for a site is described using a probability distribution which shows the number of hours that each wind speed occurs. If an hourly wind speed database is not available then this distribution can be estimated by using the average wind speed for the site and applying a Weibull shape factor.[24]

A Weibull shape factor of 2 (known as the Rayleigh distribution) is often used as a default figure by wind turbine manufacturers to give standard performance figures. The Carbon Trust's wind turbine calculator adopts a default Weibull shape parameter of 1.8 for London. The wind speed profiles measured during the Ashenden House wind trial in London gave a factor of 2.24.

The Danish Wind Industry Association's Wind Turbine Power Calculator was used in order to estimate the annual electricity that could be generated by large turbines in urban and rural locations (as shown in Figure 7.17 in Chapter 7). The key inputs were:

- Average wind speed = 4 m/s (urban) and 7 m/s (rural).
- Weibull shape parameter = 2.0.
- Manufacturer's power curves (already in calculator).

Table I.32 shows the outputs for typical 27 m and 54 m diameter turbines on Building X.

Diameter	Power (KW)	Energy output (kWh)	kWh/m^2	kgCO_2e/m^2	% of total CO_2e in Building X	Capacity factor
27 m	180	108,750	11	6.6	6%	7%
54 m	1,000	488,500	49	29.8	28%	6%

Table I.32 Energy output from 27 m and 54 m diameter wind turbines on Building X (4 m/s)

Table I.33 shows the these turbines if they were erected in a rural or off-shore location with an average wind speed of 7 m/s.

Diameter	Power (KW)	Energy output (kWh)	kWh/m^2	kgCO_2e/m^2	% of total CO_2e in Building X	Capacity factor
27 m	180	495,200	50	30	28%	31%
54 m	1,000	2,516,200	252	154	144%	29%

Table I.33 Energy output from 27 m and 54 m diameter wind turbines in windy rural location (7 m/s)

I4.6 The cost of wind turbines

There is a lot of conflicting information about the cost of wind power, making cost estimation difficult at the feasibility stage. A selection of cost sources includes the following:

- The breakdown of cost for the Ashenden House wind trials was:
  - Purchase cost of turbines: £19,000 for 6 kW HAWT and £32,000 for 6 KW VAWT.
  - Installation costs for both = £20,000.
  - This gives £39,000 for HAWT (£6,500/kW) and £52,000 for VAWT (£8,700/kW). *Note: multiple turbine installations will be cheaper.*
- The Energy Savings Trust website in February 2013 gave indicative costs for domestic systems as:
  - £2,000 for a roof-mounted 1 kW micro wind system (£2,000/kW).
  - £15,000 for a 2.5 kW pole-mounted system (£6,000/kW).
  - £22,500 for a 6 kW pole-mounted system (£3,750/kW).
- Table I.34 shows a summary of costs provided by chartered surveyors Fisher German.[25]

Turbine size (kW)	15	50	100	275
Total price from	£57,000	£150,000	£325,000	£400,000
£ per kWe	£3,800	£3,000	£3,250	£1,455

Table I.34 Indicative capital costs of HAWT in UK in 2012 (source: Fisher German)

For Building X, the costs assumed are £5,000/kW for HAWT (24 kW total) and £7,000/kW for VAWT (48 kW total) installed on the building (including roof fixings, inverters, electrics, etc.). The same turbines mounted on poles in rural locations (capacity factor > 15%) will have cheaper capital costs and generate more electricity. The built-in turbines on the Strata tower added an estimated £1.5 million to the project cost. If the cost of two turbines on Building X is assumed to cost one third of this amount (£500,000), this gives £13,000 per KW.

Table I.35 shows the capital costs and cost/benefit assumed for the three wind turbine options on Building X in Table 7.12 in Chapter 7. The results would be similar for Hotel Y. The benefits of government incentives, such as feed-in tariffs, are not included.

	1	2	3
Type	Horizontal axis	Vertical axis	Building integrated
Installed capacity	24 kW	48 kW	38 kW
Cost per installed kW	£5,000	£7,000	£13,000
Capital cost	**£120,000**	**£336,000**	**£500,000**
Annual electricity produced	16,820	33,640	16,640
Cost of electricity *	10p/kWh		
Annual cost saving	£1,680	£3,360	£1,660
Simple payback	**71 years**	**100 years**	**300 years**

* The wind also blows in off-peak periods when the cost of electricity is less than the peak tariff. The analysis above ignores this – if included it would make the financial evaluation less favourable.

Table I.35 Cost review of wind turbine options on Building X

I5. COMBINED HEAT & POWER

I5.1 Heating demand in buildings and the impact on CHP viability

Most building-based CHP systems generate more heat than electricity, typically in a ratio of 1.5:1. Chapter 7 stated that the effective use of CHP in buildings requires this heat to be used efficiently. Figure I.17 shows typical seasonal heat profiles in an office (Building X) and a hotel (Hotel Y). It is clear that a hotel is more suited to CHP than an office as it can utilise more heat all year round – it has a higher base heat load.

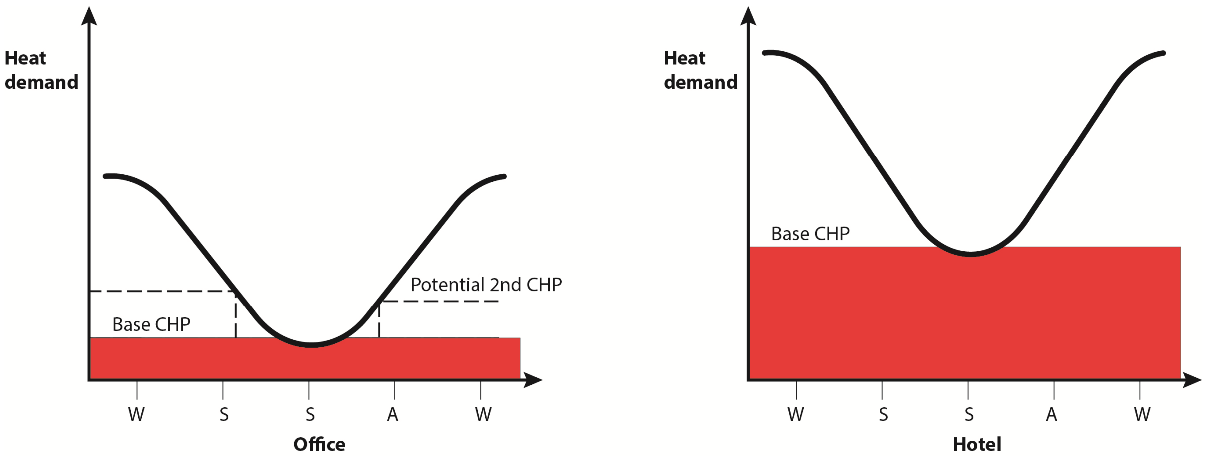


Fig I.17 Typical annual heat demand profiles (kW) showing peak and base heat loads
(the area under the lines is the annual energy consumption (kWh)

The optimum design of a CHP system requires detailed analysis, as it can be sized to deliver more than the base load and to turn off (or down) when not required to avoid wasting heat or exporting electricity. As a starting point, work out the size of the system required to meet the base load and then assess whether it is cost-effective to provide a system larger than this.

In Chapter 7, three rules of thumb were proposed to test the viability of CHP at the concept design stage:

- Annual hours of CHP operation > 4,500 (they require heat regularly).
- Heat to electricity consumption ratio > 2 (they use more heat than electricity).
- Winter to summer heat consumption ratio < 5 (they use heat in summer).

Table I.36 provides indicative values for each of these in different building types.[26] The building types which meet all three criteria (shown in bold) are not surprisingly those where CHP is most commonly used in the UK. The typical winter to summer ratio can be crudely estimated by dividing the peak heat demand by the base load.

	Heat to electricity consumption ratio	Typical hours of occupancy	Typical winter to summer heat consumption ratio
Supermarket	0.3	6,550	10
Building X (air con office)	0.5	2,550	10
General office	1.3	2,550	12
University campus	**3.0**	**6,000+**	**4**
Hotel	**3.1**	**8,760**	**4**
Leisure centre	3.5	5,830	7
School	3.8	1,800	10
Swimming pool	**4.6**	**5,830**	**2**
Hospital	**4.7**	**8,760**	**4**
Workshop	5.1	2,550	10

Table I.36 Typical heating ratios and occupancy hours for different building types

I5.2 Daily variations in heat demand affect CHP efficiency

So far only seasonal variations in heating demand have been considered – more in winter, less in summer. However, demand for heat also varies hourly. For example, in hotels there will be a big spike in demand for domestic hot water in the morning as guests take showers and the kitchen provides breakfast. Figure I.18 shows a typical heat profile for a hotel during a spring day. A CHP running at constant load may produce excess heat at some times of the day (which may be rejected), and not enough heat at other times. Thermal storage tanks should therefore be used to improve the utilisation of heat by storing surplus heat and then releasing it during peak periods of the day.

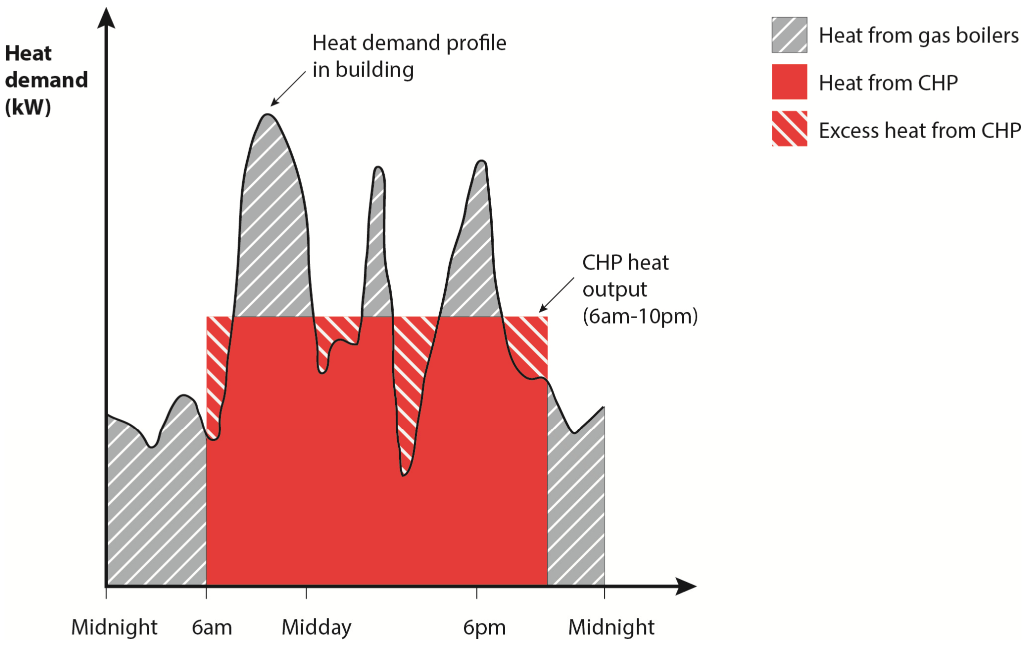


Fig I.18 Typical daily heat profile for a UK hotel in May showing heat supplied from CHP and gas boilers

Accurately determining how the heat is utilised requires specialist software, including hourly analysis of the building energy profiles and CHP outputs during the year (8,760 hours). In this book, simple annual and seasonal analyses of CHP systems are used to provide some quick 'rule of thumb' estimates of the potential benefits and viability of CHP in a building. To make some allowance for the potential hourly heat losses during the day, a Heat Utilisation Factor (HUF) has been created by the author. For small CHP systems, providing a base heat load, the HUF is assumed to be 95% (i.e. only 5% of heat is rejected due to hourly variations in heat demand). For larger systems, providing in excess of the base heat load, a HUF of 90% is assumed.

I5.3 Maximum possible CO_2e savings due to CHP in buildings

A simple annual energy calculation is used to illustrate the maximum potential CO_2e reduction in different buildings due to the use of CHP in the UK.[27] This takes an average heat demand over the year and ignores seasonal variations in heat demand. It consequently represents a *best case possible* scenario.

Figure I.17 shows the maximum possible CO_2e savings from a CHP plant (outputs: 30% electricity, 45% heat) for different heat to electricity demand ratios in a building. The two bold lines represent CHP systems supplying 25% and 50% of the annual heat consumption in the building with zero heat rejection. This idealised situation could be achieved by:

- Exporting excess heat to a district heating system if available.
- Assuming that the CHP can modulate outputs up and down to match any variation in hourly heat demand without any loss in efficiency.
- Installing an enormous thermal storage tank to store all excess heat generated in summer and reuse it in winter.

CHP runs most efficiently at full and constant capacity. Modulating the output usually reduces efficiency, reduces the life of the plant, and increases maintenance. It is like driving a car in town compared to cruising long distances on the open road – fuel consumption goes up and there's more wear and tear. The option for seasonal thermal storage is hypothetical only as the storage tank would probably end up being as large as the building.

The dotted line in Figure I.19 shows 50% of the annual heat consumption supplied by CHP, but assumes that around 30% of the heat generated by the CHP during the year will be rejected due to hourly and seasonal fluctuations in heat demand in the building.

Figure I.19 clearly shows that the potential of gas CHP to reduce the operating carbon of a building increases as the heat to electricity consumption ratio of a building increases. It also suggests that CO_2e reductions in the UK are unlikely to exceed 25%, although in countries with high carbon grid electricity, such as Australia, gas CHP can have a bigger impact.

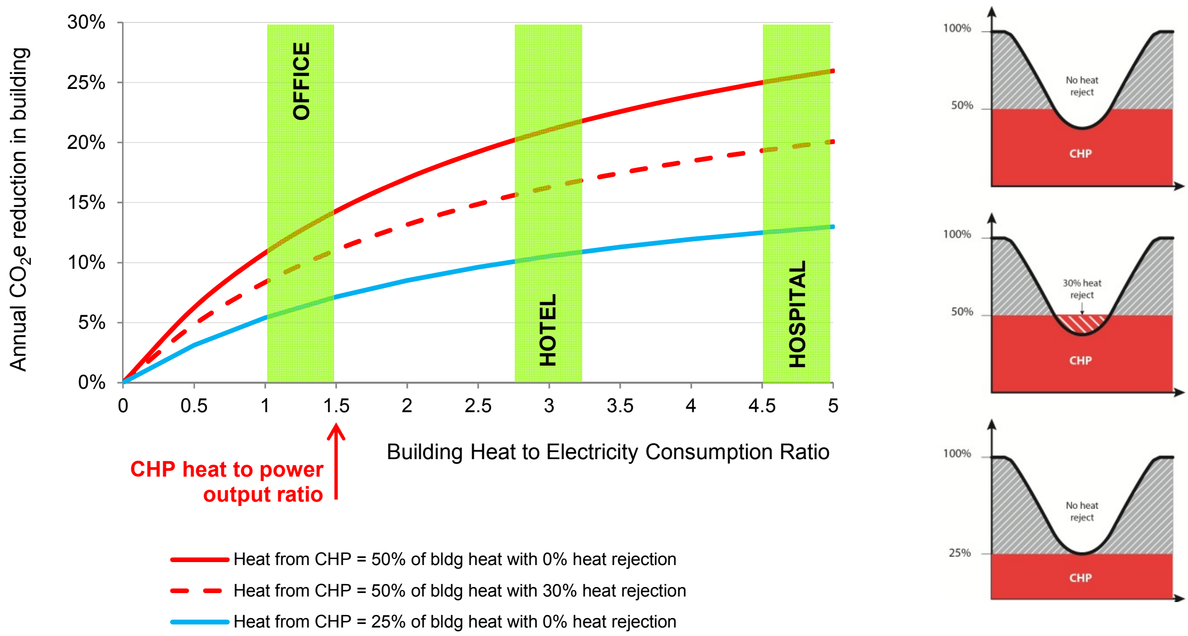


Fig I.19 Maximum possible CO_2e savings in the UK from typical gas CHP in buildings with different heat to power consumption ratios

I5.4 Energy tariffs are important for CHP viability

The seasonal and daily heat profiles are critical for CHP energy efficiency, but CHP also produces, and buildings consume, electricity. The national electricity grid acts like a giant rechargeable battery for the electricity generated by CHP, absorbing the surplus and then giving it back when the building needs more than the CHP can provide. This doesn't really impact on the net CO_2e calculations because the electricity doesn't go to waste. However, exporting electricity has a major impact on the financial viability of CHP due to the difference between the price utility companies will pay for the electricity when you don't need it (export tariff), and what they will charge when you do (import tariff).

One of the main incentives for installing gas CHP is to reduce the energy costs for large energy users. The financial viability depends largely on the price difference between grid electricity and natural gas, known as the 'spark gap.' Figure I.20 shows the same scenarios as Figure I.19, but considers the best possible energy cost savings instead of carbon savings. The biggest energy cost savings are realised in buildings which use more heat and can utilise all of the electricity. Rejecting heat and exporting electricity rapidly reduces the cost savings.

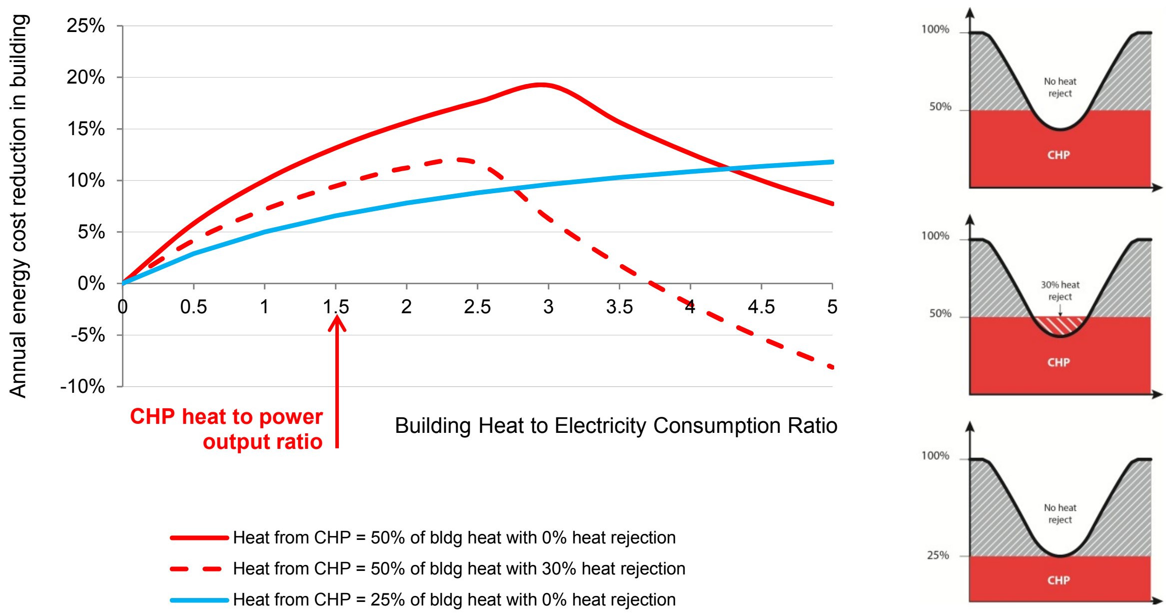


Fig I.20 Maximum possible energy cost savings from typical gas CHP in buildings with different heat to power consumption ratios

Electricity is usually cheaper to buy during off-peak hours (evenings and weekends) and is typically at least one third less than the cost of peak time electricity. Running CHP plant during off-peak hours will often cost more than buying electricity and gas (for boilers) from the grid. Figure I.20 does not allow for the reduction in cost savings resulting from this.

If excess electricity is generated and exported to the grid then the CHP owner is paid a much lower rate for this than the cost of buying it back when it is needed. Figure I.20 assumes that the CHP owner receives 3p/kWh revenue for surplus electricity exported to the grid compared to a peak import tariff of 10p/kWh. The chart does not take into account any hourly fluctuations in electricity demand because this is usually smoother (not as 'peaky') as the heat demand profile.

The financial viability of CHP requires hourly modelling of imported and exported electricity, a clear understanding of the tariffs, and comparison to the capital costs. The national energy market is quite complex and the tariffs may vary significantly over the life of the CHP plant. A detailed tariff risk analysis is essential to test the financial sensitivity of a CHP system.

SOME QUESTIONS TO ASK THE UTILITY COMPANIES

Check with the electricity company that the local network can support the connection and export of electricity. The aging infrastructure is not always up to the job. Check if you are on a long-term supply energy contract and which tariffs you can get for importing and exporting energy. This can make or break the financial viability of CHP.

Gas CHP uses more gas than a gas boiler. Check that the gas pipework supplying the building can meet the increased demand. A higher pressure is often required – a compressor can provide this, but comes with additional capital and running costs.

I5.5 Gas CHP in Building X and Hotel Y

Table I.37 shows the plant efficiencies that are used in the gas CHP calculations for Building X and Hotel Y. The fuel tariffs from Table 7.2 in Chapter 7 are 10p/kWh for electricity and 3.5p/kWh for natural gas. Any surplus annual electricity exported to the grid will receive a revenue of 3p per kWh.

The CHP in Building X is on for 2,500 hours per year (10 hours/day, 5 days/week) and for 5,000 hours per year (16 hours/day, 7 days/week) in Hotel Y. A Heat Utilisation Factor (HUF) of between 90 and 95% is assumed (i.e. between 5 and 10% of annual heat is rejected).

	Electrical output	Heat output	Losses	Heat to power ratio
CHP	30%	45%	25%	1.5

	Performance
Gas boiler	Efficiency = 90%
Electric chiller	CoP = 5
Absorption chiller	CoP = 0.7
Heat rejection unit	0.15 kWe for every 1 kW of heat rejected

Table I.37 CHP assumptions for Building X and Hotel Y

Table I.38 shows the assumed capital costs of the CHP systems. These are based on an installed capital cost of a gas CHP engine of around £1,200 per kWe. For trigeneration, an additional £100,000 is added for the absorption chiller and associated connections and controls.

	Building X	Hotel Y
CHP – 10 kWe	£12,000	-
CHP – 100 kWe	£120,000	£120,000
CHP – 250 kWe	-	£300,000
Trigeneration (250 kWe)	£400,000	£400,000

Table I.38 Assumed capital costs for gas CHP in Building X and Hotel Y

Tables I.39 and I.40 show the results of the simplified seasonal analysis of gas CHP in Building X and Hotel Y.[28] The results are summarised in Table 7.16 in Chapter 7.

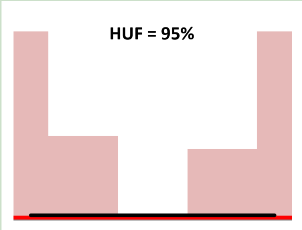
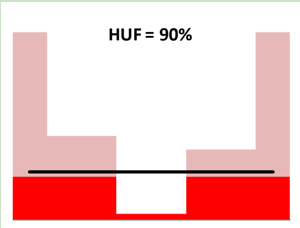
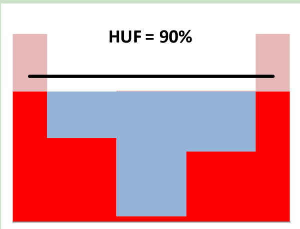
Heat profile	CHP size (kWe)	Building heat supplied by CHP	Building electricity supplied by CHP	Use of heat from CHP	CO_2e saving ($kgCO_2e/m^2$)	Energy cost saving ($£/m^2$)	Indicative payback (years)
Gas CHP							
	10	5%	2%	95% - heating 0% - cooling 5% - rejected	0.6 *(0.6%)*	£0.09 *(0.5%)*	13
	100	39%	16%	70% - heating 0% - cooling 30% - rejected	3.2 *(3%)*	£0.44 *(3%)*	27
Gas Trigeneration							
	250	77%	44%	56% - heating 34% - cooling 10% - rejected	9.3 *(9%)*	£1.3 *(7%)*	31

Table I.39 Maximum potential CO_2e and cost savings due to gas CHP in Building X

KEY FOR HEAT PROFILES IN TABLES I.39 , I.40, I.42 AND I.43

- Heat from gas boilers
- CHP heat for cooling
- CHP heat for heating
- Heat output from CHP

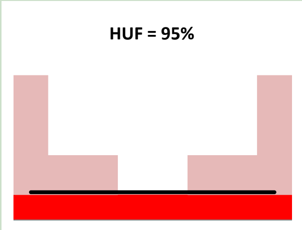
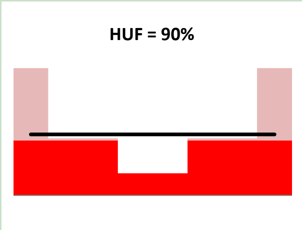
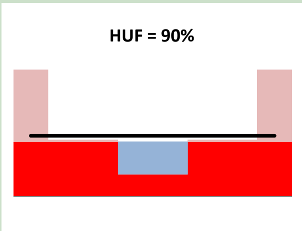
Heat profile	CHP size (kWe)	Building heat supplied by CHP	Building electricity supplied by CHP	Use of heat from CHP	CO_2e saving ($kgCO_2e/m^2$)	Energy cost saving (£/m^2)	Indicative payback (years)
Gas CHP							
	100	35%	49%	94% - heating 0% - cooling 6% - rejected	11.9 *(11%)*	£1.8 *(10%)*	7
	250	71%	118%	77% - heating 0% - cooling 23% - rejected	19.6 *(19%)*	£1.55 *(9%)*	19
Gas Trigeneration							
	250	71%	126%	77% - heating 13% - cooling 10% - rejected	24 *(23%)*	£1.77 *(10%)*	23

Table I.40 Maximum potential CO_2e and cost savings due to gas CHP in Hotel Y

I5.6 Biofuel CHP in Building X and Hotel Y

The analysis of biofuel CHP is based on the same CHP systems as used in the gas CHP analysis with biofuel (biodiesel) replacing natural gas as the input fuel. The biofuel has a CO_2e emission factor of 0.12 $kgCO_2e$/kWh and a fuel cost of 7p/kWh. This emission factor is quite low and other data sources suggest that it could be higher than this.[29]

Table I.41 shows the assumed capital costs, assuming that the installed cost of biofuel CHP is £2,400 per kWe (including fuel tanks and other equipment).

	Building X	Hotel Y
CHP – 10 kWe	£24,000	-
CHP – 100 kWe	£240,000	£240,000
CHP – 250 kWe	-	£600,000
Trigeneration (250 kWe)	£700,000	£700,000

Table I.41 Assumed capital costs for biofuel CHP in Building X and Hotel Y

Tables I.42 and I.43 show the results of the simplified seasonal analysis of biofuel CHP in Building X and Hotel Y. The results are summarised in Table 7.18 from Chapter 7.

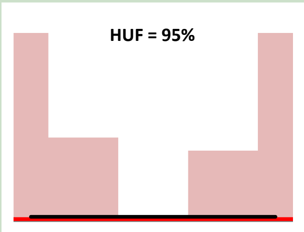
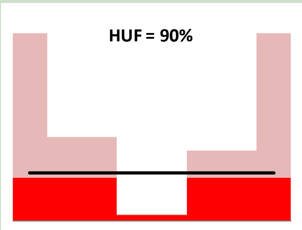
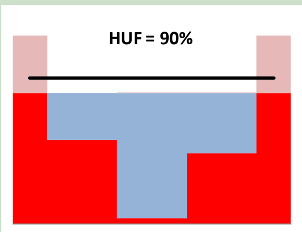
Heat profile	CHP size (kWe)	Building heat supplied by CHP	Building electricity supplied by CHP	Use of heat from CHP	CO_2e saving ($kgCO_2e/m^2$)	Energy cost saving (£/m^2)	Indicative payback (years)
Biofuel CHP							
	10	5%	2%	95% - heating 0% - cooling 5% - rejected	1.3 *(1%)*	-£0.2 *(-1%)*	no payback
	100	39%	16%	70% - heating 0% - cooling 30% - rejected	9.9 *(9%)*	-£2.5 *(-14%)*	no payback
Biofuel Trigeneration							
	250	77%	44%	56% - heating 34% - cooling 10% - rejected	26.0 *(25%)*	-£6.0 *(-34%)*	no payback

Table I.42 Maximum potential CO_2e savings (and cost increases) due to biofuel CHP in Building X

Appendix C contains some data for the 770 kWe biofuel trigeneration system in 7 More London, a 60,000m^2 commercial office building. The first year of operation saved around 9 $kgCO_2e/m^2$ of GIA using recycled cooking oil (with an assumed emission factor of 0.06 $kgCO_2e/kWh$). Assuming that the CHP operation is optimised in future years, the savings could potentially be doubled. In this scenario, the emissions savings could be around 18 $kgCO_2e/m^2$, or 10 $kgCO_2e/m^2$ if standard biodiesel is used (0.12 $kgCO_2e/kWh$) in lieu of recycled cooking oil. The 26 $kgCO_2e/m^2$ saving in Building X's operating emissions due to biofuel trigeneration (refer to Table I.42) is clearly very optimistic.

The 250 kWe system in Building X is equivalent to 25 W/m^2, which is twice that of 7 More London (13 W/m^2). If a 125 kWe system were to be installed (similar in proportion to 7 More London), then the calculated savings in Building X would be 13.9 $kgCO_2e/m^2$. This is still higher than the potential 10 $kgCO_2e/m^2$ reduction in 7 More London using standard biodiesel. The calculation methodology used in this appendix is therefore overley optimistic, and the savings shown in Table I.42 are unlikely to be achieved in practice.

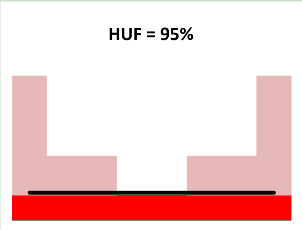
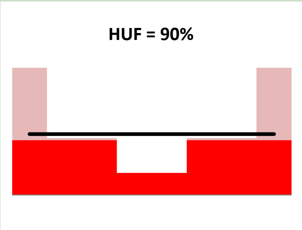
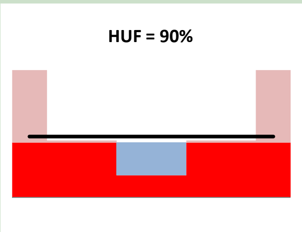
Heat profile	CHP size (kWe)	Building heat supplied by CHP	Building electricity supplied by CHP	Use of heat from CHP	CO_2e saving ($kgCO_2e/m^2$)	Energy cost saving (£/m^2)	Indicative payback (years)
Biofuel CHP							
	100	35%	49%	94% - heating 0% - cooling 6% - rejected	25.2 *(24%)*	-£4.0 *(-22%)*	no payback
	250	71%	118%	77% - heating 0% - cooling 23% - rejected	52.9 *(50%)*	-£13.0 *(-73%)*	no payback
Biofuel Trigeneration							
	250	71%	126%	77% - heating 13% - cooling 10% - rejected	57.3 *(55%)*	-£12.8 *(-72%)*	no payback

Table I.43 Maximum potential CO_2e savings (and cost increases) due to biofuel CHP in Hotel Y

The CO_2e emission reductions shown in Tables I.40 to I.43 should be treated as the maximum possible savings. They ignore practical issues which would influence the design and operation of the systems, such as the requirement for large thermal storage tanks, avoiding the export of electricity to the grid and the significant increases in operating cost (energy and maintenance).

I5.7 Biofuel storage requirements

If weekly deliveries of biofuel to the building are assumed to take place then the volume of the storage tank required can be estimated. The example below is for the base load 100 kWe CHP in Hotel Y.

• Peak operating hours per week	= 16 hours x 7 days	= 112 hours
• Electrical output per week	= 100 kWe x 112	= 11,200 kWh
• *Electrical efficiency of CHP*		*= 30%*
• Fuel input per week	= 11,200 / 30%	= 37,330 kWh
• *Calorific value of biofuel*	*= 33 MJ/litre*	*= 9.2 kWh /litre*
• Litres of fuel per week		= 4,073

Using this methodology, the weekly fuel deliveries for the various biofuel CHP options are shown in Table I.44. An articulated fuel tanker has a capacity of around 36,000 litres. The size of storage tank in the building will depend on the space available and the preferred frequency of fuel deliveries.

	Litres of fuel per week	
	Building X	Hotel Y
CHP – 10 kWe	182	
CHP – 100 kWe	1,818	4,073
CHP – 250 kWe		10,182
Trigeneration (250 kWe)	5,455	10,182

Table I.44 Weekly fuel deliveries for biofuel CHP in Building X and Hotel Y

I5.8 Are biofuels sustainable?

Biofuels can be made from a range of agricultural crops including oilseeds, wheat and sugar, and from wastes like recycled cooking oil and tallow. The two most common biofuels are bioethanol, which is blended with petrol, and biodiesel, which can be blended with diesel.

Biodiesel is produced from vegetable oil that is then reacted with methanol to form a compound chemically very similar to mineral diesel. An alternative is Pure Plant Oil (PPO), which is vegetable oil (or recycled cooking oil) that has not been chemically changed.

The biofuels most commonly used are first generation biofuels. Concern over the use of these fuels has been raised, such as the displacement of food-crops, effects on the environment (e.g. deforestation of native rainforest in Indonesia to create palm oil plantations) and higher CO_2e emissions of some compared to fossil fuels.

Significant research is now underway into the commercial production of second and third generation biofuels[30] which will have lower emissions and be sourced from more sustainable sources. If this can be achieved on a commercial scale then biofuels will become an increasingly important energy source – but, as discussed in Chapter 7, they are more effectively used in vehicles, not buildings.

I5.9 Supplying Building X and Hotel Y with biofuel

To estimate the land area required in the UK to supply first generation biofuel for a CHP system delivering a 10 $kgCO_2e/m^2$ saving per annum, two potential sources of biofuel are considered – refer to Table I.45.

	Annual energy yield per hectare	Emissions factor[31] ($kgCO_2e/kWh$)
Ethanol (from sugar beet)	33	0.18
Pure plant oil (from rapeseed oil)	11.3	0.16

Table I.45 Energy yield for two potential sources of biofuel grown in the UK

Both of the emission factors in Table I.45 are higher than the average factor assumed in Table 7.2 of Chapter 7 for a typical biofuel (0.12 $kgCO_2e/kWh$). The fuel input required to deliver a 10 $kgCO_2e/m^2$ saving in Building X and Hotel Y was estimated using the seasonal CHP calculation methodology discussed earlier. The estimated area of land required to grow the energy crop in the UK to supply the fuel is shown in Table I.46.

	Building X	Hotel Y
Type of system	Trigeneration	CHP
Hours of operation	2,500	5,000
Heat utilisation factor adopted	95%	95%
Ethanol – sugar beet		
Size of CHP to deliver 10 $kgCO_2e/m^2$ reduction	150 kWe	65 kWe
Biofuel input per annum	1,260 MWh	1,080 MWh
Yield from sugar beet (MWh/hectare)	33	
Area of plantation required (hectares)	38 Ha	32 Ha
Pure plant oil – rapeseed		
Size of CHP to deliver 10 $kgCO_2e/m^2$ reduction	120 kWe	50 kWe
Biofuel input per annum	1,000 MWh	880 MWh
Yield from rapeseed oil (MWh/hectare)	11.3	
Area of plantation required (hectares)	88 Ha	78 Ha

Table I.46 Area of biofuel plantation to provide 10 $kgCO_2e/m^2$ reduction in Building X and Hotel Y using biofuel CHP

This shows that first generation biofuels grown in the UK for use in buildings don't really stack up. The results from Table I.17 (biomass) and Table I.46 (biofuel) suggest that it is better to grow short rotation coppice (SRC) willow as an energy crop for biomass boilers than rapeseed oil or sugar beet for biofuel CHP in the UK, for three reasons:

- The energy yield per hectare of SRC willow is better (46 MWh/hectare).
- The emission factors for biofuels are much higher than biomass and are often worse than fossil fuels.
- CHP (75% efficiency) is not as effective as a biomass boiler (85% efficiency) in turning the fuel into useful energy in buildings. It gets worse if the CHP is oversized and has to reject heat or convert it into chilled water.

I6. NET PRESENT COST OF CO_2 REDUCTION

I6.1 What is net present value?

Net present value (NPV) compares the value of a pound today with the value of that same pound in the future, taking inflation, returns and risks into account. A discount rate is used to convert future costs and benefits to 'present values' so that they can be compared. For example, instead of being paid £1 today, how much would you want if this payment was to be made in 12 months' time? If you said £1.10 to allow for inflation, the loss of returns you could have made if you had had the £1 to invest for a year, and the risk of not actually receiving the £1 owed to you in the future, then the discount rate would be [1 - £1/£1.10] = 9%.

A lower discount rate (i.e. future returns have a higher net present value) makes investment in renewable energy systems more attractive, and so selecting a suitable discount rate is a key, but also highly subjective, issue. The UK Government's *Green Book: Appraisal and Evaluation in Central Government* issued in July 2011 states the following: 'The recommended discount rate is 3.5%' and 'The NPV is the primary criterion for deciding whether government action can be justified.'

The discount rate for investment in renewable energy is usually higher than 3.5% to take both technological and market risks into account. A study by Oxera in April 2011 suggested discount rates of between 6% and 14%; however, these were for large-scale energy generation.[32] Proven small-scale building technologies such as PV and solar thermal were not covered. In this book a discount rate of 5% has been adopted.

Applying this rate, the net present value of £1 over time is shown in Table I.47.

Year	Value of £1 with 5% discount rate	Year	Value of £1 with 5% discount rate
0	£1.00	5	£0.78
1	£0.95	10	£0.61
2	£0.91	15	£0.48
3	£0.86	20	£0.38
4	£0.82	25	£0.30

Table I.47 Present values based on 5% discount rate

Life cycle costs and net present values should be treated as tools to help make informed decisions about how effective different design options are. They do not give absolute or definitive answers because no one can accurately predict the future and the cost of money isn't linear over time. Sensitivity analysis should be undertaken to test the effect of different assumptions (e.g. discount rate, energy savings, energy costs, maintenance costs, life of plant, etc.).

Ultimately, investment decisions in buildings are made by humans and not by computers. We do not always act rationally, so even if the life cycle cost model is as robust as possible, we may choose to ignore it, particularly if money is tight today, the banks aren't lending and there are other bills to pay tomorrow.

I6.2 Net present cost of CO_2e

In Chapter 7, the net present value (or cost) of renewables was calculated based on the total capital and annual energy costs/savings (ignoring any maintenance costs), a discount rate of 5% and a fuel cost increase above inflation of 3% per annum. Table I.48 shows an example NPV calculation for a PV system on Building X.

The yearly cash flow (column C) is based on the capital cost in Year 0 and then annual energy costs from Year 1 onwards (savings are expressed as negative values). Maintenance or replacement costs could also be added to this column (allowing for a new inverter in Year 10, for example). All of the costs are expressed in today's prices (Year 0).

The cash flow is then adjusted to reflect expected annual increases in energy costs above inflation, in this example 3% per annum (column D). The undiscounted cumulative cash flow (column E) indicates that simple payback will occur in year 16 (compared to 19 years if energy costs are not adjusted for inflation). However, the value of money over time hasn't yet been considered.

The Discounted Cash Flow (column F) is calculated by multiplying the cash flow (column D) by the present value of £1 for each year (column B). The discounted cumulative cash flow (column G) can then be calculated, showing the value of the payments and revenue over time. This suggests that the payback (i.e. when the cumulative cash flow equals zero) doesn't occur until year 25, based on the assumed discount rate and energy cost inflation.

The cost of carbon (£ per tCO_2e) for each system is based on the net present cost of the system over 15 years divided by the total CO_2e emissions saved over the same period.

$$\text{Cost of carbon (£/tCO}_2\text{e: 15yr @ 5\%)} = \frac{\text{Net present cost over 15 years @ 5\% discount rate}}{\text{tCO}_2\text{e saved per year x 15 years}}$$

In Table I.48 the net present cost of the PV system after 15 years can be read directly from the discounted cash flow column (column G), in this case £49,387. The amount of carbon saved over the same period is 15 x 45.4 = 681 tCO_2e. The cost of carbon for the PV system is therefore:

$$\text{Cost of carbon (£/tCO}_2\text{e: 15yr @ 5\%)} = \frac{\text{£49,387}}{\text{681 tCO}_2\text{e}} = \text{£73 per tCO}_2\text{e}$$

Capital cost		£144,170			**NPV**	**NPV/tCO_2e**
Annual energy cost		-£7,565		10 year	£77,997	£172
Simple payback		19		15 year	£49,387	£73
$kgCO_2e/m^2$ saved		4.5		20 year	£23,401	£26
tCO_2e saved		45.4				
A	B	C	D	E	F	G
Year	PV	Cash flow	Inflated cash flow	Cumulative cash flow	Discounted cash flow	Cumulative discount cash flow
0	£1.00	£144,170	£144,170	£144,170	£144,170	£144,170
1	£0.95	-£7,565	-£7,565	£136,605	-£7,204	£136,965
2	£0.91	-£7,565	-£7,792	£128,813	-£7,067	£129,898
3	£0.86	-£7,565	-£8,025	£120,788	-£6,933	£122,965
4	£0.82	-£7,565	-£8,266	£112,522	-£6,801	£116,165
5	£0.78	-£7,565	-£8,514	£104,008	-£6,671	£109,494
6	£0.75	-£7,565	-£8,770	£95,238	-£6,544	£102,950
7	£0.71	-£7,565	-£9,033	£86,205	-£6,419	£96,530
8	£0.68	-£7,565	-£9,304	£76,902	-£6,297	£90,233
9	£0.64	-£7,565	-£9,583	£67,319	-£6,177	£84,056
10	£0.61	-£7,565	-£9,870	£57,449	-£6,059	£77,997
11	£0.58	-£7,565	-£10,166	£47,282	-£5,944	£72,053
12	£0.56	-£7,565	-£10,471	£36,811	-£5,831	£66,222
13	£0.53	-£7,565	-£10,785	£26,025	-£5,720	£60,502
14	£0.51	-£7,565	-£11,109	£14,916	-£5,611	£54,891
15	£0.48	-£7,565	-£11,442	£3,474	-£5,504	£49,387
16	£0.46	-£7,565	-£11,786	-£8,312	-£5,399	£43,988
17	£0.44	-£7,565	-£12,139	-£20,451	-£5,296	£38,692
18	£0.42	-£7,565	-£12,503	-£32,954	-£5,195	£33,496
19	£0.40	-£7,565	-£12,878	-£45,832	-£5,096	£28,400
20	£0.38	-£7,565	-£13,265	-£59,097	-£4,999	£23,401
21	£0.36	-£7,565	-£13,663	-£72,760	-£4,904	£18,496
22	£0.34	-£7,565	-£14,073	-£86,833	-£4,811	£13,686
23	£0.33	-£7,565	-£14,495	-£101,327	-£4,719	£8,967
24	£0.31	-£7,565	-£14,930	-£116,257	-£4,629	£4,337
25	£0.30	-£7,565	-£15,378	-£131,635	-£4,541	-£204

Table I.48 Net present cost calculation for PV on Building X

I6.3 NPV calculations for Building X and Hotel Y

Table 7.20 and Figure 7.22 in Chapter 7 were based on the data shown in Tables I.49 and I.50. These collate all of the systems analysis in Chapter 7 and this appendix, and the net present value calculations described above.

	Heat	Electricity	Carbon footprint saving $kgCO_2e/m^2$	% of CO_2e	Additional capital cost	Additional yearly fuel cost (-ve is saving)	Pay-back	15 Year Net Present Value	**Net Present Cost per tCO_2e saved (15 years)**
Solar Thermal	■		0.6	1%	£32,000	-£1,050	30	£18,800	**£209**
Biomass Boiler	■		8.9	9%	£245,000	£7,761	none	£342,200	**£256**
GHSP	■		4.1	4%	£360,000	-£7,921	45	£260,800	**£429**
Photovoltaics		■	4.5	4%	£144,170	-£7,565	19	£49,400	**£73**
Wind Turbine		■	1.0	1%	£120,000	-£1,682	71	£98,900	**£654**
Gas CHP	■	■	0.6	1%	£12,000	-£900	13	£720	**£8**
Gas Trigen	■	■	9.3	9%	£400,000	-£13,000	31	£237,100	**£170**
Biofuel CHP	■	■	1.3	1%	£24,000	£2,000	none	£49,100	**£252**
Biofuel Trigen	■	■	26.0	25%	£700,000	£60,000	none	£1,451,800	**£372**
Max Savings	■	■	31.5	30%	£964,170	£50,753	none	£1,600,100	**£338**
No Fuel to site	■	■	14.8	14%	£664,170	-£22,247	30	£385,400	**£173**

Table I.49 Building X – CO_2e savings and net present costs for different renewable systems

	Heat	Electricity	Carbon footprint saving $kgCO_2e/m^2$	% of CO_2e	Additional capital cost	Additional yearly fuel cost (-ve is saving)	Pay-back	15 Year Net Present Value	**Net Present Cost per tCO_2e saved (15 years)**
Solar Thermal	■		1.9	2%	£100,000	-£3,253	31	£59,200	**£212**
Biomass Boiler	■		29.6	28%	£350,000	£25,776	none	£673,000	**£151**
GHSP	■		7.5	7%	£360,000	-£15,000	24	£172,100	**£153**
Photovoltaics		■	4.5	4%	£144,170	-£7,565	19	£49,400	**£73**
Wind Turbine		■	1.0	1%	£120,000	-£1,682	71	£98,900	**£654**
Gas CHP	■	■	11.9	11%	£120,000	-£18,000	7	-£105,500	**-£59**
Gas Trigen	■	■	24.0	23%	£400,000	-£17,700	23	£178,200	**£50**
Biofuel CHP	■	■	25.2	24%	£240,000	£40,000	none	£741,200	**£196**
Biofuel Trigen	■	■	57.3	55%	£700,000	£128,000	none	£2,303,800	**£268**
Max Savings	■	■	62.8	60%	£964,170	£118,753	none	£2,452,100	**£260**
No Fuel to site	■	■	29.5	28%	£664,170	-£26,947	25	£326,500	**£74**

Table I.50 Hotel Y – CO_2e savings and net present costs for different renewable systems

To put the values into perspective, the cost of carbon under the UK CRC-EES scheme in 2012 was £12/tCO_2. The UK Government's cost of carbon used to appraise carbon policies (refer to Table I.51) depends on whether the carbon is covered by the European Union's Emissions Trading Scheme (traded) or is not (not-traded).[33]

	Traded cost per tCO_2	Non-traded cost per tCO_2
2013	£16	£57
2020	£29	£64
2030	£74	£74
2040	£143	£143
2050	£212	£212

Table I.51 Average cost of carbon used by UK Government for carbon policy appraisal

If the life span of building renewables is typically 15 to 20 years then any investment costing over £100/tCO_2 is not considered value for money. Many building-based renewables do not present a very convincing argument for investment in carbon abatement.

OTHER ISSUES TO CONSIDER WHEN ASSESSING RENEWABLE SYSTEMS

There are numerous other issues that need to be considered in deciding the feasibility of systems, including the following:

- Is there space available to install the size of system required?
- Will obtaining planning permission be simple or complex?
- Are there any restrictions on air quality from biomass boilers?
- What is the expected life of the system?
- Is reliable specialist maintenance support available when things go wrong?
- Where will the spare parts come from, how long will delivery take and how much do they cost?

16.4 Cost of Carbon for different evaluation periods

Figures I.21 and I.22 show the discounted cash flows for the renewable energy systems in Building X and Hotel Y divided by the tCO_2e saved per annum for different evaluation periods. The calculations ignore any maintenance costs, replacement costs, feed-in tariffs, time of use tariffs and tax benefits (such as enhanced capital depreciation), which all significantly influence investment in renewable systems.

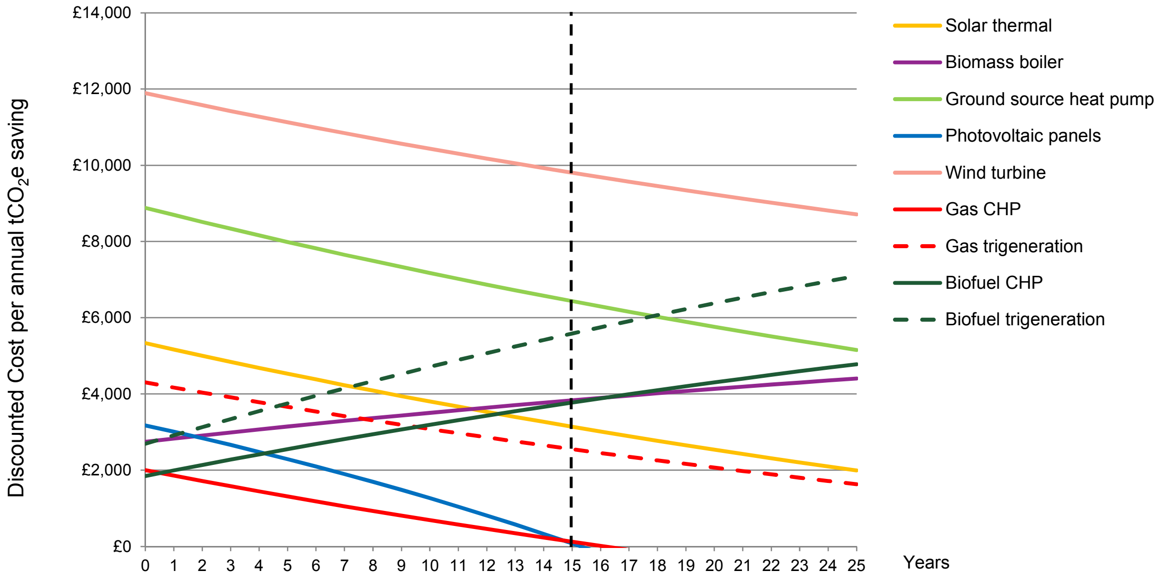


Fig I.21 **Discounted costs to save 1 tCO_2e per annum for renewable systems in Building X for different evaluation periods (5% discount rate)**

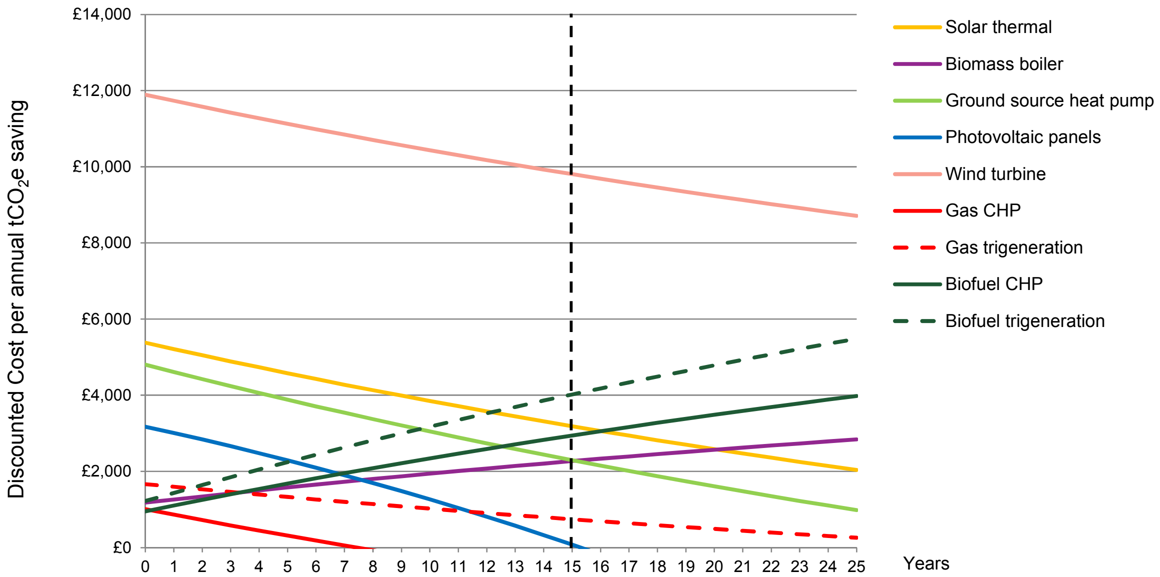


Fig I.22 **Discounted costs to save 1 tCO_2e per annum for renewable systems in Hotel Y for different evaluation periods (5% discount rate)**

Some systems cost more to install on day one, but then realise savings over time. These will provide a payback when the line crosses the zero axis. The systems which have an upward curve never have a payback – but over the short term may appear to offer better value for money in saving carbon. This is why the simple payback is often an unreliable method of assessing financial viability.

I7. CARBON NEUTRAL USING OFF-SITE RENEWABLES

It is not possible to achieve a zero carbon building using on-site renewables unless the building is super energy efficient (most aren't) *and* is low storey with plenty of roof space and/or surrounding land to install renewable energy systems.

Achieving a zero carbon building will therefore require some off-site renewable energy generation. In order to make Building X zero carbon, sufficient electricity has to be generated off site to offset the building's total CO_2e emissions due to electricity and gas consumption. If a wind turbine, located in a commercial wind farm, was funded by the building owner then the capital cost required is estimated as follows:

- Building X annual emissions are 105 $kgCO_2e/m^2$ x 10,000 m^2 = 1,050,000 $kgCO_2e$
- Emissions factor of grid electricity = 0.60 $kgCO_2e/kWh$
- Electricity required from wind turbine to offset = 1,050,000 / 0.60 = 1,750 MWh / year
- Capacity factor for wind farm = 30%
- Turbine size required = 1,750 / (8,760 x 30%) = 670 kWe
- Assumed cost of wind farm turbine = £1,500 per kW
- Capital cost = 670 x £1,500 = £1 million (or £100/m^2 of GIA)

This is similar to the capital cost of £964,100 to install the maximum on-site renewables in Building X, which only achieve a 30% reduction in CO_2e, and also result in increased building energy costs of £50,750 per year (refer to Table I.49).

In order to calculate the cost of carbon from investment in a commercial wind farm, it is assumed that the building owner receives a revenue of 5p/kWh for the wind-generated electricity (some is generated in off-peak periods and there will be a charge to use the electricity grid to get the energy to the building). The CO_2e offset by the wind turbine is allocated to the building.

Energy cost saving to building = 5p/kWh x 1,750 MWh = £87,500 per year

This provides a simple payback of 11 years. The 15 year net present cost is -£96,300 and the cost of carbon (£/$kgCO_2e$:15yr) is -£6, compared to +£338 for the maximum on-site renewable systems. From a financial perspective, large-scale off-site renewables are an obvious choice as they have superior performance (e.g. wind turbines where it's windy) and economies of scale.

Investment could also be made in other large-scale off-site renewable energy systems. Wind farms have been used here to illustrate the principle of investing off-site.

I8. OTHER RENEWABLES

The following renewable systems have not been covered in the book as they are not typically used in office buildings.

I8.1 Micro-hydro

It is rare for office buildings to have micro-hydro potential as they need to be close to a river or stream with sufficient head (height difference from extraction point to outlet) and a reliable flow. It is generally better to have more head than flow, as this requires smaller equipment. Installing micro-hydro will require approval from the relevant planning authority and environmental agencies.

For feasibility stage assessments, the output can be estimated as:

Annual Energy Generated (kWh) = 7.5 x Q x H x CF x 8,760 hours

Q is the volume flow rate passing through the turbine (m^3/s)
H is the net head of water across the turbine (m)
CF = capacity factor varies significantly from site to site, but as a guide:

40% for high head sites (where H > 50 m and rated flow is 1 to 1.3 times the mean average flow)
60% for low head sites (where H < 10 m and rated flow is lower than the mean average flow)

The exact sizing of a turbine depends on the flow profile (or flow duration curve) for the watercourse and the permissible abstraction levels. Low head systems are often only permitted (for environmental reasons) to use a limited proportion of the flow and therefore that flow is available for longer, hence the higher capacity factor.

The permitted abstractions for high head systems vary by country (the rules are different in England, Wales and Scotland). However, the percentage abstraction is generally higher and therefore the 'rated flow' is available less often, resulting in the turbine running more often at partial load and consequently a lower capacity factor.

The British Hydropower Association's *A Guide To UK Mini-Hydro Developments* published in January 2005 provides more information on the design and sizing of micro-hydro systems. Information on systems and indicative costs can also be found at www.glenhydro.co.uk.

I8.2 Wastewater heat recovery

Municipal wastewater typically has a temperature of 12 to 20°C, and in winter rarely drops below 10°C. This makes wastewater a potential energy source for ground source heat pumps. There are a number of proprietary systems available which use a heat exchanger to extract heat from the wastewater via one of two methods, and transfer it to the heat pump (refer to Figure 1.23):

- Install flat plate heat exchangers directly in the bottom of a sewer pipe with a minimum diameter of 1m.
- Divert a portion of the wastewater (via an intake structure to screen out solids) into a heat exchanger module.

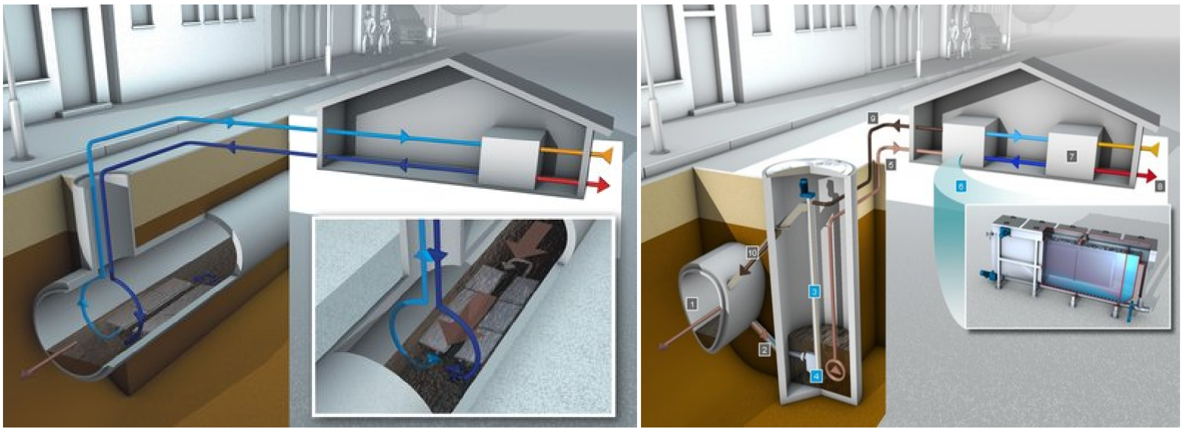


Fig I.23 Example heat recovery systems from wastewater (source: Huber SE)

A smaller scale system is a shower heat recovery system. This extracts heat from the hot shower water (either in a purpose-built shower tray or in vertical heat exchanger pipes) to preheat the cold water supply to the thermostatic mixing tap for the shower and/or the hot water tank.

I8.3 Electro-kinetic road ramps

An Electro-Kinetic Power Ramp operates by converting the gravitational energy of a vehicle into kinetic and then electrical energy. As the vehicle drives over the ramp, forcing it downwards, a series of cogs rotates. This rotation drives a generator which produces electricity. The spring-loaded ramp rises once the car moves off, generating further power.

5 to 10 kW of electricity is typically generated with every vehicle movement. A study by Cundall in 2009 found that in order to pay back the initial outlay, a vehicle movement in excess of 5,000 per day would be necessary. This would need to be located on busy roads where traffic calming is required (such as at airports, etc.).

I8.4 Footfall generators

Certain materials generate an electric field when deformed; this is known as piezoelectricity. If these materials are incorporated into walkways or dance floors, pressure from the footsteps of pedestrian movements (or vigorous dancing) can be converted into electricity. The typical output is between 5 and 10 Watt-seconds (Ws) per footfall. A trial at the London Olympics in 2012 indicated that 8.5 Ws per step was generated.

Building X has 665 occupants. If everyone stands on one pad four times a day for 240 working days a year then this is 638,400 steps. Assuming 8.5 Ws per step, this would generate 1.5 kWh per annum – enough to power one 20 W lamp for 75 hours a year. To have any benefit at all the pads must be located where thousands of people will walk on them every day. Even then, the payback could be measured in hundreds of years. A nice gimmick and a bit of fun, but not a viable solution for reducing energy consumption in buildings.

Note: piezoelectric light switches are quite handy. Pressing the switch generates enough electricity to send a radio signal to a lighting control unit, avoiding the need to have wiring to the switch in DALI control systems.

FURTHER GUIDANCE ON RENEWABLES

General

- www.nrel.gov/analysis/models_tools.html - National Renewable Energy Laboratory in the US has produced lots of tools and reports on all types of renewable energy systems including solar.
- www.cleanenergycouncil.org.au/cec/resourcecentre/plantregistermap.html - maps of renewable energy systems in Australia.

Solar

- http://solarelectricityhandbook.com/solar-irradiance.html has a simple tool giving monthly solar irradiance in different cities at different orientations and tilts.
- http://re.jrc.ec.europa.eu/pvgis/countries/countries-europe.htm has maps and data on European countries, including photovoltaic output calculators.

Biomass

- *Application Manual on Biomass Heating*, CIBSE.
- www.biomassenergycentre.org.uk
- *Biomass heating: A practical guide for potential users*, Carbon Trust guide.

Heat pumps

- *Heat Pumps: A guidance document for designers* by Reginald Brown, BSRIA BG7/2009.
- *Down to earth: Lessons learned from putting ground source heat pumps into action in low carbon buildings*, Carbon Trust, March 2011.
- *Domestic Ground Source Heat Pumps: Design and installation of closed-loop systems*, Energy Efficiency Best Practice in Housing, Energy Saving Trust, March 2004.
- BS EN 15450:2007 - *Heating systems in buildings: Design of heat pump heating systems*
- *HVAC Systems & Equipment*, ASHRAE Handbook 2012.
- *Ground source heat pumps,* TM51:2013, CIBSE.

Notes

All websites were accessed on 6 May 2013 unless noted otherwise. Information papers referenced are available to download from www.wholecarbonfootprint.com.

1. http://re.jrc.ec.europa.eu/pvgis/download/download.htm

2. Data from CIBSE Guide A - Table 2.27 - Monthly Mean Daily Irradiation on Inclined Planes.

3. Winter solstice angle from www.timeanddate.com/worldclock/astronomy.html?n=136&month=12&year=2008&obj=sun&afl=-11&day=1.

4. *Partially Shaded Operation of a Grid-Tied PV System*, C. Deline, National Renewable Energy Laboratory, (preprint) 34th IEEE Photovoltaic Specialists Conference, Philadelphia, Pennsylvania, June 7–12, 2009. Refer also to www.builditsolar.com/Projects/PV/EnphasePV/Shading.htm for a visual example showing <10% shade reducing output of a panel by 75%.

5. The specific heat capacity of water is 4.19 kJ/kg per °C and the heat of evaporation is 2,260 kJ/kg. The energy required to evaporate 1kg of water starting at 20°C is therefore:

   Energy (kJ/kg) = 4.19 x (100 – 20) + 2,260
   = 335 + 2,260 = 2,595

   The UK Forestry Commission uses 2,443 kJ/kg (0.679 kWh/kg) to calculate the energy lost to evaporate water in timber.

6. Information on typical softwood and hardwood moisture contents from an email sent to the author on 06/01/2011 by Dr Geoff Hogan of the Biomass Energy Centre: 'For conifers the typical moisture content is about 60 - 65% (wet basis), though Larch and Douglas Fir are closer to 50%. Broadleaves seem to have more variability with Ash possibly as low as 33%, Oak, Beech, Birch and Sycamore around 41 - 47%, and Elm and Poplar might be as high as 58 - 60%. For (unspecified) softwoods, to convert from green tonnes to oven dry tonnes multiply by 0.4 while for (unspecified) hardwoods multiply by 0.55.'

7. Refer to Information Paper 4 – CO_2e emissions from biomass and biofuels for further details.

8. Refer to Information Paper 5 – Emission factor for black carbon for further details.

9. Refer to Information Paper 25 – Biomass and biofuel sources and yields for further details.

10. According to Cool Earth, protecting one acre of rainforest saves 260 tonnes of CO_2. There are 2.47 acres in a hectare, so one hectare saves 642 tCO_2. The cost to protect 1 acre of rainforest in April 2013 via the Cool Earth program was £60 to £100. www.coolearth.org.

11. For heat pumps to be considered a form of renewable energy, the European Union set minimum coefficients of performance (COP) for air to water heat pumps of between 2.6 (40/45°C) and 3.1 (30/35°C) when outdoor temperatures are 2°C DB. Refer to Commission Decision of 9 November 2007: *establishing the ecological criteria for the award of the Community eco-label to electrically driven, gas driven or gas absorption heat pumps* (2007/742/EC).

12. *Microgeneration Certification Scheme: MCS 007, Product Certification Scheme Requirements: Heat Pumps Issue 2.1* (dated 26/10/2011). For compliance with this scheme, heat pumps must be optimised for heating and must achieve minimum Coefficient of Performance (CoP) when tested in accordance with EN 14511-3:2007.

13. Taken from www.cibsejournal.com/cpd/2010-10.

14. Calculated using the formula: Capacity (kW) = specific heat capacity of water (4.2) x temperature difference (°C) x flow rate (l/s).

15. *Operation, Installation & Maintenance Instructions, Installation of Ground Array (Slinky®), Horizontal Ground Coupling for Heat Pumps* – published by Baxi Heating UK Ltd 2006.

16. Table 6.1, *Ground Source Heat Pumps*, TM51:2013, CIBSE.

17. The cost of GSHP boreholes in Table I.26 (£600,000) is equivalent to £750/kW of heat pump output. Figure 6.1 in *Ground Source Heat Pumps*, TM51:2013, CIBSE, shows an installed cost range per kW of heat output for a variety of loop types. Examples are vertical (£500 to £1,300/kW), horizontal (£500 to £950/kW), open (£350 to £650/kW) and energy piles (£450 to £900/kW).

18. CIBSE Journal CPD programme, April 2013.
    In 2012 a ground source VRF system in the Oxford Earth Sciences building at Oxford University measured a performance of 3.6 for heating and 4.7 for cooling (source: Modern Building Services Journal, Vol. 9, No. 12, April 2013).

19. Refer to Information Paper 26 – Wind speed data for further details.

20. Data taken from the old NOABL wind speed database for grid reference TQ3278 on 9 February 2013. This is no longer maintained and shouldn't be used for assessing urban wind speeds http://tools.decc.gov.uk/en/windspeed/default.aspx.
    The Energy Saving Trust Wind Speed Prediction Tool is more conservative. The results for postcode SE1 6TU on 9 February 2013 were Urban = 2.6 m/s, Suburban = 2.9 m/s and Rural = 4.5 m/s. www.energysavingtrust.org.uk/Generating-energy/Choosing-a-renewable-technology/Wind-turbines/Wind-Speed-Prediction-Tool.

21. The Beaufort Wind Force Scale is an empirical measure for describing wind speed based mainly on observed sea conditions. http://www.metoffice.gov.uk/weather/marine/guide/beaufortscale.html

22. Refer to Information Paper 27 – Wind turbine performance for further details. For similar stories from the US refer to www.buildinggreen.com/auth/article.cfm/2009/4/29/The-Folly-of-Building-Integrated-Wind (accessed 12 March 2010)

23. Details of the data used in Table I.31 can be found in Information Paper 27 – Wind turbine performance.

24. The Weibull shape parameter is discussed further in Information Paper 27 – Wind turbine performance.

25. Costs taken from *Making Money From Single Wind Turbines* presentation by Mark Newton of chartered surveyors Fisher German at the Renewable UK International Small & Medium Wind Conference 2012. www.dartdorset.org/pdf/newton.pdf

26. Heat to electricity ratios based on energy benchmarks from CIBSE *Energy Benchmarks* TM46:2008. Typical hours of operation and winter to summer energy consumption ratios estimated by the author.

27. Refer to Information Paper 29 – CHP calculations for further details.

28. Refer to Information Paper 29 – CHP calculations for details of the calculation methodology used.

29. In *Carbon and Sustainability Reporting Within the Renewable Transport Fuel Obligation: Technical Guidance Part Two - Carbon Reporting – Default Values and Fuel Chains* version 2.1, published in July 2010 by the UK Renewable Fuel Agency, the values for UK-produced biodiesel can range from 0.16 to 0.22 depending on the feedstock. Refer to Information Paper 4 – CO_2e emissions from biomass and biofuels for further details.

30. Refer to Information Paper 25 – Biomass and biofuel sources for further discussion on this.

31. Refer to note 27.

32. *Discount rates for low-carbon and renewable generation technologies*, prepared for the Committee on Climate Change by Oxera Consulting Ltd, April 2011.

33. Refer to Information Paper 35 – The rising cost of energy and carbon for further details.