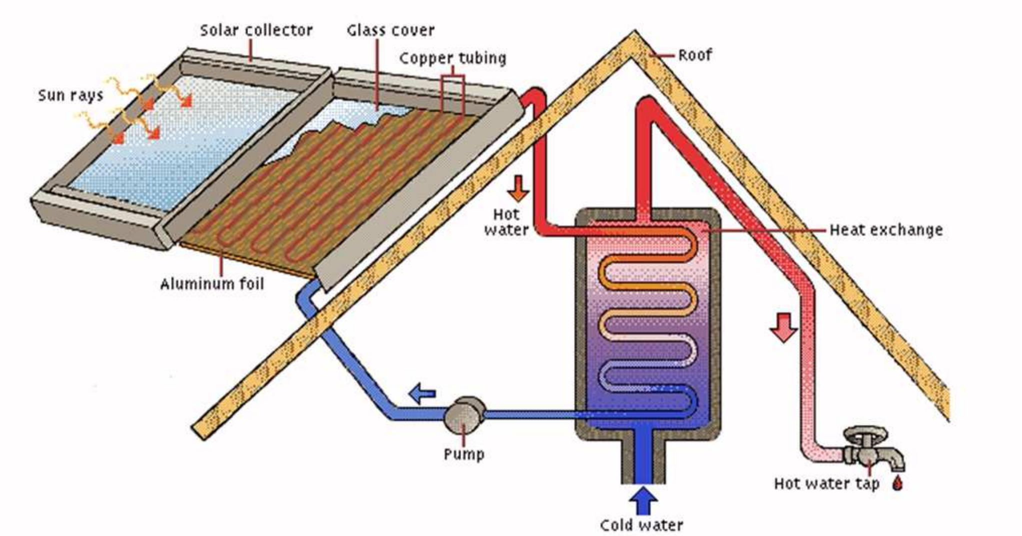
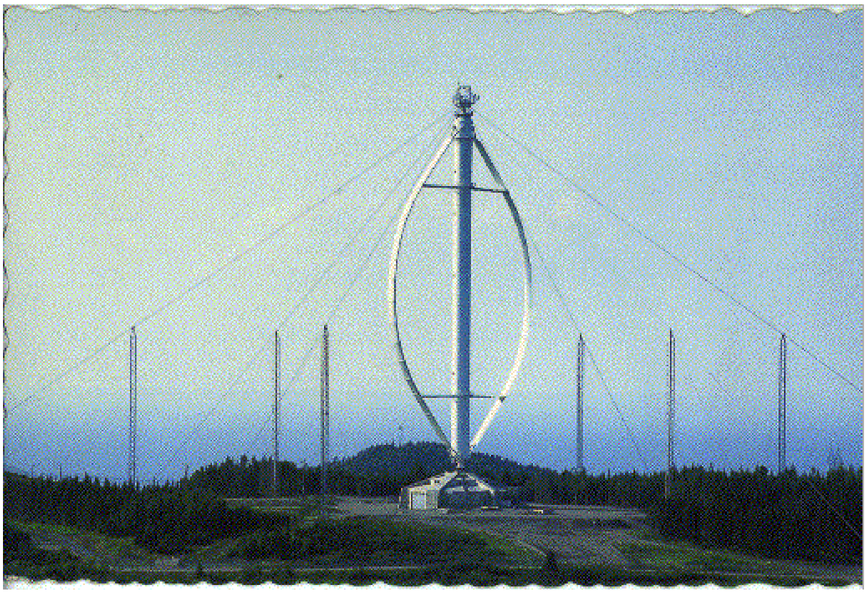
NBSLM03E Low Carbon Technologies and Solutions (2010)

PART 3 of 3: Renewable Energy



A Domestric Hot Water System



A Darrieus Rotor

Copies of this handout and also the actual PowerPoint Presentations may be found on the WEB Site

http://www2.env.uea.ac.uk/gmmc/energy/nbslm03e/nbslm03e.htm

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14. RENEWABLE ENERGY RESOURCES.

ORIGINS OF RENEWABLE ENERGY RESOURCES

Renewable energy sources may be divided into three categories as was discussed in Section 4 of NBSLM01E.

1) Solar -
    a) direct
    b) indirect - e.g. wind, waves., biomass
2) Lunar - tidal
3) Geothermal

Of these, both direct and indirect solar sources are about 50000 times the geothermal resource, and 500000 times the lunar source.

As revision you should consult section 4 of of the above course notes for the magnitudes of the different sources.

Often included in the heading of Renewable Energy is Energy from Waste. Sometimes such energy is linked with biomass. It is perhaps more correctly to consider this as an alternative Energy Source. Thus PET COKE is now often being used in the Cememnt industry and also Iron and Steel. While an alternative fuel it has an even higher carbon factor than coal

The subject of Renewable Energy is vast and a brief overview was given earlier in the course in in the earlier course. Two specific topics will be covered explicitly in more depth: Solar and Wind. Notes are also included for tidal as this has recently (2009) been the subject of a Government Consultation.

15. SOLAR ENERGY

15.1 Introduction

- The sun behaves as a nearly perfect BLACK BODY radiator at a temperature of 6000K generated from nuclear fusion.

- it emits a continuous spectrum from 200nm (ultra- violet), through visible light (400 - 800nm) to infra-red (up to 3000nm).

- Outside earth's atmosphere, the intensity of solar radiation is 1395 Wm^{-2}, although this may vary by up to +_ 5% as a result of sun spot activity, and from the variation in the distance of the sun from the earth.

- Absorption by the atmosphere (which is more significant at certain wavelengths) reduces value by about 28% to 1000 W^{-2} on a horizontal surface directly below the sun.

- Reduction for more northerly latitudes is not that great provided that collector is tilted perpendicular to the sun. Thus in UK a values of 800+ Wm^{-2} can be achieved on a clear day in summer.

- Much more significant in reducing the levels are the climatic conditions.

Typical annual averages:-

UK	8 MJm^{-2}	(about 93 Wm^{-2} - up to 115 Wm^{-2} in in SE)
France (South)	14 MJm^{-2}	(about 162 Wm^{-2})
Australia	16 MJm^{-2}	(about 185 Wm^{-2})
India	20 MJm^{-2}	(about 231 Wm^{-2})

Solar radiation has two components:-

a) direct - a direct line of sight from sun to place in question.
b) indirect (or diffuse)- solar radiation from reflections from the ground, atmosphere, clouds etc.

- Indirect radiation is always present during daylight hours. Direct radiation is present only when sun is not obscured by cloud. Diffuse radiation on a clear day is less than diffuse radiation on a cloudy day. Thus in summer, north facing windows receive more solar gain on a cloudy day than on a clear day.

- Unlike many countries, the direct component is relatively small - only 45% in summer, and about 35% in winter. Nevertheless up to 80 Wm^{-2} is still received during the day time on a dull winters day in the UK.

- Applications in situations where direct component is a major part of total radiation:-

    1) direct electricity generation from photo- voltaic cells. BP have developed a refrigerator/freezer for the storage of vaccines in Third World countries.

    2) Indirect electricity generation by raising steam. e.g. Paris exhibition 1879, Egypt 1913, Bairstow, California 1982.

    3) Adsorption cycle refrigerators, freezers, and air-conditioners.

    4) Solar cooking. e.g. China, India.

    5) Special applications - metallurgical etc., Odeillo, France.

    6) Centralised Power Plants – e.g. Bairstow, California, Gila Bend, Arizona, Seville, Spain.

- Most direct applications require focusing or semi-focusing collectors which must be tracked with the sun either automatically or manually. For some applications, some types of manual tracking collector need only be adjusted once a week.

- In UK, most applications will be for low temperature heating requirements e.g. hot water/ space heating. Diffuse radiation can be collected with stationary flat-plate collectors, and thus do not require frequent attention either for periodic tracking adjustments or for servicing.

15.2 Active and Passive systems

- Systems which deliberately collect solar radiation such as any of the devices listed above are known as ACTIVE SOLAR DEVICES.
- PASSIVE SOLAR ENERGY applications include incidental solar heating (or cooling) of buildings from architectural design, crop drying, drying washing, etc. Greenhouses exploit PASSIVE SOLAR ENERGY.
- Some people also include in the group PASSIVE, those hot water heaters etc. which operate on a thermosyphon and thus have no moving (ACTIVE) parts.

15.3 Summary of Solar Energy

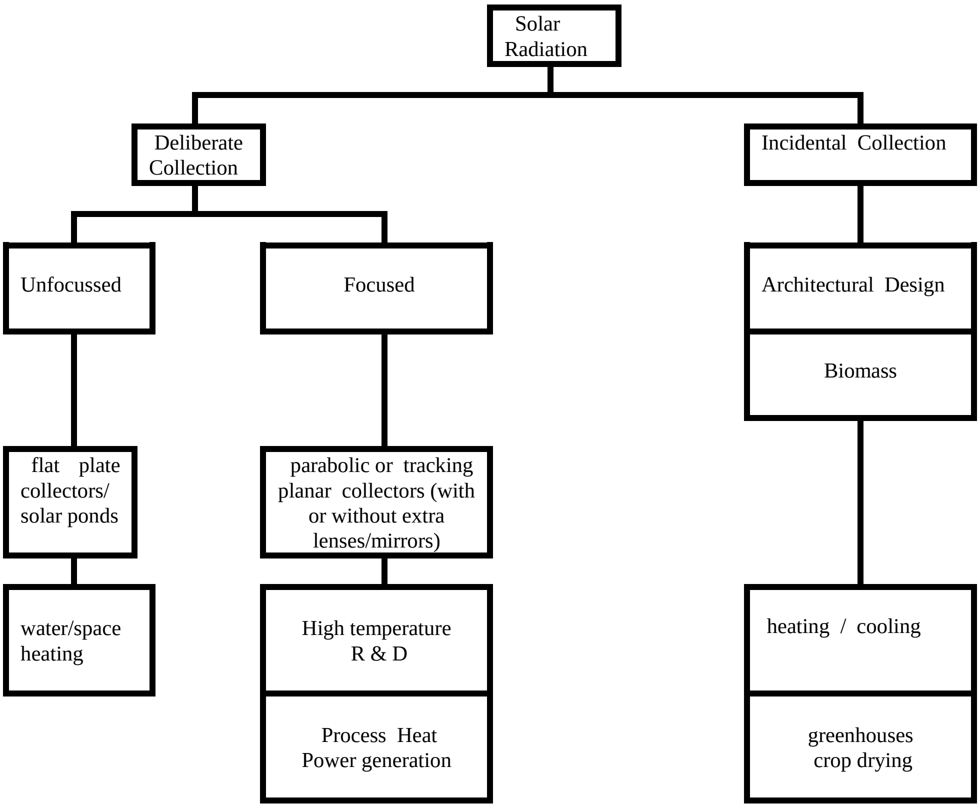


Fig. 15.1 Summary of Solar Energy

15.4 Passive Solar Energy - heating.

Solar energy (both direct and diffuse) falling on a object will cause it temperature to rise until there is a balance between the heat gained and the heat lost. A small proportion of the incoming radiation will also be reflected from the surface.

WALLS AND ROOF - often rise to a temperature ABOVE the surrounding air-temperature in direct sunlight, and this may cause some heat to flow inwards. Can be significant in hot climates. [Note: the need to insulate buildings in hot climates to prevent heat gain is often over-looked - it is as important as insulation of buildings to retain heat in cold climates].

Indeed problems of overheating are now becoming an issue even in the UK.

WINDOWS - a significant proportion (about 80 - 85% in the case of single glazing) is transmitted directly to the interior where it will be absorbed by the contents of the room.

However, the heat energy given off by these objects is of a much longer wavelength, and a large proportion of this heat will be internally reflected by the glass, and will thus be 'trapped'.

On a CLEAR day in the depth of winter a south facing room with large windows can be self sufficient in energy during daylight hours even in the UK. However, for the 17+ hours of darkness, such large windows would cause increased heat losses. Such windows, however, will often lead to over heating in summer

A BALANCED ARCHITECTURAL DESIGN IS NEEDED TO GIVE OPTIMUM IN FUEL SAVING.

NOTE:-

For SOUTH facing windows, maximum solar gain occurs in March/April and August/September. The sun is too high in the sky in June and a higher proportion of incoming sunlight is reflected. This can help to reduce overheating in summer. However, overheating in SOUTH facing rooms in summer can occur even in the UK unless overhanging shading is provided.

15.5 Architectural Features to enhance Passive Gain.

1) Minimise north facing window area
2) Maximise south facing window area and provide these rooms with SOLID uncarpeted floors e.g. polished timber or tiles. Alternatively provide a conservatory on south side of house.
3) Place most heavily used rooms, or rooms with lowest activity levels to south of building.
4) Provide inter room ventilation by mechanical means, and provide automatic ventilation of conservatories to avoid overheating in summer.
5) Provide an overhang over south facing windows and shelter conservatories to minimise overheating in summer. One method is to plant deciduous trees. In winter the shading is limited, but in summer when in full leaf, significant shading can be provided. But trees close to property can cause foundation problems.
6) Provide a Trombe Wall behind a glazed front wall, but ensure adequate ventilation is provided for summer.

Some Examples of Passive Solar Design and associated problems

A Passive Design incorporating a Trombe Wall construction includes the old people's homes in Bebbington which were designed jointly by Pilkington Glass and Merseyside Development Corporation. Success of design depends on CORRECT operation of vents A - E These were often set incorrectly by the occupants.

A second house - The Marseille House also incorporates a series of slats which had to opened and closed correctly.

A School in Wallesey requires no active heating (see separate sheet). Heat from lighting and body heat supplement solar gain through a double skinned glass wall. Part of internal layer is constructed of reversible aluminium slats - black outwards in winter, shiny side outwards in summer. Air temperatures range from 17^{o}C in winter to 24^{o}C in summer, although summertime radiant temperatures sometimes reaches uncomfortable levels over 28^{o}C.

Passive solar cooling can be achieved in dry climates by inducing a flow of air through the house. The incoming air passes over damp cloths and this cools the air as the water evaporates. Temperature depressions of 5 - 10^{o}C are possible.

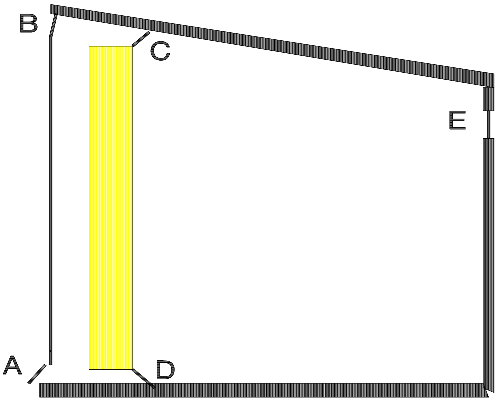


Fig. 15.2 A Trombe wall house of the design used in Bebbington scheme.

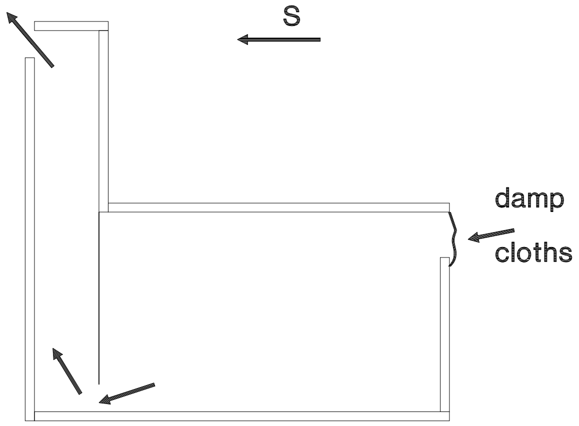
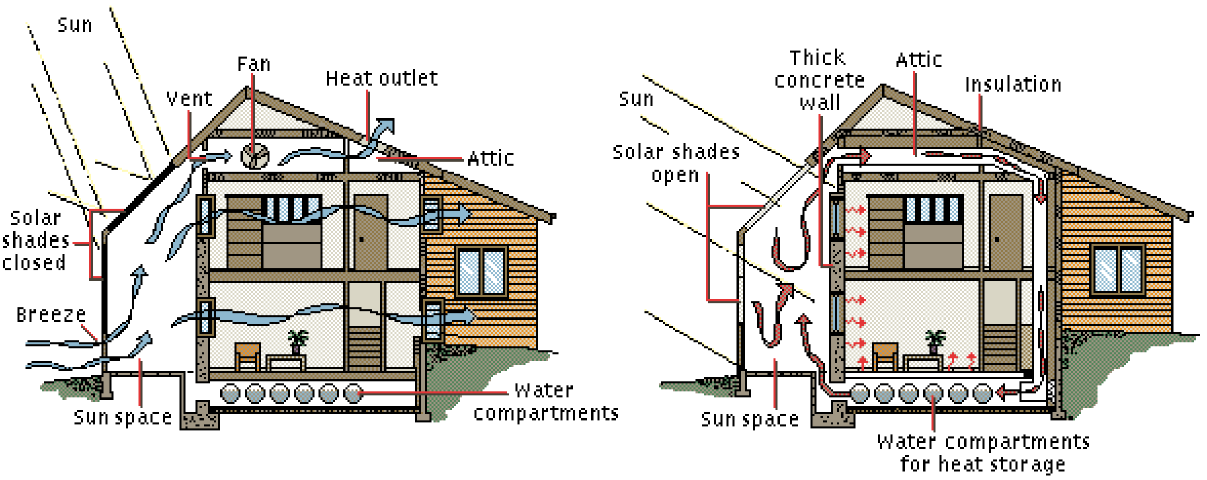


Fig. 15.3 Passive Solar Cooling



Passive solar cooling
(Summer)

Passive solar heating
(Winter)

Fig. 15.4 Example of Passive Solar Cooling and Passive Solar Heating in a European style house.

The "sun space" serves as a collector in winter when the solar shades are open and as a cooler in summer when the solar shades are closed. Thick concrete walls modulate wide swings in temperature by absorbing heat in winter and insulating in summer. Water compartments provide a thermal mass for storing heat during the day and releasing heat at night. However, frequently in summer, adequate cooling does not occur and buildings overheat – e.g. the so called "low Energy" Building at Chingwa University in Beijing.

15.6 ACTIVE SYSTEMS - Flat Plate Collectors

1) **Thermosyphon_-** hot water storage cylinder must be above top of collector.

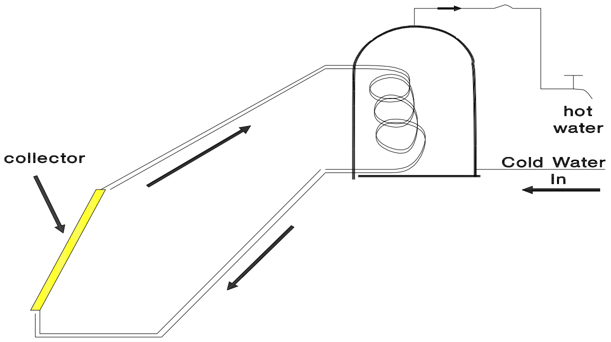


Fig. 15.5 A thermosyphon solar collector

NOTE: The contra-flow system in the tank to ensure maximum efficiency

2) **Pumped Systems:** same basic diagram except water is pumped around circuit, and cylinder can be below collector. However, active controls must be present to ensure hot water is not pumped to radiate heat from collector at night time.

3) **Pumped Trickle Type Collectors**
- these collectors allow water to run down in grooves under gravity. Some experiments have been made with additives to make water black and improve absorption.
All water runs by gravity over the collector.

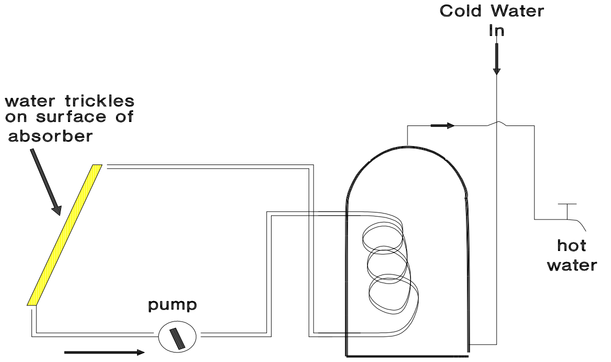
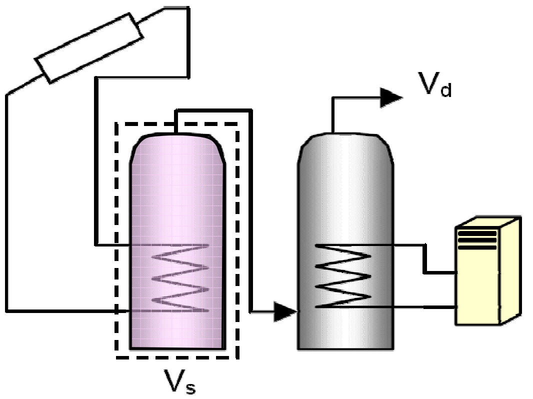


Fig. 15.6. A trickle type collector - NOTE: contra flow system through tank



4) **Indirect Systems** - use two storage cylinders, one for solar circuit to preheat the water befo conventionally heated hot water cylinder. Solar Heating pre-heats incoming hot water and can be used even if the temperature rise is small.: NOTE the contra flow heat exchangers in both tanks.

Fig. 15.7 An indirect solar heating system

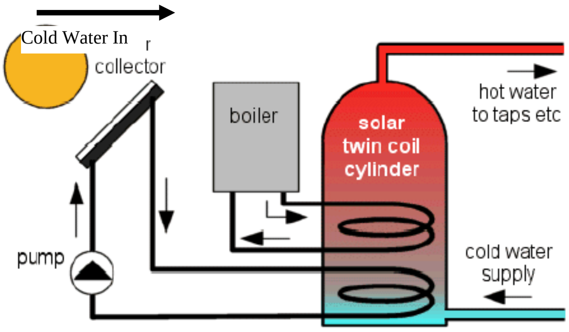


Fig. 15.8. The Broadsol variant of indirect solar heating

5) **Tubular Flat Plate Collectors** - these consist of a series of glass tubes at the centre of which is a pipe conducting the working fluid. Some such schemes have evacuated tubes which reduce heat losses from collectors.

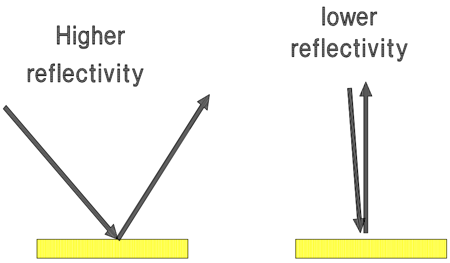


Fig. 15.9 The problem with flat plat collectors is that unless they are aligned perpendicular to the sun, the reflectivity of the cover glass can be high reducing the effective amount of energy available.

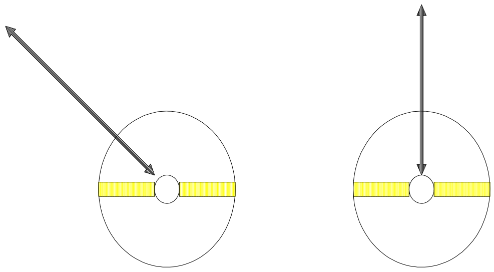


Fig. 15.10 Tubular collectors

With a tubular collects, the sun is perpendicular to the glass surface for a wide range of azimuth angles, and
thus reduces reflection. compared to flat plate collectors.

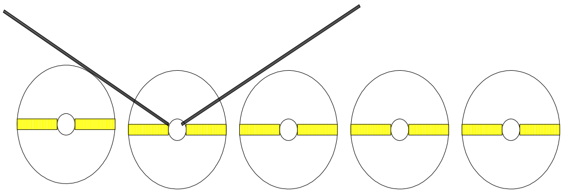


Fig. 15.11 An array of tubular collectors

Note: spacing between tubes is necessary to exploit full potential and this does reduce the effective collector area. Tubular collectors may be 3-%% more efficient..

15.7 Solar panels with combi-boilers.

Most combi boilers specify that they must have cold water as input and are unsuitable for using with a solar tank, particularly as in summer the tank water can reach over 60^{o}C. A few combi boilers do allow solar preheating using a system shown in Fig. 23:12

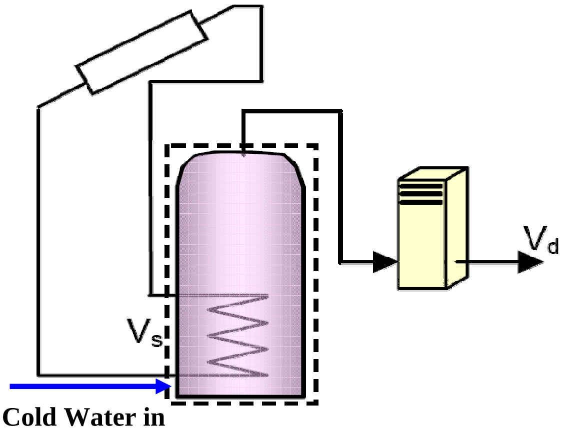


Fig. 15.12. A solar pre-heating system with a combi boiler NOTE: Most combi boilers do not allow solar pre-heating – contact the manufacturer.

15.8 Advantages and disadvantages of different types of flat plate collector.

1) ***Thermosyphons*** must have cylinder perched at apex of roof. In many houses there may be inadequate room. Care must be taken with pipe work runs to ensure free circulation.

2) ***Pumped systems*** require pump energy. It is normal to delay switching on system until collector temperature is at least 3^{O}C warmer than water in cylinder.

3) Provision must be made to avoid water in collector from freezing. - remember the collector may be several degrees colder than the air temperature on a clear night. Collectors should contain anti-freeze or should be drained.

4) ***Thermosyphon***s cannot be drained conveniently. Trickle systems are the best as they automatically drain when pump is switched off.

5) Direct systems cannot be used if anti-freeze or other additives are present. Further if water temperature is not high enough, then the storage tank becomes an ideal breeding ground for Legionnaires Disease bacteria.

6) Indirect systems are convenient in that topping up by conventional sources can be done.

7) Tubular collectors improve efficiency somewhat, but seasonal performance of all collectors will not exceed about ~40% - 50%

(DESPITE MANUFACTURER'S CLAIMS!).

NOTE: Collectors are most efficient if they raise the water temperature by only a few degrees. Double glazing REDUCES efficiency unless very high temperatures $>80^{O}$C are are needed are are generally cost ineffective.

15.9 Combining Solar Thermal with Heat Pumps

Figure 5.9 showed an integrated approach in the use of heat pumps with the opportunitiy for multiple heat sources. Though this scheme was never actually built there was the opportunity to utilise solar energy as a heat source. A system which incorporates a solar thermal panel heat soruce with a heat pump has been developed by a Portuguese company and marketed via a company in Wymondham. Such a scheme passes the water heated by solar through the evaporator of the heta pump. Since the source temperature in day time will be moderately high, the coefficient of performance of the heat pump can be very high too. The system can also be used at night time, but in this case the source temperature can drop to -10^{o}C and the coefficient of performance can be very low indeed**.**

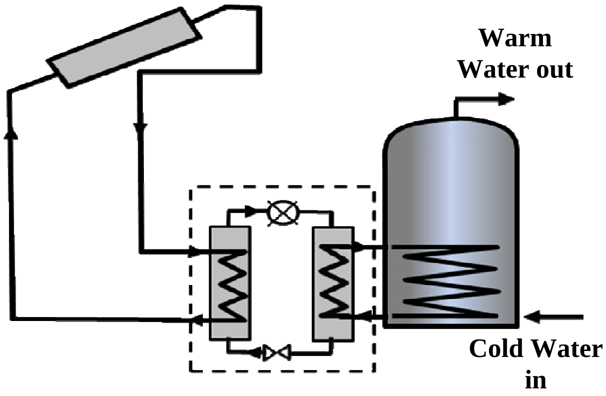


Fig. 15.13. A solar collector used in conjunction with a heat pump – significantly improved COPs in day time, but reduce COPs overnight.

15.10 Some Resuts from the Broadsol Project

The Broadsol Project was initiated by a consortium including UEA, Broadland District Council and CML Contracts who did the installation.

The aim was to involve the community and ultimately 40 householders had panels attached to their properties with 19 of them being monitored. A typical installation is shown in Figure 15.14.

Over the year one installation achieved 911.562 kWh despite manufacturers claims that the figure would be higher. Some interesting things emerge.

Up to 7+ kWh can be achieved on a sunny day – more than sufficient for requirements. Even on a March day (March 2nd 2004) when there was snow on the ground, a temperature of 59^{o}C was achieved. This was more than sufficient for a childs bath and an adult shower that evening – see Fig. 15.15

Fig. 15.14 Broadsol installation in Norwich

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15.11 Applications of active systems to space heating.

In Milton Keynes a house has been designed to use an active hot water system to assist in space heating (see separate sheet). A 43 m^2 collector feeds two 2.5 m^3 storage tanks situated centrally in the house. Computer simulations suggested that 30% savings could be achieved

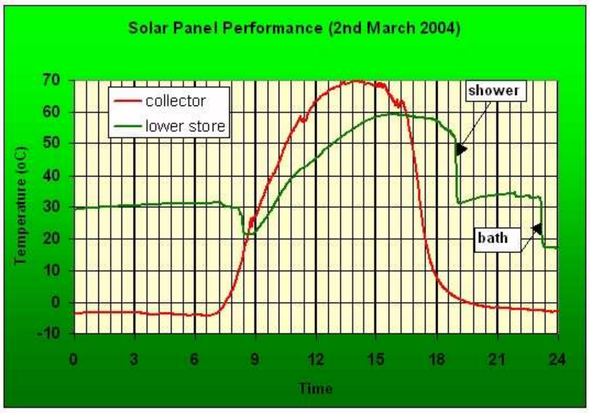

Fig. 15.15 performance of Broadsol Collector

NOTE:

1) Normal central heating systems using hot water radiators have flow temperatures of the order of 65^{o}C, and return temperatures of 50^{o}C. Unlike hot water space heating CANNOT be preheated except with separate large radiators.

2) Hot air systems run at lower temperatures - 35^{o}C - 40^{o}C, and are more suitable for incorporation into solar space heating schemes. This is used in Milton Keynes - water is circulated at 40^{o}C and fan convectors blow warm air into rooms.

3) A special three-way valve to connect in the auxiliary boiler is needed.

4) Provision must be made in summer to dissipate and continuously circulate water other water may become excessively hot and even boil! - e.g. run hot water to waste or have plenty of baths.

5) Very large storage volumes are required for inter-season storage - see section on energy storage.

6) Under IDEAL conditions, a 40 m^2 solar collector working at 60% efficiency, could provide all space heat requirements in the UK from April to September. In December only 14% can be provided, while the contributions in October, November, January, February, and March would be 82%, 28%, 17%, 31%, and 64% respectively.

15.12 Solar Ponds

Solar ponds are usually shallow up to 2 - 3 m deep which are in effect very large flat plate collectors. A fresh water layer overlies a solution of brine over a blackened base to the pond.

The upper water layer transmits the incoming radiation and acts as an insulator to the loss of heat. The solar energy is absorbed by the brine.

Temperatures as high as 90^{o}C have been reported at the bottom of the pond which is sufficient to operate an organise fluid turbine operating on the Rankine cycle.

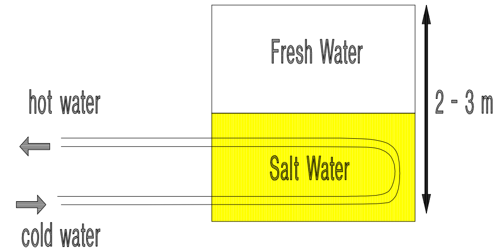

Fig. 15.16 Schematic of a Solar Pond

Pipes circulated through the brine layer may be to extract heat from the pond.

Pioneer work on solar ponds was done in Israel (see New Scientist 17th Sept. 1981), and such a facility was also running near El Paso in Texas. The Israeli system produced 5 MW, but was shut down in 1989 for economic reasons. There has also been a proposal to set up a similar system in the Salton Sea in California. Israel is reputedly also experimenting.

Losses of water by evaporation can be a problem, and mixing of the layers means that the upper layers must be desalinated and the salt returned to the lower layers. The water consumption is large amounting to about 35 times that for an equivalent conventional station.

15.13 Solar stills

Small scale desalination plants may be made as hemi-spherical plastic domes covering a shallow bowl of salty solution. Water evaporates, condenses on the inside of the dome, and runs down the surface for collection in an annular ring. There have also been proposals to link these with solar ponds.

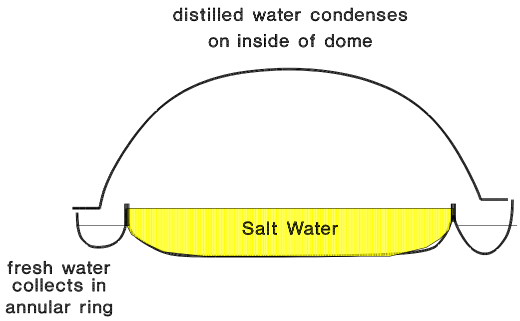

Fig. 15.17 A Solar Still for use in Hot Countries

15.14 Centralised Electric Power Stations

Solar 1 Power Station at Bairstow, California consisted of a large number of planar collectors each of which is individually controlled to track the sun and focus the energy on a central tower. Here water was turned into steam which is used to turn steam turbines as in a conventional power station. Efficiencies of conversion will depend on the steam temperatures reached, and will be limited by the second law of thermodynamics. The plant was shut down in the mid 1990's

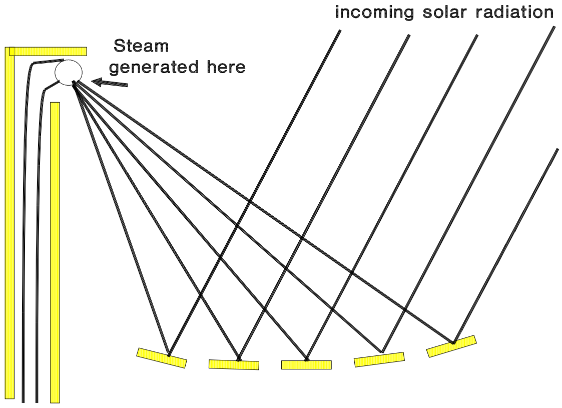

Fig. 15.18 A centralised power station:- each reflector must be steered individually to track the sun.

Other systems have been the SEGS series which have included a small natural gas boiler so that super-heating can be done - thereby improving efficiency.

Future developments suggest linking a combined cycle gas turbine with a centralised solar power station. The exhaust from the gas turbine would be used primarily for superheating and reheating, and finally the feed water heating, whereas the solar system would transfer the heat needed in evaporation. This latter is a limitation in conventional CCGT's as the temperature difference varies along the heat exchanger. Using such a combination can boost the overall efficiency of a CCGT by 5%+

To supply all the electrical requirements of the USA about 12500 sq km of the Arizona Desert would be required (assuming a conversion efficiency overall of 10%), and this would involve a huge investment in materials.

A very good review of the subject is included in Renewable Energy by Johansson, Kelly, Reddy, and Williams - pages 222-290.

15.15 Photo-voltaic cells

Semiconductors doped with minute quantities of certain elements (e.g. 1 part per million) can be arranged in pairs to generate electricity when irradiated by solar radiation.

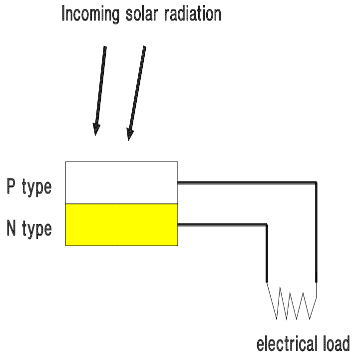

Fig. 15.19 Schemtaic of A Photo-Volatic Cell

The first type - the "N" - type consists of an element such as silicon doped an element with one additional electron - e.g. arsenic. The second or "P" type has a doping element with one fewer electron - e.g. boron.

Made up into a sandwich, of one "P" layer overlying one "N" layer these will generate an open circuit voltage of about 0.6 Volts, at an efficiency of about 15%.

Gallium Arsenide and Cadmium Sulphide will probably eventually give practical efficiencies of about 25%. Theoretically, the efficiency is about 30%.

Only wavelengths shorter than 1100 nm are effective, longer wavelengths only produce heating of device which reduces efficiency.

Costs of photo voltaic cells. The following prices in Table 15.1 were often cited in the 1990s

Table 15.1 Typical PV prices quoted in 1990s

	$ per peak watt
1961	175
1973	50
1975	20
1986	5 – 6
1991	4 – 5
1994	3 – 4

However, the reduction is cost does not seem to have been continued as there are references to current 2010 prices in the range of $4 - $6 per peak watt – and some current website are even quoting prices as high as $8-$10+ per peak watt.

A composite of several different data sets is shown in Figure 15.20. One issue of confusion appears to be whether the costs include all the installation costs or just the module costs. The main trend line from a study from the University of Manchester would appear to be just the module costs as is the study from Arizona. The other data points for post 2000 relate to complete systems. There is also one point referring to the projected price of around $8-$9 per Wpeak in 2015 for large (>20MW) schemes.

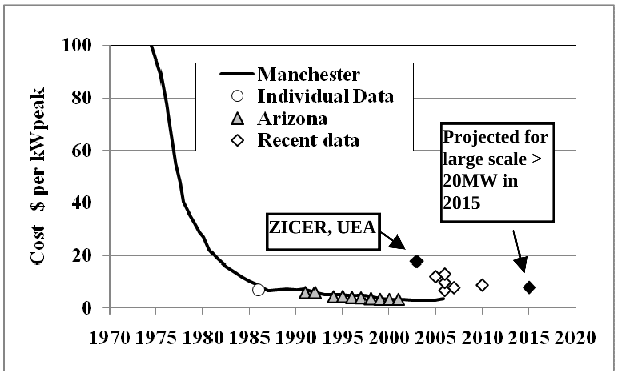

Figure 15.20 Cost of PV from different sources.

These prices should also be compared with other generation technologies in Table 15.2.

Table 15.2 Typical costs for electricity generation 2010

Technology	Cost be installed Watt
Coal	\$1.2 - \$1.8
Nuclear (PWR)	\$2.0 - \$2.3
Gas (CCGT)	\$0.8 - \$1.0
On shore wind	\$1.4 - \$1.8
Offshore Wind	\$3.0 - \$4.0

Note: for the fossil fuel these costs are only the capital costs, and do not include running costs - i.e. fuel costs).

Scope for much further reduction in price seems somewhat limited except for small scale applications - possibly eventually to \$2 - \$3. For example isolated farmsteads etc. applications in Third World for freezers/refrigerators.

The University of Northumbria installed a 40 kW photo-voltaic generator on the side of a building in 1994. Several others followed – including the ZICER building in 2003. That building produces ~22000kWh a year from a 34 kWp array implying a load factor of 8%.

Such load factors are significantly below those of other technologies and should be factored in to any cost appraisals

With the interest in integration of ideas there is the possibility of partly powering a heat pump from electricity generated by PV. However many of these claims are very optimistic and misleading as PV generally will not provide all the electricity for appliance and or lighting yet aloen any heating. The Energy Saving Trust Web Site shows such a combination but is misleading in that the PV array would have to be very much larger than implied for the system to really work and that far from exporting electricity, electricity would be imported except for a few relatively short periods ion summer. The Energy Saving Trust schematic of such a scheme may be seen at:

http://www.energysavingtrust.org.uk/extension/est/design/est/flash/flash-overlays/solarPV_groundSource.html

15.16 Solar Satellite Power Stations.

Outside earth's atmosphere in geostationary orbit, sun never sets, there is no absorption by atmosphere, and no clouds. Satellite Power Stations would collect energy and convert it into a microwave beam for transmission to earth where energy would be reconverted to electricity with an efficiency of about 80%.

Present schemes suggest placing giant solar modules in geosynchronous earth orbit. To produce as much power as five large nuclear power plants (1 billion watts each) several square miles of solar collectors, weighing 10 million pounds, would have to be assembled in orbit; an earth-based antenna 5 miles in diameter would be required. Smaller systems could be built for remote islands, but the economy of scale suggests advantages to a single large system

Power density in microwave beam as it heats earth would be beam would be 23 mW cm^{-2} at centre falling to 1 mW cm^{-2} at edge.

Exclusion zone necessary around each receiving site in case beam goes off "target". Also fail safe devices are proposed to disperse beam in fault conditions.

Standards of microwave exposure:-

10 mW cm^{-2} in USA
but only 0.1 mW cm^{-2} in USSR.

15.17 Ocean Thermal Energy Conversion (OTEC)

In tropics sea surface temperature is 25^{o}C or higher while at a depth of 500m it is about 5^{o}C.

Large potential - e.g. in Gulf Stream off Florida, but this might affect climate of northern Europe.

This temperature difference can be exploited using second law of thermodynamics.

Warm surface water is used to boil a fluid such as ammonia (or very low pressure steam) which then expands through a turbine and condensed by the supply of cold water.

As low temperatures are involved, the efficiency of conversion is low (about 1 - 2%).

Enormous volumes of water must be pumped from depth in normal operation of such a plant.

Generally non-polluting, but plant must be moored in deep water. Hence there are problems in transmitting power ashore. Suggestions have been made to use electricity to electrolyse water and pump the hydrogen ashore as a fuel in its own right.

Scheme first proposed in 1880, and first one built was off Cuba in 1929.

Second scheme off West Africa in 1950s (3.5MW). This scheme improved fishing in area as nutrients from deep ocean were brought to surface.

Current scheme (50MW) is in operation off Hawaii.

15.18 Biomass possibilities

Plants collect solar energy, and convert them into a form which might be used as a fuel - e.g. peat, wood etc.
In developed world, wood is being used faster than it is planted, so such schemes would need massive planting, and thus be in competition with areas used for food production, or alternative scrub land could be used. Once again there is a substantial environmental impact.

However, on steep slopes, planting of trees could minimise soil erosion and could be an additional benefit.

Other plants such as sugar beet, water hyacinth etc. can be used, but are probably most effective if they are digested or fermented into a secondary fuel.

anaerobic digestion (oxygen free conditions) can produce biogas which is largely methane, but also contains CO_2 which is often removed to provide a fuel of higher calorific value.

Many sewage works in UK treat their sewage in this way. However, temperature must be kept above 34°C, and a large proportion of energy is required in heating. In countries such as India and China small scale digesters are in widespread use, particularly where there are many animals.

On livestock farms in UK it could be a very appropriate form of energy.

Fermentation - Yeast can be used to break down carbohydrates in plants to form alcohols. It is used extensively in Brazil where the alcohol is used as a petrol substitute. - but see issue of New Scientist January 1993 which suggests that Brazil may be moving away from this in favour of oil.

Sugar cane is crushed an allowed to ferment. After distillation the liquid is 95% alcohol, and this is blended to give Gasohol (20% alcohol and 80% petrol). New engines could run off alcohol alone.

Advantages and Disadvantages of Biomass for UK

Advantages

1) Techniques well developed e.g. in Brazil.
2) Plants collect AND store energy.
3) Non-polluting.

Disadvantages

1). Energy used in collecting crops and in processing is not often not known with a high degree of accuracy, although information is now becoming, and there are som available. There are those who say that the energy requirements of maintenance and harvesting mean that the source is not a net energy producer. Frequetly the discrepancy comes from the deefintiion of the boundary of the system under study. Further more it also depends on how the biomass is being used. It is important to ensure that scheme will be a net producer of energy.
2). Biomass production would compete with food production.
    - thus of Land in UK:- about 75% of land is currently not built up or in conservation areas,
    - and if all non-built up or mountainous regions were used exclusively for biomass, then only 12% of UK energy needs could be produced by this means.

Three biomass plants are now in operation in East Anglia, but all of these are really using agricultural wastes as the fuel. The UEA system will use an advanced gasification technique combined with combined heat and power. The largets biomass power stations are around 20 – 30MW in size compared to up to 4000 MW for a single coal fired power station.

15.19 Economics of Solar Hot Water Heaters in UK.

Current cost is around £3500 - £4000, of which around £600 + is for a replacement cylinder and typically £1500 for installation. The cheaperst would be around £3000, but some suppliers are quoting over £6000. We shall assume £3,500 in our calculations.

A large household uses 140 litres of hot water each day at a temperature of 55°C.

Inlet water temperature is 10°C.

so energy required = 140 x 4.1868 x (55-10) kJ/day
= 9.63 GJ/annum
=============

For gas heating, seasonal efficiency for hot water is about 60%

so delivered energy requirement is:- 9.63/0.6
= 16.05 GJ/annum
=============

Cost of gas in Feb 2009 varies from around 2.6p per kWh for high useage to over 6p for low usage, with a typical weighterd average for those with gas central heating of around 3.5p
Or around £10.03 per GJ

So current annual running cost is 16.05 x 9.72 = £156
======

A 2.6 m^2 solar collector would provide 40 - 50% of total requirement. Assume 50%, so saving is £78 per annum. [This is probably an over estimate of saving as the saving is more to do with the sequence of use rather than any technical matter]. Thus if people have showers/baths in the morning, there will be much less saving than if they have them late morning etc.]

So net present value at 0% discount rate, using a lifetime of the collectors of 20 years is 20 x 78 - 3500 = - £1940, and so is far from cost effective.

With full rate electricity at prices ranging from 11p – 16p per kWh for the second tier about and up to 26p for the first tier rate, the weighted average cost per unit of full rate electricity appears to range from 13.5 – 14.5p (say 14p) per kWh. This rewpresents 7.60p per kWh (– Jan 2005 average of two tier rate) or about £38.90 per GJ. For electricity we must remember that the heating at point of end use is 100% efficient and thus the total annual cost will be 9.63 *38.90 = £375 and the saving from a solar collector may be estimated at £187.50 per year or around £3700 over 20 years giving a small net present value overall of +£200.

At a discount rate of 5%, the cumulative discount for 20 years (year 0 + 19 years of discounting) is 13.085319 (see Table 15.3) so the total effective saving for full rate electricity is now only 13.085319 x 187.50 = £2453.50 making it even less attractive as the NPV is now -£1046.50 in the case of electricity.

In practice the savings will not actually be 50% as energy is consumed in the pump. For full rate electricity, the scheme would still be just cost effective over 20 years assuming no discounting, but with a typical discount rate of 5%, the installation price would have to be no greater than £2000.

In the case of gas, the price would have to be no more than £1400 to be cost effective at 0% discount rate, but at 5%, the price would have to be under £1000. Unfortunately even with mass production, the labour installation charges are still likely to be equal to this price even if the components were free. On the other hand if the collectors were installed at the tiem of initial house construction, the labour charges could be much less and could then be just about cost effective even for gas. Even if soalr heaters are not installed initially, if dual circuit cylinders were mandatory, then this would probably shave up to £1000 of the cost of installationb of a complete system.

With mass production, the cost of all the components could probably be brought down to about £ 500 for the collector, £80 for tank, £40 for pump, £40 for pipe work and fittings or a total of £660, but the installation charge would still remain at around £1000, giving a total cost of £1660. Even then the scheme is not cost effective over 20 years under current gas fuel costs even with 0% discount rate.. [cost £1660 – saving £1560]

Table 15.3 Cummulkative Discount Table for 5% Discount Rate.

	Present value of £1	Cumulative present value of £1
0	1	1
1	0.952381	1.952381
2	0.907029	2.85941
3	0.863838	3.723248
4	0.822702	4.54595
5	0.783526	5.329476
6	0.746215	6.075691
7	0.710681	6.786372
8	0.676839	7.463211
9	0.644609	8.10782
10	0.613913	8.721733
11	0.584679	9.306413
12	0.556837	9.863250
13	0.530321	10.393571
14	0.505068	10.898639
15	0.481017	11.379656
16	0.458112	11.837768
17	0.436297	12.274065
18	0.415521	12.689585
19	0.395734	13.085319

If Government were to invest money (i.e. subsidise the installations such that they just became cost effective over 10 years over 5% discount rate – it is questionable whether people would consider things over a longer period) then the total cost if electricity were the fuel should not be greater than £1520, i.e. a subsidy of £140 for electrically heated installation), but for gas the total cost after subsidy and any discounting indicated above would have to be no more than £632, or a subsidy of around £1000 per collector.

To install collectors on all the suitable domestic properties (i.e around 15 million out of 23 million) and using this subsidy figure would involve an investment of £0.5 billion pounds per annum and £15 billion pounds in total. Remember that electric heating of hot water only constitutes a small proportion, although the Government should perhaps introduce a differential subsidy depending on fuel type used.?

We can estimate a possible installation rate assuming that financial barriers were not a limitation. Currently only about 10000 collectors are installed a year although this figure is now increasing. Let us assume that a concerted effort is made with a target in the first year of 50000 units raising by 50000 a year for 10 years until half a million are installed each year as the market would start to see saturation effects. We shall neglect the issues relating to replacement collectors and concentrate only on new installations beginning in 2009 and continuing for 35 years when all 15 million suitable houses would be equipped. With 250 working days in each year, and each collector requiring 2 people for 2.5 days to install some 1000 people would need to be employed initially solely in the installation with perhaps 50% of that number in sales, distribution, ordering, purchasing. In addition there would perhaps be a further 1500 involved in manufacture making around 3000 in total which would rise to 30000 by yerar 10 giving sufficient time to develop the necessary skills base.

15.23 Potential maximum energy saving across UK saving from solar hot water heaters

Such a deployment would mimic the start of central heating installations from the late 50's onwards and which has achieved a penetration of nearly 90% in houses. From 10 years into the program there would be an increasing development of the replacement market and the labour force involved in this and the new installation would be sustainable in the future.

Fig. 15.21 shows a possible increase in installation rate from 50000 per annum up to a maximum of 0.5 million a year and also the total number of collectors installed.

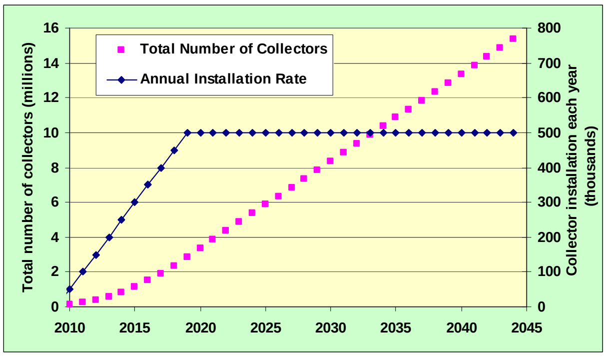

Fig. 15.21 installation of solar hot water collectros

Energy is required to produce each collector in the making of the glass pipe work etc., (about 15 GJ per collector is needed according to Chapman 1974. In two years energy investment Fig. 15.22 shows the net impact on UK Energy demand taking account of embodied energy and also energy saved. It is 2.5 years until a net energy saving is achieved to compensate for the increasing embodied energy in installations. Ultimately a potential of 120 PJ saving may be achieved and this represents 1.15% of current total UK energy use.

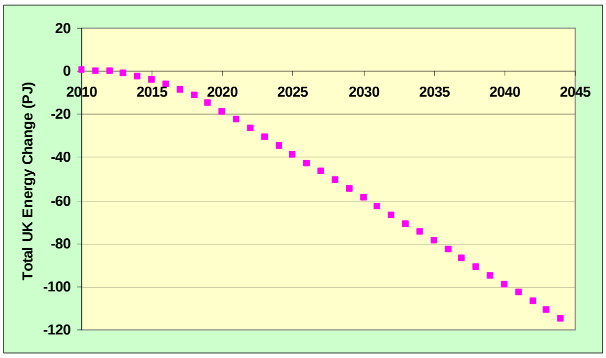

Fig. 15.22 Change in UK energy demand following installation of solar collectors.

Energy will also be consumed in the pump circulating the water assumed at 60W for an average of 5 hours per day. This will reduce the savings shown per house by about 0.39 GJ per installation (~5% per installation) or 6.3 PJ per annum overall in UK by 2045.

With regard to carbon dioxide savings – there will be a net increase in emissions of around 20 000 tonnes per annum over until 2012 after which the increased number of installations will more than compensate for the embodied energy of those collectors installed in subsequent years. Leading to a annual saving of 6 million tonnes of carbon dioxide by 2045.

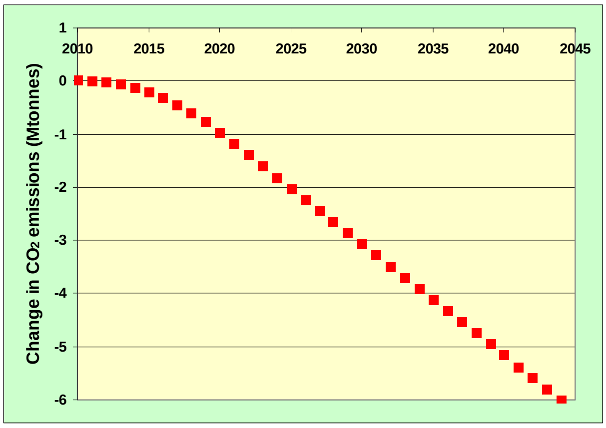

Fig. 15.23 Reductions in CO_2 emissions

15.24 Example of Space Heating by Solar Energy – an overview. Questions similar to this have been set in UEA examinations and are illustrative of some of the issues which should be considered in any appraisal

Briefly describe the options available for storing energy in the domestic sector.

Fig. 15.22 below shows the distribution of solar radiation for a clear day in March. A house has a heat requirement of 300 W^{o}C^{-1}, and the internal temperature is kept at 20^{o}C. Estimate the area of solar collector required if the house is to be self sufficient in energy in the summer months from March onwards. The following data are relevant.

mean external temperature in March	- 6.9^{o}C
efficiency of solar collectors	40%
incidental gains in house	1.5 kW

Energy storage is to be provided in the form of a hot water store operating over a 25^{o}C temperature range. Estimate also the minimum volume of the store required to be compatible with the above solar collection scheme.

The heat loss rate is 300 W^{o}C^{-1} and as there is 1.5 kW of "free heat" from incidental gains from passive solar energy, body heat appliances etc. this will automatically heat the temperature of the house through

1500 / 300 = 5 ^{o}C

Thus the effective temperature difference between inside and out = (15 - 6.9) *300 = 2430 Watts
= 209.952 MJ/day

Reading off graph, and noting that curve is symmetric = the total energy collected per square metre per day is:-

0.4 x 86400 x 2 x (10 + 50 + 175 + 325 + 485 + 575)
| | |
efficiency | |
seconds in a day data from graph

[x 2 because of symmetry]
= 4.6656 MJ/day/square meter

Thus total area of collector needed = 209.952/4.6656 = 45 square metres

Now replot the graph to show total energy gained from 45 m^2 allowing for efficiency - i.e. each value in previous graph is multiplied by 45 and 0.4 to give figure on next page.

The horizontal line at the top of the light grey area represents the mean energy lost.

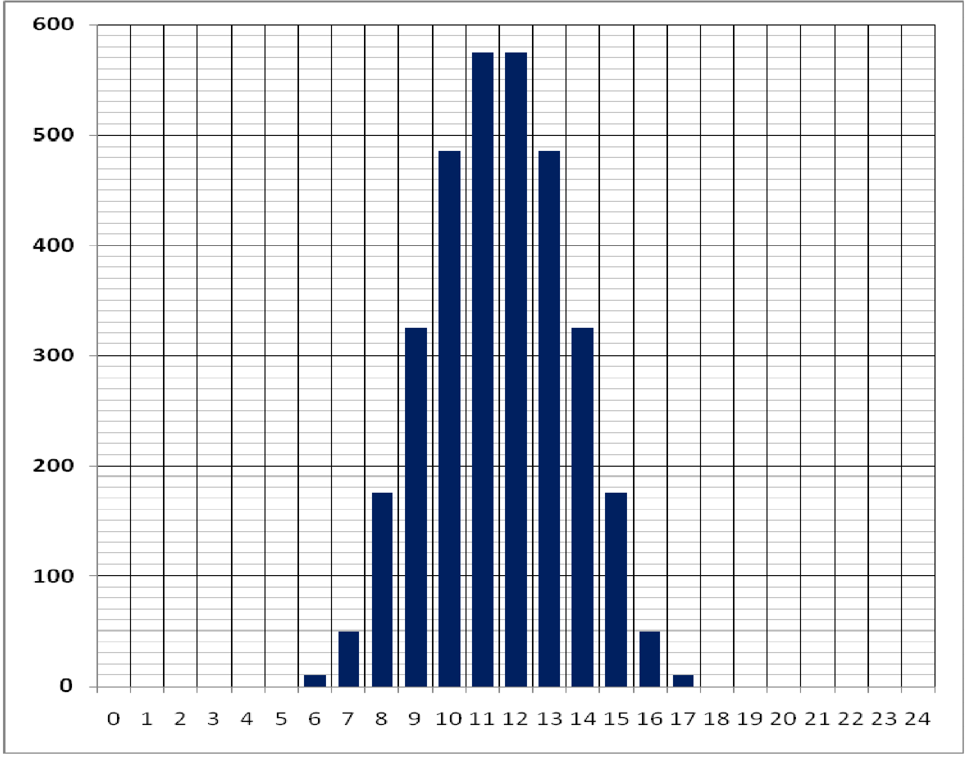

Fig. 15.22 Distribution of Solar Energy throughout a typical day in March

The light grey area represents the region where energy is being withdrawn from storage, while the dark grey area is the recharge of storage. Hence the total required storage is the light grey area.

Between midnight and 06:00 and 18:00 to 24:00, there is no solar gain, and heat has to be withdrawn from storage at a rate of 2430 W = 2430 * 12 * 3600/1000000 = **104.976 MJ**

In addition there is partial withdrawal from storage between 06:00-07:00, 07:00 - 08:00 and corresponding periods in late afternoon.

The energy withdrawn in these periods is

2 * [(2430-180)*3600 + (2430-900) *3600)/1000000
| |
6 – 7 am 7 – 8 am

= **27.216 MJ**

[the factor 2 is included to account for the afternoon period]

and total energy needed in storage

= 104.976 + 27.216 = **132.192 MJ**

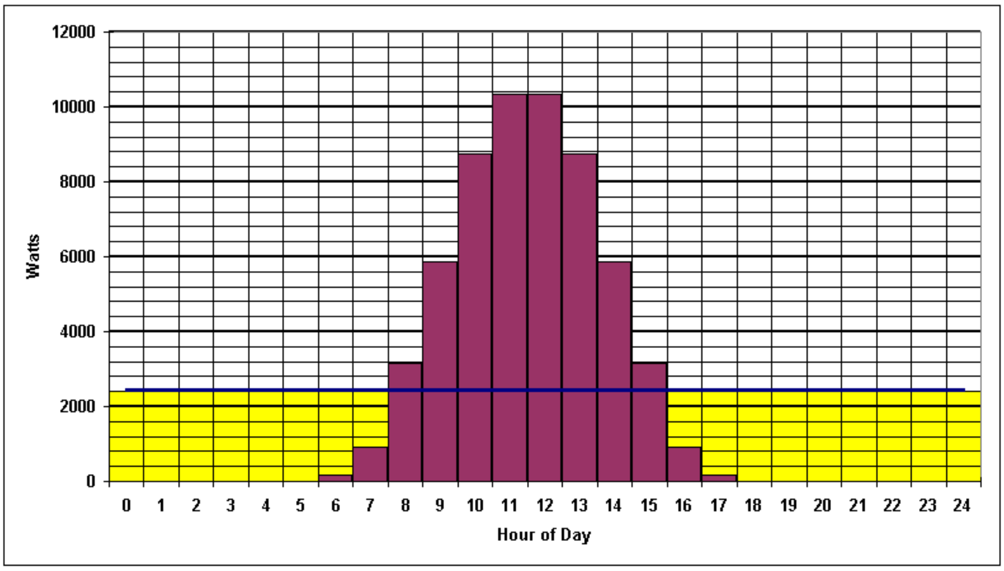

Fig. 15.23 Replotted graph showing total energy for whole collector and area where storage is necessary

The same result is obtained if the area of the solar gain histogram which is above the 2430 line is evaluated.

Each cubic metre of water weighs 1000 kg, and thus the energy stored per cubic metre per 1^0C temperature rise is 4.1868 MJ [this is specific heat of water from data book).

Thus with 25^oC temperature range, the volume required = 132.192 / 4,1868 / 25

= 1.34 cubic metres.
================

This example shows the result when the heat loss is steady. In the case of heating hot water by solar energy, the usage will be far from constant, but the same basic method may be applied. Perhaps the easiest way to tackle such a problem is to start at midnight and work out the cumulative gain over the day making allowance for use. This represents the net energy in storage. If the collector area is sized correctly then when the end of the day is reached there should be no energy remaining in storage. The maximum positive value of storage during the day represents the maximum energy to be stored, and from this the maximum storage volume can be ascertained.

16. WIND ENERGY

16.1 Introduction - theory

Energy from wind is obtained by extracting KINETIC ENERGY of wind.

$$\mathbf{K.E.} = \frac{1}{2}\mathbf{m}\mathbf{V}^2$$

where V is velocity of wind,, and m is mass of air

but mass of air flowing through blades in 1 sec.

= density x area x distance travelled in 1 sec.

$$= \boldsymbol{\rho}\ \mathbf{A}\ \mathbf{V}$$

where **A** is the area swept by the blades,
and **ρ is the density of air**

Thus $\mathbf{K.E.} = \frac{1}{2}\boldsymbol{\rho}\mathbf{A}\mathbf{V}.\mathbf{V}^2 = \frac{1}{2}\boldsymbol{\rho}\boldsymbol{\pi}\mathbf{R}^2\,\mathbf{V}^3$ **............ (1)**

Equation (1) is the theoretical amount of energy present in the wind.

HOWEVER, this assumes that all the air is brought to a standstill, which it can't be otherwise the air would pile up.

The THEORETICAL MAXIMUM POWER which can be extracted is 59.26% of the KINETIC ENERGY in the wind. This is also known as the ***Betz Efficiency,*** and is a theoretical limitation on the amount extracted

Practical Efficiencies reduce the amount of power extracted further.

The best modern aerofoil machines achieve about 75 - 80% of the THEORETICAL EFFICIENCY - i.e. 40 - 45% overall, but most rarely exceed 30%. Older machines such as the American farmstead multi-blade machine usually achieve efficiencies of less than 20%..

A typical Load Factor for Wind Energy Convertors is 30%, but often significantly less. Because of poor design and spacing, the load factor in California is only 20.8%

16.2 Types of Wind Machine - may be classified in three ways.

i) by type of energy provided.

a) electrical output
b) mechanical output - pumping water etc.
c) heat output - as a wind furnace
  - mechanical power is fed to turn a paddle in bath of oil or water which then heats up e.g. device near Southampton.

ii) by orientation of axis of machine

a) horizontal axis - HAWT
b) vertical axis - VAWT

iii) by type of force used to turn device

a) lift force machines
b) drag force machines

For electrical output, lift type machines are needed which have blade tip speeds several times the wind speed. The will have few blades as multiple blades increase turbulence and affect the lift. Most turbines are either 2 - or 3 - bladed, but some early designed had 4 - blades, and a few have just one blade.

Drag type machines (blade tip speeds are less than the wind speed) and are more suited to high torque applications such as water pumping / heating.)

Drag machines have a high solidity - i.e. the amount of the swept area is high. Typical examples are the multi-bladed American farmstead water pump and the Savonius rotor.

NOTE: The output from a DRAG type machine would have to be geared up by a factor of 100 and consequently very large transmission losses to be suitable for electricity generation.

16.3 Sizes of Machines for different Power outputs.

Output power of machine may be determined from equation (1).

POWER is proportional to swept area (i.e. square of blade diameter) and cube of wind speed.

		Wind Speed (m/s)	
Blade	5	10	15
diameter (m)	(kW)	(kW)	(kW)
1	0.02	0.16	0.53
2	0.08	0.6	2.1
5	0.49	3.9	13.3
10	1.96	15.7	53
20	7.85	63	212
50	49.1	393	1325
100	196	1571	5301

Output power assumes that overall efficiency of machine is 40% which is typical for latest machines..

Variation in output with height of rotor.

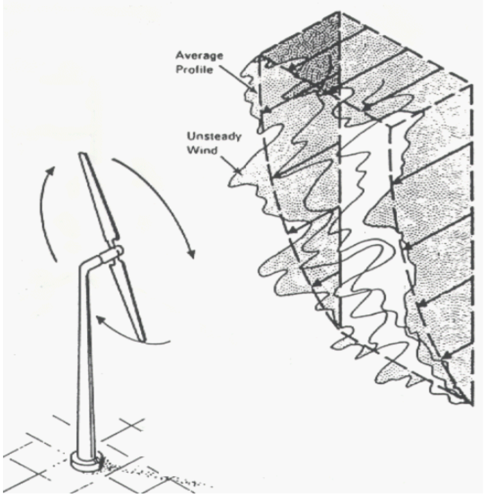

Fig. 16.1 [adapted from Cranfield University WEB site] showing variation in wind speed. Overall there is a logarithmic profile to the mean wind speed contour as shown.

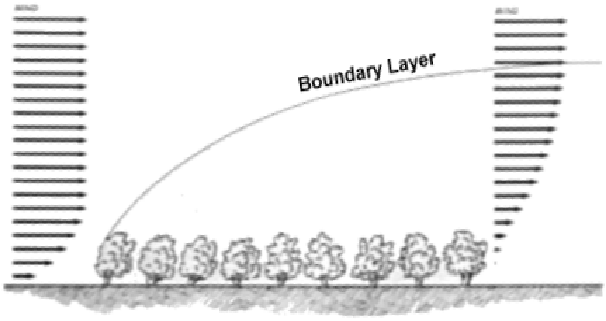

Fig. 16.2 Zone of affected wind patterns over a wood. Downwind, there can be significant change in the flow regime causing differential loading on the turbine.

Above the wind surface there is a boundary layer and the wind speed, in the absence of minor fluctuations varies in a logarithmic fashion. Fig. 16.1 shows such variation superimposed on a logarithmic profile. Thus the higher the turbine hub, the higher the wind speed, although the variation becomes less as the height increases. In the first generation wind turbines in the early – mid 1990s typical hub heights were 35 – 50m. More recently the norm has been around 70m for a 1.5 MW machine and around 90m for a 2 MW device.

Variations such as these can place severe differential loading on the blades and can lead to premature failure from fatigue. In the 1980s between 5 and 10% of the 10 000 turbines (i.e. 500 - 1000 turbines) of the turbines installed in California were showing severe signs of fatigue.

It is thus undesirable to site turbines close to areas where turbulence is likely to be significant - e.g. downwind of an urban areas or woods.

24,4 Nature of Wind Speed data for Wind Energy Predictions

Though estimates of wind speed on a 1km x 1km square basis are available, they are average values over a long period and can only give approximate estimates of output. The Uk National Database has mean annual windspeeds at 10m, 25m, and 45m for each 1km x 1km square across the whole of the UK. Thouhg such data may be used in initial planning, ideally, hourly readings over a period of a year are needed at the development stage of any project.

However, the a serious problem with the data can arise from the way in which the data is averaged. The following data shows the mean wind speed as measured on an hourly basis.

The mean wind speed for the 24 hour period is 5.5 metres per second.

On the other hand the output from a wind turbine depends on the cube of the wind speed, so more correctly in determining the effective mean wind speed we should first cubed the wind speed, determine the mean of the cubes and then take the cube root. In the example shown, the effective wind speed now becomes 6.14 metres per second,

When we compare the output using the original figure of 5.5 m/s with the revised figure, there is a difference of just under 40% i.e. the true output is nearly 40% greater than that determined from the crude mean.

Table 16.1 Example of wind speed variation during day and two methods used to estimate mean windspead.

Time	Wind Speed m/s	cube of Wind Speed	Time	Wind Speed m/s	cube of Wind Speed
00:00	3.5	42.9	12:00	8.1	531.4
01:00	4.0	64.0	13:00	8.0	512.0
02:00	4.3	79.5	14:00	7.1	357.9
03:00	4.8	110.6	15:00	6.2	238.3
04:00	5.3	148.9	16:00	5.0	117.0
05:00	5.6	175.6	17:00	4.3	79.5
06:00	6.5	274.6	18:00	4.0	64.0
07:00	7.3	389.0	19:00	3.8	54.9
08:00	8.4	592.7	20:00	3.0	27.0
09:00	8.2	551.4	21:00	2.5	15.6
10:00	8.0	512.0	22:00	3.0	27.0
11:00	8.3	571.8	23:00	2.8	22.0

Frequently data is only available on a daily mean, or even monthly mean basis, and so estimates based on such values will often be less than the true resource.

Using the corrected mean speed as indicated above will improve matters, but it may also over-compensate. Thus wind turbines for electricity generation cannot operate below a certain cut-in wind speed - typically around 4.5 - 5 m/s, and secondly, above the design speed the blades are normally feathered so that the output is at the designed speed. Finally, in extreme gale force conditions, the turbines are shut down to prevent structural damage. Thus a better way to assess the potential output is to take frequent wind speed measurements (e.g. hourly or more frequent), and use a power rating curve to evaluate the actual power output such as the one shown in Fig. 16.3.

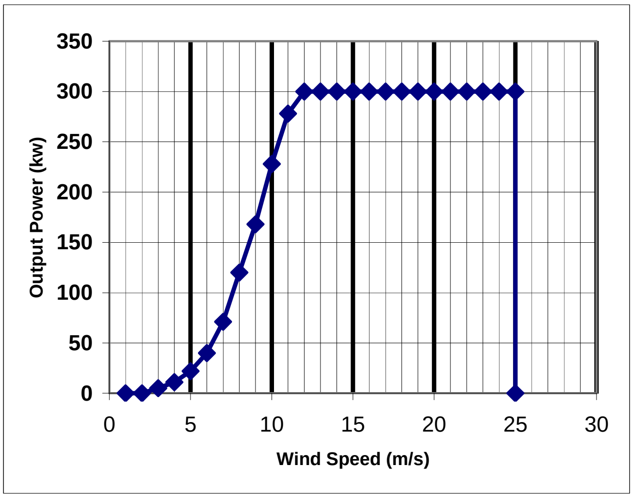

Fig. 16.3 Turbine rating Curve.

Turbines are often classified by their size, and this refers to their design output. In the example shown in Fig. 16.3 this would be 300 kW, and this output would be sustained at any wind speed between 12 and 25 m/s. Above 25 m/s the turbine would cease to operate and there would be no output. Similarly below about 3 m/s there would be no output, whereas at a wind speed of 10 m/s the output would be 228 kW or 76% of the rated output. Provided that the turbine is reliable then it should now possible to achieve a load factor of approaching 30% in the UK, although in some locations over 40% is achieved on an annual basis. On average, the figure is around

28%. Turbine rating curves for different wind turbines may be found at:

http://emd.dk/euwinet/wtg_data/default.asp

although recently (2009) it appears that this link has changed. The following link lists all the manufacturers of wind turbines and it is possible to get turbine rating curves from the manufacturers information.

http://www.windrotor.info/links/index.html

Power curves for 5 Enercon Turbines normalised to the actual rated output are shown in Fig. 16.4 while actual data values are shown in Table 16.2.

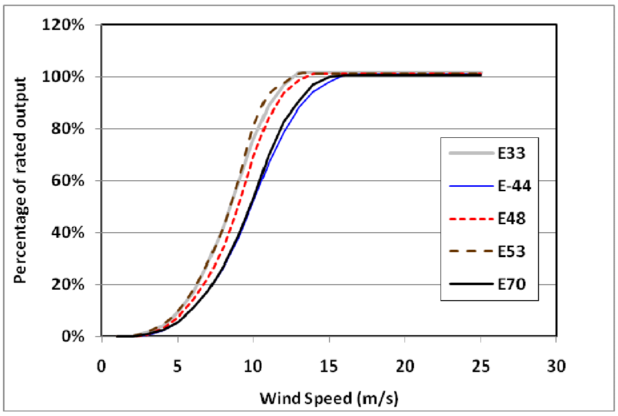

Fig. 16.4 Actual Turbine Rating Curves Normalised as a percentage of rated output for 5 Enercon Turbines.

Table 16.2 Technical details of Turbine Power Rating Curves for Enercon Turbines.

	Enercon Turbine									
Model Number	E33	E-44	E48	E53	E70	E82	E82	E82	E101	E126
Rated Power (kW)	330	900	800	800	2300	2000	2300	3000	3000	7500
Blade diameter	33.4m	44m	48m	52.9m	71m	82m	82m	82m	101m	127m
Wind Speed (m/S)										
1	0	0	0	0	0	0	0	0	0	0
2	0	0	0	2	2	3	3	3	3	0
3	5	4	5	14	18	25	25	25	37	55
4	13.7	20	25	38	56	82	82	82	118	175
5	30	50	60	77	127	174	174	174	258	410
6	55	96	110	141	240	321	321	321	479	760
7	92	156	180	228	400	532	532	532	790	1250
8	138	238	275	336	626	815	815	815	1200	1900
9	196	340	400	480	892	1180	1180	1180	1710	2700
10	250	466	555	645	1223	1580	1580	1580	2340	3750
11	292.8	600	671	744	1590	1810	1890	1900	2867	4850
12	320	710	750	780	1900	1980	2100	2200	3034	5750
13	335	790	790	810	2080	2050	2250	2480	3050	6500
14	335	850	810	810	2230	2050	2350	2700	3050	7000
15	335	880	810	810	2300	2050	2350	2850	3050	7350
16	335	905	810	810	2310	2050	2350	2950	3050	7500
17	335	910	810	810	2310	2050	2350	3020	3050	7580
18	335	910	810	810	2310	2050	2350	3020	3050	7580
19	335	910	810	810	2310	2050	2350	3020	3050	7580
20	335	910	810	810	2310	2050	2350	3020	3050	7580
21	335	910	810	810	2310	2050	2350	3020	3050	7580
22	335	910	810	810	2310	2050	2350	3020	3050	7580
23	335	910	810	810	2310	2050	2350	3020	3050	7580
24	335	910	810	810	2310	2050	2350	3020	3050	7580
25	335	910	810	810	2310	2050	2350	3020	3050	7580

Data from:
http://www.enercon.de/www/en/broschueren.nsf/vwwebAnzeige/15686F537B20CA13C125719400261D37/$FILE/ENE_Produktuebersicht_eng.pdf

16.5 Arrays of Turbines in a Wind Farm

It is easy to estimate the output from a single wind turbine using the rating curve, but interactions between turbines occurs when they are clusters in a wind farm. If the wind is predominantly uni-directional, then they may be sited in rows at right angles to the wind direction (e.g. the Altmont Pass in California), but more often the interactive effects must be considered. Turbulence from one machine can affect neighbouring ones, and particularly those downwind.

Johansson et al (1993) give a table showing the effects of clustering .

Table 16.3 Reduction in output arising from Park Effect.

Array Size	5D spacing	7D spacing	9D spacing
2 x 2	87	93	96
3 x 4	76	87	92
6 x 6	70	83	90
8 x 8	66	81	88
10 x 10	63	79	87

The above table shows the percentage production of wind power had there been no interference between turbines. Clearly, less than 7 diameters spacings are unacceptable, and current wisdom is to use between 7 and 10 diameters as the norm. In California, many early machines were sited at 1.5 - 3 diameters, and this partly explains the very poor load factors.

One reason why the load factor at Blood hill is inferior to that at Somerton is because of park effects because of the proximity of the one turbine to another.

16.6 Examples of Early modern Wind Devices.

A 1.25 MW machine was installed in Vermont in 1941, but was taken out of service when one of the 7 tonne blades broke off and flew 1/2 mile. A 60 kW device was installed in UK in 1956 but later abandoned. A 125 kW machine at Tvind in Denmark was installed in 1958 and provided energy needs for a School as well as surplus for the neighbouring community. .

In California, and other parts of States (e.g. Hawaii), wind farms have been established mostly as a result of tax incentives. Problems with blade fatigue have occurred, and most have had to have blades renewed. Some turbines have had a build up of insects on the blades which have caused the turbines to consume energy rather than generate energy.

Because of the sudden investment, many mistakes were made and the whole wind energy development nearly collapsed through people understanding the economic advantages from tax credits, but had no idea on how to site turbines or how build ones which operated reliably etc. In the early years there were many days when large numbers of machines in California were not operating despite sufficient wind, because of failure/poor maintenance,

Some very large early machines, although performing very well, and are economical in both land area and efficiency suffered from difficulties when failures occured. For example, on Oahu (Hawaii), just the cost of hiring a large crane for the week of maintenance during the early 1990s cost as much as the value of the total output of electricity for a whole year. On top of that had to be added the cost of the replacement gear box.

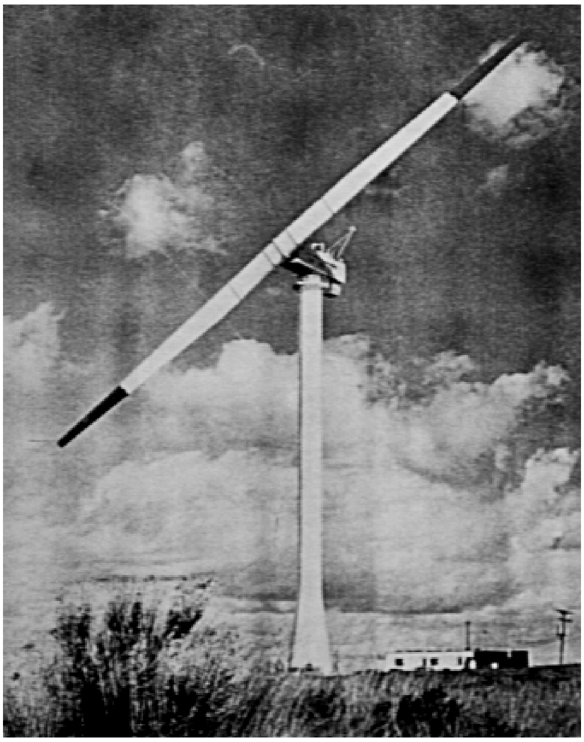

Fig. 16.4 An early 2.5 MW Wind Turbine in Hawaii. The blade diameter is over 90m.

The largest wind turbines ever built by the mid 1980s was in the Orkneys on Burgar Hill. This was a 3 MW device with a blade diameter of just under 100 m

Until 1990 there were few other wind turbines in UK, the most notable being:-

- three in Orkneys including one 3MW device - largest in world
- one 1 MW device at Richborough Power Station,
- 30 kW machine at Boroughbridge,
- one of 150 kW size near Southampton.
- odd ones in Cornwall
- four of different designs at Carmarthen Bay, including 2 vertical axis machines. [these were blown up by National Power in 1994]
- several 5-15 kW devices, and numerous 50-200W devices.

In the early 1990s several wind farms were developed, them ost notable being Delabole in Cornwall, Llandinam in mid-Wales where there were no fewer than 103 x 300kW devices, and Blood Hill (1992) in Norfolk where there are 10 x 2225kW devices..

A constraint in the development of larger turbines was the limited availability of suitable cranes and also the transportation difficulties for the long blades to the sites. It is interesting to note that near to the 10 Blood Hill turbines is a single 1.5MW Enercon turbine installed in 2003 and that single turbine generates more electricity thatn the 10 combined even though their aggregate rated output is 50% larger.

Figure 16.5 shows an Enercon E126 turbine, the largest yet installed with a rated capacity of 7.5 MW a rotor diameter of 127m and a hub height of 135m. This was a single test machine.

It should be noted that all Enercon machines unlike others have a directly coupled generator thereby eliminating the need for a gearbox. This reduces the weight at the hub, reduces gearbox noice and also maintenance. The electricity is generated at the frequency consistent with the rotation speed of the turbine and is then converted into DC and then back to AC to match the frequency of the Grid.

Fig. 16.5 An Enercon E126 wind turbine – the largest yet built with a rated output of 7.5MW, a rotor diameter of 127m and a hub height of 135m.

16.7 Expansion of Wind Power in UK.

During the 1990s, Wind Energy Development was supported in the UK by a feed in tariff mechanism under the Non Fossil Fuel Obligation. Since 2002, the support has been via the Renewable Obligation since when the installation has increased rapidly reaching 1085.63 MW of new installation in 2009. In autumn 2008, the UK overtook Denmark in having the largest capacity of offshore wind of any country.

Currently the largest onshore wind turbine is the 2.75 MW turbine, named Gulliver, situated at Ness Point in Lowestoft – see Fig. 16.6).

Fig. 16.6 Largest onshore wind turbine (2.75 MW) in UK at Ness Point, Lowestoft, although this will shortly be surpassed with 3MW machines becoming common.

Currently (May 2010) there are 2896 turbines installed with a total rated capacity of 4531.94MW. In the same month the total installed capacity of offshore wind exceeded 1GW at 1041. 2MW. Also in the same month there were 1452.6MW of offshore wind capacity under construction and a further 2334.4MW of onshore capacity.

Both the Non Fossil Fuel Obligation and the Renewable obligation will be covered in the Regulation Module later in the year. Fig. 16.7 shows the build up of wind capacity over the last 20 years while Fig 16.8 shows the current projections for the future based on known plans.

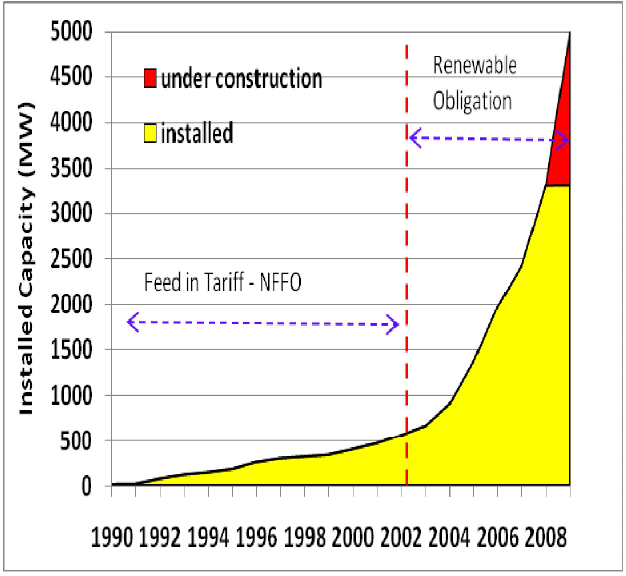

Fig. 16.7 Wind Capacity in the UK to date

The size of offshore wind turbineshas also been increasing and two turbines both of 5MW capacity have been installed offshore in North East Scotland (Beatrice). This is a European Demonstrator Project with the hub height at 88m, and the blade diameter of 126m.

Details of this project can be seen at the following WEB address

http://www.beatricewind.co.uk/Uploads/Downloads/Scoping_doc.pdf

Table 16.4 shows the current status of operating Wind Energy Projects in Europe.

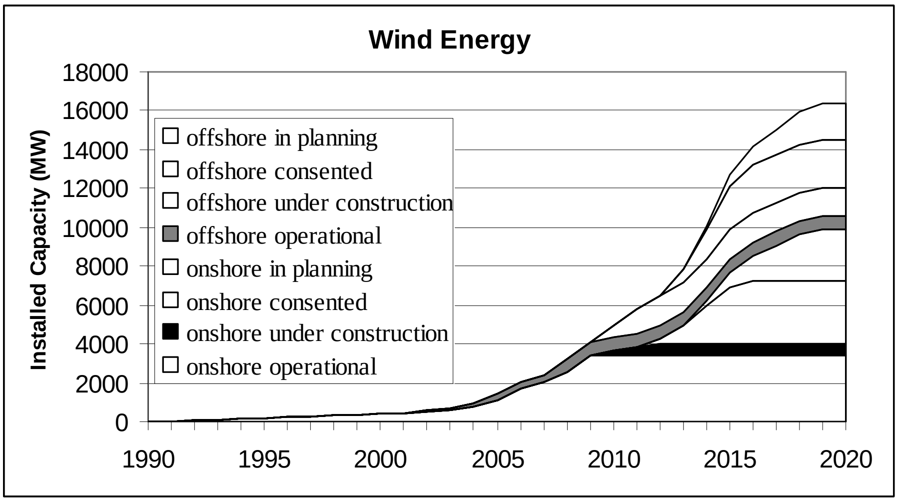

Fig. 16.8 Winbd Capcity in UK and projected capcity. For those under construction it is assumed that they will be fully operational within 2 years of construction start. For those for which consent has been received, it is asssuemd that only 80% of projects will actually be built and that construction will start in next 2 – 3 years and will be phased over 3 years. For those in planning, it is assumed that only 50% of those currently in the planning system will actually be built'

Table 16.4 Installed Capacity in Europe (May 2010)

	Installed in 2009 (MW)	Current Capacity May 2010 – (MW))	Offshore Wind capacity (MW)
Austria	0	995	
Belgium	149	563	
Bulgaria	57	177	
Cyprus	0	0	
Czech Republic	44	192	
Denmark	334	3,465	409.2
Estonia	64	142	
Finland	4	146	
France	1,088	4,492	
Germany	1,917	25,777	44.5
Greece	102	1,087	
Hungary	74	201	
Ireland	233	1,260	520
Italy	1,114	4,850	
Latvia	2	28	
Lithuania	37	91	
Luxembourg	0	35	
Malta	0	0	
Netherlands	39	2,229	228
Poland	181	725	
Portugal	673	3,535	
Romania	3	14	
Slovakia	0	3	
Slovenia	0	0	
Spain	2,459	19,149	
Sweden	512	1,560	20
United Kingdom	1,077	4,051	1041
Total EU	10,163	74,767	2352.9

16.8 Problems cited regarding Wind Power

1) Visual Intrusion - machines will be large 80+ m high with blade diameters up to 90m.. Visiual impact is usually at the heart of all anti-wind lobbies, although they will often try to cited spurious scientific evidence as a the reason to object (see below). Visiual impact is a matter of preference, and anti-wind lobbyists would do better for their cause if they concentrated on this aspect rather than the numerous fallacious scientific arguments often claimed such as:

    i) ***What happens when the wind does not blow?*** Currently we have to deal with sudden failures of large fossil fuel plant – e.g. Sizewell B tripped in 2008 causing the loss of 1188MW within 30 seconds. This would be equivalent to 40% of our wind turbines operating under gale force conditions suddenly facing a calm within 30 seconds – somethigns which certainly does not occur with the diversity of spread. In this respect wind generation is far more resilient to fluctuations than ever conventional generation is.

    ii) ***Noise is a problem. Some people say they are as noisy as being near a jet engine.*** It is true that the noise at the nacelle approaches 100+dB, but the noise falls off rapidly and at ground level will normally be below 60dB, a figure which falls off rapidly such that at around 250m, it will be down to below 40 dB which is normally taken to be a background rural noise level. Normally planning authorities will suggest a minimum of 400m. In any case less than 400m will normally cause an increase in turbulence and so a developer would avoid such locations anyway as they would result in a reduction in output.

    iii) ***TV interference*** in local region and radio interference over a larger region, particularly if an array of machines acts as a long wave radio transmitter - may affect emergency service frequencies. However, this can be overcome using suitably located repeater stations, and is less of a problem nowadays anyway with the advent of cable and satellite chanels, and digitial signals are less affected anway compared to old analogue signals.

iv) ***Land required for a wind farm of comparable output of large fossil fuel station is large.*** While the total land area is indeed large as machines have to be spaced 7 – 10 blade diameters apart, apart from a small hard base at base for cranes and also access roads, the majority of the intervening land can be used for agriculture. There are restrictions on locations of turning the machine off in such conditions. buildings close to wind turbines for trubulence effects – see above.

v) ***Ice on blades causes problems.*** In the past, ice formation on tower and blades was a problem, see Fig. 16.9, Ice build up could cause vibration and damage the blade, or ice could fly off. [It can be shown that the distance ice may fly from a 330 kW machine can be as high as 250m]. In modern turbines there are several strategies which can be adopted, the most severe being turning the machine off inadverse conditions. However, in the winter of 2008 – 2009 ice was seen to come off a wind turbine in East Anglia.

Fig. 16.9 Ice formation on a Wind Turbine

vi) Wind Turbines kill birds. This is an over-rated issue, and hazards to birds. It is true that in some locations birds have been killed, but in many locations there is little evidence. The highest incidence rate is around 3 birds strikes per installed megawatt per year, which as a worst case scenario would imply around 9000 at present in the UK. This should be compared with around 1 million killed each year on the roads and several million who collide with other fixed structures. Thus wind turbines have far less impact on birds than other man made structures or vehicles.

16.9 Economics of Wind Power

The current cost for installation of an onshore wind turbine varies from around £800 to £1200 per installed kilowatt depending on the cost of grid connections etc. For offshore wind, the cost has risen significantly recently as the larger turbines needed are in short supply at the present time and approach £3000 per installed kilowatt.

16.10 Types of Machine - Drag devices.

These devices rely on the drag present by the sails/blades of the wind device to the wind.

a) VERTICAL AXIS DRAG DEVICES

S - SHAPED ROTOR

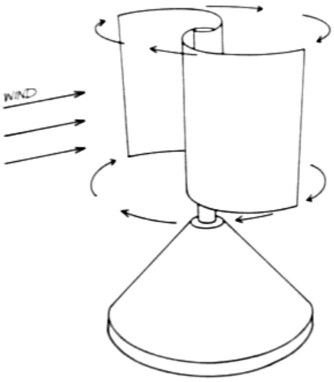

Fig. 16.10 A Savonius Rotor

In its simplest form, this device consists of two semi-cylindrical metal sheets welded together to form an 'S' shape in plan.

The concave side presents a high drag coefficient to the wind while the convex face has a relatively low drag coefficient. The device thus rotates.

It is self starting, and produces moderate torque, but the tip speed is limited to the wind speed. Efficiencies are low - typically about 10% or less.

APPLICATIONS:- water pumping, wind furnace

A variant of this device separates the two parts of the 'S' - This is the SAVONIUS MACHINE. Wind deflected by the windward cup is partly redirected to push the opposing cup. Efficiencies of this are somewhat improved - up to about 10 - 20%.

PERSIAN "TURNSTILE" DEVICE

In Iran from the 7th century AD walls were constructed across valleys, and provided with openings with vertical axis devices shaped like a turnstile. The wind pushed one sail forward while the opposing sail moving towards the wind was sheltered by the wall (i.e. its drag coefficient was low). Thus a valley was dammed to extract wind power in a similar manner to hydro power.

APPLICATION - grinding corn

b) HORIZONTAL AXIS DEVICES - RELYING MOSTLY ON DRAG

The traditional windmill was of this type with efficiencies up to 10%. The American farm wind multi-bladed device is another example. Here with careful shaping of the blades efficiencies up to 30% have been reached, but most devices have efficiencies nearer 15%.

NOTE: The forces on the blades are proportional to their area, and so the multi-bladed device has a large starting torque which makes it ideal for water pumping as it is self starting even against a pumping load. However, the multiple blades create substantial eddying and turbulence at high rotor speeds which limit the efficiency.

Horizontal axis machines must be pointed into the wind to achieve maximum output. In gale force conditions, they present very large wind loads on the supporting structure, and The multi-bladed variety must be feathered by turning the hub axis at right angles to the wind.

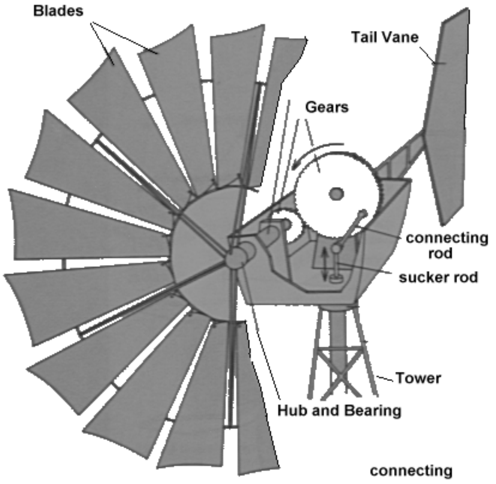

Fig. 16.11 A typical horizontal drag device used for water pumping in USA.

16.11 Lift Devices

These devices have blades which are carefully shaped into an aerofoil and rely on lift for operation (see Fig. 16.12).

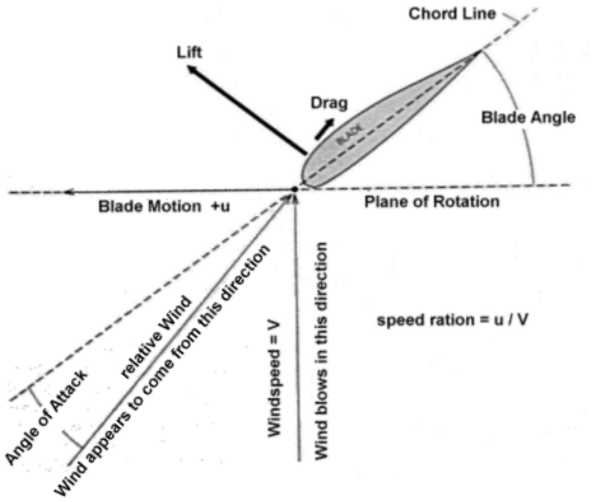

Fig. 16.12 Representation of forces acting on an aerofoil. The blade should be viewed as though the observer is above the wind turbine and looking directly down on a blade which is just reaching top dead centre.

a) HORIZONTAL AXIS LIFT DEVICES

In these devices, the axis of the machine must be pointed directly into the wind.

The blades rotate in a plane at right angles to the wind, and the relative velocity of the wind to the blade is the vectorial sum of the wind and blade velocity. IT IS THIS RELATIVE VELOCITY WHICH DETERMINES THE LIFT FORCES ON THE BLADE.

The blade is tilted at the BLADE ANGLE so that the angle of attack is optimum. Lift forces are produced by the lower pressure created on the upper side of the aerofoil and are directed at right angles to the relative wind direction.

Drag forces are also present from the friction on the blade surface and this is directed in the direction of the relative wind.

The vectorial sum of the lift and drag forces then determines whether or not the blade will continue to rotate. Thus if this relative force vector points in the direction of the blade motion, the blade will continue to rotate. If the resultant vector points in the opposite direction, then the blade will stall.

Lift to drag ratios of 50 - 100 are normal with efficiently designed aerofoils, but this ratio changes with angle of attack, and above a critical angle, the drag forces increase more rapidly than the lift forces, and thus stall conditions prevail.

To minimise turbulence and eddy currents, the number of blades must be kept low, and the starting torque of such machines is also low. To avoid slow speed stalling, the blade angles must be constantly adjusted.

Many of these devices are not self starting and need to draw power from the grid to get them going.

b) VERTICAL AXIS LIFT FORCE MACHINES

There are three types here

i) The Darrieus Rotor shaped like a three bladed egg-beater, [see front cover for a photograph].,
ii) the straight bladed Darrieus rotor
iii) the Musgrove rotor.

The Darrieus rotor is not self starting, and is very prone to stalling at slow speeds. The angle of attack of the blades cannot be adjusted, and the device is not self starting. Some devices incorporate a small Savonius rotor to start the machine, but this will limit potential efficiency because of the increased drag they cause.

The straight sided rotor is really the central part of a Darrieus rotor, but the pitch of the blades can be constantly varied during each revolution to optimise performance. Stalling is less of a problem.

NOTE: frequency of change of blade angle is much higher than for horizontal axis machines.

The Musgrove rotor (Fig 16.13) has hinged vertical blades which tilt inwards and this can be used to control speed of device and to reduce loadings during storm force conditions

16.12 Small Scale applications.

The power required by the average household is significantly larger than that likely to be provided by most small so-called “micro-wind” generators. The DIY chain B & Q did market them for installation from 2005, but there have been numerous problems with them and except when mounted on tower blocks or individually on their own mast in remote locations they usually fail to live up to expectations, some falling well short of the output expected. Of the “mini-wind” turbines – i.e. those of 6kW or above the load factor is around 10% well below that of more conventional devices.

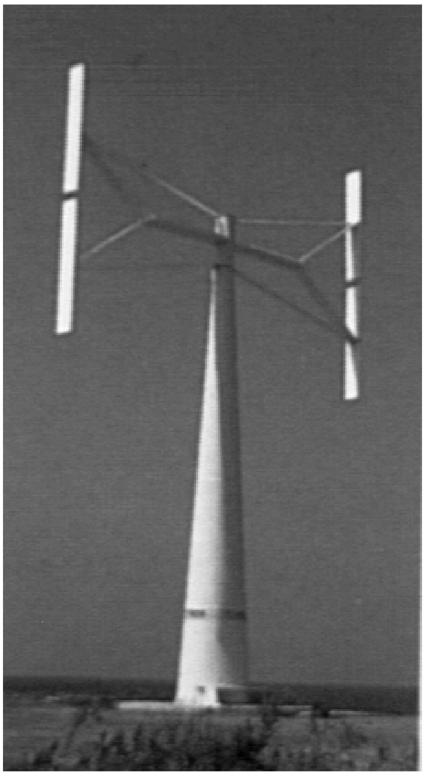

Fig. 16.13 A Musgrove Turbine

Other considerations needed for all wind turbines include:

1) safety switching - to ensure that the grid line is fully isolated should work need to be done on it,
2) the wind generator is fully protected against lighting strike surges which might damage the device,
3) considerations of costs paid for electricity exported to/imported from grid.

The above issues can significantly increase the cost of the installed devices.

16.13 A worked example for a wind turbine

Fig. 16.14 shows the rating curve for a typical 1500 kW turbine.

Estimate:

i). the annual output if the wind speed profile at the site during the year is as shown in Table 16.5.

ii). The saving in carbon dioxide emissions resulting from the operation of the turbine if the carbon dioxide emission factor for electricity is 0.5 kg / kWh

Table 16.5 Wind Speed Profile

wind speed (m/s)	days
<1	10
1 - 3	20
3 - 5	40
5 - 7	60
7 - 9	100
9 - 11	60
11 - 13	40
13 - 15	15
15 - 17	8
17 - 19	5
19 - 21	3
21 - 23	2
> 23	2

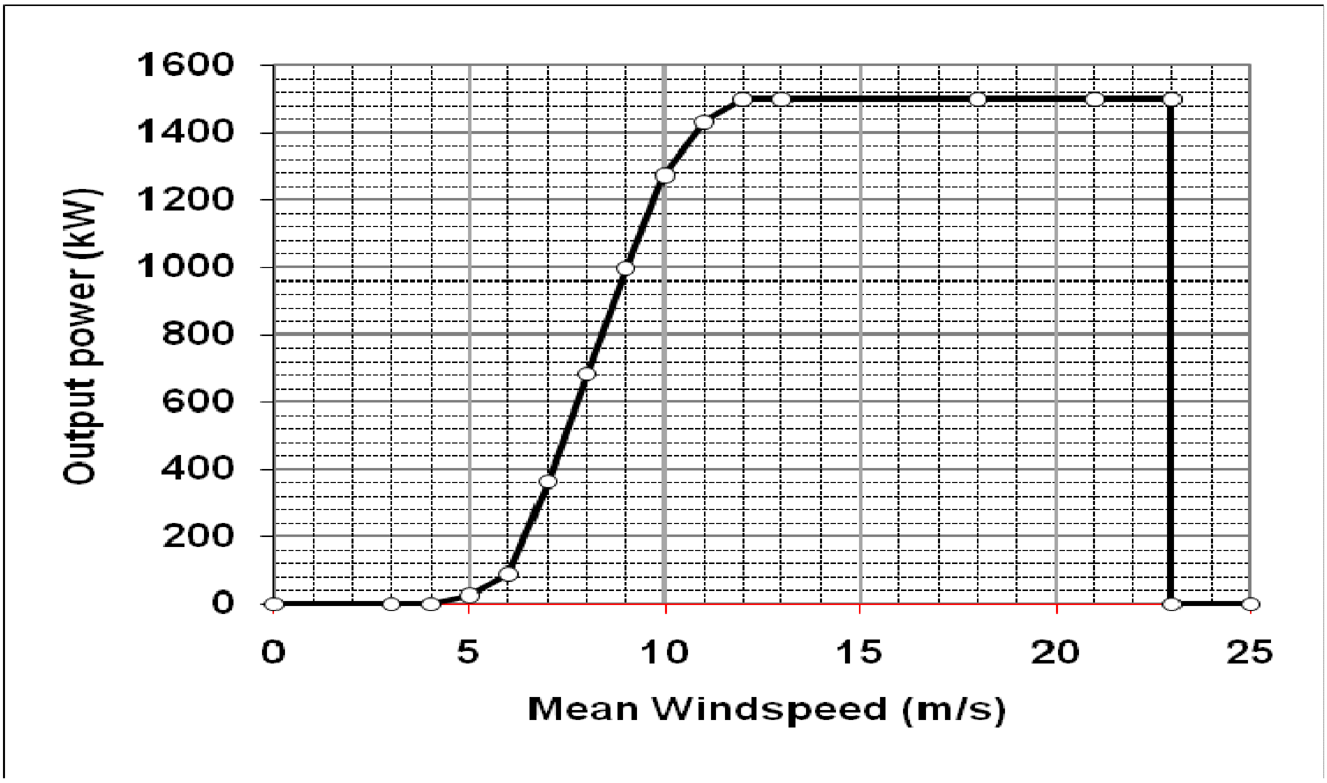

Fig. 16.14 Turbine Rating curve.

The best way to make the estimate is to do the calculations in tabular form – see Table 16.6

Column 3 is merely the mean of the range of column 1

Column 4 are values read off the gfraph for the relevant wind speed
Column 5 is the relevant output = i.e. column 2 * column 4 * 24 /1000 – the 24 is to convert to hoursw (from days) and the 1000 is to give MWh instead of kWH.

Table 16.6 Calculations for Worked Example

Wind Speed (1)	Number of Days (2)	Mean Wind Speed (3)	Output kW (4)	Energy produced MWh (5)
<1	10	0	0	0
1 - 3	20	2	0	0
3 - 5	40	4	0	0
5 - 7	60	6	90	129.6
7 - 9	100	8	680	1632
9 - 11	60	10	1275	1836
11 - 13	40	12	1500	1440
13 - 15	15	14	1500	540
15 - 17	8	16	1500	288
17 - 19	5	18	1500	180
19 - 21	3	20	1500	108
21 - 23	2	22	1500	72
> 23	2	24	0	0
TOTAL				**6217.6**

As the total output is 6217.6 MWh and 0.5 tonnes of carbon dioxide are4 displaced for each MWh generated the total carbon dioxide saved will be 6217.6 * 0.5

= **3112.8 tonnes**

In other situations, the frequency of the wind speed may be given instead of the number of days. Thus table 16.7 shows the exactly same data as in Table 16.5 but this time as percentages

Table 16.7 Wind Speed Profile shown as a percentage

wind speed (m/s)	frequency
<1	2.74%
1 - 3	5.48%
3 - 5	10.96%
5 - 7	16.44%
7 - 9	27.40%
9 - 11	16.44%
11 - 13	10.96%
13 - 15	4.11%
15 - 17	2.19%
17 - 19	1.37%
19 - 21	0.82%
21 - 23	0.55%
> 23	0.55%

Once again it is most efficient top proceed in tabuilar form – Table 16.8

Table 16.8 – Worked example when windspeed information is given as a frequenct

Wind Speed **(1)**	Mean Wind Speed **(2)**	frequency **(3)**	Output kW **(4)**	Power * frequency **(5)**
<1	0	2.74%	0	0
1 - 3	2	5.48%	0	0
3 - 5	4	10.96%	0	0
5 - 7	6	16.44%	90	15
7 - 9	8	27.40%	680	186
9 - 11	10	16.44%	1275	210
11 - 13	12	10.96%	1500	164
13 - 15	14	4.11%	1500	62
15 - 17	16	2.19%	1500	33
17 - 19	18	1.37%	1500	21
19 - 21	20	0.82%	1500	12
21 - 23	22	0.55%	1500	8
> 23	24	0.55%	0	0
TOTAL				**711**

In this approach column 5 is merely the product of the output (from column 4) and the frequency as a fraction. There is no need to multiply by 24 as in previous method. The sum of column (5) then gives the effective average output for the turbine, i.e. 711 kW. This implies that the load factor is 711/1500 = 47.4% which is on the high side, but possible.

To work out the total amount of energy produced multiply this figure of 711 by the number of hours in a years (i.e. 8760)
= 711 * 8760 /1000 = 6217.6 MWh – i.e. exactly the same as before

Note the division by 1000 is to convert from kWh to MWh.

16.14 The Future of Wind

The UK has the best wind resource in Europe and load factors significantly in excess of those being achieved in Germany are now common. In 2008 just under 1000 MW of new wind installation was completed and as this is the only technology which is currently available (other than biomass) which is technically mature and also potentially economically attractive, this will be key in reaching the target of 15% of all energy consumption to come from renewable by 2020. Indeed since non-electricity uses are likely to fall well short, the electricity target isw likely to be set at over 30% which will in trun imply the installation of at least a further 10000 MW of wind generation by 2020, or over 3 times the current installed capacity.

17. Tidal Power

Churchill No 2 Barrier, Orkney. This barrier is 620 m long and was constructed during World War II. There is a difference in tides of 1 hour 40 minutes between the east and west sides of the barrier giving the potential for a tidal barrage without much of the capital costs associated with construction and without most of the environmental problems associated with such barrages.

17.1 Tidal Power - Theory

Tides arise from the rotational motion of the earth and the differential gravitational field set up by the Earth, Moon, and Sun. The relative motions of these cause several different tidal cycles:-

1) a semi-diurnal cycle - period 12 hrs 25 mins

2) a semi-monthly cycle - (i.e. Spring - Neap Tides) corresponding with the position of the moon
3) a semi-annual cycle - period about 178 days which is associated with the inclination of the Moon's orbit. This causes the highest the highest Spring Tides to occur in March and September.
4) Other long term cycles - eg a nineteen year cycle of the Moon.

The Spring Tides have a range about twice that of neap tides, while the other cycles can cause further variations of up to 15%.

The Tidal range is amplified in estuaries, and in some situations, the shape of the estuary is such that near resonance occurs. This happens in the Severn Estuary where a tidal range at Cardiff is over twice that at the mouth of the estuary (see diagram on separate sheet).

A barrage placed across such an estuary can affect the resonance conditions, and either enhance further the potential range or suppress it. Careful modelling is therefore needed in the evaluation of any scheme.

Potential power is proportional to area impounded and the square of the tidal range. Thus about 4 times as much power can be generated at spring tides as at neap tides.

Historically most interest has been shown in Tidal Basin Schemes although in the last few years ineterst has also been shown into marine current deivces which operate in a similar manner to Wind Turbines. Such devices are described in section 17.7. There have also been ideas suggested for Tidal Lagoons which are in essence a derivative of the basin schemes. (section 17.8).

17.2 Tidal Power - Introduction to Basin Schemes

There have been tidal mills in operation for many centuries e.g. at Woodbridge in Suffolk, but only in the last 25 years have major new schemes been constructed to generate electricity.

Examples include the 240 MW Tidal Power Station at La Rance near St Malo in France, a scheme in northern USSR, and more recent schemes in China. All except La Rance are small schemes < 10 MW.

As early as 1925, consideration for a tidal barrage across the Severn Estuary was given by the Brabazon Committee. The proposal was for a barrage just seawards of the present Severn Bridge.

Subsequent schemes have favoured a more seaward barrage some as far seaward as Minehead.

Three Energy Papers on Tidal power have been written (Nos. 23, 27, and 46). The last of these is the so called Bondi Report (1981). There are also references to Tidal Power in the more recent Energy Papers 55 - 66.

Other estuaries in the UK under consideration include:-

1) Solway Firth
2) Morecombe Bay
3) The Wash
4) Humber
5) Dee
6) Mersey (recently this scheme has been promoted actively and could be the first scheme in the UK).
7) Strangford Lough

The total potential, if all sites were developed, would be to generate about 125 PJ of electricity per year, or about 16% of UK consumption.

About 147 PJ per annum (6%) could be generated by the favoured scheme for the Severn which has the second highest tidal range in the world (after the Bay of Fundy in Canada).

Tidal Basin Schmes fall into one of 5 categories.

1) schemes working on EBB flow only
2) schemes working on FLOOD flow only
3) schemes working on both EBB and FLOOD
4) Double Basin Schemes
5) Any of the the above schemes but incorporating pumping at high or low tide.

17.2.1 EBB schemes

Generation on **EBB** flow only (see Fig. 17.1) . The basin fills through sluice gates which are closed at high tide, and the water allowed to pass through the turbines as the tide ebbs.

Generation starts around 4 hours after high tide to ensure the head is large, and hence the output is greatest. Generation can be continued for up to 2 hours after low tide. Generation is possible for only one-third of time.

The water in the basin is always above mean sea level, and thus the mean water level in the basin is raised compared to conditions before the barrage is constructed..

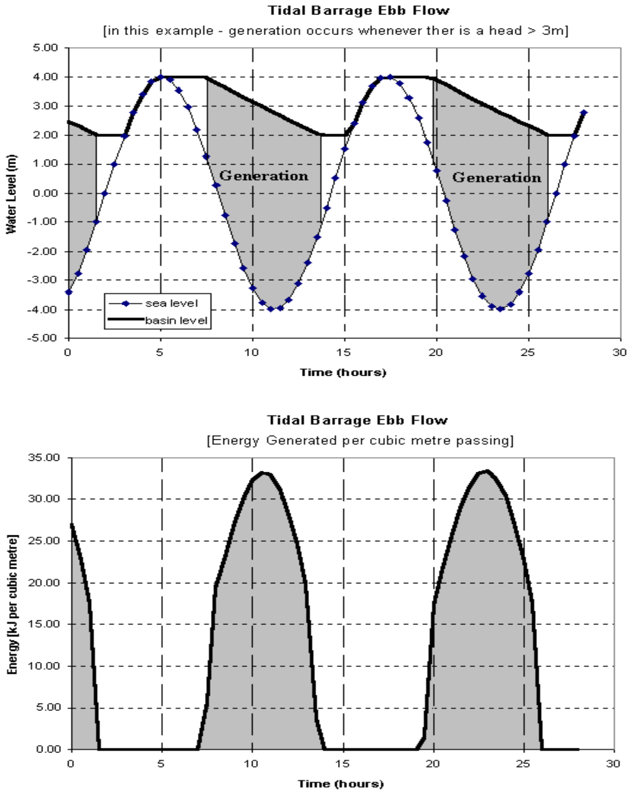

Fig. **17.**1 Generation from Tidal Power in the EBB Mode

17.2.2 FLOOD Schemes

Generation on **FLOOD** flow only. (Fig. 17.2) The basin is emptied rapidly through sluice gates which are then closed at low tide. Generation occurs as water flows in to flood the basin.

As with ebb flow schemes, generation is restricted to 4 hours in every 12 (2 hours either side of high tide).

The total energy generated would be less as less water would be able to pass through the turbines.

The mean water level in the basin would be below mean sea level, and hence would cause a hazard to shipping.

17.2.3 Two Way Generation Schemes

Two way generation on both **EBB and FLOOD**. This is a combination of the above methods (Fig. 17.3).

Generation is possible for more than 8 hours in any 12 hour cycle.

However, the total energy output is reduced as the mean height of the basin is at about mean sea level, and the effective head during generation is reduced. Also two way turbines are inherently less efficient.

Ports need relatively high water levels for shipping for at least part of the time and if, as with the Svern Barrage, there are several such ports, these would probably suffer.

The cost would be up to 20% greater than the equivalent single flow scheme.

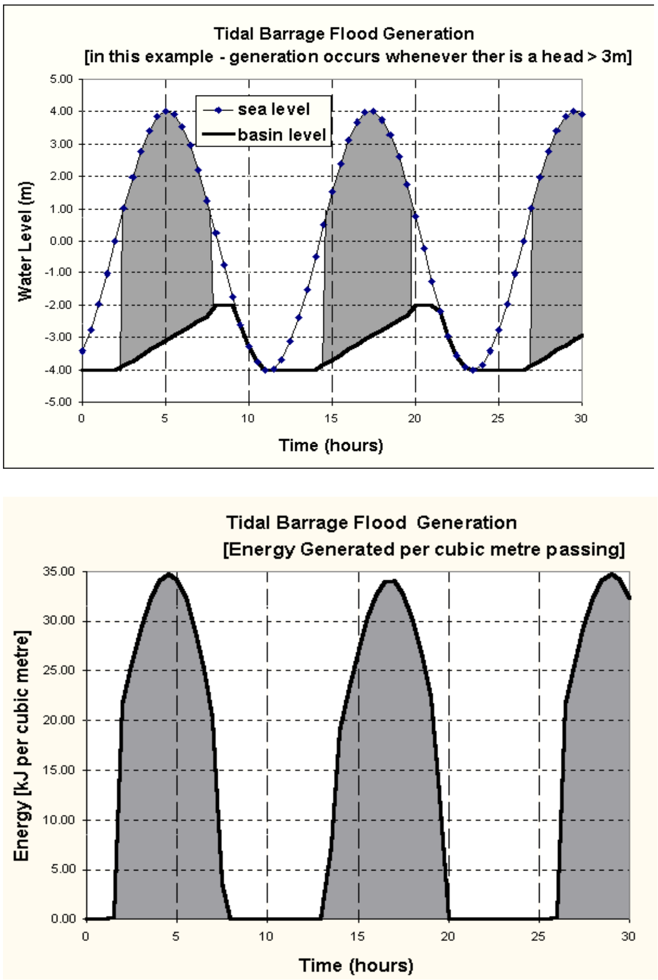

Fig. **17.**2 Generation from Tidal Power in the FLOOD Generation Mode.

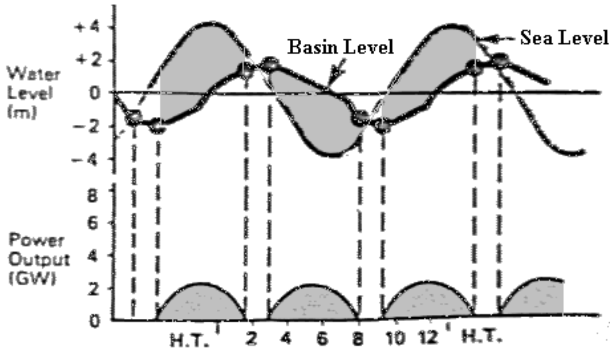

Fig. 17.3 Tidal Power - Generation on both flood and ebb.

Although generation is available for a greater part of the diurnal cycle, the total amount generated is less than in EBB mode as the mean head difference during generation is lower.

17.2.4 Double Basin Schemes

In these there are two separate basins one which fills as the tide comes in, the other empties as the time goes out. Turbines connect the two pools, and can generate power at any time. Such a scheme was proposed as one variant for a Severn Barrage (see section 17.3). However the total output may be less than a single stage EBB scheme.

A variant is to incorporate additional pumps/turbines so that the schemes may also be used as a pumped storage scheme as well as generating electricity in their own right.

17.2.5 Tidal Barrages with Pumping

Pumping can be incorporated into any of the schemes so that the head may be artificially raised (or lowered) using energy imported from the grid. Thus in EBB generation, pumping could be done for about 1 hour after high tide through a relatively small head to increase the effective head during generation. It might be thought that such pumping does not make sense as any energy used for pumping will generally be more than that obtained from the extra head provided. But as will be seen in section 17.6 where discussing La Rance, such pumping can be particularly attractive and can lead to a net energy gain.

Pumping is usually always considered for double basin schemes.

17.2.6. Turbines used in barrage schemes.

All schemes involve low and variable heads with large flow rates. Kaplan or Bulb type turbines are thus the most suitable in all schemes.

17.3 Tidal Power - The Severn Barrage Schemes

Several schemes have been considered with a variety of locations for the barrage.

Generally the schemes that have been considered can be summarised as:-

- Fig. 17.4 a single basin scheme with EBB, FLOOD or two way generatiom with the barrier between Barry and Weston Super Mare
- A Double bais schemee (Fig. 17.5) with the lower basisn following the Somerset coast.
- A single, but larger seaward barrage between Minehead and a point west of Barry.

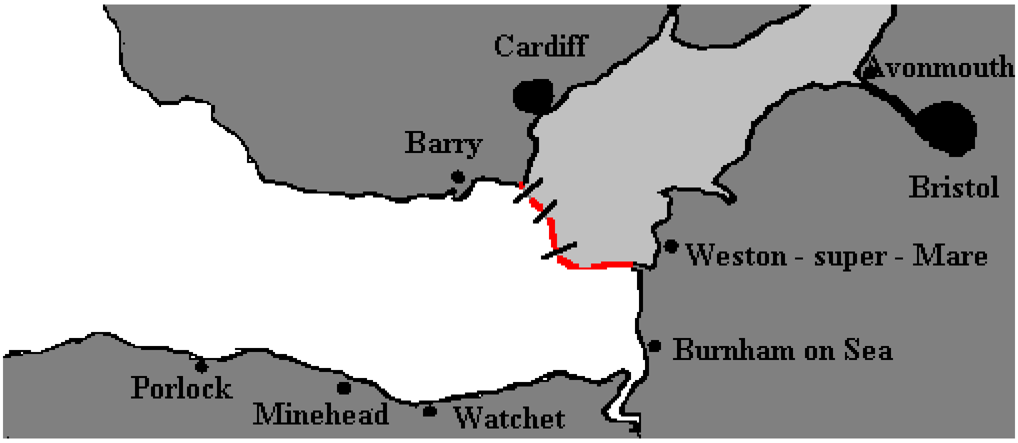

Fig. 17.4 A proposed single basin scheme

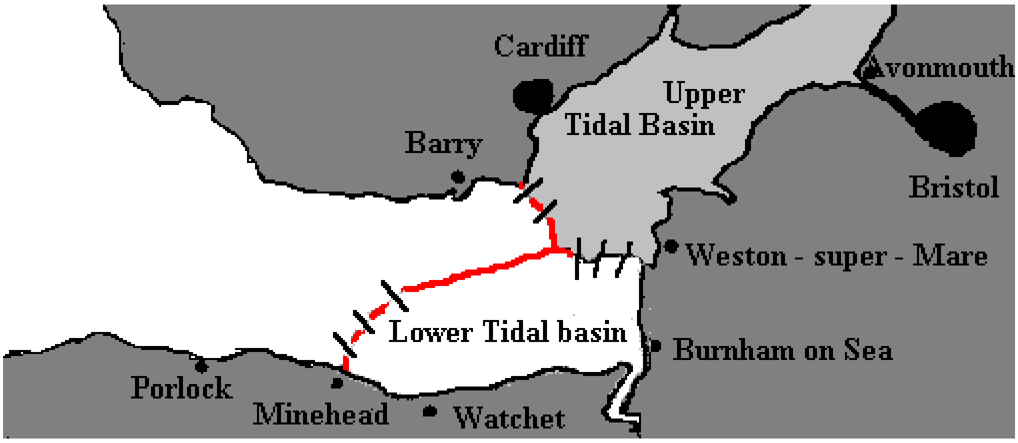

Fig. 17.5 A proposed double basin scheme. The upper basin would be filled at high tide, the lower one emptied at low tide.

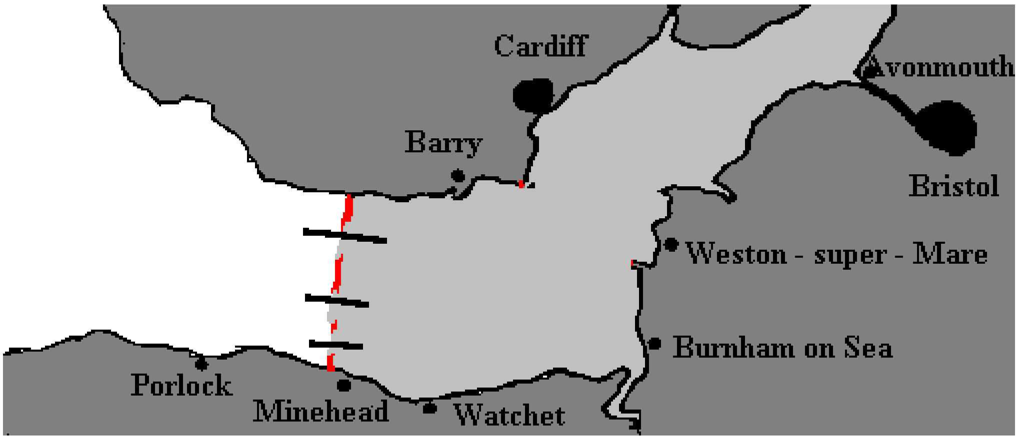

Fig. 17.6 A proposed single basis scheme. This is largest of all and would generate about 12000 MW.

After an extensive review, the Bondi Committee considered that the EBB only schemes without pumped storage were the most cost effective, and proposed three schemes:-

a) A seaward barrage near Minehead which would have an installed capacity of 12000 MW (i.e. 24% of current installed capacity, and would generated about 9% of the needs of England and Wales (Fig. 17.6).

b) An inner barrage just seaward of Cardiff which would have an installed capacity of 7200 MW (Fig. 17.4).

c) A staged scheme involving scheme (b) with the option to provide a second basin on the southern side of the estuary between Weston super Mare and Minehead.

The Bondi Committee favoured scheme (b).

Tidal Power from the Severn is predictable (unlike other renewables). However, there will be many occasions when the peak demand will occur when no power is available.

In the Bondi committee report it was estimated that an installed capacity of 7.2GW would only reduce the requirement for new fossil fuel / nuclear plant by about 1 GW because these plant would still be required to meet peak demand. Exepreince of La Rance scheme indicates that Load Factors of around 25% can be achieved – cf 20 – 40% for Wind turbines, depending on location. Tidal barrage schemes will save fossil fuel and reduce carbon emissions, but will not significantly reduce capacity requirement for new conventional stations unless pumped storage is incorporated [NKT’s comment]..

17.4 Tidal Power - Some Environmental Considerations of Basin Schems.

There are several effects which such a scheme would have including:-

1) accessibility of shipping to existing Ports
2) employment - the Severn Barrage would provide jobs for about 21000 for up to 10 years.
3) large quantities of concrete will be needed and the materials for this and the earth fill barrage will have to be shipped to site.
4) water quality in the estuary might be affected if pollutants are not dispersed so readily.
5) recreation facilities could be provided in the basin.
6) extra pumping would be needed for land drainage.
7) sea defences would be less vulnerable to attack.
8) reduced sediment transport might lead to siltation behind barrage - however, by allowing flushing during summer (or periods of low demand), much of the impact of this can be reduced more easily than for hydro schemes,.
9) some species of birds would decline (especially wading birds), but other species would probably increase. However, with the double basin scheme it is likely that the habitat for wading birds would increase.

17.5 Tidal Power - other considerations of basin schemes.

EBB generation tidal schemes would NOT increase the requirement for pumped storage schemes unless there is a high proportion of nuclear plant or if the proportion of fossil fired stations is low, or the proportion of other renewables is high.

Fossil fired plant would be used to provide firm power at times of demand with no tidal power available. However, if these stations are displaced by large numbers of other renewable resources, then the need for extra storage would increase.

During the 1980s, the CEGB were interested in Private money being spent on Tidal Schemes as large sums of money would be required - four times the capital cost of Sizewell. However, the former CEGB would NOT give a guarantee that they will purchase all or even ANY of the power at a fixed price. This makes the economics difficult to evaluate. In the new regime following privatisation, it would be even more difficult to guarantee a a purchase price unless there was legislation.

The National Grid would argue that once sources of power are available (i.e. stations constructed) the decision to use power from that source is based solely on the marginal costs (including any subsidy (e.g. NFFO), and not the capital costs. Unless there is an agreed price (as there was originally for wind under NFFO) the viability for tidal is less certain if large schemes go ahead. On other hand smaller schemes such as the Mersey might well be more viable.

Double basin schemes have an advantage in that they can enhance the storage opportunity through additional pumped storage. This aspect is not taken into account in financial considerations. Since extensive renewable energy development would necessarily lead to an increase demand for pumped storage, such an additional facility could be an added benefit and should be treated as a net economic benefit for the whole Electricity Supply System. This needs central coordination and planning to achieve..

If a double basin scheme were built, there could be further advantages by combining wind turbine generation at the site with generation as an integrated package, rather than allowing renewables to compete one with another.

17.6 La Rance scheme

The "La Rance Tidal Barrage" is situated a few kilometres upstream from St Malo at a location where the tidal range is 13.5m during Spring Tides. The enclosed basin has an area of 2200 hectares and the barrage was completed in the late 1960s. the barrage itself is 750m long and the foundations are 13 m below mean French Ordnance Datum. The barrage incorporates shipping locks and provides a dual carriageway link between St Malo and Dinard.

There are 24 units each with a maximum generation of 10 MW generating at 3500 volts which is stepped up to 225 kV for the French SuperGrid. The turbines are 4-bladed Kaplan Bulb turbines with a diameter of 5.35 m with output as follows.

TABLE 17.1 Output Power per unit for different head differences at La Rance.

	Head			
	> 9m	**7m**	**5m**	**3m**
Ebb Flow	**10**	**10**	**8**	**3.2**
Flood Flow	**10**	**9.5**	**5.5**	**2**

The generation is thus greatest in the EBB generation mode.

The barrage can operate in a one way mode, although EBB flow generation is only normally considered, or on two way flow. Overall, the output in recent years indicates a load factor of around 25%, which is higher than the 16 - 17% several text book imply.

In one way operation the sluice gates are opened on the incoming tide to fill the basin and then closed at high tide. As the tidal cycle is sinusoidal, the fall in level from high tide is relatively small in the first 3 hours, and no generation takes place. Generation will continue beyond low water as the head will still be sufficient for generation for up to 90 minutes after low water (Fig. 17.1).

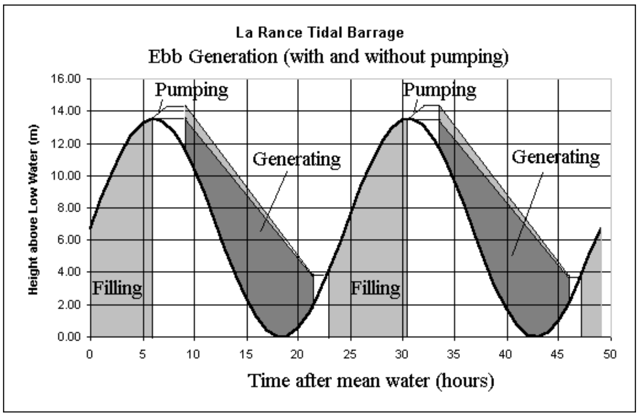

Fig. 17.7 One way operation of La Rance – incorporating optional pumping. Additional output can be obtained by overfilling basin at high tide. The head difference during pumping is less than that in generation, and hence there is a net gain in the system.

A variant of the scheme is to pump water for a period of about 1 hour after high water into the basin. Though this introduces inefficiency (~85% efficient) the head difference is small and generation can later take place over a greater head and hence this pumping arrangement is a net energy producer. Electricity for pumping is drawn from the grid, and clearly if this coincides with peak demand, no pumping will be done on that tidal cycle (Fig. 17.7).

The Two way operation which is used from time to time starts with the basin emptied with the sluice gates closed. When the tide has risen sufficiently (usually about 4 hours after low water, generation in the flood mode can occur for up to 1.75 hours. The turbines are stopped and the sluice gates opened to allow the basin to fill - with pumping if relevant. The sluice gates are closed at high tide, and generation on the Ebb tide then takes place as before except that generations ceases at low tie to allow the sluice gates to be opened to empty the basin. In theory pumping to empty the basin is possible, but cavitation problems may prevent this as the turbines must always be completely covered with water. The cycle then resumes.

In two way operation, the basin does not rise to the same level as in single way operation as the turbines form a restriction to the incoming tide. As a result, the two way generation usually provides less electricity, but the generation period is more uniformly spread over the diurnal cycle. Assume that the tidal cycle is exactly 12 hours.

17.7 Marine Current Devices

There are several regions around the coast of the UK where significant currents exists. Often these occur in narrow straits between islands – e.g. Eynhallow Sound between Mainland Orkney and Rousay, in the Fall of Warness near Eday (Orkney), the Pentland Firth, and between Cap de la Hague and Aldernay. Barrages are costly to build and several people believe they are environmentally undesirable. It is possible, in theory to construct marine current turbines which are like underwater wind turbines to harness power from the currents. Typical sizes will be 0.5 – 2MW and individual or clusters of devices can be installed. The strong currents and corrosion do mean that technical developments are still needed and the technology is probably 20 years + behind that of wind. A single demosntration scheme of 750 kW has been operating off Cornwall. The EMEC Centre in Orkney has a test site at the Fall of Warness, and it is hoped to fully commission this in mid – late 2007 with direct Grid connection. These are experimental and if successful, and if the costs could be brought down, then full scale commercial exploitation might be possible in around 10 years time or so.

. The formula to get the power from a marine turbine will be exactly the same as for a wind turbine:-

$$\frac{1}{2}\eta\pi\rho\,\mathbf{R}^{2}\mathbf{V}^{3}$$

where η is the efficiency (typically around 40% for the best machines)
ρ is the density of sea water which may be taken as 1070 kg m-3
R is the radius of the area swept
V is the wind velocity.

Typically the diameter of the blades should not be more than 50% of the water depth and it makes sense to have all turbines in an area of the same diameter. That means the size will be dictated by the minimum depth of water where the turbines are to be installed. The density of sea water is nearly 1000 times that of air, and so even though the velocity is much less, significant output is potentially obtainable from devices with blade diameters from about 10 m upwards. For a 0.5 MW device a blade diameter of around 20m is required in a current of 2 m s^{-1}, whereas for a windturbine of equivalent output a 40 m blade diameter with a wind speed of 12 m $^{s-1}$ is required.

Because the current speeds are relatively low (in normal generation terms), it would not make sense to attempt to generated in synchronism with the mains. Instead consideration is likely to be given to generating with DC and then inverting to AC when the power comes ashore.

Marine Current Turbines will have to work in a harsh environment and technical problems such as offshore and underwater maintenance still need to be addressed.

17.8 Tidal Lagoons.

A relatively recent development in Tidal Power has been the development of the Tidal Lagoon principle. Unlike the Tidal barrage, for which there is already a full scale operational device at La Rance, and several individual tidal stream devices, there is no operating Tidal Lagoon scheme. Whi8le the Tidal Lagoon does offer a considerable potential it has yet to be tested, and unlike the tidal stream devices which can be constructed in modular form, the lagoon requires the construction of very large devices which will not only be a long time in construction, but also have significant initial investments in embodied energy and associate carbon in the construction phase. While in the long term there will be a significant saving tin carbon, the initial heavy carbon outlay is an issue which must be addressed, and may require a significant phasing (and consequential limit on the rate of deployment) of such schemes if there is not to be a significant increase and overshoot in carbon emissions in the criticval period between now ond 2017.

A tidal lagoon requires the construction of a large barrier to enclose a large tidal area. Unlike a barrage this is not connected to land, and is located in relatively shallow areas in tidal esturaries such as in Swansea Bay in the Severn Esturary.

A barrier some 90 miles long would be constructed with the requirement of some 200 million tonnes of aggregate. This would create an artifical basin from which both flood and ebb generation is possible (probably supported by pumping).

It is probable that the lagoon wmight be built in stages, but until a complete section is isolated from the main estuary, no generation can take place and this is a disadvantage compared to tidal stream edevices. A normal tidal barrage would require only around 7 – 10% of the amount of aggregate, and this should be somewhat quicker to construct and start recover the benefits.

It is claimed that a laod factor of 61% might be achieved, which is high for renewable generation, although experience with other technologies suggests that such levels are unlikely to be achieved in the early schemes. However, if it does then there could be significant advantages.

Perhaps the best aspects of such lagoons is, like the double basin scheme for barriers the potential ability to provide a level of pumped storage, particularly if multiple basins schemes are used.

17.10 Consultation on Severn Tidal Schemes January – April 2009

In January 2009, the new Department of Energy and Climate Change launched an extensive public consultation relating to several different proposed schemes for extracting energy from the tides in the Severn Estuary. The consultation may be consulated at:

http://severntidalpowerconsultation.decc.gov.uk/

Essentially there are 5 separate barrage schemes, several lagoons, some of which are connected to land, and two tidal fence schemes. These are summarised in the following:

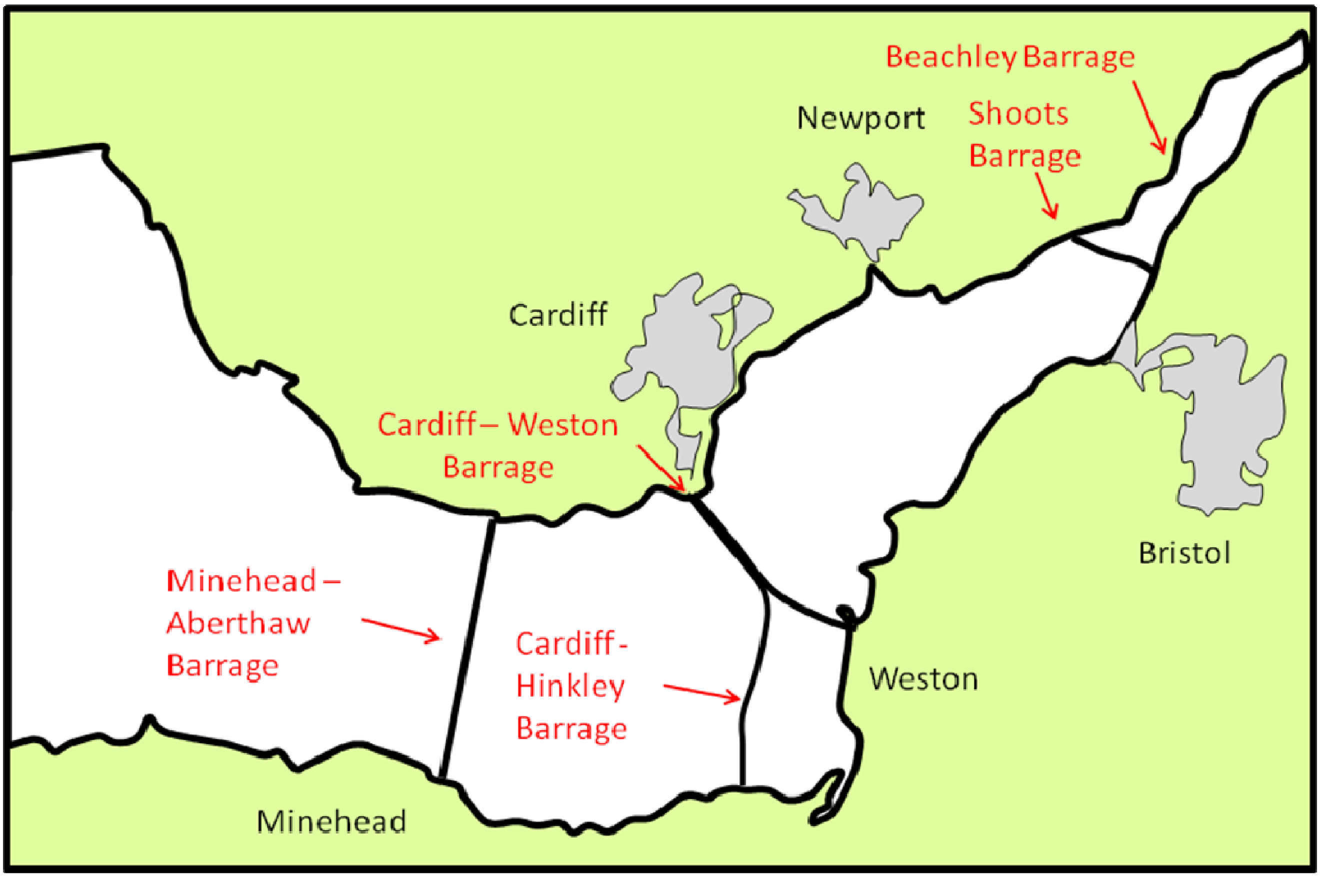

Fig. 17.8 Proposed Barrier schemes in the 2009 consultation

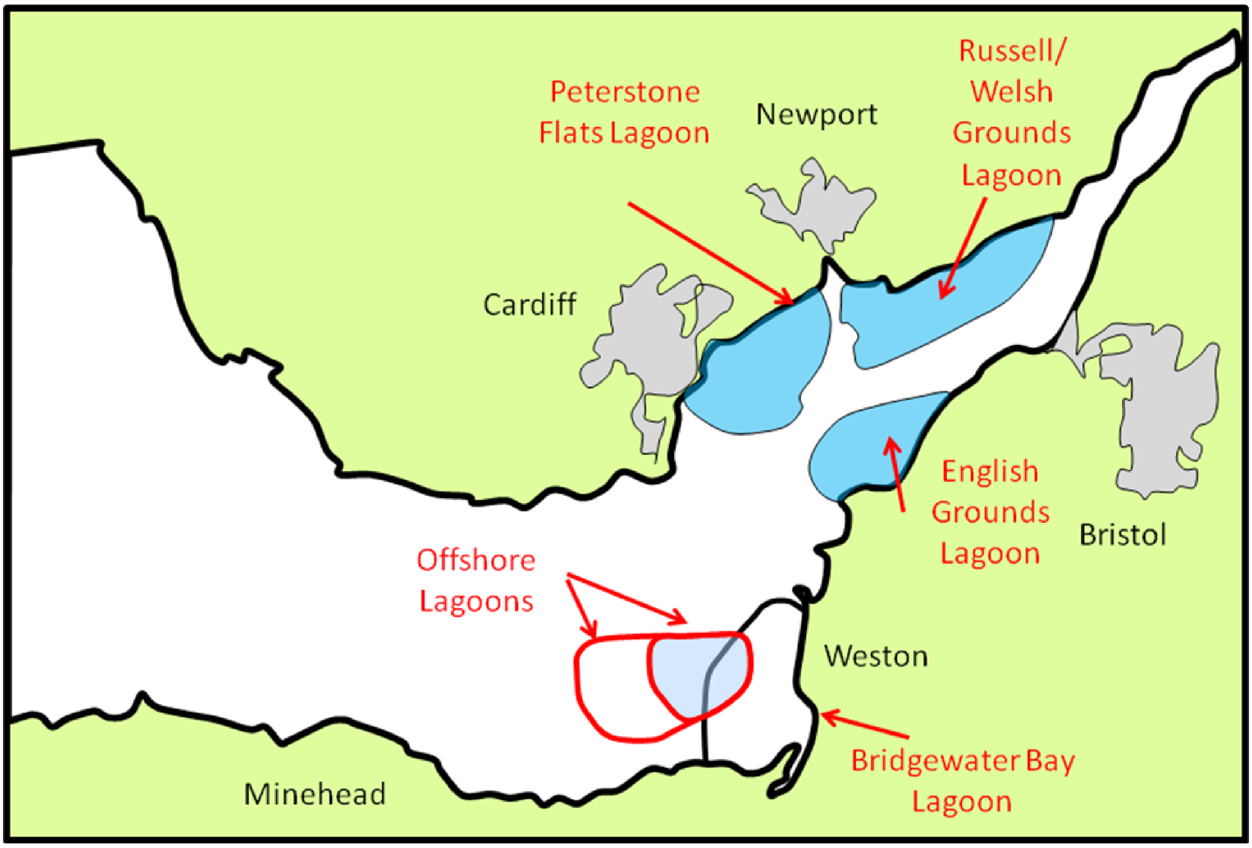

Fig. 17.9 Proposed Lagoon schemes in the 2009 consultation

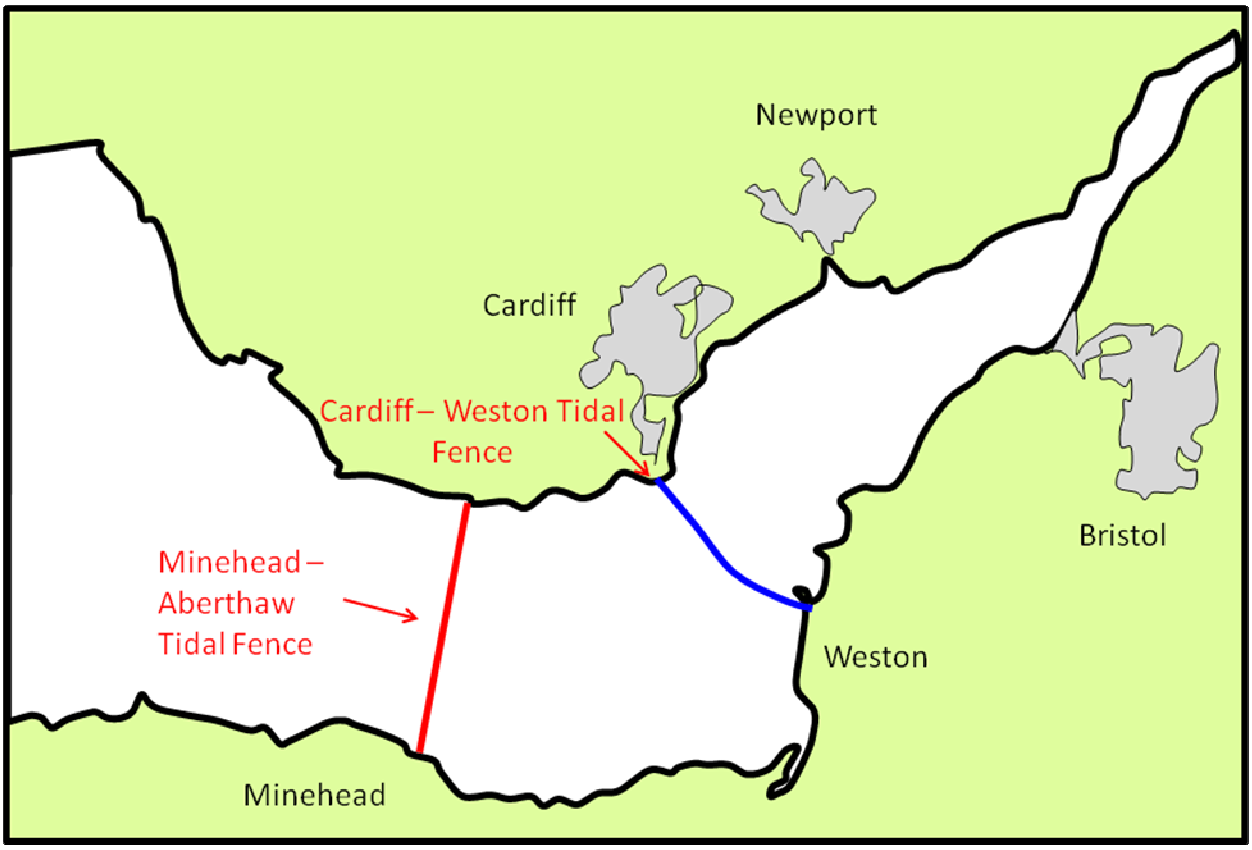

Fig. 7.10 Proposed Tidal Fence Schemes in the 2009 consultations.

Table 17.1 Comparison of different schmes

		Installed capacity MW	Annual Generation TWh	Earliest operation	capital cost £bn	Cost per unit p/kWh
B1	Outer Barrage from Minehead to Aberthaw	14800	17.3	2022	29	7.3
B2	Middle Barrage from Hinkley to Lavernock Point	~9950	19.3	2021	21.9	7.82
B3	Middle Barrage (Cardiff - Weston)	8640	16.8	2020	18.3	7.39
B4	Inner Barrage (Shoots Barrage)	1050	2.77	2019	2.6	6.69
B5	Beachley Barrage	625	1.59	2018	1.8	8.21
F1a	Tidal Fence (Cardiff - Weston)		0.7	?	4.4	40.47
F1b	Tidal Fence (Minehead -Aberthaw)		3.3		6.3	14.33
L3a	English Grounds Tidal Lagoon		1.41	2018	3.1	11.35
L3b	Welsh Grounds Tidal Lagoon	1360	2.31	2019	2.6	11.27
L3c	Peterstone Flats	1120	2.33	2019	3.3	9.03
L3d	Bridgewater Bay	1360	2.64	2020	3	8.29
L3e(i)	Offshore Tidal Lagoon 1	1360	2.6	2020	5.8	12.86
L3e(ii)	Offshore Tidal Lagoon 2	760	1.32	2019	3.5	15.05

- Tidal Fences are unknown technology so uncertainty over operation date.
- For comparison Sizewell B generates ~8.0 TWh per annum.
- Data do not consider potential advantages of double barrier scheme with pumped storage – something which will be needed with more renewables

NOTES:

- In 1979, construction of Dinorwig Pumped Storage Power station (1800 MW) was started and cost £0.45bn
- Compared to January 1979, the RPI in Jan 2009 was 399.89, i.e. prices were 4 times those in 1979. Thus the cost of similar station today would be £1.8bn or £1m per installed MW.
- If 50% of capacity were available as pumped storage, the Minehead – Aberthaw basin if made a double basin would provide same capabilities as spending £7bn elsewhere on alternative pumped storage and is thus a net benefit to the scheme.
- Such additional spending will be needed in future with increased renewable generation such as wind
- A holistic approach is needed

  See http://www.independent.co.uk/opinion/letters/letters-tidal-power-1517932.html
- See http://severntidalpowerconsultation.decc.gov.uk/ Where more details of schemes may be found

17.10 Numeric Example of a Tidal Barriers.

The following are two numeric examples of how an assessment of tidal energy may be made. On the Energy Field Courses in 1999 and 2001 estimates were made of the potential of the Race of Aldernay between Cap de la Hague and Aldernay, while in 2005, and 2007, barrier and tidal streams in Orkney wefre examined.

17.11 Example of an existing Tidal Barrage where there is a tide height difference – e.g. Churchill Barriers, Orkney.

A man made causeway is built joining two islands. After construction it is found that there high tide on the east is 3 hours before high tide on the west.

The tidal heights are shown in the following table and graph

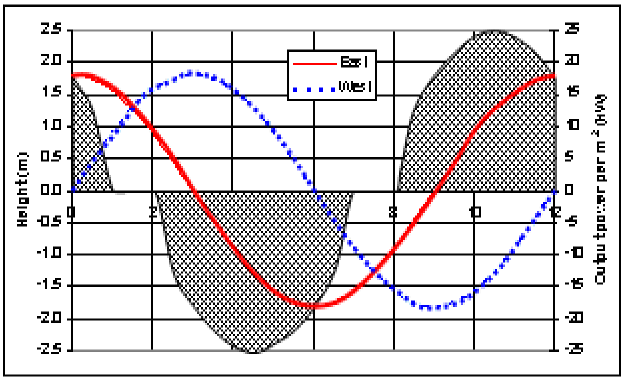

Fig. 17.10 Tidal heights on two sides of causeway – example approximates to the Churchill Barriers in Orkney.

Table 17.2 Tuide heights on either side of Causeway

Time relative to east side (hrs)	*Height on east side (m)*	*Height on west side (mj)*
0	*1.80*	*0.00*
1	*1.56*	*0.90*
2	*0.90*	*1.56*
3	*0.00*	*1.80*
4	*-0.90*	*1.56*
5	*-1.56*	*0.90*
6	*-1.80*	*0.00*
7	*-1.56*	*-0.90*
8	*-0.90*	*-1.56*
9	*0.00*	*-1.80*
10	*0.90*	*-1.56*
11	*1.56*	*-0.90*
12	*1.80*	*0.00*
13	*1.56*	*0.90*

The shaded area shows the output for each cubic metre flowing through the turbine [thisshaded area is shown for information only].

Estimate the daily electricity production and the mean power produced if a turbine with a diameter of 4047mm is inserted into the causeway. Power can be extracted whenever the height difference between the two sides of the barrier exceeds 0.9m. The density of sea water is 1070 kg m^{-3}, and the efficiency of the turbines is 80%.

First work out the height difference in column 4 and then the effective height in column 5. Whenever the height is less than the critical 0.9m there is no generation available. The shaded columns are direct copies from the data. Notice the data are symmetric and many values are the same value (or same value but opposite sign).

Table 17.3 Worked Exampel of Tidal Energy

Time relative to east	Height east	Height west	Height differ-ence	Effective Height	Velocity	Cube of velocity
	(m)	(m)	(m)	(m)	(m/s)	
0	1.80	0.00	1.80	1.80	5.94	209.87*
1	1.56	0.90	0.66	0.00	0.00	0.00
2	0.90	1.56	-0.66	0.00	0.00	0.00
3	0.00	1.80	-1.80	-1.80	5.94	209.87
4	-0.90	1.56	-2.46	-2.46	6.95	335.08
5	-1.56	0.90	-2.46	-2.46	6.95	335.08
6	-1.80	0.00	-1.80	-1.80	5.94	209.87
7	-1.56	-0.90	-0.66	0.00	0.00	0.00
8	-0.90	-1.56	0.66	0.00	0.00	0.00
9	0.00	-1.80	1.80	1.80	5.94	209.87
10	0.90	-1.56	2.46	2.46	6.95	335.08
11	1.56	-0.90	2.46	2.46	6.95	335.08
12	1.80	0.00	1.80	1.80	5.94	209.87*
					Σ	**2179.8**

Now water flowing through turbine, must show continuity

i.e potential energy of head difference = kinetic energy flowing thorugh turbines

i.e. $mgh = 0.5\, m V^2$

or $V = \mathrm{sqrt}(2\, g\, h)$

where g is the acceleration due to gravity = 9.81 m s^{-1}

Hence enter the values of velocity as computed in the manner outlined above in column 6. Notice you should disregard the –ve sign in these calculation as this merely implies two way flow. This will be the velocity of the water through the turbine.

Note the values of 209.87 in the last column for periods 0 and 12 should be halved as the values at all other hours represents a full hour period whereas that at 0 and 12 relate to just 30 minutes.

Now by continuity

the mass passing per second = density x volume
= density x velocity x cross section area
$= \boldsymbol{\rho V \pi R^2}$

and kinetic energy = $\mathbf{0.5\, m\, V^2}$ multiplied by efficiency

so energy available = $\boldsymbol{0.5\, \eta\, \rho\, V\, \pi R^2\, V^2 = 0.5\, \eta\, \rho\, \pi R^2\, V^3}$

substituting values for **η, ρ, π and R**

i.e. $\mathbf{0.5 * 0.8 * 1070 * 2.0235^2\ V^3}$

gives the theoretical energy at any instant $\mathbf{= 5505.09\ V^3}$

(remember that density of SEA water is 1070 kg m^{-3}).

Alternatively the energy available in a day will be
$\mathbf{2 \times 5505.09 \times \Sigma\, V^3}$
[the factor 2 comes from two tidal cycles per day)

Thus to find total energy work out V^3 and enter values in column 7 and sum

total energy will thus be **2 * 5505.1 *2179.8 /1000/1000 MWh** per day.

= 24.00 MWh per day

and the rated output of the turbine will be **24.00/24 =** 1MW

17.12 Example 2: Enclosed basin Tidal Power Example (La Rance):

The height (h) of the water level above mean sea level in the Rance Estuary in Northern France may be approximately found from the relationship:-

$$\mathbf{h = 0.5\ d}\ \cos\left(\frac{\mathbf{360\,t}}{\mathbf{p}}\right)$$

where t is the time in hours after high tide,
d is the range (maximum-minimum) of the tide = 9m,
and p is the period between high tides (12.5 hours in this case).

Generation of electricity takes place whenever there is a head difference of 2.089m or more, and continues until the level of water in the basin falls to 0.779m below mean sea level. The turbines have an efficiency of 60%. You may assume that the density of water is 1000 kg/m^3.

Estimate how long generation can continue during each tidal cycle. Estimate also the mean output from the power station if a total of 108.73 x 10^6 m^3 of water pass through the turbines during generation.

SOLUTION:

First use the equation to work out the height of the tide at each hour from 0 up to 12.5 hours. It is only necessary to do this once an hour:

Table 17.4 Tide heights based on equation

HOUR	HEIGHT (m)	HOUR	HEIGHT (m)
0	4.500	7	-4.184
1	3.943	9	-0.843
2	2.411	10	1.391
3	0.283	11	3.280
4	-1.916	12	4.359
5	-3.641	13	4.359
6	-4.465		

Now plot a graph with the time as the x-axis.

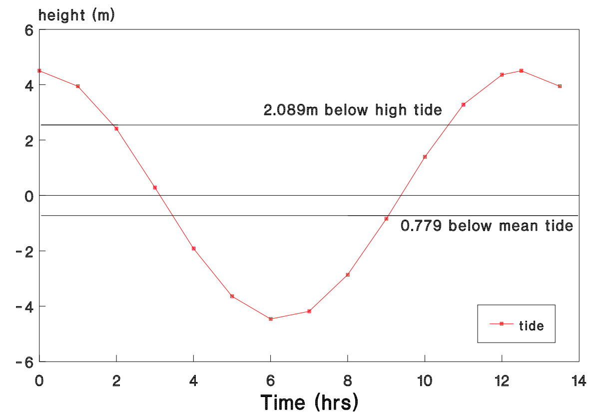

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Fig. 17.11. Tidal Variations

Now draw on lines which are 2.089m below high tide (representing start of generation), and 0.779m below mean tide (representing the end of generation.

The start coincides exactly with the 2 hour point. This can be checked as at two hours the difference from high tide is 4.5 - 2.411 = 2.089m).
Similarly the generation ceases when the level is 0.779m below mean tide, but the head of 2.089 must still be maintained. So the level of the tide when generation ceases will be:-

-0.779 - 2.089 = - 2.868 i.e. exactly the height after 8 hours.

So generation will occur for 8 - 2 = 6 hours (answer to first part).

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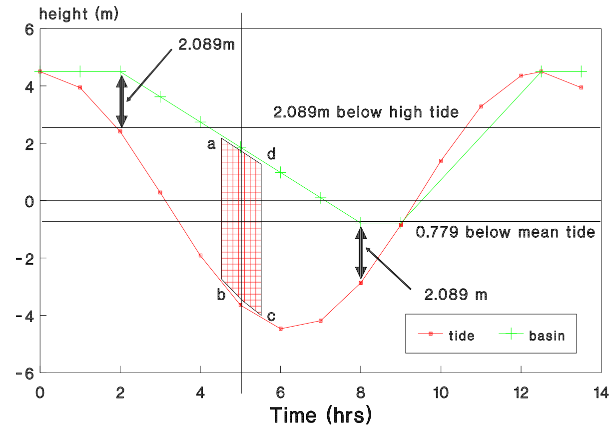
There are now two ways to proceed for the second part:-

Method 1: Graphical Method

Plot on the basin level assuming a linear decline from the start to the end of generation.

Then measure off at each hour the height difference between the basin level and the tide as shown in the following table:-



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HOUR	HEIGHT	HEAD
0	4.500	no generation
1	3.943	no generation
2	2.411	2.089
3	0.283	3.337
4	-1.916	4.656
5	-3.641	5.502
6	-4.465	5.446
7	-4.184	4.285
8	-2.868	2.089
9	-0.843	no generation
10	1.391	no generation
11	3.280	no generation
12	4.359	no generation
13	4.359	no generation

This method continues after the Numeric Method

NUMERIC METHOD

It is not difficult to linearly interpolate to get the height of the basin at any hour between the start and end of generation as shown in the table below. This is then subtracted from the tide height to get the effective head.

HOUR	HEIGHT	BASIN	HEAD
0	4.500	4.500	no generation
1	3.943	4.500	no generation
2	2.411	2.089	2.089
3	0.283	3.620	3.337
4	-1.916	2.740	4.656
5	-3.641	1.861	5.502
6	-4.465	0.981	5.446
7	-4.184	0.101	4.285
8	-2.868	-0.779	2.089
9	-0.843		no generation
10	1.391		no generation
11	3.280		no generation
12	4.359		no generation
13	4.359		no generation

BOTH METHODS

The figures in the final columns for both methods are the same.
The energy generated at any one instant is ...... m.g.h

To find out the MEAN OUTPUT we need to find the mean head over the period. There is a small catch here:-

For the shaded area we can take the approximation that the head is that for 5 hours, similarly for 4 hours and 6 hours etc. But for both 2 hours and 8 hours, the generation is for only half the time, so the mean generation height is given by:-

$$\frac{\mathbf{0.5 \times 2.089 + 3.337 + 4.656 + 5.502 + 5.446 + 4.285 + 0.5 \times 2.089}}{\mathbf{6}}$$

$$\mathbf{= 4.219\ \text{m}}$$

The time interval is 6 x 3600 seconds

$$\textbf{So mean output} = \frac{\overset{\substack{\textbf{volume}\\ |}}{\mathbf{108.73 \times 10^6}} \times \overset{\substack{\textbf{density of water}\\ |}}{\mathbf{1000}} \times \mathbf{9.81 \times 4.219}}{\mathbf{6 \times 3600}}$$

$$\mathbf{= 125\ \text{MW}}$$

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