ELREN
European Leader+ Renewable Energy Network

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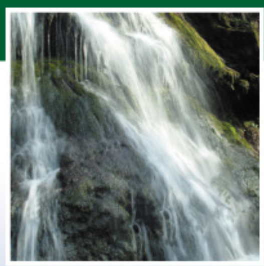

Chapter 6
Solar Thermal

TIPPERARY INSTITUTE

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6 Solar Thermal

Eugene Kelly, Tipperary Institute

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6.1 Objectives

Having completed this section of the training course and manual, learners should:

- Be familiar with the solar energy resource for Europe
- Understand how insulation is quantified
- Be able to calculate a u-value for a given combination of material layers
- Understand the Passive House concept
- Be familiar with the different types of solar thermal collectors
- Be aware of the scale of solar thermal across the EU

6.2 Introduction to solar energy

It is obvious that solar energy refers to energy whose source is the Sun. What is not so obvious is the ways in which this energy manifests. With the exceptions of nuclear energy, the lunar component of tidal energy and true geothermal energy (heat energy originating in the Earth's core) the sun is responsible for all other forms of energy. It is responsible for solar heating and solar electricity and is also directly and indirectly responsible for geothermal applications. In addition it is indirectly responsible for wind, hydro, biomass, ocean current (expected to become an important resource in a decade or so) and even fossil fuel energy sources. The purpose of this chapter is to focus on direct solar thermal applications.

6.3 *Solar energy availability in Europe*

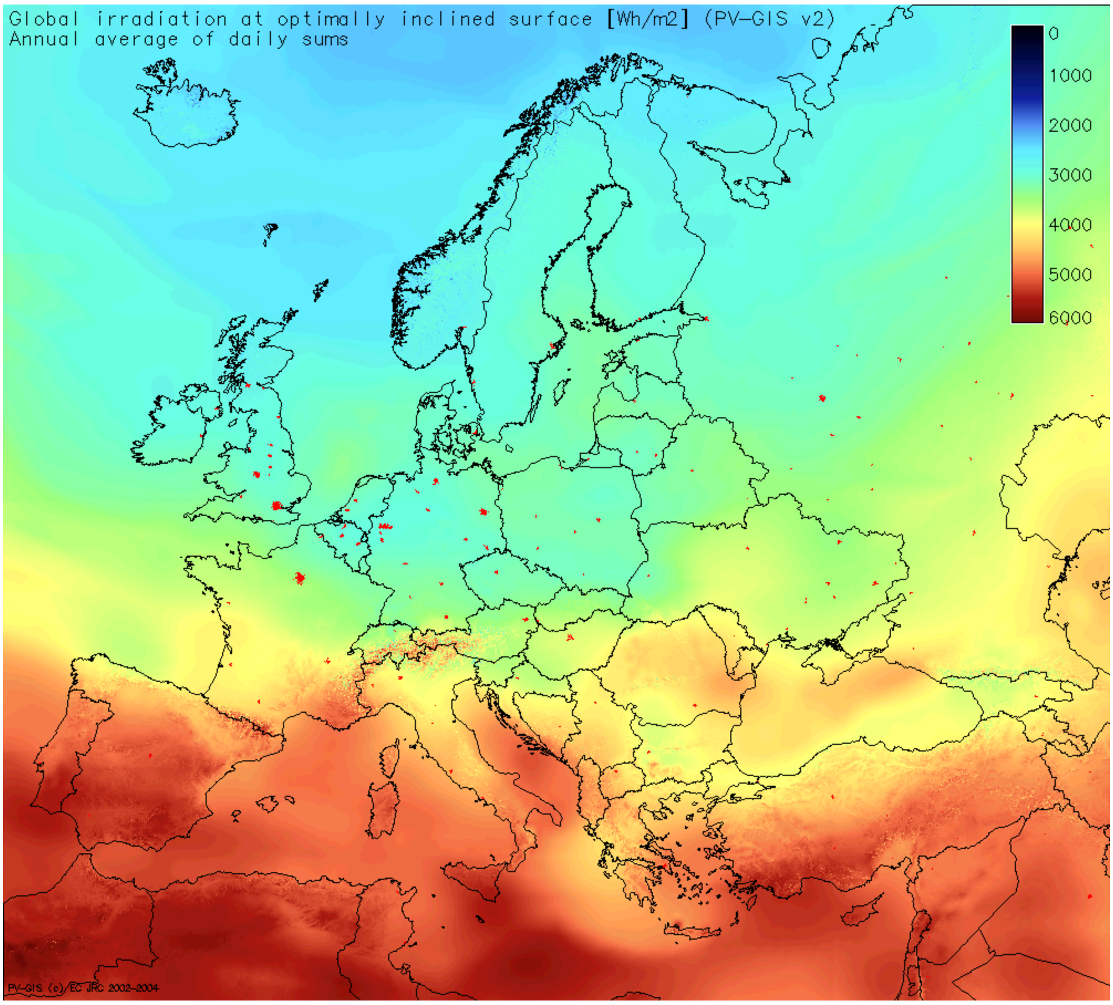
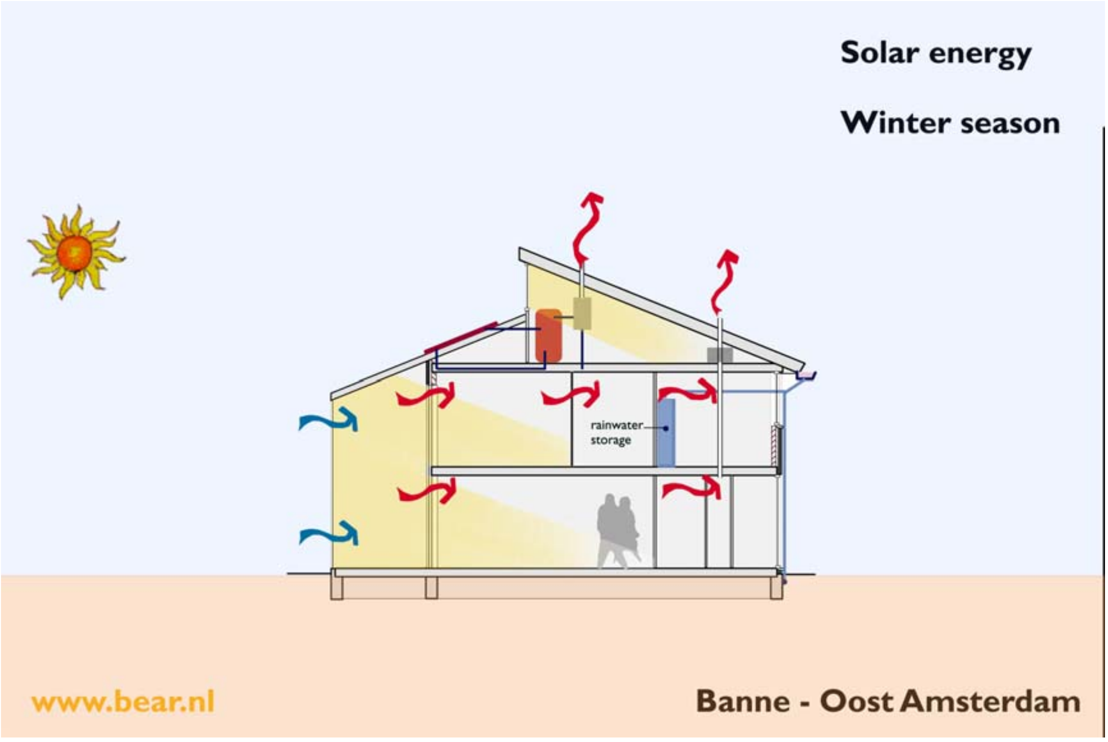


Figure 6.1 Annual solar energy available for optimally inclined panel in Wh/m^2
(European Commission Joint Research Centre, 2006)

6.4 Passive Solar Houses



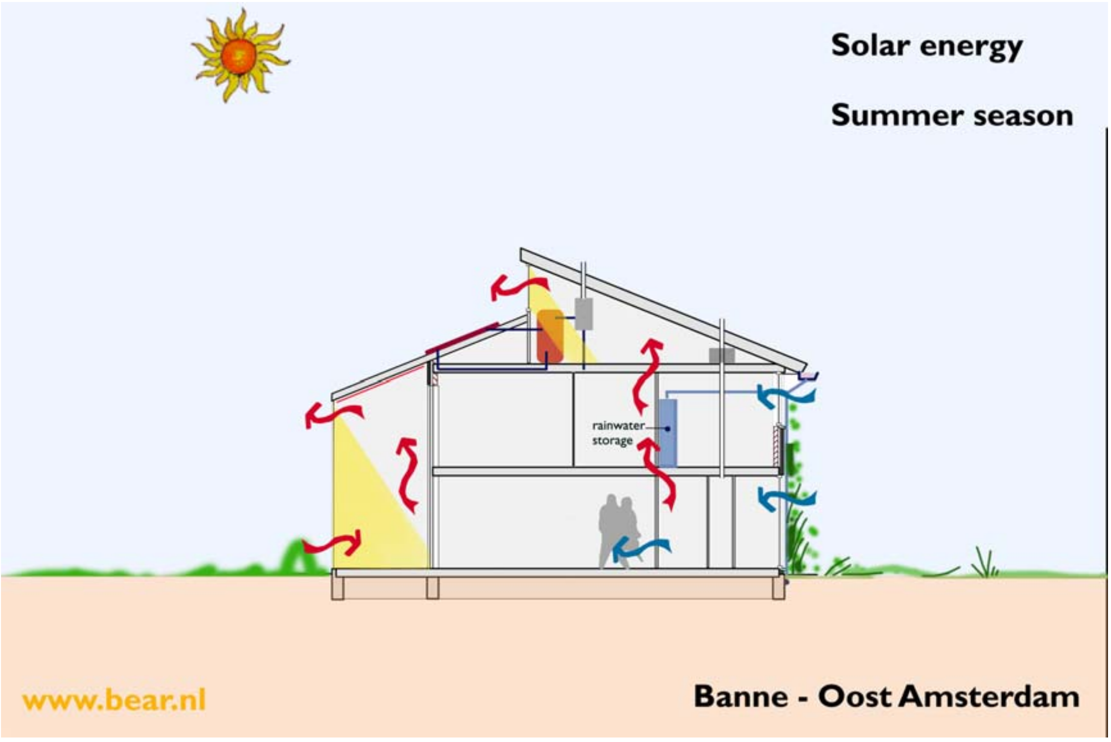


Figure 6.2 Passive solar schematics
(BEAR Architecten – © Tjerk Reijenga, 2006)

For the purpose of this topic we will focus on the application to house design but, with suitable adjustments, the same principles can be applied to a wide variety of building types.

The basic idea here is that by designing houses in a certain way and building to a particular standard the interior of a house can be a net beneficiary of solar energy. In particular, by following good solar energy design guidelines and building to a high thermal standard then the house may be referred to as a Passive Solar House or just a Passive House. There is no absolute definition of what the term Passive House means but in general the term refers to houses that get a significant proportion of their space heating requirements directly from the sun. The PassivHaus Institute in Darmstadt, Germany is promoting a quantitative definition that has been gaining acceptance. The main conditions that a house must satisfy to meet the PassivHaus Institute's criteria to be called a Passive House are:

- Annual heating demand less than or equal to **15kWh/m^{2}a**
- Total energy demand less than or equal to **42kWh/m^{2}a**
- Maximum heating load less than or equal to **10W/m^2**
- Ventilation late less than or equal to **0.6 ac/h** (air changes per hour) (when pressure tested at 50 Pascal above or below the ambient atmospheric pressure)

The term 'heating demand' refers to the total amount of heat energy that the heating system must supply into the house over the period. Likewise the 'total energy demand' refers to all the energy that must be supplied to the house (including heat) to do such things as power electrical appliances, provide lighting and to power fans and pumps. The term 'maximum heating load' refers to the rate at which power must be supplied at any one time to meet the heating requirements of the house and is important in sizing the supplementary heating system. To put things in perspective the heating footprint of older European houses would be of the order of 180 kWh/m^{2}a and low energy houses would need about 40 to 75 kWh/m^{2}a.

It is important to note that these Passive Houses are not Zero Energy houses. They do require the input of some heat. They are mostly passive however as the amount of heat required to top up the passive component is only about 10% of what a conventional house would need. The reason for not making them Zero Energy houses is because the economics of this approach is not so attractive. It should also be noted that what is stated above about heating also applies to cooling. This approach can be followed anywhere in Europe but the designs have to be adjusted to the local climate.

6.4.1 U-values

Since there are certain target parameters set for a Passive House expressed in terms of u-values this section explains the underlying concepts. High levels of insulation are required to make a house a passive house. This is true of all European climatic regimes since insulation aids heating in cold weather and cooling in hot weather. The amount of insulation in any particular context is measured by its u-value. This is the rate at which heat energy passes through one square meter of the material when there is a one degree centigrade temperature difference across it. It is therefore measured in $W/m^{2o}C$. Thus smaller is better as far as u-values are concerned.

To compare the insulative properties of different materials it is necessary to standardise on a unit thickness of the material, in order that we can compare like with like. The insulative property scaled in this way to apply to a thickness of one meter is referred to as the lambda value and is denoted by the Greek letter λ. Its units are $W/m^{o}C$. This is sometimes referred to as the thermal transmittance or conductance of the material. Thus to get the u-value for a particular thickness of a material we use:

u = λ value of material /thickness of material (expressed in meters).

6.4.2 R-values

It should be noted that sometimes the R-value is quoted instead where R=1/u. (This is standard practice in the US but it is further complicated in this case by the fact that they are not using metric units. To convert a US R-value to a metric R-value multiply the US one by a factor of 0.1761. Thus a US R-value of 40 corresponds to a metric one of 7 which in turn is equivalent to a u-value of 0.14).

Material	λ value W/m^{o}C	Material	λ value W/m^{o}C
Limestone	1.53	Cork	0.043
Concrete	1.44	Fibreglass	0.04
Brick	1.15-1.47	Hemp/flax/sheepwool	0.037-0.039
Plasterboard	0.18	Cellulose	0.035-0.036
OSB/Plywood	0.13	Expanded polystyrene	0.033
Wood	0.14-0.16	Extruded polystyrene	0.027
Strawbales (dry)	0.09	Phenolic	0.03
Woodwool slab	0.082	Polyurethane/polyiso	0.023

Table 6.1 Representative λ values for common building and insulation materials (exact values depend on production & installation factors)

6.4.3 Sample calculations

Calculate the u-value achieved by using 140mm sheepwool.

From Table 6.1 get a λ value for sheepwool of 0.038 W/m^{o}C.
The thickness of 140mm is just 0.14m.

u =
(λ value sheepwool) / (thickness in m) =
0.038/0.14 W/m^{2o}C =
0.27 W/m^{2o}C

Example 6.1 Sample u-value calculation for a single element

While individual materials have their own characteristic u-value we usually have to deal with combinations of materials such as in the wall or roof of a house. This combination of materials will have a particular insulative property and a particular thickness.

The u-value for a combination of layers of different materials is calculated by summing the R-values of each layer to get the total R-value and then inverting this to get the overall u-value.

Calculate the u-value for a 12mm layer of plasterboard followed by 140mm of sheepwool insulation followed by a 12mm layer of plywood.

Terms used in calculation

R_1= $1/u_1$=R-value of plasterboard

R_2= $1/u_2$=R-value of sheepwool

R_3=$1/u_3$=R-value of plywood

Calculation (using values from Table 6.1)

$u_1=0.18/0.012=15$ W/m^{2o}C

$u_2=0.27$ W/m^{2o}C (from previous calculation)

$u_3=0.13/0.012=10.8$ W/m^{2o}C

$R_1=1/15=.07$ m^{2o}C/W

$R_2=1/0.27=3.7$ m^{2o}C/W

$R_3=1/10.8=.09$ m^{2o}C/W

$R=R_1+R_2+R_3$

$= (0.07+3.7+0.09)$ m^{2o}C/W

$= 3.86$ m^{2o}C/W

$u = 1/R$

$= 1/3.86$ W/m^{2o}C

$= 0.26$ W/m^{2o}C

Example 6.2 Sample u-value calculation for a combination of elements

6.4.4 Passive House Design Guidelines

The basic approach is to orient the house as close as possible to due south, avoid shading during the heating season, to insulate the entire shell to a very high degree and to seal the house as much as possible to prevent unwanted cold air infiltration during the heating season.

- **Face south** – the long side of the house should face as close to true south as possible. A 20^o deviation from south will only incur about a 5% reduction in solar gain. The house should not be shaded from the south during the heating season especially during the peak heating time which is three hours on either side of solar noon. The solar gain in a Passive House can contribute approximately 30% of the heating requirements.
- **Concentrate window placements on the south side** and minimize window area on the other sides, especially the north side. (The amount of glazing on the southern wall should be in the region of 20% of the floor area that is to be heated in the case of Ireland, Britain and North Central Europe.) Effective shading needs to be provided to avoid over-heating during the warm season.
- **Construct boundaries (exterior walls, floor and roof) with a u-values <= 0.15 W/m^{2o}C**. This high level of insulation is essential to reduce heat losses to an acceptable level. A simple and compact house form also helps by reducing the boundary area and also reduces the amount of thermal bridging (this happens when, for example, a wall that is insulated has structural elements that bypass the insulation such as the timber studs in a timber frame house).
- **Windows should have a u-value[1] <= 0.8 W/m^{2o}C and a g-value[2] >= 0.5**

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[1] The u-value for a window must be calculated for the entire assembly of glass and frame elements.

[2] The g-value (also known as the Solar Heat Gain Coefficient or SHGC is the fraction of the Sun's heat that makes it through a window. Thus a window having a g-value of 0.6 means that 60% of the incident solar heat penetrates through the window).

- **Incorporate adequate thermal mass into the interior house space** to store heat and avoid temperature extremes. (Thermal mass is something that has the ability to absorb and store a significant amount of heat and is usually some form of masonry (concrete, stone, clay or water.)
- **The building envelope should have a high degree of air tightness** measuring approximately 0.6 air changes per hour
- **Use a heat recovery forced ventilation system**. (These systems use the heat from the outgoing air to heat the incoming air).
- **Use energy efficient (A rated) appliances and low energy lighting** based on CFL (compact fluorescent) or LED (light emitting diodes) light sources.

The above steps can be augmented by the incorporation of active renewable energy features such as solar hot water heating. Also the u-value requirements can be relaxed slightly in climatic regimes that have less severe winter weather than north central Europe.

6.4.5 Financial viability

The CEPHEUS (Cost Efficient Passive Houses as European Standards) project incorporated a study of the performance of a variety of passive houses built in Germany, Austria, Switzerland, France and Sweden. Most of these 'houses' were actually accommodation units within multi-family apartment type developments (it should be noted that the term Passive House is also used in reference to non domestic units such as commercial offices). A study published in 2003 (ECEEE 2003 Summer Study, Jurgen Schnieders, pp341-351) found that, on average, the extra investment required to build to the Passive House standard was about 8%. The annual space heating costs were reduced by an average of about 84% over new building stock built to existing standards. A calculation was then made in which the extra building costs invested at 4% over 25 years was divided by the kWh saved. This yielded a value of 0.062 €/kWh (6.2 c/kWh) which allows a direct comparison to be made with the final (or delivered) energy costs. Thus if it costs more than 6.2c to buy a kWh of heat then it is economically attractive.

To put this in perspective the current (February 2007) delivered price to domestic consumers of a kWh of electricity in Ireland is over 16c. In fact, over the lifetime of the house, the increase in energy prices is expected to be very substantial with double digit percentage increases possible over the next few years. The increase in insulation standards that newer building regulations are requiring across Europe means that the cost differential in taking the Passive House route is decreased.

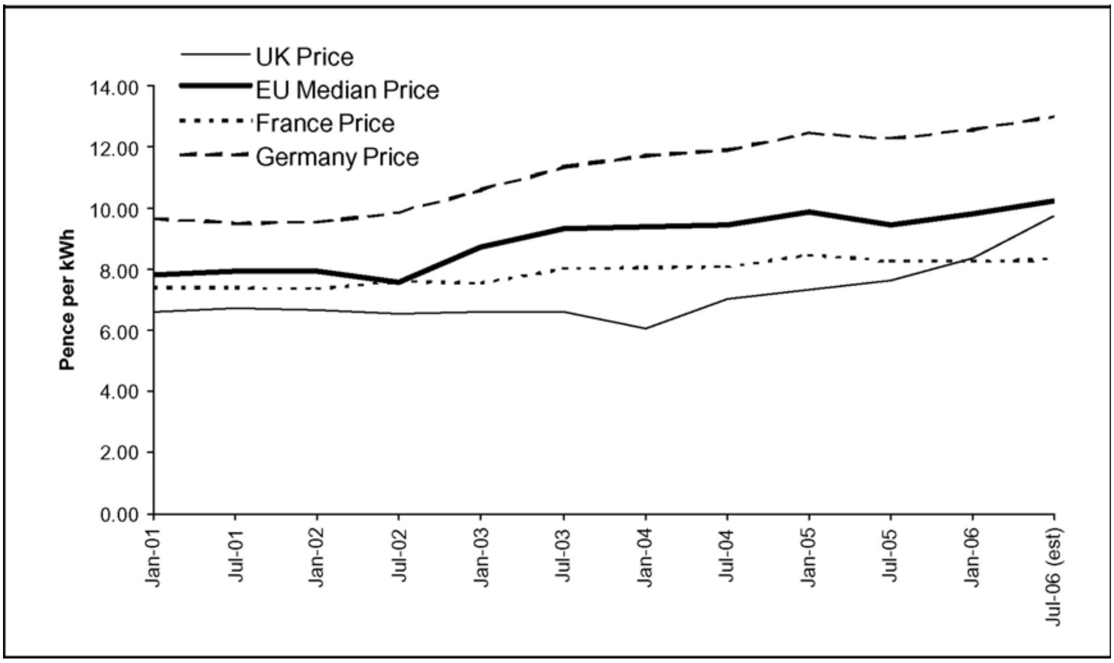

Figure 6.3 Recent price trends for domestic electricity prices in Europe
(UK DTI, 2005)

6.5 Solar Hot Water

Solar collectors are devices designed to use heat from the sun to heat water. The water in question is usually hot water for domestic purposes but it may also be used for other purposes such as heating swimming pools and commercial laundries. Unlike electricity and space heating where our consumption is higher in winter we actually use more hot water in summer than in winter so this fits in very well with the availability of solar energy.

6.5.1 Technologies

The most common form factor for solar collectors is a flat panel which may be glazed or unglazed. Glazed panels may also incorporate vacuum technology (evacuated tubes) to minimize heat losses. Usually single glazing is used but some products are available with double glazing. Unglazed panels are less efficient but cheaper and more robust and are often used when the ambient temperature is high and the target temperature is relatively low and because of this are widely used for heating swimming pools.

6.5.2 Flat panel collectors

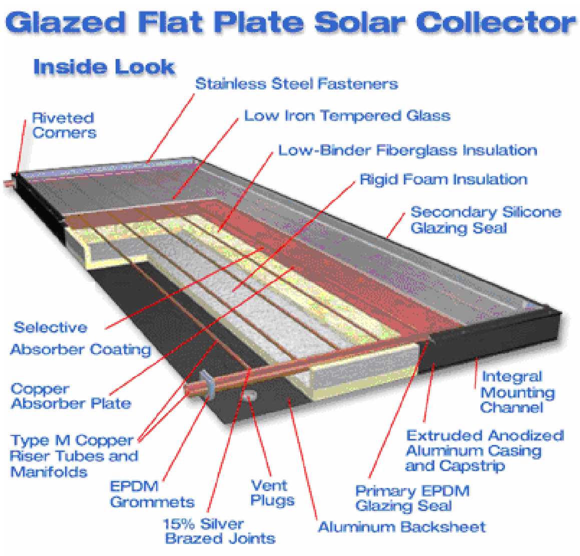

Figure 6.4 Typical flat plate collector
(SunEarth Inc, 2007)

Flat panel solar heaters usually consist of a glazed rectangular box containing a copper pipe that winds up and down the box from a single inlet point to a single outlet point. It is easy to connect them is series with the outlet of one panel being connected to the inlet of the next panel and so on. A thin metal sheet of copper or aluminium is attached to the pipe in order to maximise the area being heated by the sun. This sheeting or fin is given a special coating to maximize its absorbency and, in the case of the better coatings, to minimize its thermal radiation back to the environment.

These better coatings are referred to as selective materials and characteristically absorb more than 90% of the radiant heat that they receive and yet radiate back only a small amount of heat. The coatings used for this purpose include Black Chrome, Black Nickel, Aluminium Oxide and Titanium Oxy-Nitride or TiNOX. The latter is considered the best coating to use both from its performance metrics and because of its environmentally attractive properties.

Flat panel collectors may be installed on a roof in two ways. One way is where the panels sit into the roof and is called roof integrated. In this mode the panels are less conspicuous as they sit lower on the roof and may easily be mistaken for a roof light at first glance. In the second approach the panels sit proud of the roof covering and are therefore more conspicuous.

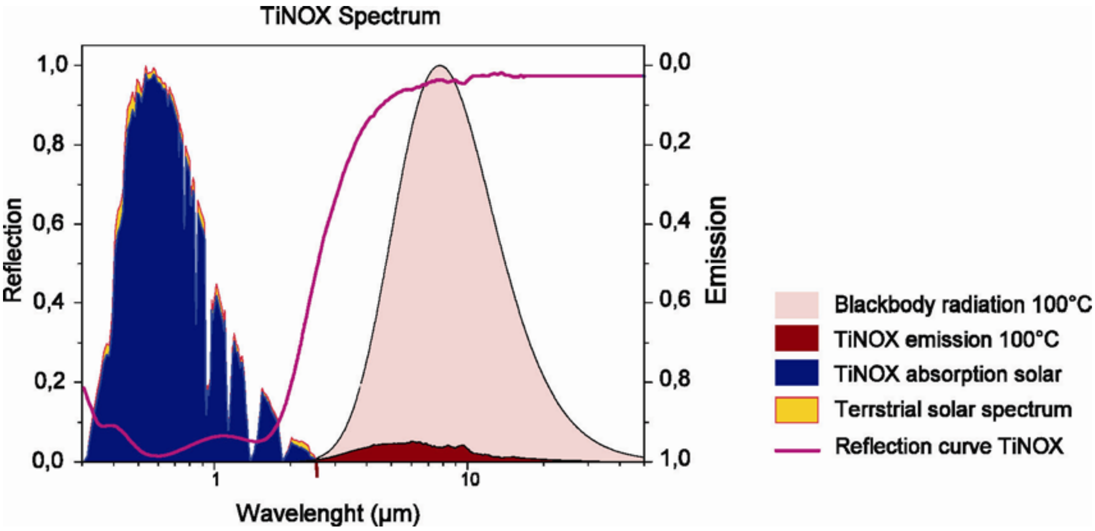

Figure 6.5 TiNOX absorber characteristics
(TiNOX, 2007)

6.5.3 Evacuated tube collectors

There are several different approaches used in this category but they all make use of glass tube with a vacuum to reduce heat losses from the panel back to the environment and these tubes are combined into an array that is connected to some type of header element usually referred to as the manifold.

(a) (b)

Figure 6.6 Evacuated Tube Collectors
(a) Typical evacuated tube collector (Navitron, 2007)
(b) Structural detail example (Apricus Solar, 2007)

6.5.4 Glass-glass evacuated tube collectors

In this approach a twin wall glass tube consisting of a tube within a tube is used with the evacuated space occurring between the inner and outer tube. This is a very durable configuration as the seal between the two tubes is not likely to fail.

6.5.5 Glass-metal evacuated tube collectors

This design uses a single wall glass tube with a seal created between it and the absorber assembly that is located within the tube. The vacuum is formed within this glass tube. The glass-metal seal poses technical problems due to the different rates of expansion of glass and metal and it is a possible point of failure.

6.5.6 Heat absorption in evacuated tubes

The same basic method of heat absorption that is used with flat plate collectors is used with evacuated tubes i.e. a metal absorber, usually copper, is coated with a selective coating. The main difference is that the absorber is contained within a vacuum and therefore loses very little heat to the environment. This reduction in heat loss also means that evacuated tube collectors operate at higher temperatures than flat plate collectors.

6.5.7 Heat pipe method

In this ingenious approach a sealed copper pipe containing a working fluid (usually some type of alcohol) is located within the tube and connected to the absorber plate. The fluid in the heat pipe evaporates at around 30°C and, as long as the tube is tilted at a sufficiently steep angle, rises by convection to the top of the pipe where the pipe broadens out to form a chamber. This chamber is located in the manifold through which the fluid that transports the heat to the hot water cylinder is flowing (heating circuit fluid). This contact incurs a heat transfer that heats the heating circuit fluid and cools the heat pipe working fluid so that it condenses. When it condenses it falls back into the heat pipe proper where the cycle begins again. This heat transport mechanism is so efficient that it is more than a thousand times better at conducting heat than the best metal conductors. A big advantage of this approach is that individual tubes may be removed and replaced without draining the system or affecting any other tubes. A slight disadvantage is the requirement that a certain minimum tilt angle is required in order for it to work. This means that for flat or very low pitch roofs a frame has to be erected to hold the panels at the appropriate angle.

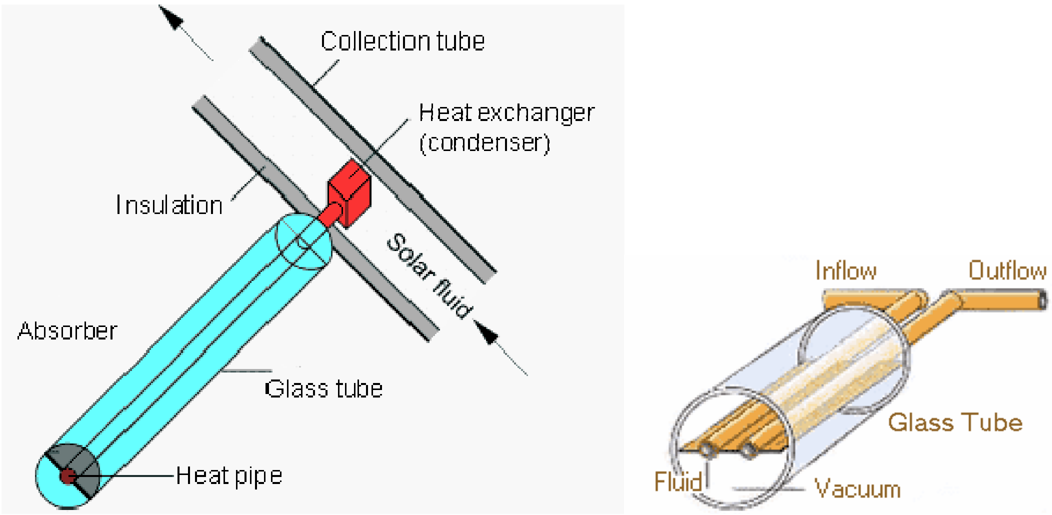

Figure 6.7 Schematic of evacuated tubes
(a) Heat pipe (Solarserver, 2007)
(b) U shaped copper pipe (adapted from Solarserver, 2007)

6.5.8 U shaped copper pipe

In this approach a copper pipe is routed into and out of the evacuated tube. This pipe carries the heating circuit fluid bringing cold fluid in and heated fluid out. The absorber is attached to this pipe.

6.5.9 Concentric copper pipe

In this configuration the inner copper pipe, which is open at its bottom end, carries in the cool fluid which then flows out in the layer between the inner copper pipe and the outer copper pipe which is sealed at its bottom end. The absorber is attached to the outer pipe so that the fluid is heated when it flows in the layer between the pipes.

6.5.10 Direct Heating

In this approach the water itself is allowed into the tube and heated by direct contact with the absorber. One problem with this approach is that the whole system has to be drained in order to replace a single tube and, if a leak develops in a tube, it will spill out over the roof or whatever surface it is located on. There have been many stand-alone water heaters manufactured using this approach. In these heaters the hot water cylinder, possibly 150 litres in capacity, is located directly at the top of the panel assembly.

Figure 6.8 Example of a stand-alone water heater
(Tsinghua, 2007)

Other approaches to providing hot water from the sun include bulk heaters which are essentially absorber and hot water tank rolled into one (think of a black metal barrel) and metal roofs as absorber with a means of transferring the heat from the metal roof to a heating circuit.

6.5.11 Collector efficiencies

In order to get the most out of a solar hot water panel it is important to position it carefully. It should be facing due south and not shaded while the sun is in the southern half of the sky. Its optimum angle of tilt depends on the latitude of the site and the amount of cloudy weather experienced at the site. If the sky were always clear then the optimum tilt angle would equal the latitude of the site. If the sky was always overcast then the optimum tilt angle would be zero i.e. the plate would be horizontal. The optimum angle therefore is usually some degrees lower than the angle of latitude. Thus in Ireland where the latitude is mostly in the low 50's and the cloudiness factor is typically in the sixties (i.e. the percentage of overcast skies is about 65%) then the optimum tilt angle turns out to be about 35^{o} but anywhere between 30^{o} and 40^{o} is good. In general vacuum tubes outperform flat plate collectors especially in cold and windy conditions but this advantage may be reduced when the panels have a layer of snow or frost on them as it is slower to melt in the case of evacuated tubes. Because of plumbing considerations solar tracking is not normally an option for solar hot water panels.

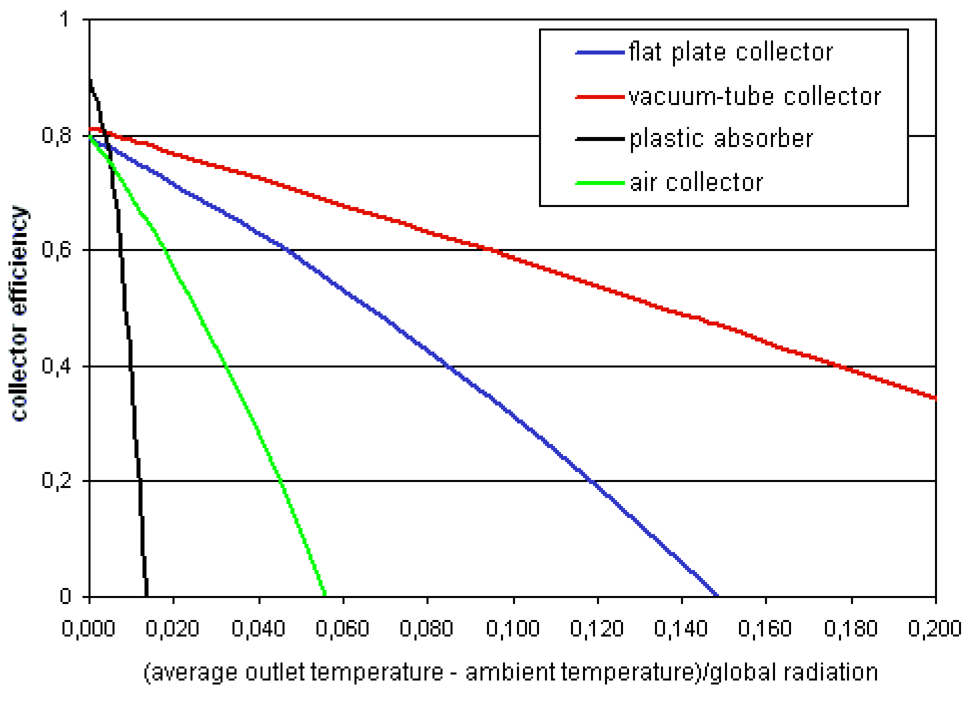

Figure 6.9 Efficiencies of different collector types
(Energytech, 2000)

In spite of this extra efficiency flat plate collectors are more popular than evacuated tube types. The reasons for this appear to be threefold: cost, fragility and durability with the evacuated tube collectors being more expensive (even allowing for increased efficiency), more fragile and more likely to need repairs. The cost reason appears to be getting less important as cheaper evacuated tube panels are now being imported from China. A final reason why some people prefer flat panels is purely aesthetic as evacuated tube panels cannot be roof integrated and are more conspicuous to look at. However there are significant market differences across Europe.

Country	Ratio of Flat Plate capacity to Evacuated Tube Capacity installed in 2005
Austria	160:1
Germany	9:1
Italy	23:1
Spain	26:1
UK	2:1
EU	32:1

Table 6.2 Flat plate to evacuated tube ratios
(adapted from ESTIF, 2005)

6.5.12 Solar hot water heating components and configurations

Indirect or closed loop systems

The copper pipe (copper, as opposed to plastic, piping is generally required because the temperatures realised in solar thermal circuits are often higher than would be reached in conventional domestic hot water systems) carrying the heating circuit fluid forms a circuit connecting the solar panel array to the hot water tank. This pipe normally connects to a coil located in the lower (cooler) end of the hot water tank. This coil acts as a heat exchanger where the heat from the solar panels is finally transferred to the water in the tank. The fluid in the heating circuit is usually water with some antifreeze and is referred to as brine.

Direct or open loop systems

In an open loop system cool water is drawn from the hot water tank and circulated through the solar panels and back to the hot water tank. Because such a system heats the domestic hot water directly it is not possible to incorporate any antifreeze into it which means it is vulnerable to freezing in the panels on cold winter nights. Steps to avoid this include draining the fluid from the panels at night (drainback systems), switching a pump on when the temperature of the panels drops below a certain threshold and using double glazing on the panels themselves.

6.5.13 Controller

Both the open and closed loop systems described above are usually pumped systems where the pump is switched on by a microcontroller that monitors both the temperature of the solar panels and the temperature of the water at the top of the hot water tank. The controller can be configured to switch on the circulation pump when the temperature difference between these passes a certain threshold value and when the solar panel temperature is above a certain minimum value.

6.5.14 Thermosyphon method

Solar hot water circuits may also be gravity driven (thermosyphon). The difference in density between the heated water in the solar panels and the cooler water in the hot water tank causes the warmer water to rise into the hot water tank by convection. Therefore a gravity driven system requires that the panels be placed lower than the hot water storage tank.

In general the following components will be needed:

- Solar panels and fixings
- Pipework
- Circulation pump
- Controller (decides when to start and stop pumping)
- Temperature sensors
- Expansion tank
- Hot water tank with solar heating coil

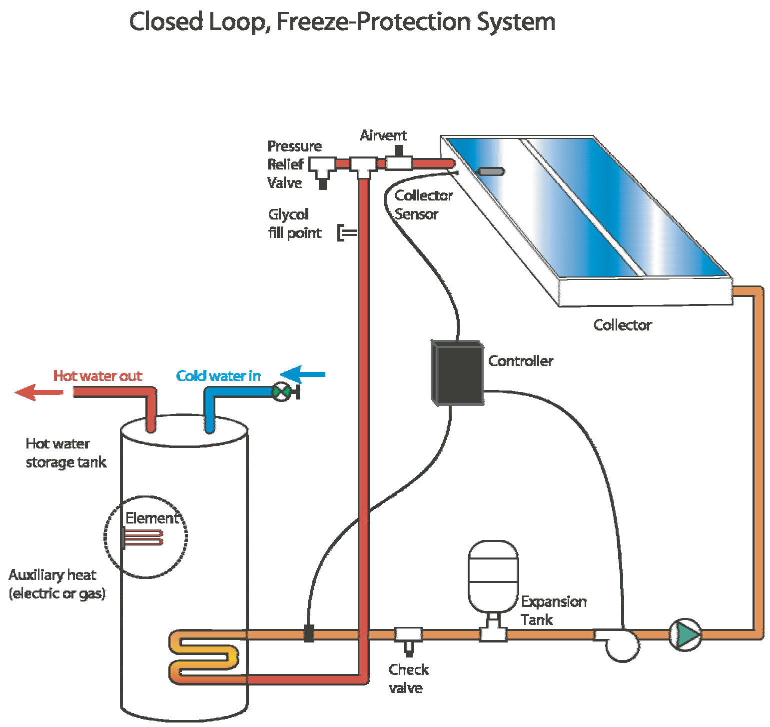

Figure 6.10 Closed-loop (or indirect) hot water heating circuit (Southface, 2007)

6.6 National Installed Capacity

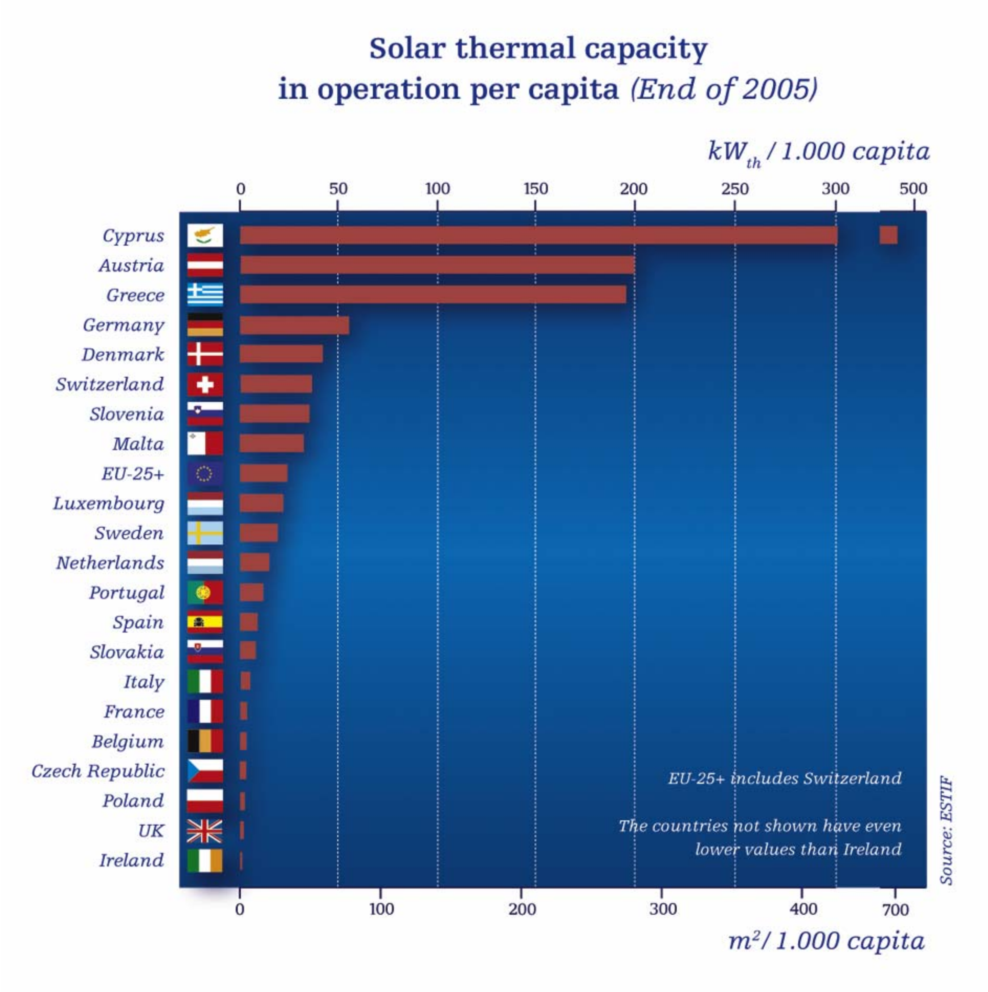

Figure 6.11 Installed solar thermal capacity in 2005 (ESTIF, 2007)

Most EU countries exhibited strong growth in the rate of solar thermal panel deployment in 2004-2005. The following table gives some representative figures.

Country	Increase in 2005 relative to increase in 2004
Austria	28%
France	134%
Germany	27%
Ireland	75%
Italy	24%
Netherlands	-23%
Spain	16%
UK	12%

Table 6.3 EU Solar thermal capacity increase in 2004-2005 relative to increase in 2003-2004 (ESTIF, 2005)

6.7 *Financial viability*

Assuming the annual availability of solar energy is 1200 kWh/m^2 (which is achievable in parts of Ireland) and that the panel efficiency is 40% then this translates into 480 kWh/m^2a. For a fairly typical 6m^2 collector area this yields 6x480 = 2880 kWh/a. The current value of this in Ireland, if provided by electricity would be, 2880x14.4c = €416 per annum. The cost of buying and installing such a system in Ireland (including all the necessary components and a new 300 litre hot water tank) would be around €6500.

An idea of the payback period is arrived at by dividing the capital costs by the annual savings i.e. 6500/416 = 15.6 years. If we increase the efficiency of the panel by 5% to 45% then the payback period becomes 13.9 years. The period decreases even more if we incorporate any government subsidies that are available. In Ireland this system would get €1800 in grant aid under the Greener Homes Scheme and this would reduce the payback periods to 11.3 years and 10 years respectively. Also any increase in energy prices will reduce the payback period. In addition to the financial benefits that will accrue after the payback period has passed there are also benefits in terms of reducing CO_2 emissions and the security of energy supply.

6.8 *Solar Air Heating*

It is less common to see solar energy panels designed to heat air rather than water but a number of products exist for this purpose. Such panels may be wall or roof mounted and are lighter in weight than their water heating counterparts. Some systems can provide hot water as well as hot air (combi-system). Solar warm air systems also ventilate the house by bringing in fresh outside air and can be used for bringing in cool night air in warm weather. One manufacturer claims that a typical system of theirs (combined air and water) would contribute about 3300kWh per annum on a 30^o south facing roof in London.

(a) (b)

Figure 6.12 Airpanels
(a) Wall mounted warm air panel (Cansolair,2007)
(b) Roof mounted warm air panel (Sunwarm 2007)

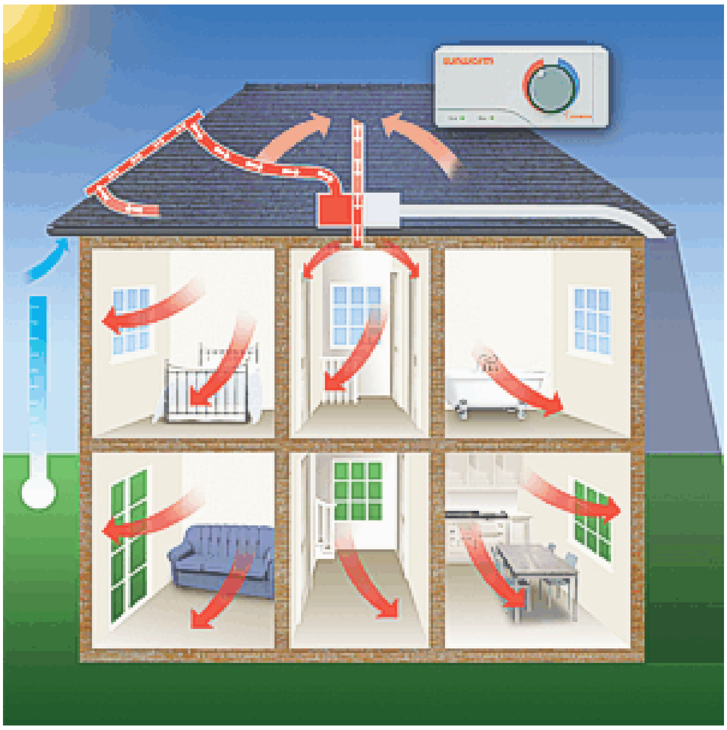

Figure 6.13 Schematic diagram of warm air solar system
(Sunwarm, 2007)

6.9 Solar Combi-systems

This rather imprecise term is used to refer to active solar thermal systems that provide hot water and space heating. A study of such systems, the European Altener Programme Project: Solar Combi-systems can be looked up at http://elle-kilde.dk/altener-combi/index.htm (Figure 6.14). Typically such systems are larger in scale. The solar panel area would usually exceed 7m2 and the warm water storage would usually be at least 800 litre (unless another storage strategy for space heating storage is used, usually a concrete floor) with many systems exceeding these values. There are some combi-systems that have small panel areas and storage capacity but the economics is generally not as strong in such cases.

Figure 6.14 Example of a combi-system solar thermal collector of 16m2 on a house situated in France
(ALTENER, 2003)

6.10 Barriers to entry for solar thermal

- Capital cost
- Consumer ignorance
- Skills shortages
- Consumer indifference
- Patchy availability

6.11 Government Supports

Ireland has a Greener Homes Scheme under which grants are available for solar thermal systems. The value of the grant available is €300 per installed m^2 up to a maximum of €3,600. This is applicable to solar space heating and solar hot water systems. Further details can be obtained from Sustainable Energy Ireland (www.sei.ie).

6.12 Sources of Further Information

Altener Combi-System Project	http://elle-kilde.dk/altener-combi/index.htm
CEPHEUS Project	http://www.cepheus.de/eng/start.html
European Solar Thermal Industry	
Federation	www.estif.org
International Solar Energy	
Passiv Haus Institut	www.passiv.de
Practical solar resource	www.builditsolar.co
Society	www.ises.org
Sustainable Energy Ireland	www.sei.ie
Various solar articles	www.wikipedia.org

6.13 References

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