# INTEGRATION OF SOLAR ENERGY TECHNOLOGIES WITH CCS

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# Forward

This report was commissioned as an internal study of the issues and potential for integrating renewable energy technologies with carbon capture and storage. A prime purpose was to identify possible areas for further study by the IEAGHG R&D programme. Both CCS and renewable energy sources will be integrated into the overall energy system by virtue of their being connected to the same electrical distribution system. The subject of this report, however, is possibility for deeper and closer integration at the level of individual power plants with a view to enhancing overall performance.

The report gives insights into some of the issues which closer integration would need to address and highlights a number of reasons why such integration may not be particularly effective or efficient. The conclusions of this first scoping study are thus not encouraging but this should not be taken as being in any way a criticism of the individual technologies. The study documents a number of possible types of integration but the list should not be considered as exhaustive.

# INTEGRATION OF RENEWABLE ENERGY TECHNOLOGIES WITH CARBON CAPTURE AND STORAGE

A PRELIMINARY STUDY

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## Executive summary

This study was undertaken to identify and quantify opportunities for Carbon Capture and Storage (CCS) and renewable energy technologies to be combined in a synergistic way and to identify any options which would tend to leave a permanent legacy for the renewable power generation industry. Several interesting options were studied and the key option of providing renewable thermal energy to compensate for the parasitic losses incurred by post combustion CCS was studied in some detail. The options investigated were:-

- Concentrated solar thermal energy for CCS solvent regeneration and other power plant heating duties
- Hydrogen from Gasification/CCS as emission free support fuel for Concentrated Solar Power (CSP) thermal power plants
- A compressed air energy storage (CAES) system to provide load following capability for a Gasification/CCS/Hydrogen/CCGT power plant
- Use of concentrated solar heat for high temperature chemical reactions in support of CCS-calcining reactions and hydrogen production.
- Use of surplus wind energy for water removal from $CO_2$ storage reservoirs

The use of solar energy for CCS solvent regeneration and other power plant heating duties is the most promising combination. The amount of energy which might be collected in reasonable proximity to a large 1GW power plant sited in a typical location was considered. Such locations are more likely to be in temperate climates where insolation levels are far lower than those at desert sites favoured for CSP applications. It was also considered that the solar collection should occur in a band around the site and that the furthest arrays should be no more than 2km distant. In temperate climates on sunny days at peak radiation times it is possible to gather enough energy to defray all of the CCS losses and several internal low temperature feedwater heating duties. However over 24-hours only part of the parasitic losses can be covered. The net result is that plant fossil fuel efficiency would improve by up to 3%. To do more requires thermal storage which, while possible, is shown to be very large. A further consideration is the ratio between diffuse and direct radiation since only direct radiation can be used in highly concentrating solar thermal systems. At prime solar sites in low latitudes much as 80% of the insolation is direct radiation. This figure falls to as little as 40% in northern latitudes.

Investigations show that it is rather inefficient in both land area use and overall power conversion efficiency to provide thermal energy using heat storage or by backing out the extracted steam normally used for solvent regeneration and boiler feed water heating. This is at first sight a surprising result. The reason for the former is that there are exergy losses in heating and cooling the thermal storage medium and the full potential of linear solar arrays to generate high temperatures is not utilised. The reason for the latter is that daily cycling of the extraction rate of steam cause slight reductions in steam turbine efficiency. Even though these are very small they apply to a large proportion of the power. It is thus found to be far more efficient to install a dedicated steam turbine suited to processing the heat derived from the solar arrays.

Furthermore the investigations suggest that direct steam generation at moderately high temperatures in linear Fresnel arrays makes the best use of the practically available collection area around the plant. The role of the host CCS plant is limited to that of managing the warm up and standby of the solar turbine. The solar turbine provides an opportunity for $CO_2$ capture to be interrupted at times of high power demand without loss of thermal efficiency since it can be used for efficient conversion of extracted steam leaving the main turbines operating at maximum efficiency. The legacy left by the CCS plant is a small but effective solar power plant which would be capable of stand alone operation with little modification.

Of the other options investigated the two involving supply of hydrogen generated by a Gasification/CCS process to high temperature CSP and to CAES systems are the only ones which exhibit potential. However the first option makes poorer use of the hydrogen in conversion to power than a stand alone IGCC/CCS plant. The alternative of using natural gas as a supplementary fuel for CSP will be more economical but would create significant $CO_2$ emissions and again would make less efficient use of the gas than a stand alone CCGT plant. The CAES option may be able to utilise hydrogen with the same efficiency as an IGCC/CCS but there is not enough data on efficiencies to determine if this is the case. In both options a hydrogen store would enable capacity variations to be smoothed out and hence enhance overall power conversion efficiencies.

The other two options investigated do not seem to be viable. High temperature solar chemical conversion processes are still in their infancy. Heat and material transport requirements make integration infeasible. The option to use surplus wind energy to power extraction of water from $CO_2$ storage reservoirs to create additional storage volume or enhance injection rates is viable. However the power requirements are extremely small and therefore not significant as far as power balancing is concerned.

It is recommended that further work is considered to characterise the use of CSP in post combustion capture. Several quite optimistic papers have already been published on this subject. The scope could include:-

- Survey of power plant sites to establish land areas available and solar intensity patterns.
- Detailed analysis of steam turbine performances at the off load conditions under which such schemes require them to operate
- More detailed calculation and verification of true efficiencies of the various alternatives
- In depth consideration of all the environmental impacts and secondary land use implications

It is recommended that if further work is undertaken on the life cycle analysis of CCS in the near future that reduction of impacts through integrating renewable energy is not considered as its application is too uncertain.

It is recommended that further work is undertaken to understand what the essential supplementary fuel requirements of high temperature CSP systems are. It would also be worthwhile to establish the true efficiency with which supplementary fuel is converted to power in a CAES system.

## Introduction

A study was initially proposed to investigate how renewable energy might be harnessed to provide some of the low grade heat required in conventional capture processes thereby reducing fossil fuel consumption. This represents a small segment of the opportunities for CCS to work with emerging renewable energy technologies. The scope was subsequently expanded to encompass a wider range of opportunities particularly those which could leave a permanent legacy by enhancing the deployment of renewables thus anticipating the eventual retirement of CCS technology.

At the same time a study on life cycle assessment of CCS revealed that the reduction of environmental impacts from reduced greenhouse gas emissions might be considerably offset by other impacts especially those associated with the fuel supply chain.

This internal IEAGHG study was instigated in order to better identify and evaluate the opportunities for CCS and renewable energy technologies to be combined to the mutual benefit of both. The information would also assist in assessing the scope and boundary conditions for a follow on study on CCS life cycle assessment, which would aim to better understand the supply chain impacts and how in the future technology advances may be able to substantially reduce these.

## Scope for CCS – Renewable integration opportunities

A number of possible integration opportunities were identified at the time the scope for a full study of this subject was being drawn up. Of these the last item is already the subject of other studies. Hence this study will consider items 1-5. Items 2 and 3 are closely related and will be considered together. Items 4 and 5 will only be considered briefly as they relate to possibilities which can only mature rather further in the future.

| Item | Brief description |
|---|---|
| 1 | Concentrated solar thermal energy for CCS solvent regeneration and other power plant heating duties |
| 2 | Hydrogen from CCS as emission free support fuel for CSP thermal power plants |
| 3 | Hydrogen from CCS as emission free support fuel for compressed air energy storage (CAES) systems |
| 4 | Use of concentrated solar heat for energy storage or hydrogen production using chemical processes |
| 5 | Use of surplus wind energy for water removal from CO2 storage reservoirs |
| 6 | Supplementary biomass firing of CCS plants |

## Concentrated solar as supplement to CCS power plant

### General description.

Concentrated solar thermal devices are able to collect solar energy at a range of temperatures and could thus serve as a supplementary heat source for a CCS plant. Depending on the degree of solar concentration, working fluids can easily be heated up to temperatures of 600°C and in principle to well over 1000°C. The main limitation is the material of the target collection device for which the choice is limited by much the same considerations as for fossil fuelled power systems. Conventional metallic materials are not available for operation at temperature much above 850°C and for applications requiring significant stress such as high pressure coils in steam boilers the limit is around 650°C. This is likely to be extended to around 700°C by development of special alloys although the higher content of expensive alloying metals to achieve strength at these temperatures impacts on the overall economics. The trade off is between slightly higher thermal efficiency and thus reduced fuel consumption and the extra capital costs. [1]

Gas turbines are already able to work with working fluid temperatures up to around 1500°C with 1600°C in prospect [2] but are only able to do this by limiting the actual temperatures of any metal parts by a combination of air or steam cooling and ceramic thermal insulating layers.

The maximum operating temperature of the materials of a solar collector will be influenced by heat flux and heat conduction and transfer in exactly the same way as it is with boiler tubes. There has to be a temperature gradient across the material in order for the heat to flow into the working fluid. Thus the maximum surface temperatures have to be higher than the working fluid temperature and this difference goes up with heat flux. The surface temperature of tubes in a steam boiler has to be significantly higher than that of the steam itself. The area of collector surface exposed to concentrated solar radiation will thus also have to be of similar magnitude to that required for fossil fuel fired devices with the same thermal capacity.

However there is one arrangement which to some extent gets round this problem and that is the use of volumetric receivers in which a porous matrix is heated by concentrated solar radiation whilst a fluid such as air flows through the heated medium. This has the disadvantage that it is difficult to use at pressure because then a pressure resistant window has to be engineered for the solar beam to enter the device. The matrix itself is not subjected to significant forces other than those due to differential expansion and can work at much higher temperatures than the working fluid.

### Advantages of utilising concentrated solar energy in conventional fossil fuel fired plants.

In order to expose any possible advantage a comparison is best made with the stand alone situation. A stand alone CSP plant has a number of limitations which affect its performance. Firstly the size of the unit is limited by the area from which energy can be conveniently collected to a single point. As a consequence the size of the power plant which converts the energy to power would normally be limited to some 10’s of MW at most. Consequently the efficiency with which heat in the working fluid is converted to power will be lower because in general smaller machines are less efficient. It might be possible to transport the heat from several collection arrays to a central point allowing larger and hence more efficient machinery to be used. Any gains would have to be weighed against heat losses in the transport system

A second limitation is the diurnal variation in output. This means that unless some form of energy storage is used the power plant cannot run at optimum capacity and hence optimum efficiency. In addition there will be heat losses from re-warming the system each morning or if the system is kept warm overnight through ongoing heat loss which would have to be supplied either from heat storage or by using some fossil fuel.

Another important factor in the stand alone situations is location. CSP plants have better economics if they are placed in locations whether there is high annual insolation. On the other hand conventional fossil fueled plants are generally in locations with much lower insolation. However electricity transmission costs and losses also have to be considered as the high insolation locations do not generally coincide with high power usage locations.

In order to resolve these multiple considerations some simplifying assumptions need to be made. The aim of this study is to identify ways in which the two technologies CCS and renewables can complement one another. Hence whatever hybrid systems are investigated they need to be in credible settings, thus where the CCS plant is the “main” unit it will be assumed to be in a typical location for such plants. Where CSP plants are the “main” units they will be located in favourable locations i.e areas of high solar insolation.

The first hybrid system to study is thus a large commercial scale CCS plant in a typical temperate location to which a certain amount of concentrated solar thermal energy is added to the thermal input.

Consider first the possibilities for integrating CSP with a modern conventional coal fired steam power plant. Such a plant will be operating under supercritical conditions with steam temperature in excess of 600°C and steam pressures of around 240Bar. To maximise efficiency reheat will be applied and the unit would recuperate heat for feed-water heating and air preheating. Any introduction of additional heat from CSP could impact on this heat integration and so would have to be designed to maximise efficiency gains.

In order to supplement the heat provided to the working cycle by burning of fossil fuel the solar thermal heat would have to be used ultimately to heat one or more of the working fluid streams. Alternatively it could be applied to the air preheating duty. The cumulative heat content v temperature of the heated fluid streams and the flue gas stream gives an indication of the temperature differences in the typical power plant. It shows that for much of the trajectory flue gas can be well above the working temperature of the fluids with which it is exchanging heat. This large gap accounts for the relatively low power conversion efficiency. In a conventional system notice that the “initial heating” i.e that part of the heating of the water is usually done using the principle of regeneration, it is heated progressively by steam extracted at different pressures from the steam turbines.

**What streams are available for use of solar heating**

In a conventional steam boiler there are a number of streams which could be heated by an external addition of solar heat. For a conventional power plant without CCS they are typically as shown in the following table (1):-

Table 1 Streams in Steam power plant with CCS potentially available for supplementary heating by solar thermal energy

| **Stream** | **Temperature trajectory** | **Fluid** | **Heat source displaced** | **Approx Thermal duty as % of total** | **Expected power conversion efficiency** | **Observations** |
|---|---|---|---|---|---|---|
| Preheated boiler feed water to main boiler | 250C - ~600C | Water – supercritical steam | Flue gases in radiant and convection sections | ~80% | ~45% | Upsets balance with reheat section. Less flue gas for reheating duty. Have to transport HP water and steam |
| Steam to superheater coils | 450C - ~600C | Supercritical steam | Flue gases at start of convection section | ~10% | ~45% | Upsets balance of superheating section. Less steam to cool shock tubes. Have to transport HP water out and steam back |
| IP steam for reheat | ~300C - ~600C | Steam at ~ 40bara | Flue gases later in convection section | 18% - 20% | ~45% | Upsets balance in reheat section. Load transferred to air preheater and superheater. Have to transport IP steam out and back |
| LP steam for BFW heating | ~35C - ~190C | Water at ~15 bar | Extracted LP steam | ~15% | 7% - 20% average 14% | Difficult to transport LP steam. Very poor use of collected energy. |
| IP steam for BFW heating | ~190C – 250 C | Water at 30 - ~250 bar | Extracted IP steam | ~12% | 27% - 37% average 33% | IP steam transportable, Better use of collected energy |
| Cold inlet air | Ambient to ~300C | Air at atmospheric pressure | Cool flue gases from convection section | ~12% | 45% | Best to heat air further otherwise cannot extract all heat from flue gases. Intermediate transport medium needed. |
| LP steam for regeneration of solvent (CCS pre and post comb only) | 130 – 140 C | LP steam or other transport medium | LP steam and recovered heat of CO2 compression | ~25% post and ~say 5%? pre. | ~20% | LP steam not transportable so need to use intermediate heat transfer fluid. Poor use of collected energy. |

Of these, those requiring heating to temperatures above around 400C are not amenable to use of linear single axis tracking collectors. They would need to use systems based on two axis tracking collectors which can achieve much higher concentration factors.

## Geographical considerations

A typical modern coal fired power plant will have a capacity of at least 500MW and may have an output of 1GW or more. Such plants occupy an area of around $1km^2$ the actual size depending on scarcity of land, the amount of coal storage required. The area beyond the perimeter of such installations may be desirable for use by other industrial enterprises but is generally not so desirable for housing or commercial use. It may be useable for farming. This is illustrated by the adjacent aerial shot of a typical power plant. This one in Florida is surrounded by land which has not been used for other residential or industrial purposes. In contrast a similar plant in the United Kingdom is also surrounded by largely un-built land but the surrounding area is used extensively for farming and there are some buildings and several roads. Even so even in this more densely populated area a considerable area around the plant might be useable for energy collection.

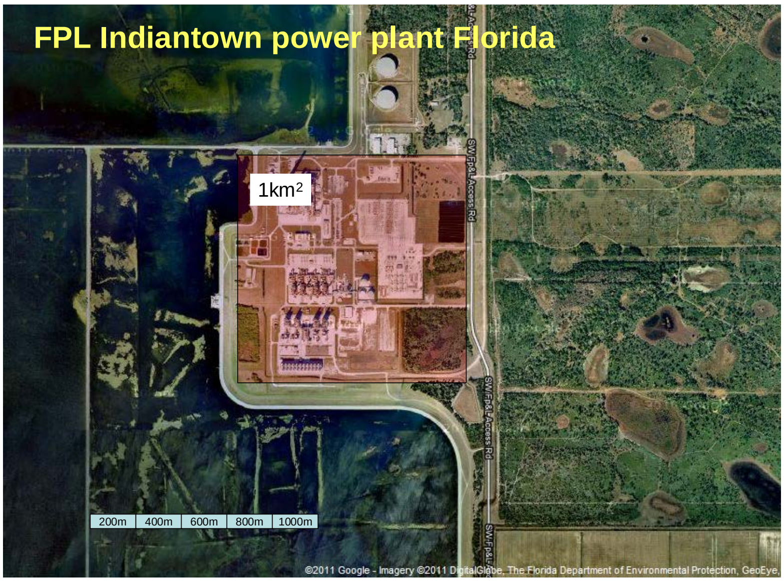
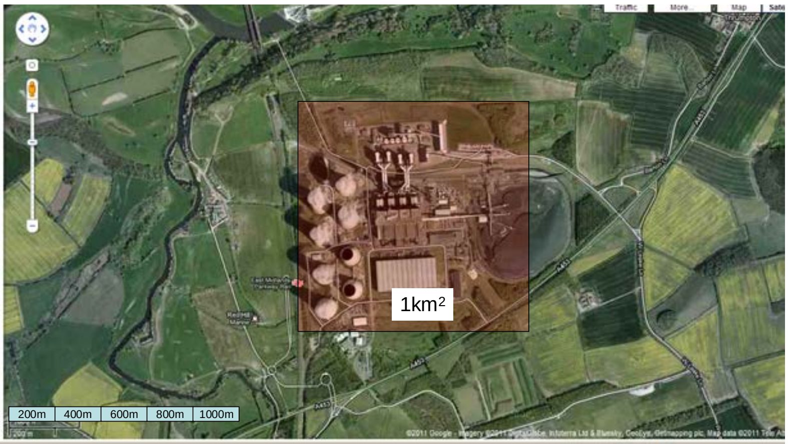



**Figure 1 Aerial view of typical US power plant**

In the context of this part of the study the collection of supplementary solar energy would be in a band around the main power plant thus making use of what is sometimes a "sterile" area for other developments and yet is close enough to enable transport of collected energy to the main plant. Effective transport of thermal energy cannot be done over long distances and hence the band of useable collection area around the central CCS plant could be no more than 1-2km wide.

This thus sets the areas which might be available for solar energy collection. If the central plant is considered to generate 1GW and occupy a square area of $1km^2$, the effective electrical energy intensity is 1000 watts per $m^2$. Taking the power plant efficiency to be 45% the thermal energy intensity is $2222watts/m^2$




Ratcliffe-on-Soar Power Station UK. Main plant area ~ 1km² , capacity 2GW

**Figure 2 Aerial view of typical UK power plant**

The area available for solar collection arrays if a 1km wide band is assumed would be 8 times this area, for a 1.5km band it would rise to 15 times and for a 2km band 24 times as illustrated in Fig 3.

Solar incident radiation can have peak values varying between 500 and 1000watts/$m^2$. However average insolation over a year is much lower, Typical figures for mid latitude regions such as the UK show that about 100watt/$m^2$ falls on average over the entire year. Thus the amount of solar energy falling on the 1km collection band is equivalent to about 800$MW_{thermal}$. On the 1.5 and 2km bands 1500 and 2400 $MW_{thermal}$ respectively. The amount which could actually be collected will be just a fraction of this and it is instructive to consider three "options", using the land for biomass production, using it for photovoltaic arrays and using it for solar thermal energy collection. The estimates are based on using the largest i.e. 2km band

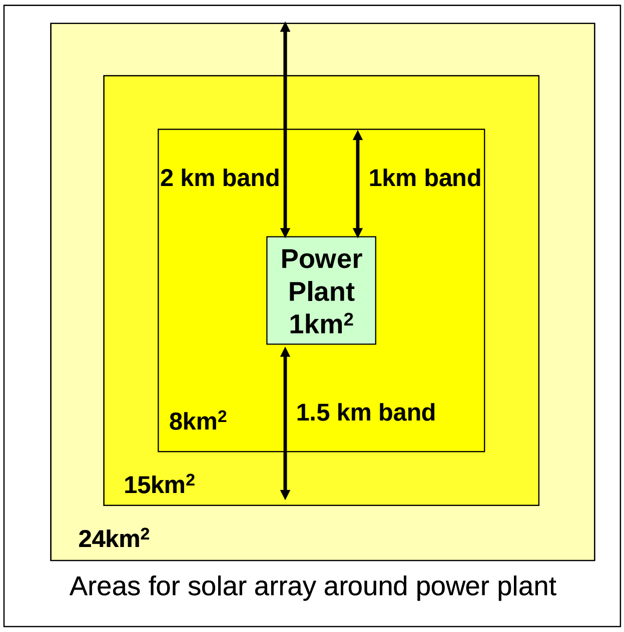



**Figure 3 Relative areas of bands around typical power plant**

Photosynthetic processes using plants can capture only a small fraction of incident solar energy, as little as 0.3 to 0.8 % so that allowing for say 80% utilisation of the area for growing only between 2.6 and 6.9 MW of power could be collected using the available land. The efficiency gain would be only 0.26% to 0.69% percent. Photovoltaic arrays would fare better as they may convert 10% - 15% of the incident radiation to power. Assuming the lower figure, that only 70% of the area could realistically be covered with cells and allowing a 90% efficiency for power inverters and other electrical losses an average of about 150MW could be collected or the equivalent of an efficiency gain of 15%.

Solar thermal energy collection can have a much higher efficiency again but the onwards conversion of thermal energy to electricity involves further substantial losses. Concentrating collectors are only able to utilise direct radiation and this reduces the amount collectable particularly in higher latitudes where cloud cover is more frequent. The fraction of insolation which is direct and hence can be concentrated is typically around 70% in desert areas and even as high as 90% in specific areas such as Namibia.

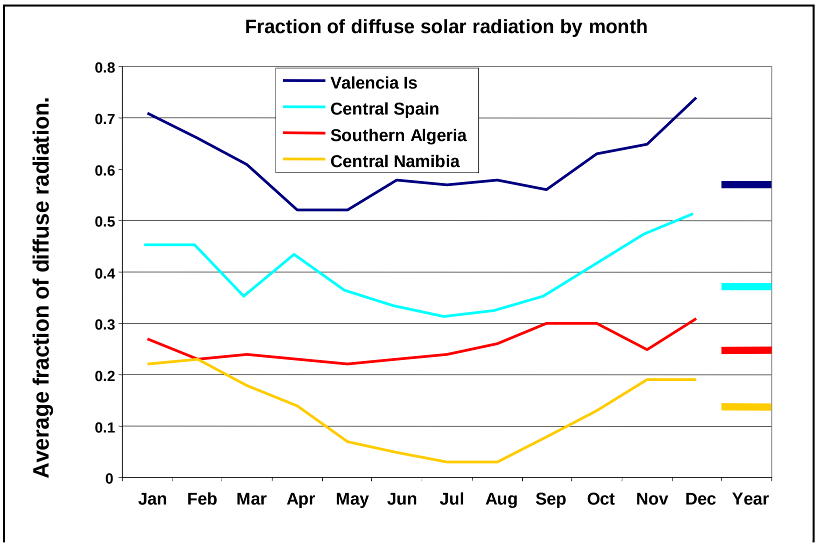



**Figure 4 Fraction of diffuse solar radiation**

However in higher latitudes the fraction falls to around 40% or even 30%. Data on the ratio between diffuse and total insolation has been collected and can be explored for example at the European Joint Research Centre website [3]. The effective area which can be utilised is affected by the type of collector and the degree to which collectors shade one another. Linear collectors are a lot better in this respect than those employing a central collection tower. Thermal collection efficiencies can be above 50% for temperatures around 200°C but for this calculation a conservative estimate of 30% is used. This is further reduced by a factor of about 0.7 , i.e to about 20%, to allow for the typical ratio between diffuse and direct radiation. A maximum of 70% of the area is presumed to be utilised for collectors and the effective conversion efficiency for heat at this temperature using a team expansion cycle would be around 20%. This implies that on average about 500MW thermal or 100MW of electrical power equivalent could be collected equivalent to a 4.5% gain in power plant efficiency. As an alternative the use of fully concentrating collectors could be considered. For large capacities the central tower type is most suitable as it is cheaper to install and would have far less pipework for delivery and collection of the heated fluid. The central tower system uses available space far less efficiently because of shading effects. It is likely that no more than 30% of the land area could be used but this would be compensated by higher electrical efficiency if for example superheated high pressure steam was generated. The conversion efficiency could then rise to say 45%. However the net result is that the amount of power which could be generated by the array would be about the same.

These numbers show in broad terms that the solar thermal option would obtain about 1/2 the amount of electrical energy that could be acquired using photovoltaics using the same area but would be far cheaper to install and operate.

Table 2 Relative electrical power generable per unit land area

| Method | Collection efficiency | Area useable | Conversion to AC power | Relative power |
|---|---|---|---|---|
| Biomass Low yield | .3% | 80% | 45% | 2.1 |
| Biomass high yield | .8% | 80% | 45% | 5.5 |
| PV high eff | 15% | 70% | 90% | 180 |
| PV low eff | 10% | 70% | 90% | 120 |
| CSP low temp | 20% | 70% | 25% | 67 |
| CSP high temp | 20% | 30% | 40% | 46 |

The pictures below illustrate some aspects of the layout and design of concentrating solar power systems. Notice in the aerial photo of the central tower system installed in California and Barstow that much of the area is not covered by heliostats because of shading effects particularly further away from the central tower.

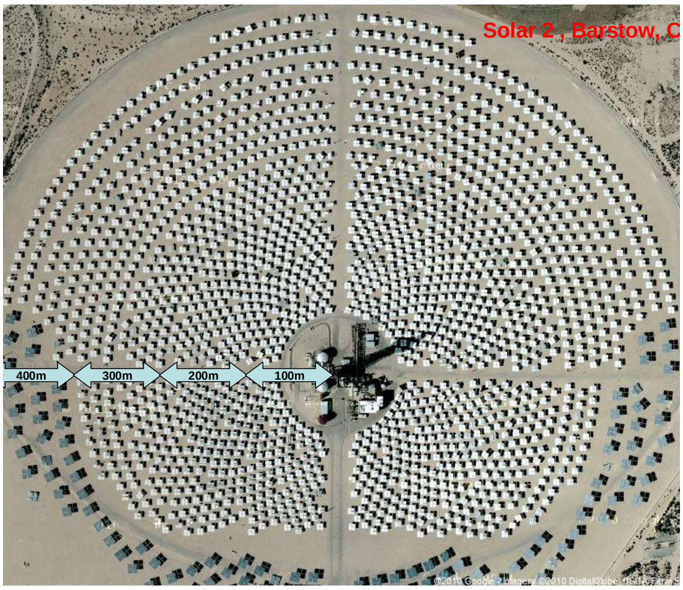



Figure 5 Solar 2 at Barstow CA – Aerial photo

Figure 6 Steam boiler at Ivanpah solar power plant

The composite photo below shows the 4 main types of solar concentrating systems. The parabolic trough system top left focuses onto a collection tube rigidly attached to the collector at the focal point. The entire reflector moves on one axis to follow the sun. Bottom left is a Fresnel linear array. Here a series of parallel mirrors, each independently tilting on one axis, focus on a central collector pipe supported on a separate structure above the mirror array. Construction is much lighter and much wider collectors can be built. Reflectors at the edges can be interleaved with adjacent devices to minimise shading effects. The other two use point focussing and can thus achieve much higher temperatures. They can also use two axis tracking.

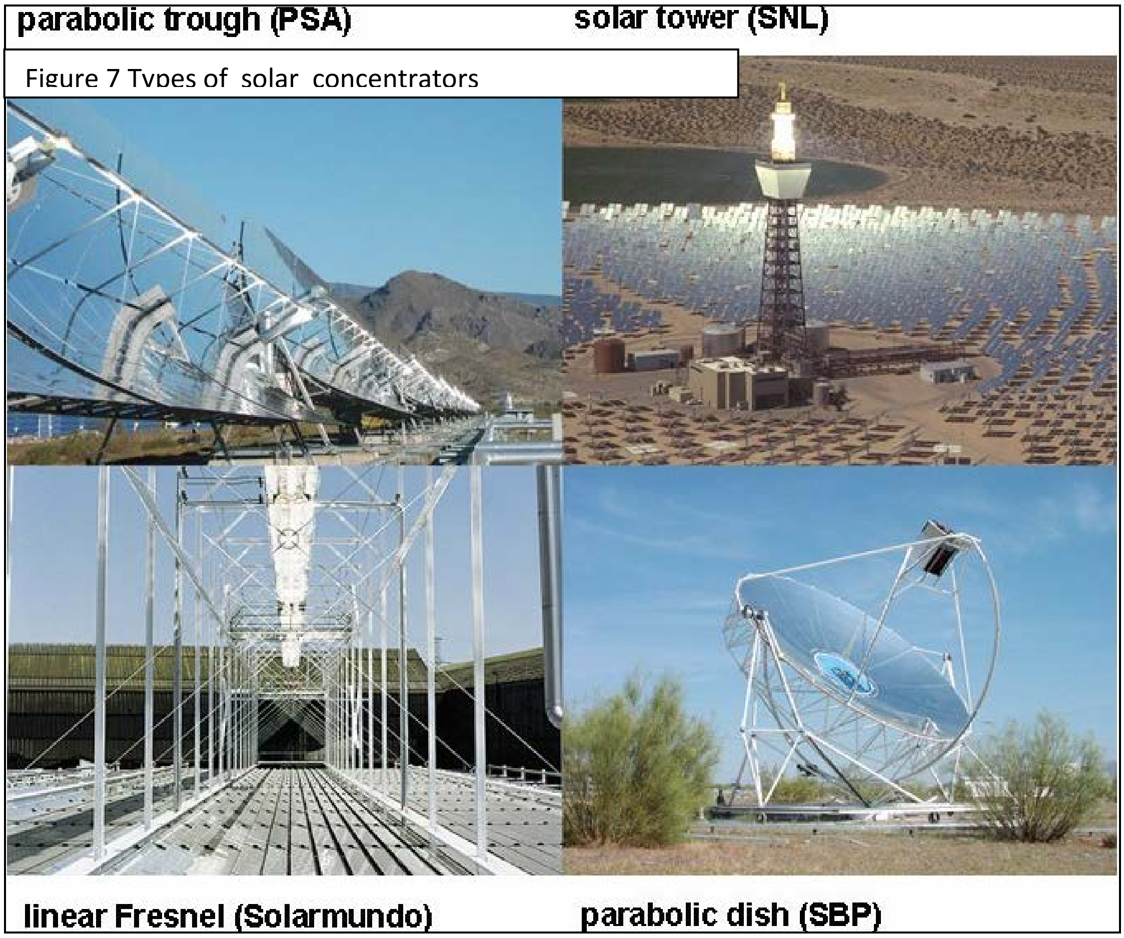



Figure 7 Types of solar concentrators

**Energy storage considerations**

The available destinations for supplementary solar thermal energy all require a constant supply of heat when the plant is running but are amenable to variation in the amount being supplied at any one time. If the peak amount of heat supplied by the solar thermal array is less than the amount which can be accommodated by the plant all of this heat could be used by simply backing out fossil fuel when the solar thermal heat is available. If the peak amount is higher then thermal energy storage would be needed to smooth out the supply. Providing energy storage will add to costs and would not be justifiable if the peak thermal power could be absorbed. It is this important to consider what the peak thermal load could be and whether the host CCS plant would be able to accommodate this without thermal storage. In higher latitudes the maximum insolation peaks at around 500W/m$^2$ and in lower latitudes can be up to 1000W/m$^2$ so that the peak amount of thermal energy collected from the arrays would be as shown in table 3 below.

Table 3 Peak thermal collection power from area around power plants

| Peak solar intensity | 1km collection band | 1.5km collection band | 2km collection band |
|---|---|---|---|
| 500W/m$^2$ | 830 $MW_{th}$ | 1560 $MW_{th}$ | 2500 $MW_{th}$ |
| 1000W/m$^2$ | 1660 $MW_{th}$ | 3120 $MW_{th}$ | 5000 $MW_{th}$ |

An important consideration is the ratio between diffuse and direct radiation. The above figures are representative of the direct radiation when the sky is completely clear. In practice this is not the case and cloud cover further reduces the amount of radiation which is direct. Systems which concentrate the suns radiation to any degree cannot make use of the diffuse component of the radiation. This effect is greatest in higher latitudes where as little as 40% of the total yearly radiation can be direct compared to 70-85% in prime desert locations. Extensive data on insolation patterns can be found for Europe and Africa at The EU commission Joint Research Centre PVGIS website. [3]

These figures need to be contrasted with the energy destinations identified earlier. From the table of streams which could be supplied with solar energy the following seem most amenable to implementation.

Table 4 Selected thermal energy destinations for supplementary solar heat

| **Duty to be replaced** | **MW thermal** |
|---|---|
| LP steam for BFW heating | 430MW |
| IP steam for BFW heating | 340MW |
| LP steam for solvent regeneration | 750MW |
| **TOTAL** | **1520MW** |

The forgoing suggests that where there is no energy storage a solar array of maximum 1.5km band width around the main plant would be the maximum worth installing. Given that the average power would be 1/5$^{th}$ the peak in higher latitudes this would provide on average about 300MW of thermal power. The effective conversion efficiency is likely to be around 20%, possibly a little higher if the steam is generated at higher temperatures than required and is effectively used. Thus about 60MW of extra power would be generated equivalent to a 2.7% overall efficiency increase, considerably less than the overall potential of 4.5% mentioned earlier. Where there was a low fraction of direct radiation this figure would be proportionately reduced. The potential would be further reduced to half this value (1.35%) if only the solvent regeneration duty was supplied. This considerable reduction is due to the lack of suitable destinations for the collected solar thermal energy at times of peak insolation.

**Energy transport considerations**

The considerations discussed above set an approximate limit to the distance over which energy would need to be transported to the CCS plant. The suggestion is that the edge of any solar collection field would be no more than 2.5 km from the centre of the CCS plant. Allowing for realistic routing, this means that the longest distances would be up to 3km. This limits the choice of transport fluid where thermal energy is gathered. It also influences the size of lines which are practical this being determined by pressure drop and heat loss both of which favour larger diameter lines. The choices of transport fluid are hot water, steam at various pressures, hot oils and molten salts shown in the table. Some key properties are shown in table 5 which follows.

Table 5 Characteristics of solar heat collection fluids and transport lines

| Fluid | Pressure/Temperature | Heat capacity cal gm with typical return temperature | Density kg/m$^3$ | Limitations | Line size for transport of 100MW electrical equivalent. (inches) |
|---|---|---|---|---|---|
| Hot water | Up to 60bar/up to 290°C | 278 | 730 | High pressure needed to reach high temperatures. Large diameter lines needed to have practical pressure drop. Only practical to store heat at temperatures up to just over 100°C | 20 in<br><br>Assumed efficiency 20% |
| LP steam | 2-5bar/ 120-165°C | 630 | 3.7 | Can only transport over short distances due to pressure losses. No possibility to store heat | 38 in<br>Assumed efficiency 20% |
| MP steam | 20-50bar/200-600°C | 845 | 12.7 | Moderately high pressures needed for containment. No possibility to store heat | 22 in<br>Assumed efficiency 37% |
| HP steam | 100-200bar/300-600°C | 815 | 55 | Very high pressures require thick tubing. No possibility to store heat | 16 in<br>Assumed efficiency 45% |
| Hot oil | 5-10bar/up to 315°C for mineral and 400°C for synthetic oils | 140 | 800 | Expensive and slowly degrades at higher temperatures. Has to transfer heat to working fluid of power generation cycle. Can store heat but inventory is very expensive. | 22 in<br>Assumed efficiency 27% |
| Molten salt | 5-10bar/up to 540°C | 150 | 1680 | Freezes at temperatures around 100-150°C. Has to transfer heat to working fluid of power cycle. Provides possibility to store heat. | 16 in<br>Assumed efficiency 35% |

The quantity of thermal energy to be transported from the collection area depends upon what maximum portion of the duties will be satisfied by the solar array. Regardless of whether thermal storage is installed the peak flows will be those based on peak insolation rates unless peak energy collection is deliberately limited for example by defocusing the arrays. If no energy storage is installed there is little point in collecting more thermal energy the can be utilised in the CCS plant. However there is some scope to install a bigger array than strictly required as this would enable some additional energy to be collected during off peak insolation.

The system average capacity was calculated at approximately 300MW based on average insolation over the year of 100W/m$^2$. However the peak flux can be between 500 and 1000W/m$^2$ implying that the peak capacity of the transport system needs to be between 650 and 1300MW. These figures for a 35% efficient 1GW power plant this represents between 25% and 50% of the total thermal energy input to the plant. The lower figure is close match with the required thermal input for solvent regeneration (in IEAGHG study PH4/33 it was estimated at 26%) so could be absorbed without affecting the main boiler circuits. Higher quantities, which would be available in lower latitudes, would necessitate some of the solar thermal input having to be applied to heating other streams in the process.

The last column in the table provides indicative figures for the size of lines which would be required to transport the equivalent of 100MW of electricity in the form of thermal energy. As each fluid can transport heat at different temperatures, an appropriate conversion efficiency for heat to power has been used when making these line size estimates. Taking into account line size, pressure drop limitations and operational issues, MP steam would appear to be an excellent choice of transport medium. Despite the need for somewhat larger lines than for HP steam the difficulties of operating and sealing collector tubes at very high pressure are avoided and the steam will be at a pressure more compatible with the usual steam extraction pressures of the steam turbines.

The heat would have to be transported by a number of lines running out and back from the plant. The exact arrangement of these will depend on the layout of the solar field and this is considered in the next section.

The forgoing implies that some of the heat available would be at temperatures in excess of that required for solvent regeneration. In the case of MP steam being used this could be expanded down to the appropriate pressure. This steam would be cooler than the IP steam in the main plant which is generally superheated to over 600°C, a temperature which is not attainable by linear solar collectors. Some could be used for condensate preheating replacing IP steam extraction. Alternatively it could be passed through a stand alone turbo-expander although this would create operational problems with daily startup, shut down and part load operation. There is potentially better match of temperatures at the conditions of IP steam extraction for BFW preheating as the temperature is somewhat lower after the reheated steam has been partially expanded. A suitable steam injection point would have to be established between the stages of the IP turbine. Another alternative would be to provide a superheating coil in the main steam plant for the MP steam coming from the solar field.

**Solar field layout considerations.**

An the basis that direct generation of medium pressure steam in linear arrays is the best match with the CCS plant duties, the impact on the layout of such solar arrays and heated fluid outgoing and return lines can be considered. Linear arrays are usually laid out East West or North South and these alternatives give slightly different seasonal output profiles, with the N/S having a higher seasonal variation. The arrays would best be aligned so that water is fed to the periphery of the collection area to flow towards the central plant thus minimising transport distance for the hot steam. A star shaped arrangement would be geometrically difficult but arrays could be arranged to run either N-S or E-W with flow such that the exits are closer to the plant. It appears possible to construct long arrays which deliver steam near to the boundary of the main plant. For example the arrays at the Almeria GDV site in Spain are already 650m long and it would seem reasonable that this might be increased to 1500m which is about the width of the of the solar arrays surrounding the main plant which are proposed.

Feed water would then be supplied to the periphery of the array and these lines and headers would be of much greater total length. Since they run at lower temperature they would require much less insulation. Taking into account the density difference with MP steam the lines could be expected to have around half or less than the diameter of the steam lines depending on how much additional pressure drop was acceptable.

Another issue is whether to occupy land progressively outwards or whether to develop specific segments. For a small array the collection zone could be placed in the annular area surrounding the plant minimising distance to the main plant. However developing a N-S or E-W block even if parts are further away allows a greater concentration of reflectors in one area and may be more favourable for land acquisition. If long enough runs can be accommodated, thus minimising heat losses during transport back to the plant, this solution would be preferred.

A possible layout is shown in figure below. Here most of the blocks are using N-S collector arrays and steam is collected into headers at the northern and southern edges. However the blocks which lie to East and West are set up with arrays running E-W and need only short collection headers at the Eastern and Western edges nearest to the central plant.

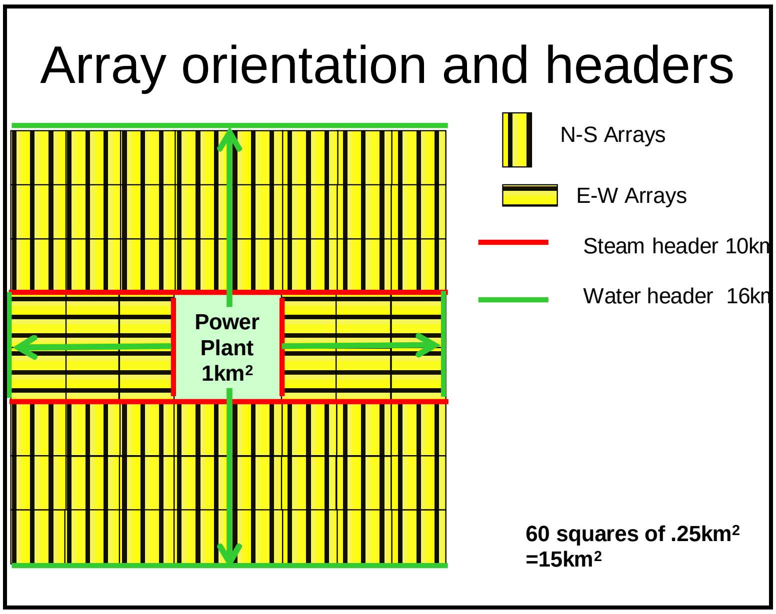



Figure 8 Suggested orientation of linear arrays

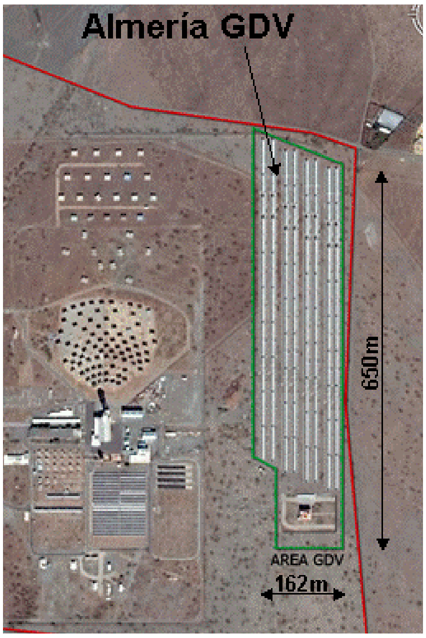



Fig 9 Almeria GDV Aerial photo

This arrangement results in much shorter steam headers than initial considerations would suggest. In the conceptual example below there are just 10km of main header to get to the plant boundaries as the crow flies. Allowing an additional 50% for practical routing and onward routing to the main turbines suggest about 15km for the 15km$^2$ array.

**Heat losses from collection system**

Absolute heat losses from the pipelines in collection system are largely proportional to the length only and not the diameter. If a fixed ratio of insulated to un-insulated diameter is maintained then the diameter as such does not enter into the heat loss equation. This implies considerable economies of scale apply when heat losses are considered. The heat loss per km of line which could be expected for well insulated lines (by which is meant insulated diameter of twice un-insulated diameter) for lines running at 300°C would be about 0.15MW.

Another consideration is the losses which occur overnight when inevitably the lines would cool down. A choice would need to be made between keeping lines warm or allowing them to cool. Whilst the insulated sections could be kept hot without excessive heat loss, the pipes making up solar collector arrays would be subject to increased heat loss. In principle the collector tubes would be contained inside evacuated glass tubes. The losses are thus largely by radiation and dependent on the emissivity of the coatings at the operating temperature.

In this example in which 15km of main steam gathering lines are required, if well insulated, losses would be about 22MW thermal if running at 300°C. In addition it is expected that re-emissions from the solar collectors could amount to several percent of the collected energy. From emissivity figures the re-radiation of surfaces at 300°C is calculated at about 0.75KW/m$^2$ of surface. This would be radiated through the evacuated tube covering of the collectors. Exact calculations have not been attempted. Rather a rough estimate can be made on the basis of the concentration factor and peak insolation. If these are taken as a factor of 100 and insolation of 500W/m$^2$ then the flux falling on the collectors would be 50KW/m2. To collect the 1500MWth peak power in the 15km$^2$ site the collector area would thus be 30,000m$^2$ and the emission losses due to radiation from the collector surfaces would also amount to about 22MW. This give a rough estimate for total heat losses of 44 MWth which compares with the average power which is only about 1/5$^{th}$ of the peak i.e 300MWth. Undoubtedly the system would cool down overnight and it would not be worth expending fossil fuel energy keeping it warm.

**Choice of concentration factor and steam temperature**

The foregoing focuses on the choice of medium pressure steam as the preferred transport medium. This allows some freedom in choice of peak operating temperature. Higher temperatures lead to more efficient conversion to power but also require higher concentration factors in the solar collectors. A linear Fresnel type array appears to be a good choice as this makes efficient use of land and because it uses multiple mirrors is able to achieve quite high concentration factors since several linear mirrors can focus onto a single overhead collector tube. The collector tube can be supported on an independent structure rather than being part of the structure as for a typical single parabolic trough system. There are some shadow effects with the multiple mirror arrays of linear Fresnel systems but these can be reduced by interleaving the mirrors at the outermost edge one line tilting one way, the adjacent one the other way. Linear Fresnel systems can achieve concentration factors of 25 -100. It is possible to estimate the optimum working temperature of the working fluid considering the concentration effect and also the effect of the heat to power conversion cycle. This temperature varies with the intensity of the solar radiation. Maximum temperature (stagnation temperature) is achieved with zero fluid flow and would not allow any power generation. As flow increases the attained temperature decreases but more energy is transported. However the conversion efficiency in the power cycle also decreases and an optimum can be calculated. For a concentration factor of 100 the optimum is around 360°C and with concentration factor of 25 about 220°C. These figures are based on a solar insolation of 500W/$m^2$.

At present direct steam generating linear solar collectors have been developed to produce temperatures up to 400°C and plans to increase this to 500°C are in hand [4,5] However a consideration when choosing the temperature is that, to avoid uneccessary losses when streams of different temperature are mixed, steam should be generated at a similar temperature and pressure to that existing at the extraction point of the main steam turbine.

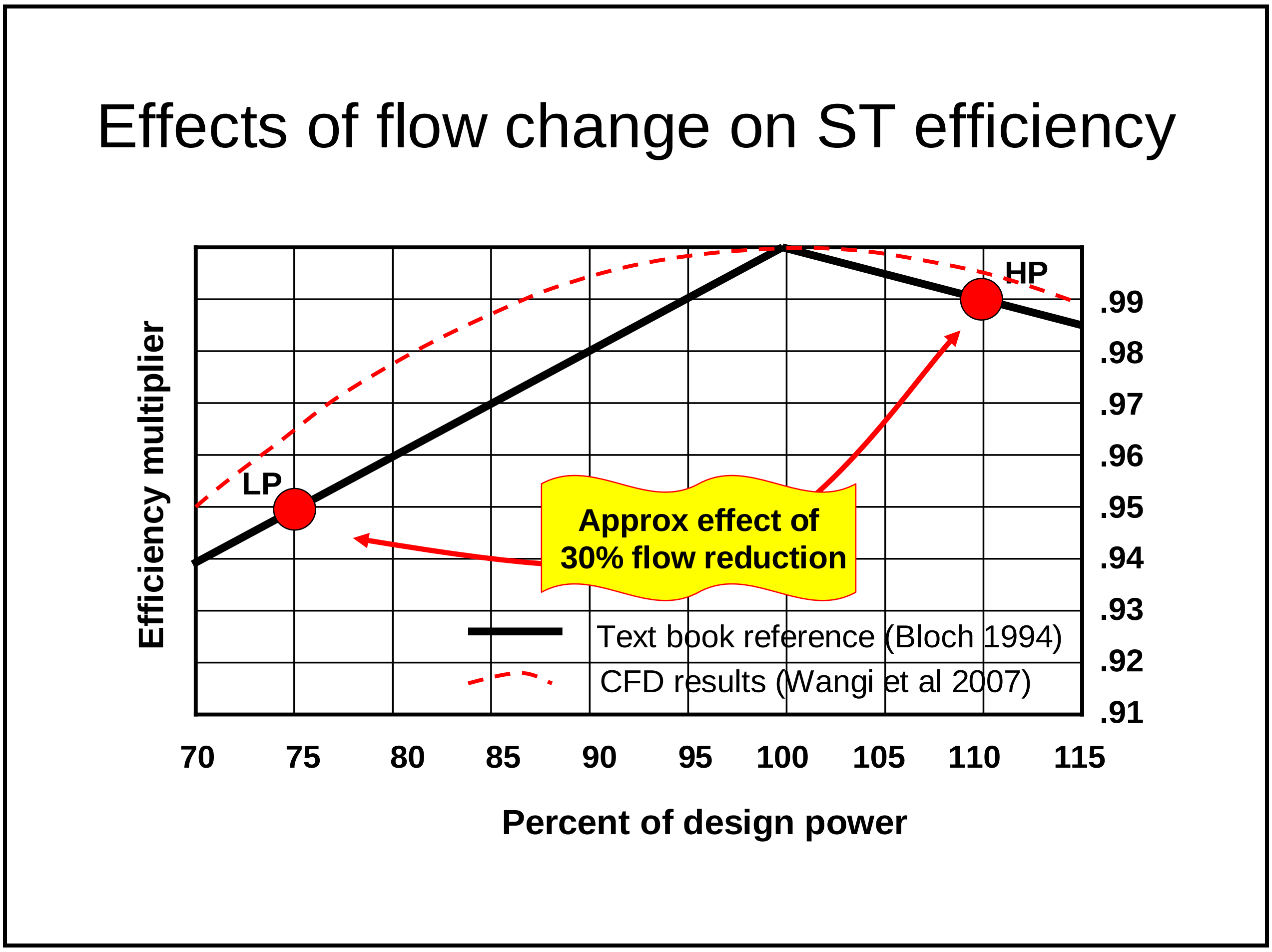
Early designs have favoured a system in which the evaporation and superheating is conducted in separate parts of the solar array in order to avoid thermal stresses associated with the change from two phase to single phase flow. This is achieved by recirculating feedwater and separating water from the steam before it enters the superheating section. Final temperatures can be altered both by varying steam flow and by defocusing.

**Effect on steam turbine performance and control.**

Steam turbines are relatively flexible and it is possible to turn down stage flows to as low as 10% of design without creating instability. However deviations from design conditions will incur an efficiency penalty. Increasing stage flows is also possible but the extent to which this can be done will be limited by the ability of the blades to handle the increased forces which result. The effect of harvesting additional solar energy will be initially to reduce the amount of steam being extracted from the steam turbines. This will raise all the stage flows downstream and will affect the inlet pressures both downstream and upstream. Steam turbine power plants have a number of options for control but in major modern power plants only some of these are used. In large turbines steam may be supplied and controlled separately to a number of arc shaped segments or steam may be bypassed from the inlet to an intermediate stage. Possibilities to cope with flow reduction are thus:- to throttle the entire inlet flow which by reducing pressure maintains flow velocity so that the angle of incidence on the rotating blades is maintained at the optimum. A second option is to turn down or turn off flow to one or more of the arcs. Those which remain open can thus maintain the appropriate inlet velocity and hence efficiency. A third method is to allow the inlet pressure to slide. In some processes it is necessary to maintain the pressure at which steam is extracted and internal throttling valves can then be included between the relevant stages in the machine. Another method is to bypass steam around some of the stages. The methods which apply throttling reduce the overall efficiency most since the throttled pressure energy is not recovered. The arc throttling control causes much lower losses but does apply asymmetric forces and temperature gradients on the turbine and is currently loosing out in favour of sliding pressure control. Furthermore only the inlets to the first of the stages in the barrel can be controlled in this way, so later stages still experience changes in the angle of incidence away from the optimum. The sliding pressure method may have side effects on the distribution of heat transfer in the boiler and convection section coils which has to be accommodated in the furnace and HRSG designs to avoid localised overheating. For USC designs it is essential to maintain supercritical conditions in the main boiler. [6]. Also while optimum incidence angles are maintained in the first stage, subsequent stages will see velocities and hence angles progressively further from optimum.

In order to accommodate varying amounts of solar generated steam the main steam turbine of the host plant would have to be designed specifically to handle the minimum levels of steam extraction. It would also be possible to design for complete elimination of extraction and beyond such that additional steam was added at various interstage locations. Because the period during which solar generated steam is available is only a small part of the day the designs would need to optimise efficiencies under the various loading conditions to give an overall optimum.

In principle it will be possible to design a machine capable of accepting significant solar generated steam flows yet still able to allow stable operation with full extraction of steam for BFW heating and solvent regeneration when no solar steam was available. However there would be an efficiency penalty. The variation of efficiency with capacity of steam turbines has been modelled using simple correlations [7] for the purpose of optimising utility systems. For typical conditions this model suggests an almost linear reduction in efficiency with load of 1.025 for each percentage point




of load reduction. It does not however provide a correlation for overloaded conditions. A very simple correlation between efficiency for both load and speed variations is shown in [8]. In CCS power plants the steam turbines will be fixed speed machines because they are directly coupled to the generators which are synchronised with the grid. The load correlation suggests that peak efficiency is reduced by a factor of 1.02 for every 1% reduction in power output (very close to that derived from the earlier reference) down to 75% and by 1.01 for every 1% increase in power output up to 110% of rated power. More recently it has become possible to model flows through turbine blades using CFD techniques. Results of this type of modelling suggest that the efficiency reductions are proportionately less for small deviations from design optimum increasing progressively as the deviation increases [9]. The expected efficiency variations for a single stage are illustrated in the diagram above.

These figures have been used to estimate offsets due to reductions in steam generator efficiency which will apply when utilising solar generated steam. Furthermore unless there is energy storage the percentage of time during which this happens will be large. The calculations show that unless the percentage of energy provided by the solar plant is available for more than about 15% of the day the losses completely outweigh the contribution from the additional solar energy. The effects are more or less independent of the proportion of solar energy which is supplied since even small reductions in flow from optimum incur losses.

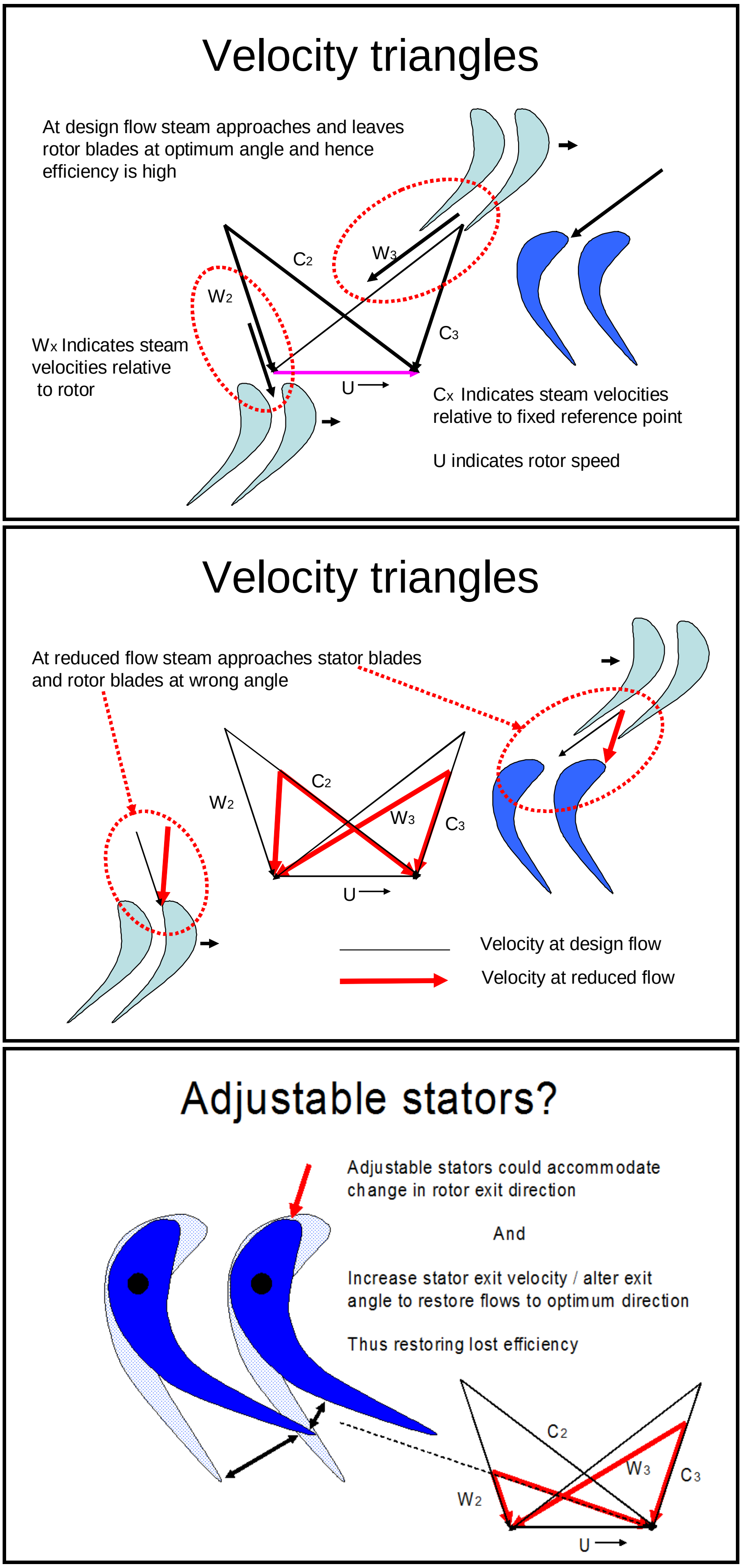
A better option by far would thus seem to be to have a second steam turbine in parallel with the main turbine to which the solar steam would be directed once a significant quantity of steam was being produced. The main plant would in effect provide some buffer capacity during the switchover periods. It would absorb steam from the solar array up to a certain point and would then divert sufficient steam to the solar steam turbine for this to start up and run efficiently. The solar turbine would need to have stages with appropriate capacities between all the pressure levels at which extraction steam is to be replaced. Analysis of this option indicates that as long as the typical turbine capacity/efficiency relationship is valid there will be losses in output whenever the turbines are not fully loaded and, to the first order, it will make no difference how the under-loading is split between the two machines during the switch in.  In other words losses from off optimum loading cannot be avoided.

The only way around this would be to introduce capacity controls which reduce the normal loss of efficiency when there is reduced  flow,  for example by allowing pressures to slide or by stopping or restricting flow to some of the inlet arcs. It is likely that this would require significant development and may prove to be difficult to achieve particularly in turbines with many stages. Another option would be to engineer the additional solar steam turbine as a variable speed machine which could maintain its efficiency over a wide capacity range. However this would require voltage and frequency conversion for the generator which would be an additional cost and also would incur some losses. These would be in the order of 5-10% with modern solid state conversion devices. Thus it would only be worthwhile to do this if the efficiency drop due to off load operational periods was greater than this conversion loss. Given that the estimates of efficiency v capacity are only suggesting a 5% reduction for a 25% capacity reduction this option does not look attractive.

In order to maximise efficiency the best option would still appear to be to have separate solar steam turbines in parallel with the main plant. Having two or more of these extra machines would allow high efficiency to be maintained between summer and winter, mornings and midday by switching machines on and off. By tying in to the appropriate pressure levels in the main plant it would be easy to warm up, start and stop the machines.

A further advantage of such a system could be the enabling of temporary cessation of $CO_2$ capture without loss of steam turbine efficiency. The option of having additional steam turbines has been proposed [10] as a way to utilise the surplus steam which would be available if for example $CO_2$ capture was suspended during periods of high demand and peak prices. The additional turbines would thereby acquire a dual function, either to utilise solar generated steam or to generate extra power by ceasing solvent regeneration at times of peak demand. Note that compressor heat recovery would also be suspended during this mode of operation. An additional advantage of such a system would be that it would no longer be necessary to choose a steam temperature similar to that at the extraction point as for most of the time streams would not be mixed. In fact mixing to any substantial degree would only occur during start-up and shutdown of the auxiliary solar steam turbine with steam "borrowed" from the main plant.

A final option which has been considered but not developed is to have variable geometry stator blades in the main steam turbines which could maintain efficiency over a much wider range of capacities. The vanes would work by adjusting both the angle and the velocity of steam exiting the stators. This is illustrated in the 3 diagrams on the next page. However the environment in which the stator blades operate is very severe and not conducive to reliable operation of the adjustable parts which would be required. Another consideration is that introduction of such a system might slightly reduce peak efficiency even though loss of efficiency away from the design point could be greatly reduced. Simple calculations reveal that even a small loss of peak efficiency (1-2%) would negate the gains provided by the additional flexibility.




Figures 10 a/b/c  Velocity triangles and variable stators in turbines

A further consideration relating to turbine efficiency will be how to handle the variations on steam flow which occur as insolation varies. Again the main plant can do little to alleviate these effects as in doing so it is likely to suffer an equivalent efficiency loss. However there will be flexibility to operate the solar turbine in sliding pressure mode. As long as the solar collectors can handle this the efficiency of the solar steam turbine can be maintained. In fact as the machine will be relatively simple having only one inlet flow it should be possible to maintain high efficiency over all of the stages. The CCS plant will leave as a legacy a highly efficient solar energy plant but one only capable of delivering power intermittently since no energy storage is provided.

In conclusion it seems that the main steam plant turbines cannot easily offer high efficiency power conversion capability in a hybrid solar/fossil fuelled steam power plant. It is not attractive to design the main plant to operate with off-load flows for a substantial portion of the day in order to accommodate solar generated steam. Furthermore there are some constraints on the temperature at which solar steam is generated as this should match that of steam at the extraction point. The simplest option is to install a separate turbine system for the solar generated steam and use this with sliding inlet pressure. Another option to consider is the use of a thermal storage but this would need to be capable of fully smoothing out the diurnal flow variations. Furthermore seasonal variations in capacity would not be handled efficiently if they lead to under-loading of the turbines for substantial periods of the year.

**Re-evaluation of energy storage option**

The option of including energy storage was discussed earlier. However with understanding of the effects on turbine efficiency it is worth revisiting this option because it has the potential to eliminate the thermal energy flow variations which lead to reduced efficiency when the thermal energy is introduced to the host plant as a steam flow. An alternative is to engineer the solar collection system to provide all of the energy required for solvent regeneration [11]. This effectively decouples the main plant steam turbine from the solar energy input as long as sufficient thermal storage is provided. This option also has the advantage of enabling larger amounts of solar energy to be collected. In principle this input could be extended to the boiler feed water heating duties. The amount of solar energy storage required is considerable, especially to cover winter days in the Northern hemisphere. There would also be efficiency losses in the main plant on days when insufficient solar energy was available as then steam extraction would be needed to drive the regeneration. Additional inefficiencies are introduced since a large portion of the collected energy has to be exchanged with the heat storage medium and there will be further exergy losses when it is again withdrawn. This compares with the use of direct steam generation feeding a steam turbine where these heat exchange losses are not incurred and the turbine can be engineered to give state of the art power conversion efficiency.

In order to collect enough energy to operate at full capacity for 24hours, assuming a normal days irradiance, a multiple of the array area needed to generate the peak capacity is required. The further from the equator the greater this multiple becomes in the winter season. The chart illustrates the typical diurnal variations in solar irradiance for two locations. One is on Valencia Island in Ireland and this represents the lower levels of solar radiation collectable in temperature latitudes. The other curves are for the area in California where the Dagget Barstow solar array is located. This represents the expectations at prime solar energy locations. The amount of energy collectable annually will be further reduced due to the frequency of cloud cover at the locations as these charts are based on clear days. From these figures it is possible to calculate a solar multiple which is the factor by which the collection area has to be increased so that the nominal peak radiation level can be supplied through use of energy storage through the day. An even larger factor can be calculated which indicates the factor required to enable the peak in the most productive season to be matched in the least productive. At Dagget Barstow for example it would be necessary to install 2.35 times the area (not accounting for any additional losses due to storage) to provide the peak summer power level for 24 hours. To provide this same amount of energy in the winter the area would need to be 3.83 times greater. The situation in the northern hemisphere is similar in summer, there for the

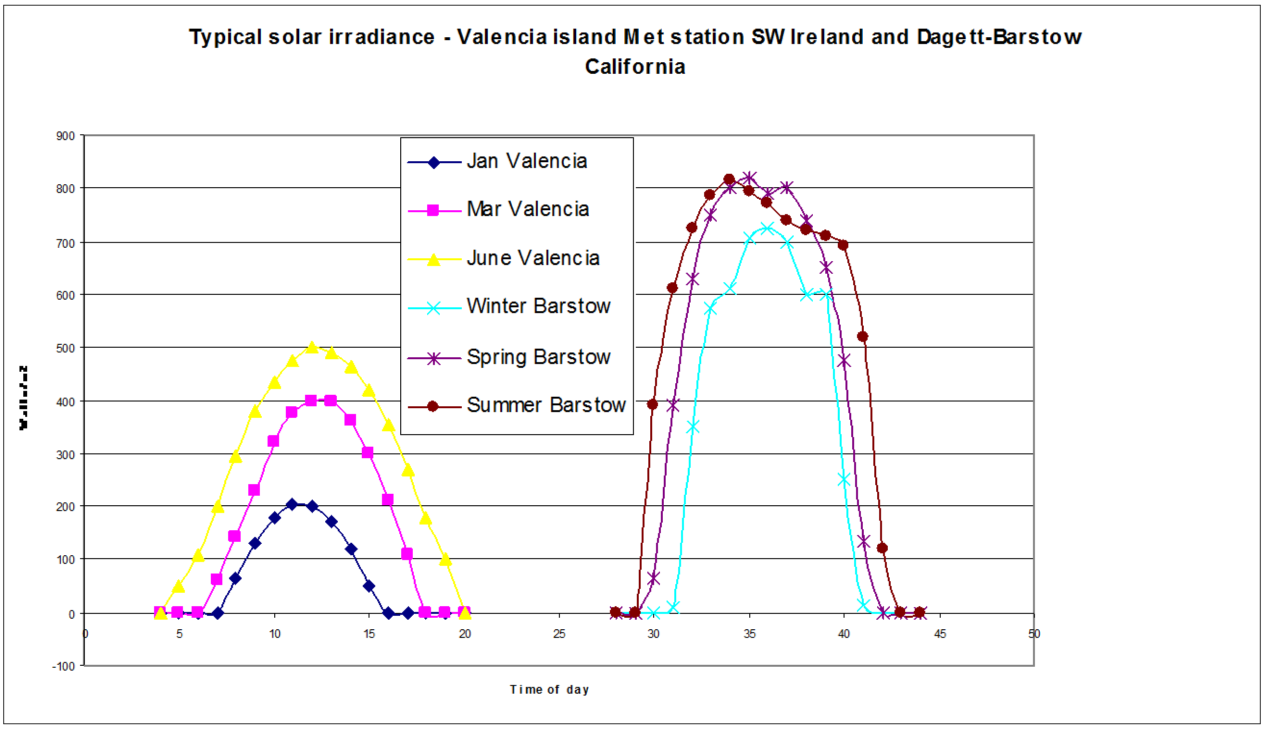



Figure 11 Typical solar irradiance

Valencia island June radiation pattern 2.54 the area would be required. However in April and January the multiples rise to 4.12 and 10.71. The extra energy collected becomes increasing capital intensive both due to the need for extra solar collection area and the need to provide more thermal energy storage.

A range of thermal storage materials have been developed [12]. They can be either liquids or solids. One of the cheapest liquid options is mineral oil although this has a limited temperature range. Nevertheless the quantities which would be required illustrate the practicality of this approach. Based on the foregoing reference heat could be stored over the temperature trajectory 200-300°C giving a thermal capacity of 260Kj/Kg. For the Barstow case a maximum of 62% of the daily thermal duty would have to be derived from the store in the winter. For Valencia the figure is 71%. To meet the 750MW regeneration duty for a 1GW CCS plant the store would need to hold 12,750 MWh of heat. Based on the thermal capacity of the heating oil this would require approximately 230,000m$^3$ of oil which would require several of the largest size storage tanks to hold. The concept is thus feasible but costly. It would also at least double the width of the area required for solar arrays around the plant.

**Multiple land use**

The land to be occupied by solar arrays around major power plants is likely to have significant value and dedicating it solely to power generation may not be the most acceptable use. Some of the land will need to be reserved for access and this could include public access if for example public roads run through the area. There will be spaces between the solar arrays and also the space under the solar arrays might have an alternative use. Although shielded from most sunlight the land will still have the potential to support plant and animal life. It will also inevitably retain a local drainage function, one which might be affected if it is developed as a solar array. Serious consideration can be given to multiple uses for some or part of the land particularly in more populated regions. These could include covered storage under the solar arrays, farming of crops requiring little sunlight. Because of the presence of high pressure steam or other hot pressurised fluids there would be safety issues for any dual use so that all access and activities would need to be controlled.
Because the land will still be agriculturally active, even if shaded by solar arrays, vegetation will grow and some form of additional land management, even if only regular control of weeds, will be required. Another consideration is that in principle no trees of any size would be wanted within the array area because of shading effects, leaf debris and risks of damage through falling. Designating such large areas to be devoid of trees may not be acceptable. Hence an essential area of study when considering this type of system is shared land use, environmental and societal impact and land maintenance.

**Overall conclusions CSP as thermal energy supplement to CCS**

It is feasible, subject to land prices and ease of acquisition, to envisage a solar array of 1 to 2 km width surrounding a power plant with CCS. The amount of thermal energy collectable would significantly defray that needed for solvent regeneration but would also be useable for boiler feed water heating. However, unless expensive thermal energy storage was installed, the maximum increase in power plant efficiency is likely to be limited to less than 3% and this would require heat to be used to supplement both solvent regeneration and boiler feed water heating duties.

The best way to collect the solar energy would appear to be through direct steam generation in linear Fresnel arrays. These should be arranged partly in N/S oriented and partly in E/W single axis arrays for simplicity and to minimise the length of high temperature steam headers. Steam at medium pressure would be the preferred condition for transport.

It is not advisable to use the steam to back out extraction as the reduction in the main turbine efficiency is likely to be considerable. Therefore a separate steam turbine or turbines should be used and steam from the main plant used for start up and to maintain hot standby where appropriate. The turbine could also be used should the CCS plant wish to operate without $CO_2$ capture for a period. This could provide a significant incentive at times of peak demand and price. It would also enable plant efficiency to be maintained if the capture plant had to be taken out of service.

Heat losses will be significant and the system would cool overnight. It would not be economic to try to keep the solar array warm.

In order to avoid installing a separate turbine or turbines it would be necessary to develop steam turbines for the main the plant with variable geometry stator blades but in such a way that current

peak efficiency is retained. To date this service is considered far too onerous for such devices and they have not been developed for application in large steam turbines.
An alternative which could be considered is to develop an array with extensive thermal storage which would supply some or all of the regeneration duty. However this option does not seem to make most efficient use of the near plant land area and would require thermal storage at the limit of feasibility.

## Fossil fuels with CCS as support for Concentrated Solar Power plant

### General description

Developers of concentrated solar power plants are developing systems which can concentrate solar energy so as to attain the highest possible temperature for the working fluid. The reason for doing this is to increase the efficiency with which the thermal energy can be converted to electrical power. Plants in this category make use of central towers onto which solar radiation is concentrated from a field of surrounding heliostats. Working fluids can be steam or air. Water and hot oil have temperature limitations which are too low to make their use in this high temperature application worthwhile. Molten salts capable of withstanding higher temperatures may be considered but cannot be used to reach the full high temperature potential of these systems.

Because the systems work at very high temperature it is advantageous to consider use of high temperature heat storage and or a supplementary fossil-derived storable fuel. This is for two main reasons, firstly to be able to maintain power output during periods of darkness and secondly to minimise the daily thermal cycling. An additional reason could be to boost the attained temperature thus further increasing the efficiency of the power conversion process.

### Advantages of using fossil fuel with CCS to support CSP

The use of supplementary fossil fuels in support of CSP would compromise the low greenhouse gas emissions footprint of the technology. Furthermore if the fossil fuels are not used efficiently in the power conversion process there would be an additional emission penalty compared to using the fuel more efficiently elsewhere. However, if an efficient way of utilising such fuel could be found, combining it with CCS to minimise emissions is an option worth considering.

### Geographical considerations

In contrast to the use of solar thermal energy to supplement CCS plants, the host plant in this combination would be the CSP plant. Hence the preferred location of the plant would be in a region of high solar insolation. The CCS plant would thus not be the major unit. Thus in order for this combination to be successful it would be necessary for the location of the CSP arrays to be suitable for building a CCS plant. This implies that a source of coal or natural gas should be nearby. There are regions of the world, such as the Sahara, where there is an abundance of gas, direct solar energy and $CO_2$ storage capacity both in deleted hydrocarbon reservoirs and deep saline formations. Biomass is also a potential candidate for hydrogen production by gasification but typically biomass production would not be possible in the desert regions best suited to exploit this synergy.

**Scale considerations**

The cost of providing supplementary energy to CSP using fossil fuel with CCS plant is affected by economies of scale. One consideration is the cost for development of a suitable storage site. A minimum of one injection well is required and unit costs would increase if the capacity was less than could be delivered to such a single well. The costs for the required well or wells could be low if a suitable deep saline formation was available at moderate depth and for smaller capacities use could be made of slim hole drilling techniques. The other consideration is the scale of the CCS unit. There are two main options, one is to generate hydrogen from coal or natural gas with attendant capture and storage of the $CO_2$ using a gasification and water gas shift process. A key process in the hydrogen-supply plant is the gasification. The gasifiers used are of limited capacity so that for larger plants multiple trains have to be built. However the rest of the plant can usually be executed as a single train.

The second option is to use post combustion capture technology so that the fuel is used simply to provide supplementary heating. However the fuel would have to be used to heat the circulating fluid in the solar system, hot oil, molten salt or steam. The heaters would have to be distributed, this function could not be sufficiently centralised to create reasonable economies of scale. Hence only the distribution of gasifier/CCS derived hydrogen would seem to be worth considering further.

**High temperature CSP technologies**

A key feature of high temperature CSP technology is the use of high concentration factors to create very high temperatures at the collector. This requires two axis tracking of the sun and can either be achieved by individual parabolic reflectors or an array of reflectors concentrating radiation on a central tower. Both systems have to take account of shadow effects which tend to make less efficient use of land area. Thus this type of system is most suitable in sparsely inhabited desert areas where land is more freely available. This is exemplified by the work done on the "Desertec" concept for generating solar power in the Sahara region. Different power cycles have been used including steam in a Rankine cycle, air in a Brayton cycle and various working fluids including hydrogen in a Stirling cycle. Of these the high temperature Rankine and Stirling cycles seem to be more successful. Test with high pressure high temperature collectors for heating air using a matrix collector encased in a pressure vessel with a transparent window have been conducted but not further developed at present. On the other hand there are significant developments of central power towers using steam generators and also individual parabolic reflectors with a Stirling engine [13] and generator at the focal point. The latter concept is likely to result in a large number of distributed generation points with a capacity of a fraction of a MW whereas the central tower concept can be sized to produce as much as 150MW. [14] Of these concepts the parabolic dish achieves higher concentration ratios, up to 3000, enabling temperatures up to 1500°C to be reached. The power tower concept can have concentration ratios up to 1000 and is thus more suited to raising high temperature steam for a Rankine steam cycle.

By contrast the linear parabolic reflector systems are limited to producing steam at lower temperatures, current maximums for direct steam systems for example are around 500°C.

**Efficiency considerations**

In order to evaluate the true worth of integrating the CSP and CCS technologies it is necessary once again to consider the performance of these on their own. Hydrogen produced in a Gasification/CCS plant would be converted to power by a gas turbine operating in combined cycle mode (CCGT). The efficiencies of large natural gas fired CCGT plants has been pushed to 60% [15] by a combination of advances including higher turbine inlet temperatures, 3D blade design, lower clearances and reheat burners. Gasification/CCS to hydrogen plants will make use of this same technology but will suffer a slight reduction in efficiency from hydrogen compared with gas fired units. The main reason is that the combustion gases produced by burning hydrogen have different thermal properties of conductivity and specific heat which renders the blade cooling systems, essential to reach the highest turbine inlet temperatures slightly less effective. A hydrogen burning turbine must either reduce inlet temperatures with respect to those in a natural gas fired machine or increase blade coolant flows. The latter may degrade performance less. Any comparison with an integrated plant will need to consider how efficiently the hydrogen is used in the power conversion process. In particular if the integrated process is of intermediate efficiency between those of the stand alone CSP and Gasification/CCS/CCGT processes an assessment of overall efficiency change should be made.

The technology which would make the best use of the supplementary hydrogen fuel would be that using a Brayton cycle since it would be possible in principle to raise the turbine inlet temperature to state of the art values and apply a steam bottoming cycle thus preserving high overall power conversion efficiency. However this technology seems at present unlikely to develop. The next most efficient technology is possibly the Stirling cycle. However the efficiency of the rather small units, whilst good, is not high. For example reference [13] suggests a cycle with a 29.4% net efficiency. The literature indicates that the receiver temperature is 720°C so the Carnot efficiency of this cycle cannot compare with that of a modern gas turbine based system where inlet temperatures are approaching 1500°C. This efficiency is about half what could be expected if the hydrogen was consumed in a CCGT plant.

The central tower system using hydrogen as supplementary fuel in such a cycle would still be considerably less efficient than using the hydrogen in a CCGT system. However if the hydrogen was burnt first in a gas turbine and the exhaust gases used to raise steam it would be possible to deliver supplementary heat whenever required but without significantly reducing the efficiency with which the hydrogen is used. The size of the units would be smaller than used in large CCGT plant and the efficiency of smaller units will be lower.

In conclusion it is suggested that the most energy efficient way in which to use Gasification/CCS hydrogen as supplementary fuel for high temperature concentrated CSP applications is to install a supplementary gas turbine and HRSG to provide supplementary steam to the CSP plant steam system. If the fuel supply was natural gas an alternative would be to fire the gas turbine directly with gas and apply post combustion capture. But this would not allow centralisation of the capture process. Use of a gaseous fuel, be it hydrogen or natural gas, other than in a state of the art CCGT process is not efficient.

The next most efficient way to provide supplementary heat is to use the fuel to directly heat the solar working fluid. This would only be an efficient option for coal and then only if it were used to attain state of the art working fluid temperatures which currently for steam systems are 600-620°C. However the capture of $CO_2$ would be decentralised and thus expensive and logistically difficult.

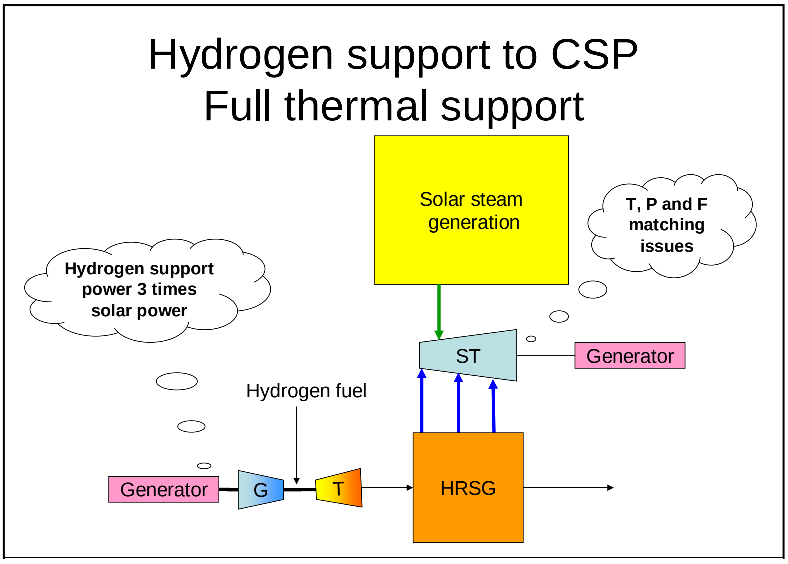



Figure 13 Full thermal support using hydrogen powered CCGT

## Matching considerations

From the foregoing the only option which enables CCS generated hydrogen to be used with reasonable efficiency is that based on using hydrogen fired gas turbine exhaust gases to provide the supplementary heat needed to improve the continuity of the CSP process. Two issues need to be addressed when matching the two systems. The first is to consider how to match the relative power outputs of the two systems. The second is to consider how to match the temperature levels and flows of working fluids.

A CCGT system generates about 2/3 of the power from the gas turbine so one consequence of adopting this highly efficient method of thermal support is that total plant electrical power output with 100% replacement of the solar thermal energy would be three times that of the solar plant on its own. It is unlikely to be desirable or economic to generate such large amounts of power using hydrogen in the remote locations favoured for CSP plants so designs should try to minimise the capacity of the hydrogen system. One option would be to install a hydrogen CCGT system with maximum power equal to the output of the solar array. This would in principle enable full power output to be maintained at all times. However the amount of heat available to directly support the solar power generation system would be only 1/3 of its full power.

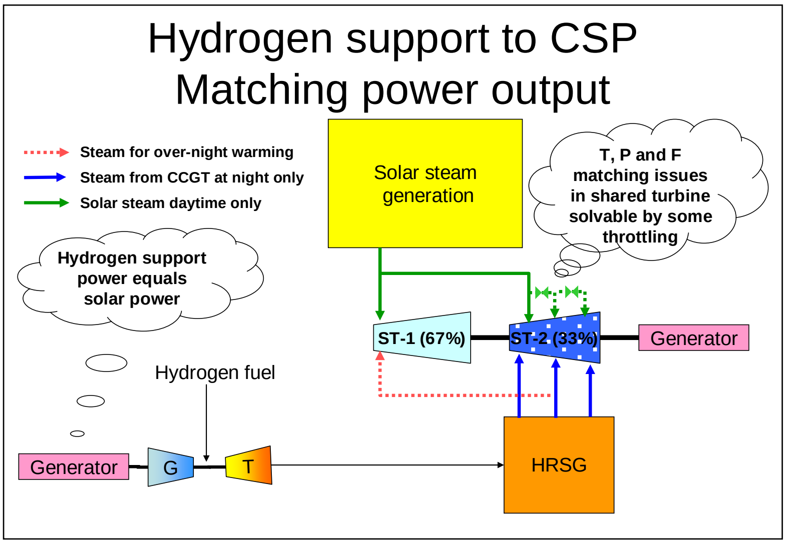



Figure 14 Matching electrical support from hydrogen powered CCGT

The solar plant will use hot oil, molten salt or steam as the main collection fluid. However if hot oil or molten salt is circulated this will be used to raise steam for power generation. Thus the steam pressures, flows and temperatures generated in the CCGT plant HRSG will need to be matched to those generated by the solar system. In DSG systems the most common arrangement is to generate superheated steam at one pressure. Reheat is not applied and to do so would require additional lower pressure steam lines to and from a re-heater array. The HRSG system

of a CCGT plant usually produces steam at three different pressures in order to improve efficiency. This makes better use of the exergy in the hot gas stream. A similar arrangement would most likely be employed for hot oil or molten salt solar systems for the same reason. However the temperatures currently reached in such systems are often lower than in gas turbine exhausts as a result of which the pressures and temperatures at which the steam is generated will also be lower. For successful sharing of steam turbine equipment stage pressures would need to be matched and temperature differences kept to a minimum. In addition the stage flows would need to be maintained close to design to avoid degrading efficiency as was discussed earlier in this study.
If a reasonable match is not possible the best option will be to have separate steam turbines for the Hydrogen CCGT and solar power plants and have interconnections only to assist with start up and shutdown and to keep equipment warm.

The option to have a fully shared steam turbine is not favoured as the hydrogen support plant would then have 3 times the peak output of the solar plant. If the Hydrogen CCGT has equal capacity it would only produce 1/3 of the steam required to replace that from the solar array. To maintain steam turbine efficiency all inlet pressures would need to be lowered. A better option could be to split the turbine into a 33% and a 67% unit and share only the smaller unit. The larger unit could be kept warm but not generate at night. The smaller turbine would be matched largely to the CCGT plant and some steam from the solar plant may have to be throttled to supply the lower pressure stages to match stage flows. The HP steam pressure from the HRSG may have to be reduced at times when the turbine is being shared.

**Turn down considerations**

Turn down in the arrangement described in the foregoing may be an issue during the changeover from solar to hydrogen power. As the period when this occurs is short any efficiency losses will be of limited duration. Approximately 8-9% of CCGT efficiency is lost when capacity is reduced to 50% [16]. One effect of this reduced efficiency will be to raise the turbine outlet temperature so that proportionately more heat will be recoverable in the HRSG. To minimise hydrogen support the changeover sequence should allow the smaller steam turbine to be progressively fed by solar steam. The CCGT would then be stopped and the larger steam turbine would be spun up as more solar steam was generated. Inlet pressure would be varied to maximise steam turbine efficiency.

**Heat only provision using Hydrogen**

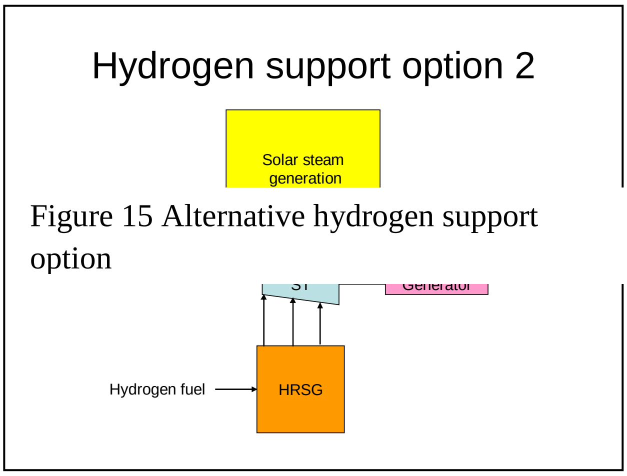


Figure 15 Alternative hydrogen support option

Although the foregoing option is intrinsically the most efficient it is not flexible and incurs considerable investment costs and will require significant additional maintenance. A slightly less efficient option would be to burn hydrogen to produce steam in a boiler and generate power from this in the solar steam turbine system. It should be possible to generate steam at USC conditions so that the thermal efficiency of generation could be as high as 45-48% using today's materials of construction. Such a system would be far simpler and could be designed for a much greater capacity turndown. Furthermore the full capacity of the solar plant could be provided through use of steam so that out of hours efficiency of the steam turbine would be maximised. Despite the less efficient use of hydrogen this option may be preferred because of its better flexibility and turndown.

### Capacity of hydrogen generation and distribution system

The hydrogen plant would be required to provide back up capacity to all of the solar arrays in a development during the hours of darkness and transition. The capacity in the absence of any storage would need to equal what ever minimum fraction of the solar plant output was required out of daylight hours. However as the hydrogen is not required all the time there is scope for a considerable reduction in plant capacity through installation of an underground hydrogen storage system. The pressure at which hydrogen has to be delivered depends on whether the hydrogen turbine or hydrogen boiler system is adopted. The former requires the gas at elevated pressure typically above 20 bars whereas the boiler option only requires it a nominal pressure above atmospheric for operation of the burners and to overcome pressure drop in the distribution lines. Thus for the latter option an underground storage without additional compression can be envisaged. For the other option some recompression out of storage might be required if storage pressure was not high enough. Adopting hydrogen storage in this way could reduce the required hydrogen plant capacity by up to 50%.

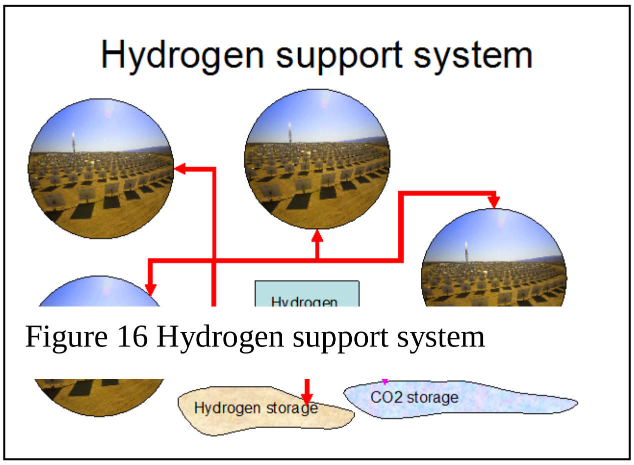


Figure 16 Hydrogen support system

### Conclusions

Of the high temperature CSP applications only the central tower raising steam as working fluid seems worthwhile as a partner to a CCS plant utilising hydrogen produced from coal or natural gas with $CO_2$ capture. Even this option makes rather less efficient use of hydrogen than a stand alone pre-combustion CCS plant. The cost would be significantly higher than that of using natural gas as backup fuel because of the cost of the conversion equipment and the energy losses during conversion. The scheme would work best if coupled with a hydrogen store. Because of the high cost the support to the solar systems should be limited to the minimum needed to prevent undesirably fast thermal cycling and for provision of essential power requirements during hours of darkness. Longer periods of support may be better provided by thermal storage systems. Given that direct use of the fossil fuel without capture would be cheaper any decision to use hydrogen derived in a Gasification/CCS process in this way would depend on the importance attached to minimising greenhouse gas emissions.

## Compressed air energy storage

### General considerations

Compressed air energy storage (CAES) is not *per se* a renewable technology but is closely associated as it provides the only viable large scale energy storage alternative to pumped storage. The latter cannot be applied in flat regions and creation of the necessary reservoirs has environmental impacts. The system involves compression of air into an underground reservoir and its subsequent expansion through a turbine to recover energy. The heat of compression is lost in this process. The efficiency can be improved by combining it into a Brayton cycle. The compressed air is heated as in a conventional gas turbine before expansion. The emissions of this process could be reduced if instead of conventional fuel hydrogen derived from a Gasification/CCS plant were used. It is claimed that the heat rate of a CAES plant with firing is lowered from that of a typical CCGT of 7000Btu/KWh to 4000Btu/KWh. [17]. The CAES turbine exhaust is not used in combined cycle. The inlet pressure of the air is somewhat higher than that used in a conventional gas turbine. These figures imply that around 40% of the power is derived from the compressed air energy and 60% as a result of the additional heating. CAES operates intermittently and the effects on the operation of a Gasification/CCS plant need to be considered. If the hydrogen requirement is a small fraction of the Gasification/CCS plant capacity that plant could simply be turned down. If the requirements are larger, say above 30% then it would make sense to install underground hydrogen storage to smooth out the production requirements. However if the operating hours of the CAES are short the advantages of emission free operation may not justify the extra expense of consuming hydrogen. Further work is needed to establish exactly how the efficiency of conversion of fuel in a CAES plant compares to that of a CCGT.

This arrangement could be considered as an optimised Gasification/CCS/Hydrogen/CCGT power plant running at steady state. At times of low electricity demand compressed air would be drawn off the GT compressor and put into high pressure storage. At times of high electricity demand compressed air would be drawn from the store (possibly boosted in pressure to compensate for pressure losses in storage) directly into the GT combustor. The operability of this system would depend on the extent to which the GT compressor could be operated away from its normal operating conditions.

## Solar heat for high temperature chemistry in support of CCS

Solar energy can be concentrated to produce the very high temperatures which can be used for driving chemical reactions. A brief assessment of the possibility of usefully combining this capability with CCS processes was carried out. Within the family of CCS processes there are two which involve separate high temperature endothermic chemical reactions. These are calcination in the high solid looping process and reforming in those pre-combustion capture processes which use this rather than partial oxidation.

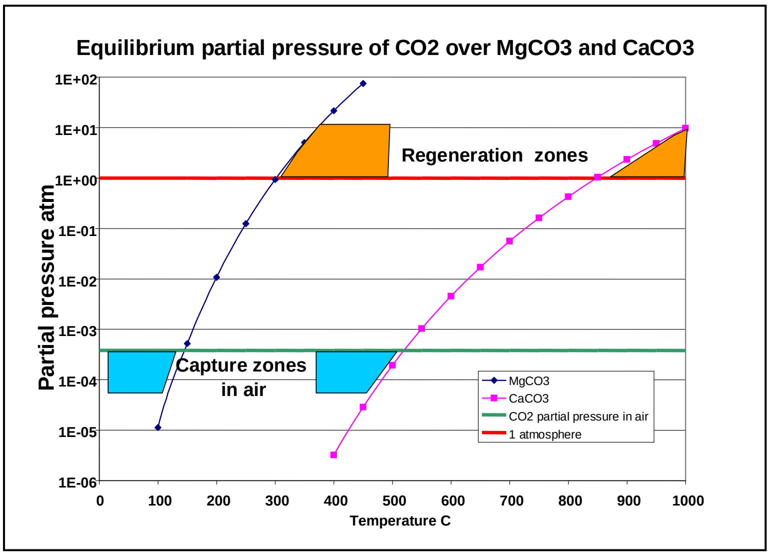
The calcination process is carried out at temperatures of 900-1000°C in a fluidized bed and heat is added by burning oxygen and fuel within the bed. The offgas consisting of $CO_2$ and steam is used to raise high pressure steam. The key to efficiency in this process is that this, and the lower temperature exothermic carbonation reaction, all take place at temperatures high enough for all the off gases to be used to generate steam at state of the art conditions of temperature and pressure for onwards conversion to power. A small bleed of spent material is taken from the loop and has to be made up with fresh limestone. The energy required to release the $CO_2$ from the fresh make up is largely lost as the bled material has lost most of its activity and contains only around 15-20% of the initial carbonate content. Thus a small contribution might be made if a solar process could be used to prepare an already calcined limestone make up as long as the $CO_2$ released in the calcinations was captured.

Examining the thermodynamics of such a process it is clear that a considerable amount of sensible heat would have to be provided to heat the limestone up to calcination temperature and unless this were recovered the overall process would not be very efficient. In effect the solar process would become a combination of calcination and solar electrical generation. The small gains for the associated CCS plant would not seem to warrant such a complication.

If the solar heat could be applied directly to a hot slipstream from the main CCS process the sensible heat losses could be avoided. However it is not feasible to transport the hot fluidized material any distance so only that energy which could be beamed directly into the plant could be used and this would be minimal. Calcined material is a very effective compound for capturing $CO_2$ and might be used in a distributed capture system for smaller sources. Its free energy of reaction is such that the direct extraction from air can proceed almost to completion. However the downside is that the very high heat of reaction which is required to produce it makes it energetically uninteresting. Some work is proceeding on these reactions [18] using simulated concentrated solar energy and small fluidised bed reactors. However apart from the fact that the solar arrays could be placed above a $CO_2$ storage site there is no other significant synergy with CCS.

The reforming route to hydrogen from fossil fuel is not favoured for large scale systems because of the cost and size of the high temperature reforming furnaces which are needed, the requirement for regular catalyst changes and the sensitivity of the catalyst to sulphur. In principle it would be possible to use solar heat for driving the endothermic steam reforming reaction. However the engineering challenges are considerable and the capacity of individual units would be small. Collection and storage of $CO_2$ from such small installations would also not be economic.

An interesting possibility would be to use solar thermal energy to regenerate solid materials which could capture $CO_2$ directly from the atmosphere. The issues around this were briefly investigated. The value would be in using solar energy available in places where neither power nor conventional carbon dioxide capture were useful but where $CO_2$ storage might exist. The principle would be to react a solid material with $CO_2$ from the air and release the $CO_2$ by heating it using solar energy. Two materials which react with $CO_2$ are calcium oxide and magnesium oxide. These exhibit different equilibrium with $CO_2$ as shown in the chart. Both oxides have equilibria such that they will react with $CO_2$ in air at ambient temperatures. $MgCO_2$ can be regenerated at around 300°C whilst $CaCO_3$ requires 900+ °C. Both regeneration temperatures are within reach of solar concentrators but that for $MgCO_3$ is easily possible with linear concentrators. A system in which a tube of reactive material is



cycled between exposure to an air flow followed by sealing and solar heating to release the $CO_2$ could be envisaged. However the capacity would be negligible because of the contacting step. The required quantities of air not pass through the devices quickly enough and the gas/solid reaction rate at ambient temperatures is extremely low. Carbonation of CaO proceeds reasonable quickly at 600-700°C but may also be slow at the maximum of 400-500°C at which equilibrium for capture is still favourable. However even if reaction rate was adequate the transport rate of air over the devices would be a severe limitation. To make significant use of the incident solar energy the material would need to be cycled as quickly as possible. The cycle time would be limited for regeneration by the warm up time and for capture by the air transport rate and reaction rate. The collectors would have to be defocused and refocused to achieve this. If the cycle could not be done in situ the logistics of collecting the solids and arranging for them to be exposed to the focused radiation so that released $CO_2$ could be collected would be considerable. Materials of this type typically loose reactivity after a few cycles of regeneration so that only 10-20% of theoretical amount of $CO_2$ might be taken up. Nevertheless the amount of air present in the voids would be quite small compared to the amount of $CO_2$ which would be release so that purities in the high 90%'s could be expected.

In conclusion whilst thermodynamically possible air collection of $CO_2$ with in situ release and capture using solar energy appears to be impractical. A key limitation is the ability to circulate air over the absorbent material in a reasonable time. Rough calculations show that with a superficial velocity of 10cm/sec over a material with only 10% reactivity it would take some hundreds of days to flow enough air to feed the reaction.

## Surplus wind power for pressure control of $CO_2$ storage reservoirs

The capacity of deep saline formations may be limited by pressure rise and one way of increasing their capacity may be to remove saline water by extracting water from relief wells. It is unlikely that such wells will flow naturally and even if they do the economics of such pressure relief is likely to be improved by applying down hole pumps. Such a scheme is tentatively planned for the Gorgon project where saline waters may be pumped from the target Dupuy formation to the Lower Barrow Group of reservoirs. As control of pressure is a very long term activity this operation could be performed intermittently, hence would be amenable to powering using surplus electricity.

Rough calculations can give an estimate of the power which would be required. In fact the total power required is very small even with intermittent pumping for just 10% of the time. The main advantage of deriving it from nearby wind energy would be the ready availability. In fact the amount required on a continuous basis could easily be supplied

| **Power for water extraction** | |
|---|---|
| Density of stored $CO_2$ | 550kg/m3 |
| Density of displaced brine | 1030kg/m3 |
| Injection rate of $CO_2$ | 4million tpa |
| Fraction of displaced brine removed | 25% |
| Pumping pressure differential | 30bar |
| Pump efficiency | 60% |
| Volume to be pumped (Continuous) | 110M3/HR |
| Time for which peak energy used | 10% |
| Volume to be pumped intermittent | 1100m3/hr |
| Calculated pump power | 1.5MW |

## Solar energy for conditioning of $CO_2$ prior to injection

Captured $CO_2$ is typically transported to the storage sites by pipeline in the dense phase. However in order to control injection it may need to be conditioned to have a lower density. Otherwise excess hydrostatic pressure will build up in the injection tubing. Throttling cannot be used since this will cause cooling and potentially may cause freezing in the injection zone. To condition the $CO_2$ it has to be heated and this duty, particularly in remote locations, might be provided by ambient air heaters. A more effective method might be to use solar arrays to collect sufficient thermal energy. These could be combined with a hot water storage system to provide day and night operation. The quantities of energy involved are relatively small but might offer an opportunity to save some fossil fuel energy and reduce accompanying emissions.

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