Brunel University

Institute for the Environment

Sustainability: A New Approach?

By

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September 2011

DECLARATION OF OWN WORK

I declare that this thesis entitled “Sustainability: A New Approach?” is entirely my own work and that where material could be construed as the work of others, it is fully cited and referenced, and/or with appropriate acknowledgement given.

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WORD COUNT

The word count for this script is **9915** excluding Figures, Tables, References, Appendices and Abstract.

Abstract

There is an urgent need to decarbonise global energy supply with about 20 years of business as usual (BAU) remaining to achieve an 80% calculated chance to limit global stabilisation temperatures to +2°C by 2100. Conforming to this aim, more than half of fossil fuel reserves should be left un-burnt or their emissions captured and sequested. It is argued that funds invested in development of carbon capture and sequestration (CCS) technology for fossil power plant, may be better invested in a truly sustainable electricity infrastructure utilising solar energy. Emissions trading schemes have also tended to set the carbon price such that they are deemed inadequate to effectively mitigate carbon emissions. Sustainability is shown to be of central importance in energy policy, from the perspective of satisfying demand, environmental and energy security issues. Solar radiation in deserts is evaluated as the most plentiful and opportune resource available to meet sustainable energy requirements, including the UK and European electricity demand. Solar energy falling on deserts is shown to equal world electricity generation (2008) in under 3 hours and to be equivalent to global primary energy supply from all fossil and fissile sources in 19 hours, with a reserve which may be considered of unlimited duration. A model of sustainability using life cycle assessment (LCA) and ecosystem service (ES) availability was tested in assessing the concentrating solar energy pathway but was found to be vulnerable to the need to keep LCA data up to date. With overall system efficiencies increasing and currently as high as 22%, concentrating solar photovoltaic (CPV) and concentrating solar thermal power (CSP) were found to offer an attractive way of converting solar energy to electricity on a large scale while critically, conserving water at the same time. High voltage direct current (HVDC) networks and smart grids were considered as efficient ways to transmit and distribute electricity to European population centres and that the benefits to Middle-Eastern and North-African (MENA) countries of access to clean electricity and water in exchange for their solar resource in under-utilised desert lands, would benefit sustainable development.

Acknowledgements

Many thanks go to Dr. Dan Pickford, Director of my course in Climate Change Impacts and Sustainability at Brunel University, for his continuous encouragement and open ears to my questions. And to Prof. David MacKay in the Department of Physics at Cambridge University, who’s book ‘Sustainable Energy - without the hot air’ was inspirational.

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Glossary of Terms and Abbreviations

Base load	The minimum amount of power generation necessary to meet predictions of minimum expected power demand
BAU	Business As Usual (ie. with no policy interventions)
BM	Biomimicry
Capacity Factor	The ratio of actual power output to rated output over a period of time (see base load)
CCS	Carbon Capture and Sequestration
CPV	Concentrating Photovoltaic power
CSP	Concentrating Solar Thermal power
CWC	Cumulative Warming Commitment - the peak temperature change expected as a function of anthropogenic carbon
DNI	Direct Normal Irradiance - directly received solar radiation as compared with diffused and reflected
ES	Ecosystem Service
EU ETS	European Union Emissions Trading System. A carbon trading system which issues 'allowances' to industry to emit CO_2 under an overall cap or limit for the EU. Industries may then trade their allowances if they require more emissions rights or have surplus capacity from savings they have made. Consequently a carbon price is set. If the initial cap is high however, the price of carbon will be too low to incentivise sufficient CO_2 emissions reduction by participants to meet global decarbonisation targets.
EUMENA	Countries of EU, Middle East and North African region
GHG	Greenhouse Gas. The Kyoto basket of GHG's includes: Carbon dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O), Sulphur hexafluoride (SF_6), Hydrofluorocarbons (HFC), Perfluorocarbons (PFC)
HVDC	High Voltage Direct Current
HVAC	High Voltage Alternating Current
Kyoto Protocol	An instrument of the UNFCCC, ratified and legally binding by 37 industrialised countries and the EU, to reduce GHG emissions by an average of 5% compared to 1990 levels which came into force in 2005. In 2012 this Protocol will come to an end. It's successor will hopefully be agreed upon in Copenhagen in December 2009 during negotiations between industrialised and non-industrialised members of the UNFCCC.
LCA	Life Cycle Assessment (also known as Life Cycle Analysis)
$MtCO_2e$	Mega-tonnes CO_2 equivalent (the quantity of CO_2 that would provide the same degree of global warming as a mixture of GHG's over a 100 year period)
ppm	parts per million
UNFCCC	United Nations Framework Convention on Climate Change (an intergovernmental policy network with 192 member countries to facilitate cooperation and coordination of efforts to tackle climate change. Established 1994.)
Units used conform to SI standard	E - Exa (10^{18}); P - Peta (10^{15}); T - Tera (10^{12}); G - Giga (10^{9}); M - Mega (10^{6}); K - kilo (10^{3}).

1- Introduction

***Sustain**, v.t. to hold up: to bear: to support: to provide for: to maintain: to support the life of: to prolong.*

- Chambers Twentieth Century Dictionary, 1980.

Exploration into a tangled conceptual jungle where watchful eyes lurk at every bend.

- O'Riordan, (1985) on the difficulty of defining sustainability.

The point of this project: the research questions

This project has been inspired by the author's worry that something is very unsustainable about the way we are doing things, which may cause dramatically negative consequences - dangerous climate change forcing being the most obvious - if necessary action is not taken to align greenhouse gas (GHG) mitigation policies coherently with environmental sustainability. While the author regards this as a global necessity, this work will consider the UK electricity supply. GHG emissions from electricity generation make up around 33% of the UK carbon budget, (Fig.1) and about 75% (60GW) of our electrical energy currently comes from fossil fuels (Fig. 2). The point of this project is to look at the motivation for sustainable energy and test a model designed to support environmental sustainability within policy making. The test will be done by applying the model to the concentrating solar energy technologies which it will be argued belong to the most sustainable energy pathway currently open to us.

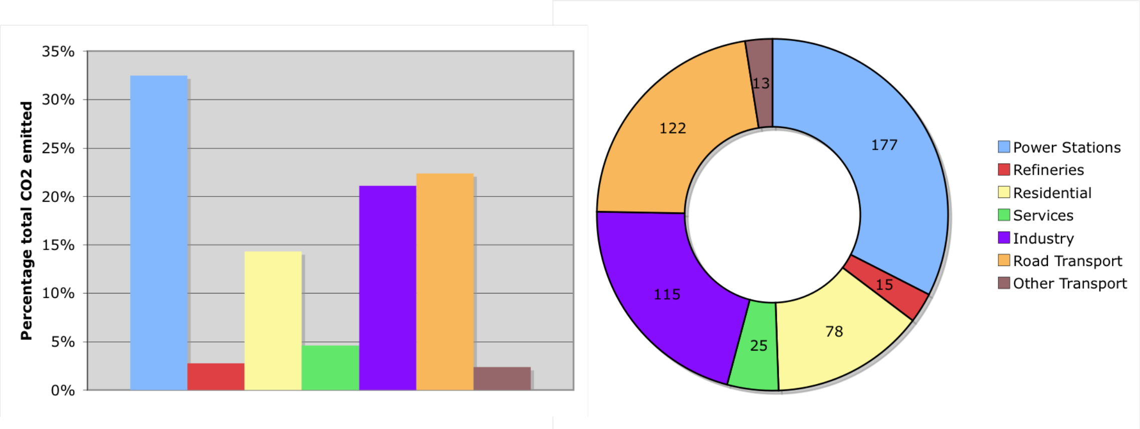


Fig. 1. UK GHG emissions by sector in 2007. The graph on the left indicates share of the total account by percentage. The graph on the right indicates share of the total account by $MtCO_2e$.
Adapted from: DECC[1], 2009. UK Low Carbon Transition Plan Emissions Projections, p7.

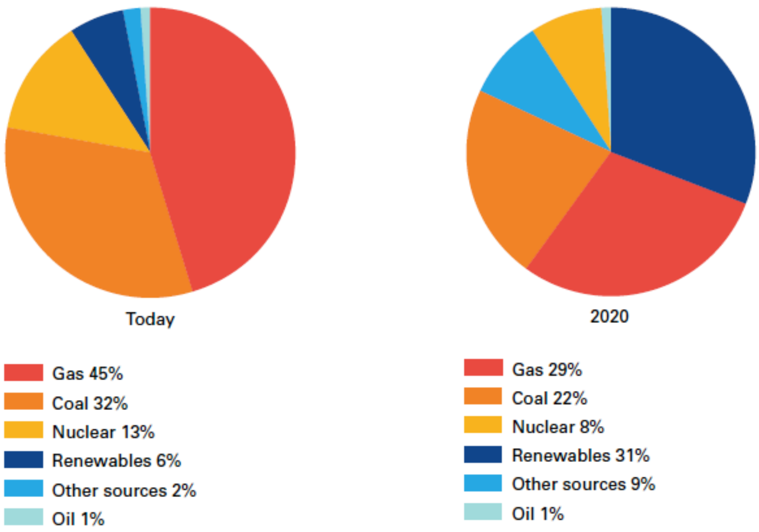


Fig. 2. Breakdown of fuel sources for UK electricity generation, today and predicted for 2020.
Source: HM Government, 2009. The UK Low Carbon Transition Plan, p55.

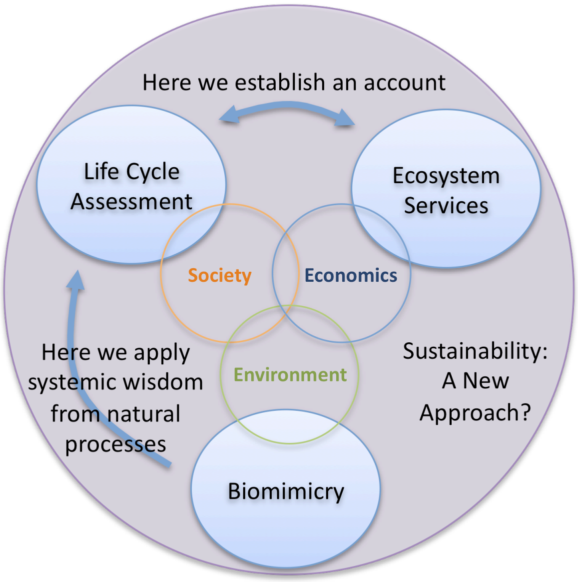
The pathways to be assessed will be Concentrating Solar Thermal Power (CSP) and Concentrating Photovoltaic Power (CPV) based on the concept of generating electricity from installations based in the desert of North African countries and transmitting the power via an interconnected, regional and European high voltage DC (HVDC) grid network. The Desertec Foundation proposal for electricity generation from renewable technologies mainly located in Middle Eastern and North African (MENA) countries (Desertec, 2009), is the inspiration for this work but is simplified by its scope being limited to the potential for CSP and CPV generation only.

The model and its components

Haas (2004), in his article on commuting sustainability science into policy, argues that sustainable development requires an interdisciplinary approach brought together by insights from different academic disciplines. Accordingly, a tripartite model is proposed as a lens through which a comparative study of these de-carbonisation pathways can be made. The aim is to assess the suitability of the model as an approach to aiding policy-making from an environmentally sustainable basis.

The model utilises life cycle assessment (LCA) and ecosystem service (ES) availability because there is a logical connection made between what are identified as the inputs and outputs of an activity by LCA, and the impact they will have upon an ecosystem's capacity to support that activity. Why this is an important consideration will be discussed further in Chapter 2. The third component of the model (Fig. 3) is Biomimicry (BM), which is an approach to learn from, and then emulate, the way Nature does things. This can be advantageous because 'natural methodology' can reveal elegant solutions to man-made problems through the benefit of evolutionary development. Inclusion of this technique in the model may be a helpful way of improving the efficiency and appropriateness of the best actions derived from the first two components.

Fig. 3.
The model as a lens through which to view environmental sustainability in energy policy decision making. At its heart is the concept of the *triple bottom line* of society, economics and environment - a basis for life support.



Benyus (1997), makes some valuable observations on the way Nature does things, some of which appear directly applicable to this study:

- Nature runs on sunlight
- Nature uses only the energy it needs
- Nature fits form to function - structure grants function
- Nature recycles everything
- Nature rewards cooperation
- Nature banks on diversity
- Nature demands local expertise
- Nature curbs excess from within
- Nature taps the power of limits (ie. lives within the carrying capacity of the land and temperature to maintain an energy balance)

The Case Studies

In Chapter 4, the model will be applied to a comparison of the electricity de-carbonisation pathways introduced above. Both cases acknowledge the imperative to de-carbonise electricity supply and have a similar lead-in timing of around 2020, but their approaches are quite different. They are yet to be developed as operational entities on a scale that would seriously address the decarbonisation challenge and so pose an interesting question in terms of which one would be the best option to pursue in a policy seeking sustainable, de-carbonised, electricity for EU and MENA countries. In asking this question it is assumed that both approaches form part of an electricity generation technology mix, however the thrust of the enquiry also questions the potential for electricity to be entirely generated from renewable, non-fossil resources compared with conventional practice based on carbon and uranium. This is an important debate because, as the UK Energy Research Council (UKERC) identify, when driving energy system change, there is a danger of ‘locking-in’ to known technologies and infrastructures, without strong and sustained policy interventions (UKERC, 2009). The price paid by such an outcome is that the benefits of emergent technologies may become a missed opportunity.

Limits and scope of this work -

This project covers a diverse range of considerations in order to make the argument for sustainable energy and look at solar electricity, but due to the word limit must deliberately over-look others of importance.
Issues which will not be covered:-

- Financial considerations - investment in R&D, credit to build power stations, feed-in tariffs, costs per kWh output and returns on investment.
- Manufacturing capacity to produce the necessary hardware
- Land agreements and international politics
- Technology transfer in politics and commerce

2 - Why Sustainability?

Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

- Brundtland, 1987, on sustainable development.

If the current global trends of primary energy consumption and CO_2 emissions increase are not changed, if the developing countries try to copy the unsustainable production and use patterns of energy systems in the North and if energy policies remain 'business as usual', the risks of climate change, or of nuclear accidents, or of resource wars will increase.

- Hennicke & Fischedick, 2006.

The importance of sustainability

The Club of Rome's report, 'Limits to Growth' (Meadows *et al.,* 1972) is creditable for setting the stage upon which environmental sustainability was raised as a crucial issue alongside the economic development of society. Its conclusions predicted that continuation of 'business as usual' would lead to population and industrial growth *stopping* before the end of the next century. This theme was later championed by the UN sponsored Bruntland Commission, who's report, 'Our Common Future', laid the basis for the Earth Summit in Rio de Janeiro in 1992. Sustainability was recognised as the underpinning principle, encompassing our need to respect an essentially limited relationship between mankind and the natural environment if there was to be a future for generations to come. Since then, in various legislative guises, sustainability has been receiving mixed acceptance at the policy table into the *triple bottom line* - economics, society and the environment. Sustainability science has come of age however, in seeking to understand the complex interactions between society and nature by asking questions such as, 'is it possible to scientifically define limits beyond which *nature-society systems* risk serious degradation?' (Kates *et al.,* 2001). With respect to climate change, currently the most pertinent field of enquiry into nature-society limits, an answer to this question has already been proposed. Considerable consensus of scientific thought has been inducted into policies to limit man-made global warming by 2°C relative to pre-industrial times, (Rijsberman *et al.,* 1990; EU, 2005; Kintisch, 2005; IPCC, 2007) to avoid dangerous and unsustainable impacts from climate change. But setting this goal and what constitutes ‘dangerous’ is still very much open to debate due to the uncertainty of Earth’s climate sensitivity in response to various ‘forcings’ (Swartz, 2008).

Climate’s unpredictable response to our unsustainable development

Climate change is a natural phenomenon which has been present since the Earth had an atmosphere and has responded throughout history to such involuntary factors as volcanic activity, the movement of continental land masses and the orientation of the planet with respect to the sun. Climate forcing is a function of solar insolation and GHG interactions with climate sensitivity mechanisms to manifest global warming or cooling. Palaeoclimatic records indicate that Antarctic glaciation began around 34M years ago (Fig. 4) after the atmospheric CO_2 concentration dropped below 425±75ppm, initiating the cooling conditions in which civilisation eventually developed (Hansen, *et al.,* 2009).

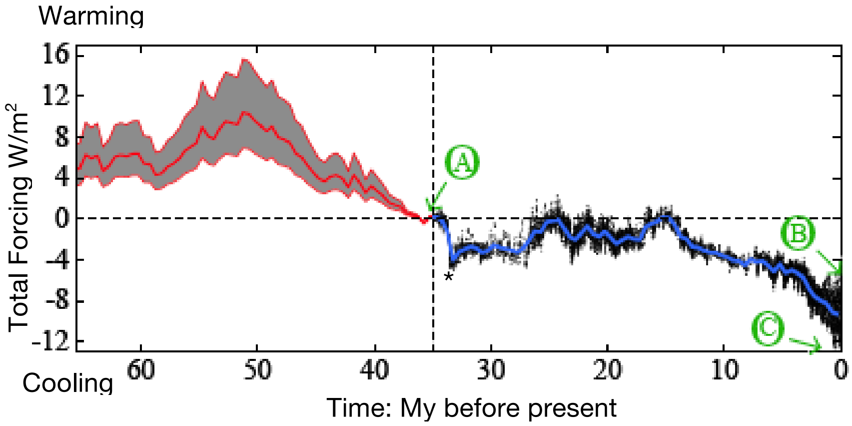


Fig. 4. Total climate forcing for the Cenozoic era, showing uncertainty bounds in shaded areas. Antartica glaciated* just after point A, point B indicates forcing in recent interglacial periods and point C, the depth of recent ice ages.
Source: Hansen *et al.* 2009

Climate sensitivity is based around fast and slow feedback mechanisms responding to forcing, from which equilibrium temperatures eventually arise (Table 1). Averaged over thousands of years, a global energy balance has been historically established between forcing from solar radiation and the Earth’s feedback mechanisms. Climate forcing during this time was largely a result of changes in solar insolation due to the tilt of the Earth’s axis, (Hays *et al.,* 1976;

Zachos, 2001), *lagged* in time by changes in naturally released GHG's and ice sheet size. (Hansen *et al.,* 2007; Caillon *et al.,* 2003).

Feedback Mechanism	**Fast/Slow**	**Yrs to trigger activity**	**Activity**	**Possible Forcing**
Ice sheet	slow	≤ 100	Melting - albedo loss	Prolonged surface warming, sea level rise
Ocean CO_2 absorption	slow	≤ 100	Saturation - loss of carbon sink	Prolonged warming, acidification
Soil CO_2 absorption	slow	≤ 100	Saturation - loss of carbon sink	Prolonged warming
Tundra	slow	≤ 100	Thawing - methane release	Prolonged warming
Water vapour	fast	1 ~ 100	Increase	Accelerated surface warming
Clouds	fast	1 - 100	Increase	Accelerated surface cooling, some warming
Sea ice	fast	1 - 100	Melting - albedo loss	Accelerated surface warming - sea thermal expansion

Table 1. Examples of feedback mechanisms affecting climate change sensitivity. The trigger times indicate that there is some overlap between fast and slow feedback triggers and should not be confused with the duration of the arising feedback effect which can last far longer. Adapted from Hansen *et al.,* 2007, 2009. NAS, 1979.

Recent man made GHG emissions however, have added their effect to the natural feedbacks at such an unprecedented rate that they now *lead* the equilibrium temperature response (Fig. 5), forcing global warming and leaving us to estimate what might become of global temperatures in future.

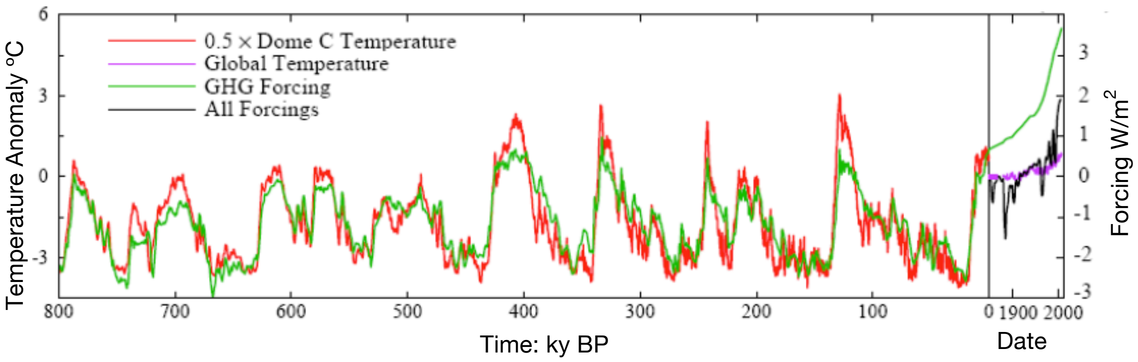


Fig. 5. Historical Climate Forcing and Global Temperature. The right hand end of the time scale shows forcings during the industrial period from 1850 and illustrates the wide temperature anomaly yet to be equilibrated with the degree of man made GHG forcing. Source: Hansen *et al.,* 2009.

Atmospheric CO_2 concentration has elevated from around 275ppm in 1950, to over 390ppm today, becoming the dominant GHG forcing agent (Fig. 6). With an annual mean global atmospheric concentration growth rate of 1.8ppm in 2008 (NOAA, 2009), we may already be in an unsustainable danger zone and heading towards exceeding 425ppm within decades, especially if certain tipping points were to be exceeded, such as the release of methane (about 25 times more potent than CO_2 as a GHG) hitherto stored as methane hydrates in the Arctic permafrost. It is estimated that the amount of carbon in the atmosphere (currently about 760 Gt) is about 13 times less than the amount contained in methane hydrate deposits (IPCC, 2007).

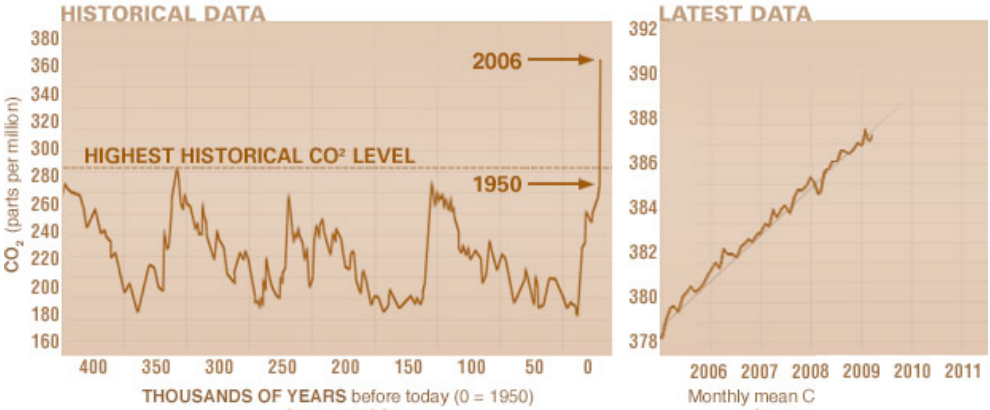


Fig. 6. Historical and latest CO_2 concentrations. The left hand graph shows the highest historical concentration for 650ky.
Source: NASA, 2009.

With the temperature anomaly currently around +0.7°C compared to pre-industrial times (Fig. 7), and further warming in the pipeline due to unequilibrated GHG forcings, the risk of *not* maintaining the 2°C target threshold looks increasingly likely.

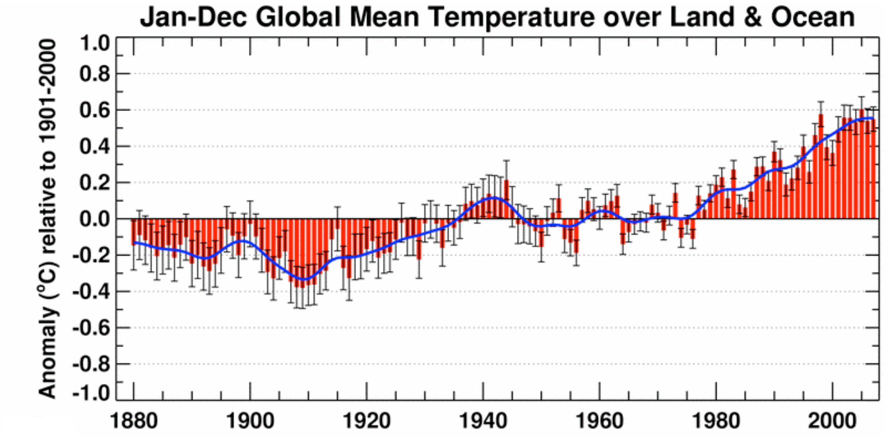


Fig. 7. Global surface temperature anomaly relative to mean temperature of 20th century, showing increase of approx 0.7°C over 1880.
Source: NOAA (2), 2009.

How much emitted carbon is 'sustainable'?

Policies to limit global warming within a certain temperature increase based on regulation of the atmospheric concentration of CO_2 could also be prone to uncertainty (Meinshausen *et al.,* 2009; Allen *et al.*, 2009). This uncertainty arises because climate models based on CO_2 concentration may not incorporate all carbon-cycle and feedback mechanisms attributable to climate sensitivity, making it impossible to precisely predict the climate's stabilisation temperature response to GHG concentrations in the atmosphere. The cumulative warming commitment (CWC) of total carbon emissions generated during industrial times may be a more robust policy basis, and has the attraction that it can be linked to the carbon content of known reserves of fossil fuels. Probabilistic models have thus been created to estimate the warming arising from burning fossil fuels (Fig. 8) to show the likelihood of remaining within the 2°C target under different emissions scenarios.

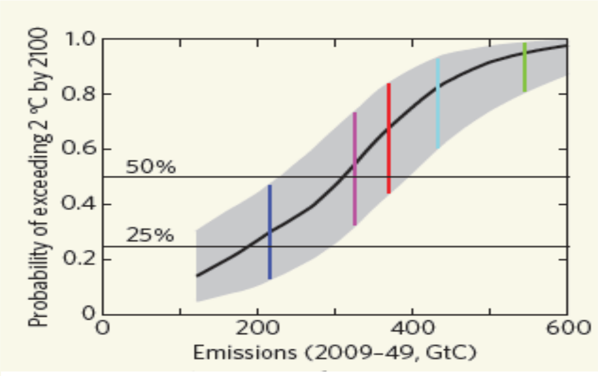


Fig. 8. Probability of warming exceeding 2°C relative to pre-industrial levels by 2100 (black line) from Meinhausen *et. al.,* 2009. Coloured lines show cumulative emissions to 2050, for different scenarios.

— Meinhausen *et al.*, 2009.
— Emissions constant at 2008 values until 2050.
— Emissions grow at 1% per year until 2050 then fall rapidly.
— Emissions grow at 2% per year until 2050 then fall rapidly.
— Emissions of developed countries cut by 80% linearly from 2010 to 2050, and 1% growth from developing countries.
— Emissions cut by 80% by 2050, globally.
Source: Schmidt & Archer, 2009.

There is no measure of sustainability from limiting global temperatures to a 2°C increase, a target in uncharted territory. In any case, Earth's sensitivity to climate forcing may be higher than estimated, making the 2°C target even harder to attain. So the question of what is the acceptable probability of attaining that target and the associated carbon emitted becomes further abstracted from what is safe or sustainable (Victor, 2009). On the other hand, the Earth's history has provided empirical evidence of the range of atmospheric CO_2 concentrations viable for life as we know it. Taking this view, and the fact that climate change due to CO_2 forcing is largely irreversible for 1000 years, (Solomon *et al.*, 2009), it becomes obvious that de-carbonisation of anthroprogenic activity is urgently required in order to keep equilibrium temperatures within current, life-sustaining interglacial levels. Hansen *et al.* (2009) propose an atmospheric CO_2 concentration target of 350ppm and Allen *et al.* (2009), a cumulative global anthroprogenic emissions total of 1000 Giga-tonne (Gt) of carbon (1Gt carbon = 3.7Gt CO_2) half of which has already been released since pre-industrial times (Fig. 9). Meinhausen *et al.,* (2009), offer a range of probabilities with associated emissions (Fig. 8) estimating around 270 Gt carbon (1000 Gt CO_2) emitted between 2000~2049 would offer a 75% chance of *not* exceeding the 2°C target by 2100, and 240GtC (886Gt CO_2), for an 80% chance. While it is difficult to make exact comparisons, both of these approaches point to a similar conclusion that total carbon emissions must be stopped within the next few decades to avoid increasing and prolonged warming by 2100 and beyond.

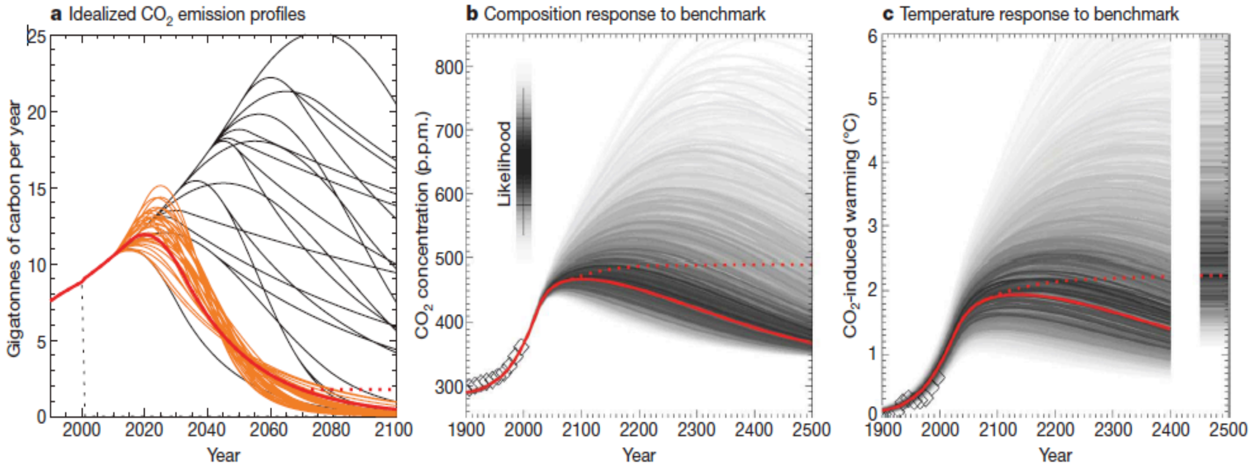


Fig. 9. Responses to simple climate model emissions profiles and a 2°C benchmark scenario (red line). The integral of the area under the red line in **a** bounds total carbon emissions to 1TtC by 2100 and corresponds to a resultant warming of almost 2°C by 2100, after which temperatures decline. **b** and **c** show the likelihood of simple climate model responses. The dotted red line in **b** & **c** shows possible responses to a 490ppm CO_2 concentration 'stabilisation scenario' in **a**, indicating that CO_2 levels and temperatures could continue to rise for centuries if climate sensitivity is higher than estimated.
Source: allen *et al.,* 2009.

World primary energy consumption (including coal, oil, natural gas, nuclear and hydro) has increased at an average rate of 2% since 1998 (BP, 2009). Schmidt and Archer (2009) and Raupach *et al.,* (2007), give a figure for carbon emissions increase at a rate of 1-3%. In 2006, the global total of carbon emitted from burning fossil fuels was 8.379GtC (EPI, 2008), which puts us in the region of 9GtC ($33GtCO_2$) in 2008. Taking the two 'safest' emissions ranges from Meinhausen *et al.,* (2009), at this rate of carbon emission, we can see that total decarbonisation of the world's emissions is called for sometime around 2027 ~ 2034 (Fig. 10). This gives us a calculated chance of limiting global warming to 2°C over pre-industrial times, but no guarantee due to the uncertainties already mentioned.

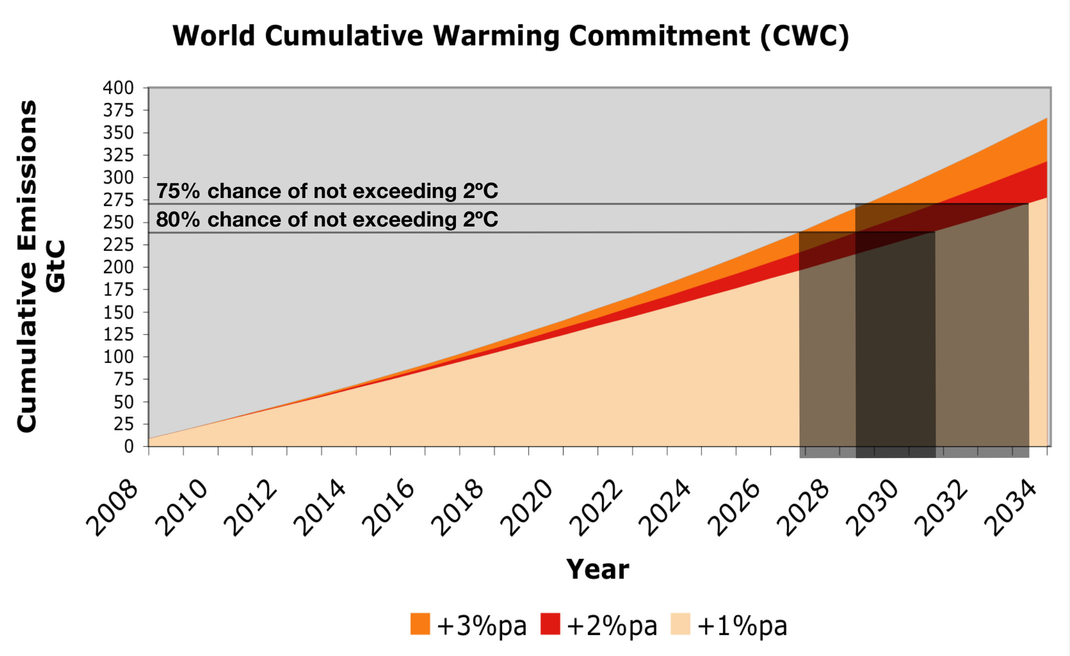


Fig. 10. World CWC in GtC with linearised year-on-year emission rates. The grey boxes on the right indicate the span of target dates for reaching the CWC's corresponding to a 75% (270 GtC) and 80% (240 GtC) chance of not exceeding 2°C warming relative to pre-industrial time given by Meinhausen *et al.,* (2009). Emissions rates are unlikely to be linear but may fall within the ranges shown from 1~3%.
Adapted from Meinhausen *et al.,* 2009; BP, 2009.

As well as setting out the magnitude of the task ahead and the speed with which action is necessary, it tells us that a significant amount of known fossil fuel reserves must be left in the ground (Fig. 11) - unless they can be burnt without emitting any carbon, such as in the case with carbon capture and sequestration (CCS). A strategy to simply reduce emissions even by 80% globally by 2050 is uncertain to keep global warming from exceeding 2°C relative to pre-industrial times.

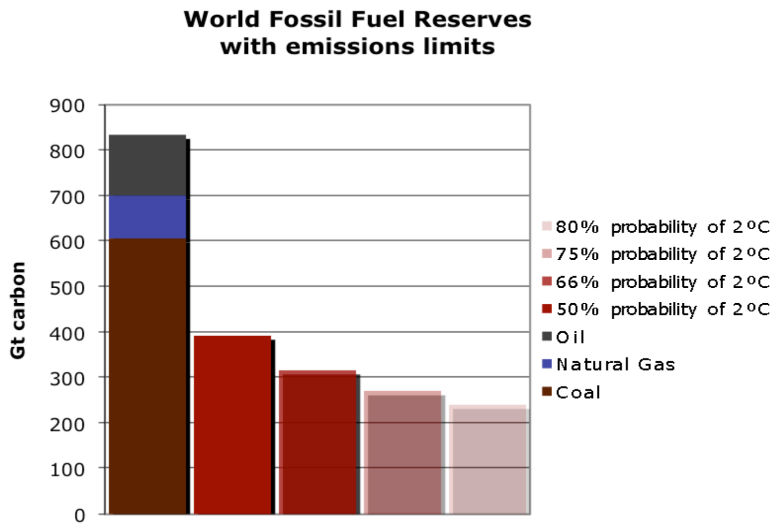


Fig. 11. World proven fossil fuel reserves and limits to conserving global warming to 2°C with given probabilities according to Meinhausen *et al.* (2009). The stacked bar on the left is an estimate of carbon that would be emitted from burning world fossil fuel reserves and the bars on the right show emitted carbon to conform to probabilities of achieving a 2°C limit on global warming by 2100.
Source: Fossil fuel reserves, BP (2009); Carbon conversion factors, CDIAC (2009).

Projections by the International Energy Agency (IEA) offer three possible future scenarios based on a BAU reference case in which CO_2 concentrations increase by 45% and global average temperatures are set to rise by 6°C (Fig.12). This shocking projection is tempered by the other two scenarios which result in lower rises in CO_2 but nevertheless present an extreme challenge to

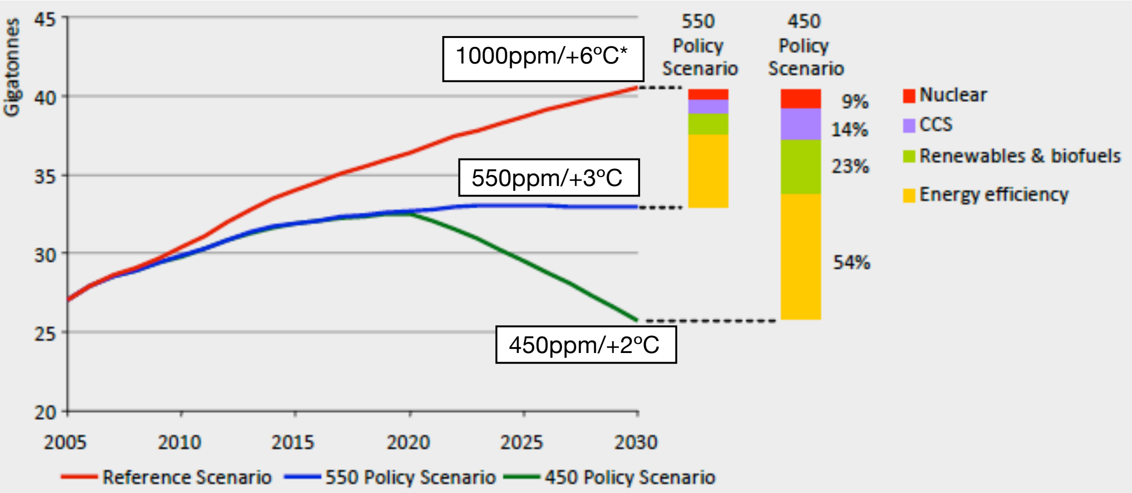


Fig. 12. IEA projections of emissions from world energy use to 2030. Bars on right indicate policy measures to reduce emissions from Reference Case scenario. Atmospheric CO_2 concentrations and approximate stabilisation temperatures are given in boxes. Reference case assumes no policy interventions beyond 2008. *Figures reached by 2100.
Adapted from: IEA, 2008[1]; IEA, 2008[2].

implement due to the level of investment required, the pace at which innovation can spread through power generation plant (responsible for 61% of total GHG emissions) and the persuasion of hundreds of millions of households and business to use energy differently (IEA[1], 2008).

Carbon reduction policy targets and the UK electricity supply

Within the global framework of the UNFCC, the Kyoto Protocol binds the European Union (EU) to a GHG reduction target within which the UK has taken up its share of the commitment. It's target under the Kyoto Protocol, is to reduce the basket of GHG emissions by 12.5% compared with 1990 levels (779.9MtCO_2e) over the period 2008 - 2012, making the average yearly emissions target over this period below 682.4MtCO_2e (MtCO_2e is used because it includes the Kyoto basket of GHG emissions). So far, three carbon budgets have been created by the UK Government to conform to this carbon reduction trajectory (Fig. 13). Over the years to 2020, the EU has also created an extended commitment to reduce its GHG emissions by at least 20 to 30% (compared to 1990 levels), increasing the use of renewable energy technologies (RET's) by 20% and reducing energy consumption by 20% through higher efficiency (Europa, 2009).

The UK, with its extensive industrial history and record keeping, is responsible for a *cumulative* carbon footprint between 1880 and 2004, *second only* to the USA (MacKay, 2009). Under the concept of 'polluter pays', it would therefore have a high obligation to decarbonisation. Emitting around 2% of the world's total CO_2 emissions in 2006, (CDIAC, 2009), which was equivalent to 145 MtC in 2008 (DECC[2], 2009), UK CO_2 emissions have fallen by about 10.3% since 1990. This is largely due to increases in energy efficiency and gasification of electricity generation with a reduction in coal-fired generation, but power stations still remain the largest contributor to UK emissions (Fig. 1).

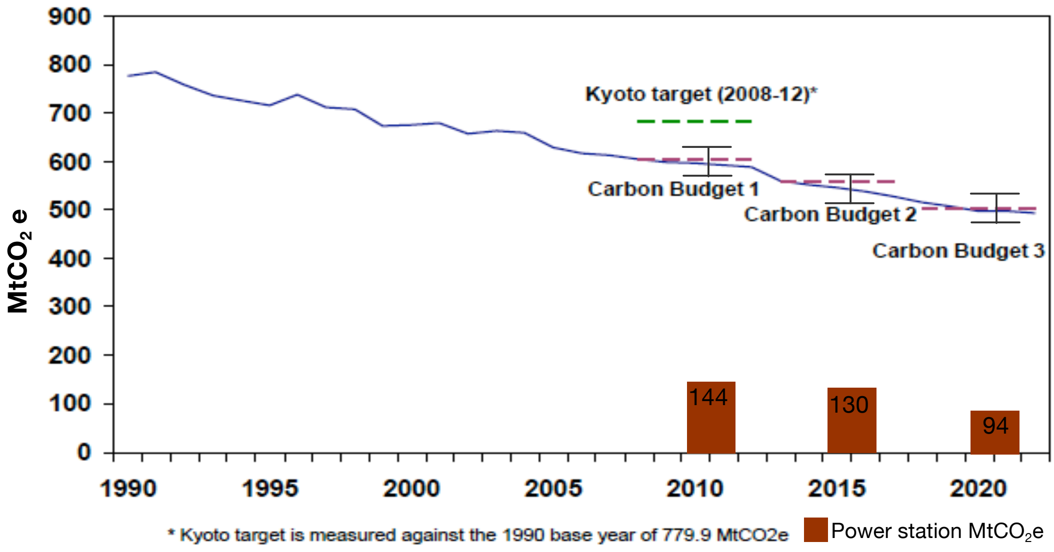


Fig. 13. UK total GHG projections 1990 - 2012. Error bars show uncertainty in projections. Carbon Budgets are derived from GHG emission reduction targets under the EU ETS 2008 - 2020. Brown bars indicate projected CO$_2$e emissions from power stations. The UK Low Carbon Transition Plan anticipates a 40% reduction in CO$_2$ emissions from the electricity sector through the use of the EU ETS and increasing the amount of low carbon technologies. Included in these are actions to bring forward the use of nuclear and renewable energy generation as well as carbon capture and storage. The implementation of a 'smart grid' is also seen as a necessity to facilitate more efficient handling of fluctuating supply and demand.
Source: Adapted from DECC[1], 2009.

Currently, the most important policy instrument to the Government is the EU Emissions Trading System (ETS), which covers about half of all UK CO$_2$ emissions, otherwise known as the 'traded sector' (the non-traded sector now includes road transport, aviation, residential and land use - but in future more of these will be included within the cap and trade system). By raising the price of carbon in emissions, the aim is to force energy providers and consumers towards de-carbonisation and use of more renewable energy generation technologies. However the first period of the EU ETS has been a failure in making CO$_2$ costly enough to force emissions reduction according to MacKay (2009), who suggests the cost should rise to the region of $100/ton permanently. With the price currently at €14/t ($20/t), and never having risen above €30/t since the inception of the ETS in 2005, (UK Government decarbonisation plans are based on a price projection of €20/tCO$_2$ - €43/tCO$_2$ in 2020), it casts doubt on whether a free-market approach to saving the world from over-heating is a sustainable option.

Energy considerations

Although UK electricity consumption has increased since 1990, emissions from generation have decreased and were responsible for 46.4 MtC in 2008, representing nearly one third of total UK CO_2 emissions. Government projections showing electricity demand in 2020 to be less, overall, than in 2007 (DECC[2], 2009), reflect the transition in generating capacity, infrastructure, technology and consumer demand to a low carbon economy rather than a continuing trend beyond that. With aging generating technology (particularly nuclear) being decommissioned within the next 20 years, an expensive research and development programme for CCS and demand set to rise, we are also likely to see an increase in the price of fossil-fuel based electricity to consumers, perhaps by as much as 60% by 2020 (Crossley, 2009). But the primary medium of sustainable energy is likely to become electricity and consumption will be increasing in future as electrification of services, ranging from domestic heating to transport and industry, becomes imperative to reduce CO_2 emissions (Fig. 14). MacKay (2009), suggests a viable scenario for UK electricity consumption with increases from 18 to 48kWh per person, per day, by 2050.

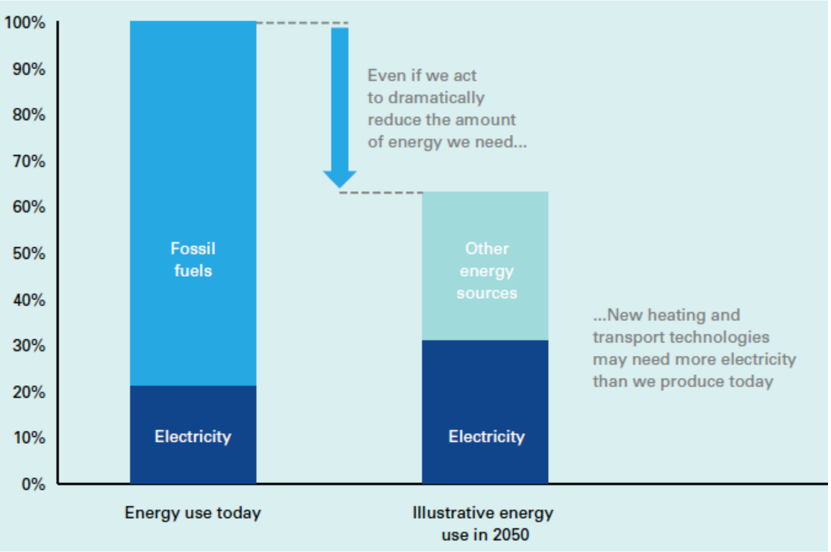


Fig. 14. Illustration of the role electricity will play in supplying low carbon energy demand.
Source: HM Government, 2009, p167.

This places increasing relevance on the electricity generation technology employed and the timing of its implementation. The amount of carbon per unit of electricity generated, depends on the type of fuel being burnt (Table 2). From a sustainability perspective the wider environmental burden should also be taken into account. This would include the carbon emitted in creating the generator, resourcing it’s fuel and decommissioning the plant as well as the drawdown on ecosystem services such as land and water consumed in these actions. In Chapter 4, we shall study this perspective in more detail with regard to CSP and CPV while testing the sustainability model, but at this point it is worth noting that Fthenakis and Kim (2008) found that concentrating solar technologies posed the least environmental burden upon land usage of all major energy generating technologies.

Fuel type	**Emissions tC/GWh**	**Emissions tCO_2/GWh**
Coal	240	880
Gas	97.4	357
UK mix of generators, 2008 (includes nuclear, RET’s, hydro, etc)	156	572

Table 2. Carbon emissions per GWh of electricity from different fuels in UK power stations where 1tC = 3.664 tCO_2. Figures do not include the wider scope of sourcing materials and de-commissioning defunct technology which would be considered within LCA.
Source: BERR, 2009.

3 - Sustainable Energy

Within 6 hours deserts receive more energy from the sun than humankind consumes within a year.

- Dr. Gerhard Knies (DESERTEC, 2009)

The benefits of solar power are compelling: environmental protection, economic growth, job creation, diversity of fuel supply and rapid deployment as well as the global potential for technology transfer and innovation.

- Brackman *et al.* (ESTIA, 2005)

What is meant by sustainable energy? The world's energy systems have been developed around the advantages of fossil fuels but arguably with ease of access and conveyance of energy between source and consumer, rather than sustainability in mind. Fire has been around a long time, but we simply didn't have the technology to turn sunlight directly into electricity 100 years ago (the first PV cell was developed in 1954 [Chapin *et al.,* 1954]) when we were developing the internal combustion engine to run on oil. By contrast, a broad definition of sustainable energy by Boyle *et al.,* (2003), includes the following criteria:-

- not substantially depleted by continued use;
- its use does not entail the emission of pollutants or other hazards to the environment on a substantial scale;
- its use does not involve the perpetuation of substantial health hazards or social injustices.
- Policy-focus in the development of fossil-based energy systems has been primarily upon increasing energy efficiency. It has therefore, become subject to being overtaken by demand (Fig.15), which has given rise to energy security issues and more recently, the added threat from pollutant-induced global warming. We have been active in extending the supply of fossil energy reserves but with global economic growth and development now a wider geographic reality, this approach does not reach beyond the medium term (Cassidy, 2000), evident by the increasing rate of oilfield depletion for example

(otherwise known as ‘peak oil’).

Taking a longer-term perspective, access to energy in order to drive development further without threatening the environment must call for substitution of fossil fuels. But how long is *long term* in respect of sustainability? MacKay (2009) bases calculations on a definition of sustainability as lasting for 1000 years. Not unreasonable, given the time it takes for some GHG’s to decay from the atmosphere, or the length of climate warming and cooling cycles. He calculates that a sustainable use of world coal reserves would offer a burn rate of about 1.6Gt/y compared to the current burn rate of around 6.3Gt/y and rising. Applying CCS to power stations (which reduces their efficiency by a further 25%) and taking the average coal consumption rate from the last decade (which is increasing), and projecting it into the future, he calculates would result in world coal supplies under BAU lasting only another 60 years! In the UK, to make coal reserves last for a 1000 years, we would yield around 0.7kWh(e) per day per person. Currently the average energy consumption of a European is about 125kW per day per person, (UNDP, 2007).

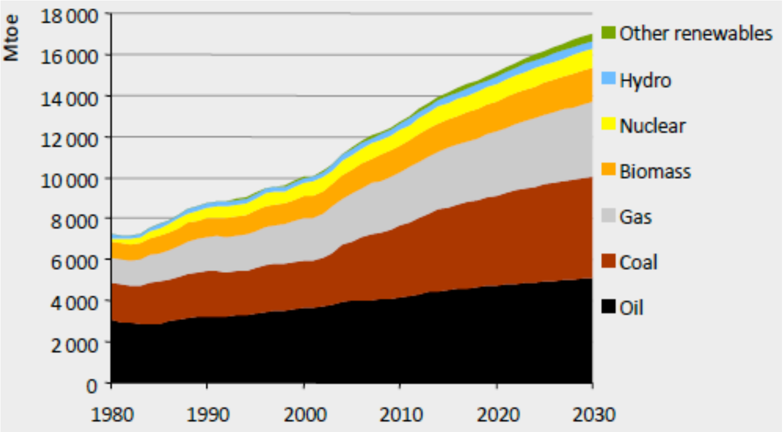


Fig. 15. Reference Case outlook from the IEA showing world energy demand increasing 45% from 2008-30 at an average 1.6%pa. With China, India and the Middle East emerging as major demand centres. Coal accounts for more than one third of this rise. Under this BAU scenario, no policy constraints are assumed beyond 2008 and fossil fuel accounts for 80% of the world’s energy in 2030.
Source: IEA[1], 2008.

Hennicke & Fischedick (2006) suggest that industrialised countries should take the lead in constraining global warming and proposed the following points that sustainable energy paths should follow, in contrast to the BAU approach:-

- Access to energy services for all and fair partnerships with developing countries.
- Effective conservation of resources and protection of environment, climate and health.
- Social acceptability now and in accordance with the needs of later generations.
- Low risks, fault tolerance and contribution to mitigate international conflicts.
- Cost-effectiveness (including external costs).

Voss (2006), notes that when making comparisons between sustainable energy systems it is important to apply comparative measures to the production of units of energy such as a kWh of electricity or a unit of energy service provided. He regards a sustainable energy system to reflect the following criteria:-

- the potential for economic provision of energy services increases or does not decrease for the next generation
- the substance release due to energy use does exceed the natural assimilation capacity of the environment
- the energy related risk for human health is smaller than the avoided natural risks due to the provision of energy services
- energy services are provided with the least resource input possible, including the environmental resource

According to Cassidy, (2000), another criterion for assessing energy in harmony with sustainability is *recyclability* (of waste products and the technology itself), which raises the prospect for LCA and cradle-to-cradle design in a truly sustainable approach.

From these and the definitions we have seen above, it seems that sustainable energy, unlike its fossil counterpart, has a high degree of social justice and equity attached. There is also a greater awareness attached to the health and safety of future generations for which it is ‘undepletable’. And that its development is seen to go in hand with the interests of developing countries as well as the developed. EU cooperation on energy acknowledges that sustainable development requires technological cooperation and cross-border investment with developing countries, particularly through exchange of knowledge and new platforms for renewable energy (Eurostat, 2009, p7). It begs the question, ‘what kind of energy source is available to us that is not likely to be subject to the level of international competition and protectionism associated with the ‘oil rush’ for example’? Perhaps the answer lies in one that is universally available for conversion and readily accessible.

Solar energy is sustainable energy

The oldest and most sustainable energy source known to man is our local nuclear fusion reactor, the sun. The primacy of solar energy has sustained life on this planet from its origins and to some it seems the obvious choice for sustainable energy today, as much as it has been the preference of others in the past through the combustion of stored solar energy in biomass and coal, or its use to propel sea vessels through wind and wave (Fig. 16). The difference between then and now however, is that now we have the technology to harvest the sun in its raw form without the pollutant emissions of its derivatives and convert sufficient amounts of it into a useful entity (electricity and heat) to meet our energy demands.

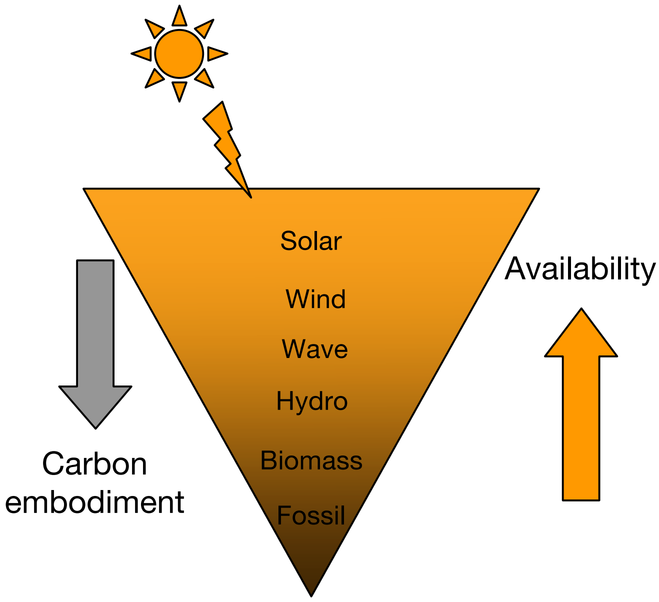


Fig. 16. Simplified depiction of the primacy and universality of solar energy and its derivatives.

We are reminded here, of the biomimetic observations Benyus (1997) has made (see Chap. 1), regarding the way Nature runs on sunlight. Notably, several other of her observations, such as reward for cooperation, use of local expertise and remaining within the carrying capacity of the land appear to conform with our criteria for sustainable energy. Is it now time for us to apply our technological capabilities to another lead from Nature?

By fitting form to function we may harvest solar energy through modern collectors reaping a sustainable resource. But is it possible to provide the UK with a sustainable, de-carbonised electricity supply from solar energy to meet the expected demand?

Despite the conversion losses involved in turning this raw energy into electricity, Goswami, in the World Energy Council's Survey of Energy Resources (2007), says "If only 0.1% of this [incident solar energy over all regions of the earth's surface] energy could be converted at an efficiency of only 10% it would be four times the world's total generating capacity of about 3000GW… the total annual solar radiation falling on the earth is more than 7500 times the world's total annual primary energy consumption of 450EJ" (Fig.17)

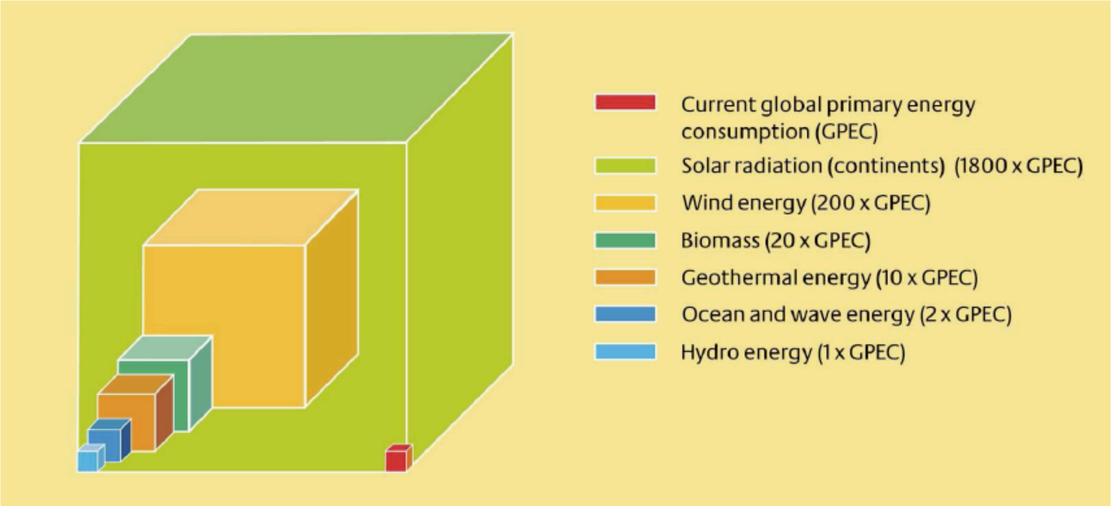


Fig. 17. The relative potential of renewable energies.
Source: Nitsch, F., 2007.

Solar power from deserts

Deserts are defined by ranges of aridity, specialist ecological adaption, vegetation and soil exposure. They cover about one quarter of the earth's land surface (around 33.7M km^2) but an average figure for the world's deserts (half way between estimates of deserts from broad and narrow definitions) would be about 26M km^2 (UNEP, 2006). Incident solar radiation upon the earth's surface varies according to region with typical figures being between 105W/m^2 in the United Kingdom and 300W/m^2 in the Red Sea Area (Table 3).

Solar Region	Incident Radiation W/m^2
United Kingdom	105
United States	185
Australia	200
Red Sea	300

Table 3. Incident solar radiation guide for different regions of the world.
Source: WEC. 2007.

Taking a nominal value for desert solar insolation half way between the values for the United States and Red Sea regions, we arrive at 240W/m^2. This derives a rather conservative solar resource of 2100 kWh/m^2/y, (Fig. 18), or a total power availability of around 55 million TWh/yr.

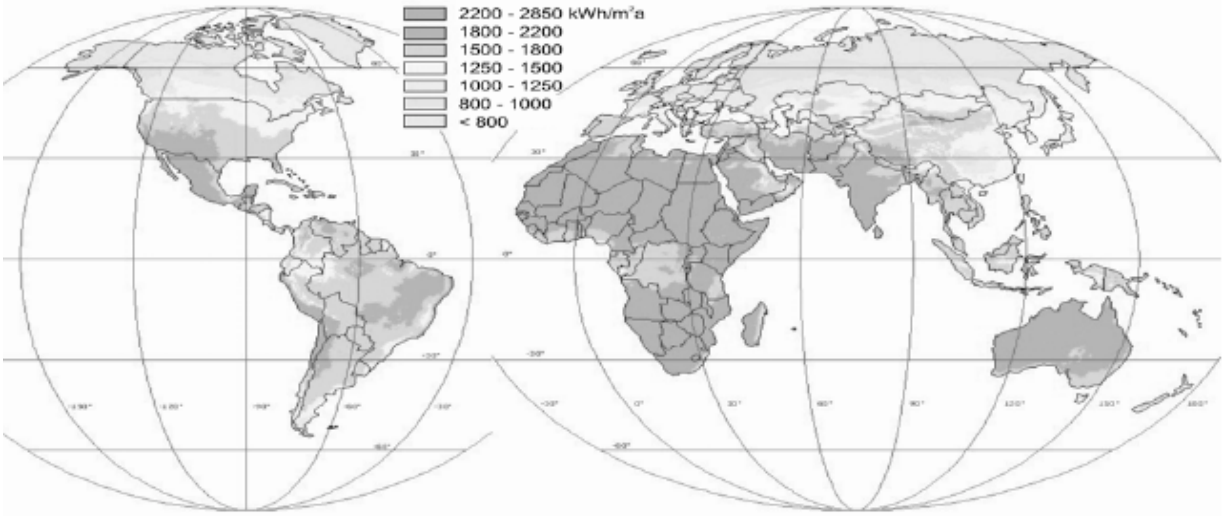


Fig. 18. Average yearly solar radiation in kWh/m^2/yr, mean values 1981 ~ 2000
Source: Energie-Atlas GmbH

Plants are inefficient converters of solar energy with a conversion efficiency of around 2%, yielding about 0.5W/m^2 of carbohydrate energy in Europe, according to MacKay (2009). In their concentrated, fossilised form the solar resource in deserts far outweighs not only the current supply (production) of energy from fossil fuels but their reserves also (Table 4), making solar power an attractive and sustainable proposition.

Non-renewable Energy in 2006 compared to desert solar resource of 2100 kWh/m^2/y	**Crude Oil**	**Natural Gas**	**Coal & Lignite**	**Uranium & Thorium**	**All**
World Total Primary Energy Supply (IEA, 2008) *1000TWh*	47	28	36	8	119
Equivalent solar delivery time in deserts *hours*	7	4.5	6	1	19
Proven reserves (possible additional resources) (WEC, 2007) *1000TWh*	1900 (950)	1910 (2180)	5900 (70800)	470 (1730)	10180 (75660)
Equivalent solar delivery time in deserts *days*	12.5 (6)	12.5 (14.5)	39 (470)	3 (11.5)	67.5 (502)
Depletion time of reserves at static (2006) consumption rate *years*	40	68	164	60	86
World electricity generation by non-renewables (IEA, 2008) *1000TWh*	1.1	3.8	7.8	2.8	15.5
World electricity generation, equivalent solar delivery time in deserts *minutes*	11	36	75	27	148

Table 4. Non-renewable energy supplies, reserves and potential resources (not yet economically or geologically possible to access), in 2006, compared with desert solar resource over 26M km^2 at 2100kWh/m^2/yr.

The relatively high solar radiation energy density in deserts, compared with more temperate lands, is behind the Desertec Foundation's proposal to generate energy for the European region (Desertec, 2009) (Fig. 19).

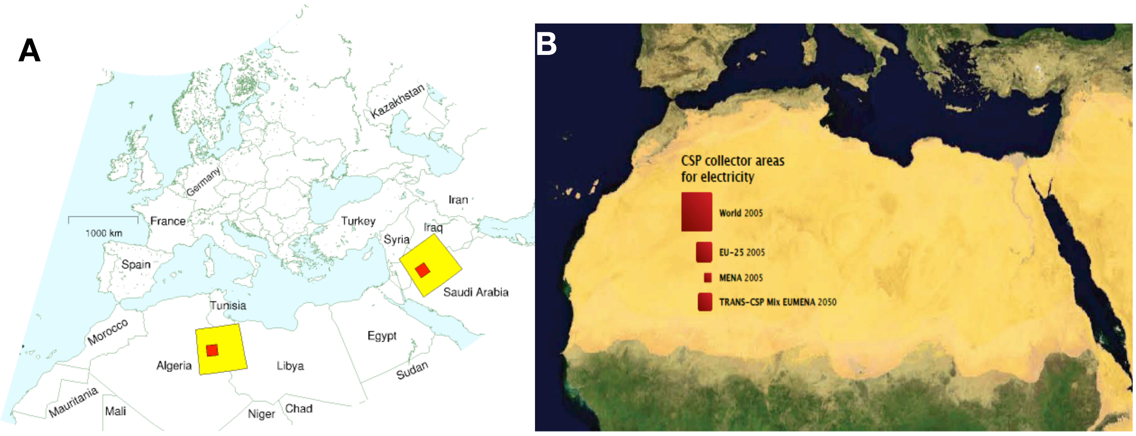


Fig. 19. A - Each yellow square measures 600km x 600km. One of these filled with CSP equipment would be sufficient to satisfy 125kWh/d power demand for 1 billion people. Each small red square measures 145km x 145km - the necessary area required to satisfy the UK population's power requirements. B - Red squares show the area of CSP collectors required to supply the 2005 electricity consumption of the World (17000TWh/y), EU-25 (3200Twh/y) and MENA countries (600TWh/y) respectively. The fourth (lowest) square indicates the estimated area of CSP facilities requred in 2050 to supply MENA countries with about two-thirds of their electricity, desalinated seawater and about one-fifth of Europe's electricity demand (2940TWh/y).
Source: A - MacKay, 2009; B - Broesamle *et al.,* 2000; Desertec, 2009.

MacKay (2009) calculates that an area of 600km x 600km completely filled with CSP facilities delivering about 15W/m^2 would be sufficient to generate the average European personal energy consumption of 125kWh/d for 1 billion people. Concentrating solar receivers not only generate electricity but may also be configured to utilise the by-product of heat as a means to desalinate water, providing another much needed commodity in parched lands (Trieb *et al.,* 2002).

If sustainability were our foremost concern, and political and economic concerns could be put aside, calculations of this kind would indicate fossil fuel's limited future should lie only in providing the energy we require now to build a new renewable energy infrastructure which will begin to pick up the job of powering us through the rest of the century and beyond from about 2030. It would appear from this analysis that proposals to develop and fit carbon capture and sequestration (CCS) technologies to fossil-fuelled power stations in the future must be questionable from a sustainability perspective which includes a probabilistic estimate of global stabilisation temperature trajectories. CCS on the scale required is undeveloped, adds to power station inefficiency and the unproven security of CO_2 storage in underground cavities may present the highest risk of all for future generations if the gas were to escape back into the atmosphere. Yet this intention is within the fourth objective of the Government's five point 'National strategy for climate and energy', (HM Government, 2009, p2) and a major mitigation strategy for other world economies. While CCS is such an obvious non-starter in the sustainability stakes, nuclear fission may only provide a very limited and risky (politically-speaking) alternative. Perhaps it would be better to use the next 20 years to begin the massive engineering and diplomatic efforts required develop a truly sustainable solar energy supply with technology that is already proven? With the planned closure in the coming decade of several UK fossil power stations, now would seem an excellent time to make a step change in our energy-technology future.

What about energy security?

Energy security affects us all and has an important part to play in sustainability. The continuous supply of energy has paved the way for economic development as our appetite for it has increased. However the traditional means by which we sourced our energy and generated our electricity have, as we have seen, become limiting not only in terms of emissions but also in terms of supply longevity. Security of access to fossil energy and continuity of generated supply are therefore key concerns of energy security.

The EU-27 countries are heavily dependent on imports of fossil energy commodities from distant countries, with import dependence steadily increasing since the 1990's (Eurostat, 2009). The UK currently fairs below the EU import dependence average (Table 5), but as North Sea resources deplete, this picture will deteriorate with over 75% of our energy supplies being imported by 2025 according to the Royal Academy of Engineering (2006).

Imports in 2006	**Hard Coal**	**Oil**	**Gas**	**EU-27 Average (Eurostat, 2008)**
EU-27	58%	83%	55%	54%
UK	75%	11%	12%	21%
Origins	Russia, Australia, Columbia, South Africa	Russia, Middle East, North Africa, Norway	Russia, North Africa, Norway, Middle East	

Table 5. Fossil energy imports (minus exports) to the UK and EU-27 countries in 2006 as a percentage of primary domestic production.
Sources: Eurostat, 2009; BERR, 2007.

This prospect, if it were to become reality, is a cause for concern. Supply interruption and dramatic price increase, are examples of energy insecurity demonstrated in the recent incursion by Russian forces into Georgia (euobserver, 2008), a country through which major EU supply pipelines pass. Under such conditions of dependence, with our primary energy being resourced from Kazakhstan, Kuwait and equally distant lands, it may be acceptable to realise a scenario involving solar electricity generated in the world's deserts, but with some distinct differences. Firstly, the energy resource is unlimited and widely available, being derived from solar radiation. Sources are therefore not prone to manipulation or stockpiling in the same way as fossil fuels. 'Pipelining' large amounts of electrical power over long distances using HVDC may be inherently safer and more secure than fossil fuel transport as cables can be laid under the ground and under water with relatively maintenance-free ease compared to large diameter pipes. Environmental damage in solar collection and conversion is likely to be far less damaging of local ecosystems compared with fossil fuel extraction, the processing and leakage in transit of which have precipitated major environmental crises.

The greatest and most advantageous difference between the trade in fossil and solar energy however, may be the benefits to both the host nations and the importing nations becoming more equitable (Scheer, 2007). By conforming to the principles of sustainability, the sharing of solar technology in exchange for use of desert could establish a mutually beneficial partnership which furthers development and makes regions of the world more secure.

How the actual negotiation of international agreements for access to solar resources in deserts of foreign countries is actually worked out is beyond the scope of this work, but the author sees the issue as no more of a challenge than the complexity of current international fossil fuel negotiations. The fact that the outcome may lead to a safer and environmentally cleaner world, makes the prospect very attractive however. Other important factors contributing to energy security are diversity of supply technology (eg. use of wind, tidal and wave power in an integrated energy economy), storage capacity, reducing waste and increasing efficiency. None of these would conflict with solar becoming a primary energy source but detailed discussion of these factors is also beyond the scope of this work.

Towards a new electricity network

Infrastructure to carry electrical power of the future will look different to the common 'root and branch' installations of today (Chebbo, 2007; Higgins, 2008). As decentralised sources of renewable energy take on a more significant role in the supply of electricity, the tradition of distribution networks from large centralised power stations built near to coal fields will be forced to change into inter-connected 'smart', supergrid systems spanning national borders across the EU to an extent not seen before (EC, 2006; Battaglini *et al.,* 2009). As most of the current UK electricity grid infrastructure was built in the 1950's and 60's, grid renewal and reconfiguration is due for re-engineering to suit the energy landscape of the future (POST, 2007). There are other issues to consider as well: such as storage to cope with matching supply and demand fluctuation, the connection of numerous small-scale generators, AC to DC and DC to AC conversion and the management of supply outages across the European continent. In the scenario where UK electricity is generated renewably under the North African sun, transmission, and how that integrates with a wider European network becomes very significant (Czisch & Giebel, 2007).

Currently there is a 2GW HVDC interconnection between the UK and France and a 1.3 GW connection under construction to the Netherlands. While a £4.7 billion upgrade to the UK electricity network is envisaged by 2020 to accommodate a further 34GW of offshore and onshore wind generation, the focus of UK strategy appears to be concentrating on reinforcement to networks around the British Isles (ENSG[1,2], 2009). But far more ambitious proposals are being made elsewhere to address the energy security and environmental imperative for an EU-wide electricity network. Airtricity, for example, envisage a 10GW wind energy project in the North Sea, interconnected by subsea HVDC cables between the UK, Germany and the Netherlands, as a foundation for a more extensive European network of wind

Fig. 20. Airtricity's 10GW Foundation Project will connect wind generated electricity through an HVDC network to the UK, Germany and the Netherlands as the first phase of a Europe-wide network.
Source: Airtricity, 2006.

farms (Fig. 20). The Desertec Foundation (2009) proposal goes further to encompass the EUMENA countries and interconnects a variety of renewable energy power sources on a continent-wide HVDC supergrid (Fig. 21).

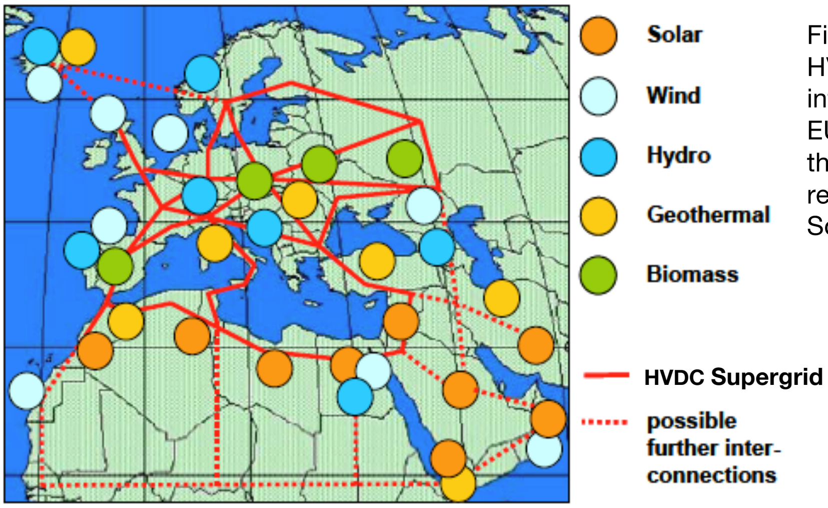


Fig. 21. Projection of a HVDC supergrid interconnecting EUMENA countries and their renewable energy resources.
Source: DLR, 2005.

Why HVDC is important in long distance electricity transmission

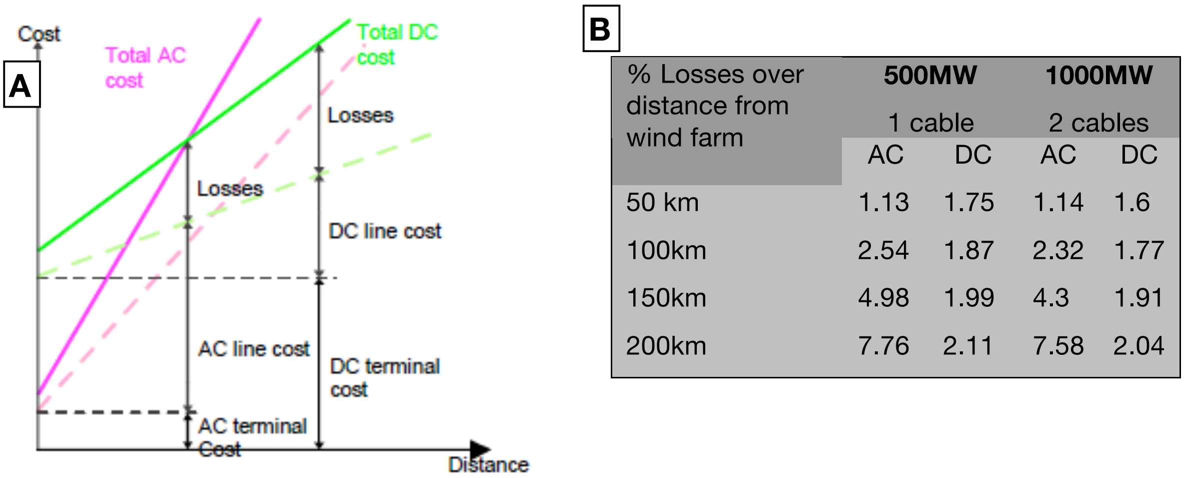
The UK is about 2000km from the foreseeable solar power plants of North Africa, so how will this affect its integration with a trans-European mesh of electricity networks? High Voltage Direct Current provides many practical advantages over High Voltage AC (HVAC) as a long distance transmission medium when used in combination with remote fluctuating supplies such as from solar and wind. Rudervall *et al.,* (2000), offer the following key points in it’s favour:-

- Economically transmits large amounts power (>500MW) over large distances (>50km)
- Virtually no limits in the transmission distance whether overland or underground/water
- Direction of the power flow can be changed very quickly
- Interconnect between networks at different frequencies possible
- Stabilises irregular supplies and surrounding AC systems
- Fewer conductors necessary to carry large loads. HVDC can carry more power than AC for a given size of conductor
- Lower environmental impact than AC of similar power. [Ravemark &

Normark (2005), using LCA, calculate cradle to grave material consumption of a DC cable as 64.5 $kgCO_2e/m$ compared with 365.4 $kgCO_2e/m$ for an AC overhead line.]

- Smaller electromagnetic fields minimising ‘right of way’ land area

In contrast to HVAC where power handling over distance is limited by the capacitive-reactive current component, the power handling capacity of HVDC is limited only by the ability of the insulating cable sheath to not break down under thermal stress (Reddy, 2009). While cable construction, converter station and type of transmission system employed will affect the losses from high voltage cables (Fig. 22), the use of cryogenic cooling of an HVDC cable core has been shown to significantly increase carrying capacity.



% Losses over distance from wind farm	500MW 1 cable		1000MW 2 cables	
	AC	DC	AC	DC
50 km	1.13	1.75	1.14	1.6
100km	2.54	1.87	2.32	1.77
150km	4.98	1.99	4.3	1.91
200km	7.76	2.11	7.58	2.04

Fig. 22. **A** - Comparison of costs in HVAC and HVDC systems, showing economic advantage of HVDC as distance increases. AC/DC and DC/AC converter stations currently add a premium to HVDC installations. **B** - Technical analysis of different transmission configurations from large offshore windfarms showing loss advantage of HVDC at distances > 50km.
Source: A - Ruderval *et al.,* 2000; B - Adapted from Negra *et al.,* 2000.

Yamaguchi *et al.,* (2008), have demonstrated that an HVDC cable with it’s core cooled to 72K~80K by liquid nitrogen can carry a current of 2.2kA at 20kV. With an estimated energy capacity of 4.5MJ/km such a cable would not only damp the supply variation incoming from renewable energy generators, but would also act as powerful energy storage medium. This addresses another critical issue relating to a grid fed by renewable energy - matching supply to demand when both are variable, but critically, when the sun doesn’t shine or the wind doesn’t blow (Strahan, 2009). Until storage of renewable energy has advanced such that daily variations in supply can be smoothed-out, reliance will be placed on conventional means of storage such as from hydo-electric plants and thermal stores to make the supply secure.

Demand matching considerations in solar power production

Plant sizing and capacity factor are important considerations in power generation for load matching. In the case of solar power, array structures are designed around a ‘solar multiple’ (SM). An SM of 1, equates to the minimum array size necessary to drive the power plant turbine at capacity at 12:00 noon in mid-summer. Configurations with an SM >1 provides excess power such that some of the plant capacity may be used for other processes (eg. heating) and storage, or to offer the capability to increase the plant capacity factor on cloudy days. At other times in peak conditions, some solar collectors may also be turned off-focus, discarding electrical or thermal energy, to facilitate maintenance.

Coal and nuclear generators offer base load generation but this may not be the best strategy to meet human demand patterns according to Mills & Morgan (2008), who argue that solar power correlates more closely with demand due to our relationship with the sun, while the concept of base load suits the technology involved. We have evolved to be more active when the sun is up and therefore require most energy then. Solar power with storage, (which could utilise super-cooled HVDC lines and electric vehicle batteries), augmented by other renewable and stored resources such as wind and hydro and a ‘smart grid’ which matched supply with demand more intelligently, would provide a more efficient load-following alternative to the present generation mix (Fig. 23).

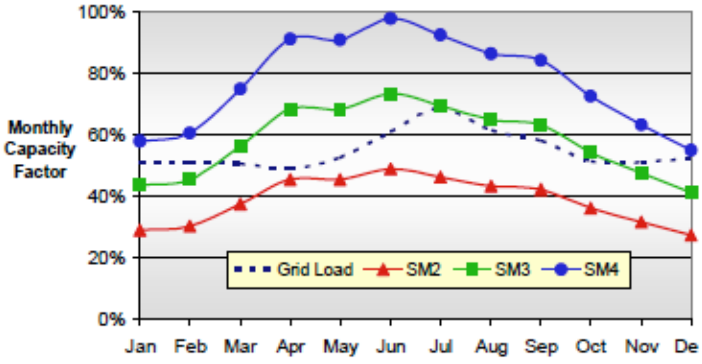


Fig. 23. Modelled solar load-matching from plant with different Solar Multiples and a 16 hour storage capacity. Data from a 50GW plant feeding the Californian CAISO grid with aggregated monthly output and demand. SM3 correlates to 92% of Grid Load without need for augmentation, and only 3% energy dumping.
Source: Mills & Morgan, 2008.

4 - The Case Studies

When compared with solar thermal approaches, CPV provides a qualitatively different approach, typically with lower water usage, greater flexibility in size of installation, and the ability to respond more quickly when the sun returns on a cloudy day.

- Kurtz, S., 2008

CSP will not only create thousands of jobs and boost economy, but will also effectively reduce the risks of conflicts related to energy, water and climate change.

- DLR, 2003

In the previous chapter we have established the considerations for sustainable energy, revealing sunlight as our primary sustainable energy resource, but the question of how best to transform its energy into electricity remains. In this chapter different high efficiency solar-electric technologies suitable for desert-based large scale power generation will be investigated using the model described in Chapter 1 as a basis for comparison (Fig. 3).

Parabolic trough solar electricity generating systems (SEGS) have been operating in the Mojhave desert of California since the 1980's (at Daggett, Kramer Junction, Harper Lake) and so CSP has a much longer technical record than the emerging cell technologies of CPV, which are inspired by the latest satellite power systems. Both pathways are rolling out new approaches though, so a short survey of their characteristics follows before proceeding to make a comparative assessment.

Concentrating Solar Power

CSP is a general term for the use of heat from collected and concentrated solar energy focussed upon a receiver which is converted into mechanical power, which is then used to drive an electrical generator. Different technologies exist for this purpose with various configurations (Fig. 24).

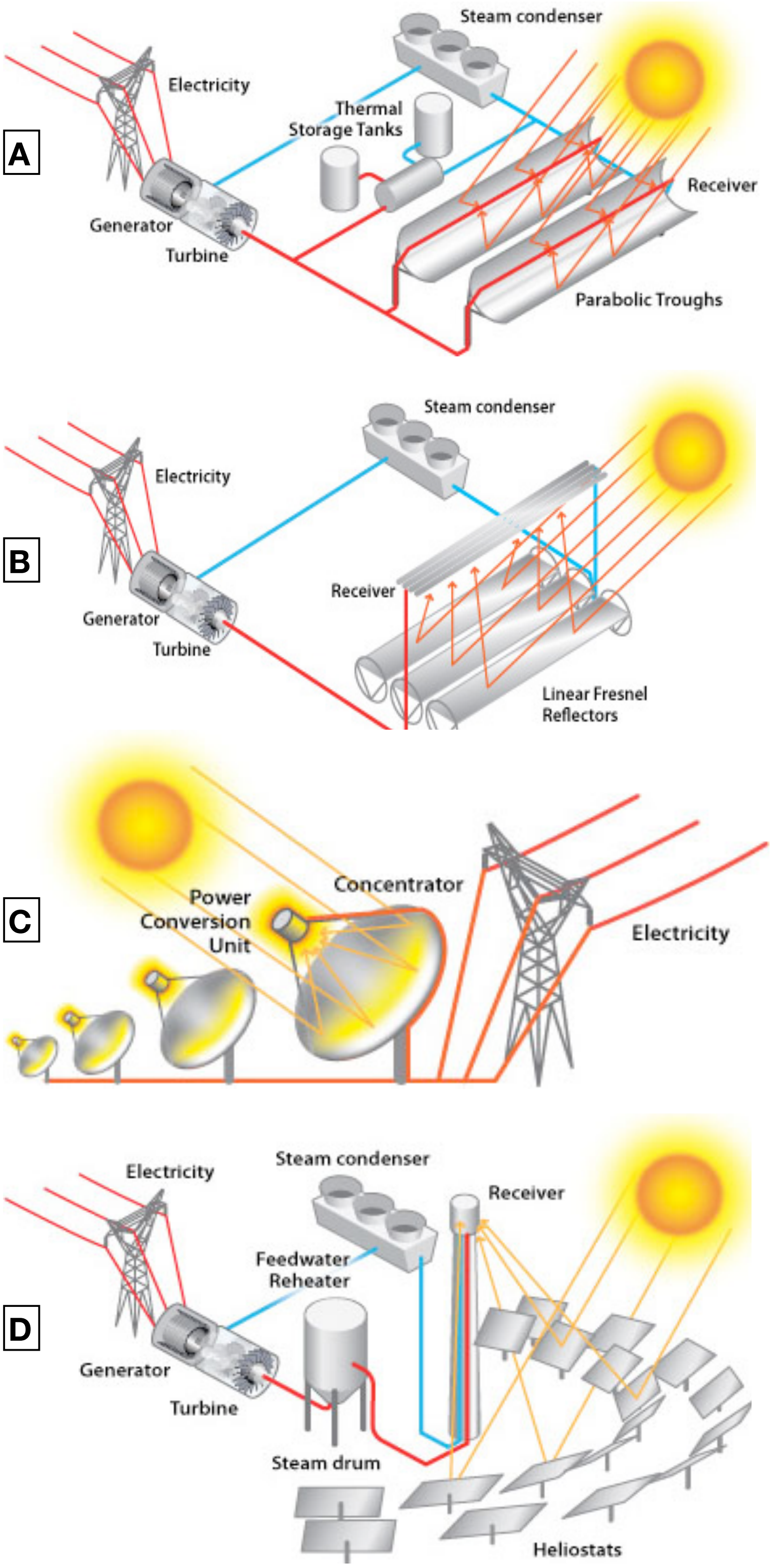


Fig. 24. CSP Collector and Generator Configurations.

A - Linear Parabolic Trough. Troughs of unidirectional-tracking, parabolic mirrors focus sunlight onto a receiver tube which caries heat to a steam generator or makes steam directly to drive an electricity generating turbine. Systems currently 10MW to >200MW.

B - Linear Fresnel Reflector. Multiple small unidirectional-tracking, parabolic mirrors are coordinated to heat a receiver along the focal line in a similar fashion to a trough collector. Sometimes a further concentrating mirror is placed above the receiver.

C - Dish/Engine System. A continuously tracking collector dish reflects heat onto a receiver/engine/generator system mounted at its focus.
Output range 3kW ~ 25kW per unit.

D - Solar Tower System. Numerous bidirectional, heliostatic flat -plate mirrors focus heat onto a central receiver which is transferred into a fluid (eg. water/steam, oil or molten nitrate salt) which drives an electricity generating turbine. Largest working system currently 15MW.

Source: USDoE, 2008.

An essential attribute of some CSP configurations is the use of heat and power to aid the desalination of water. Some systems may also be configured for co-generation with another fuel source and coupled to a heat storage system (eg. molten salt, concrete or pressurised steam) to offer output capacity when sunlight is unavailable (Fig. 25).

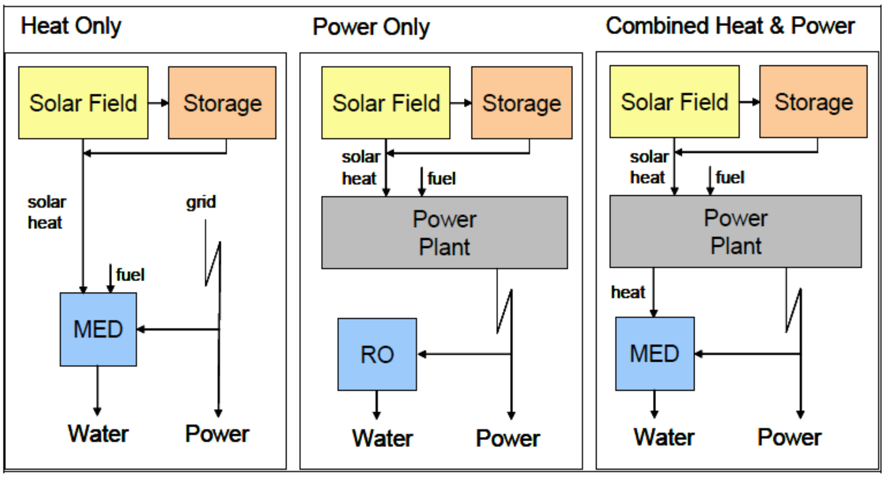


Fig. 25. Configurations for power generation, desalination and heat storage by concentrated solar power showing direct and indirect use of collected heat. MED - Multi-effect desalination. RO - Reverse Osmosis desalination.
Source: DLR, 2007.

Examples of CSP power station configurations which are currently in use in USA, Spain and Australia can be seen in Fig. 26.

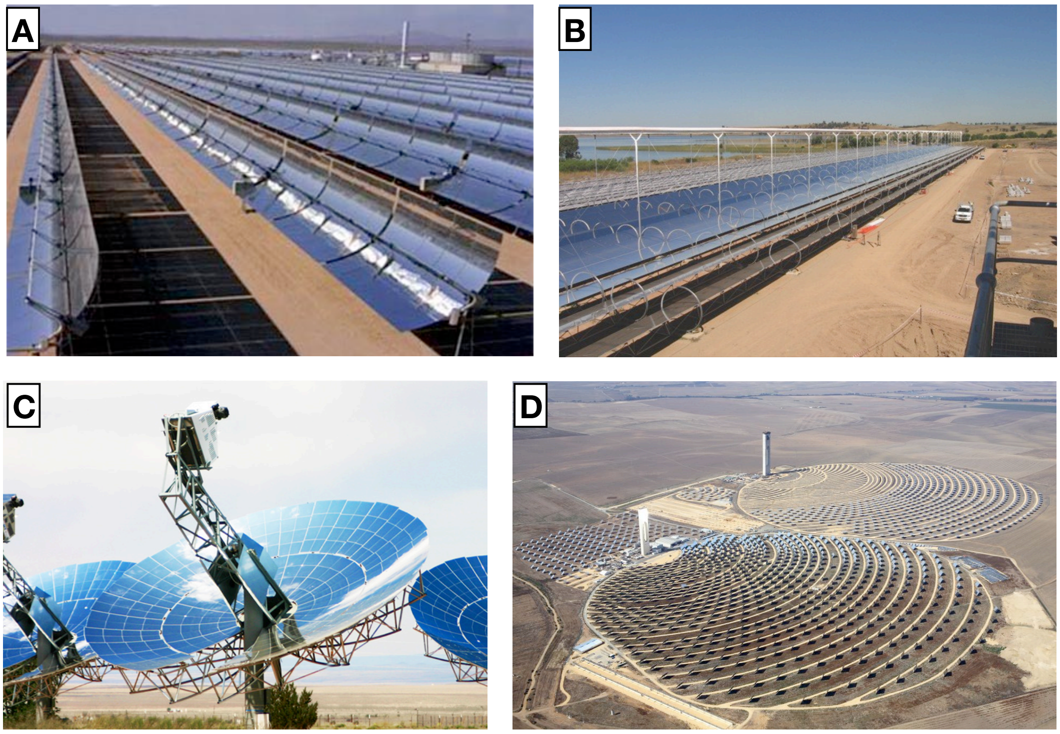


Fig. 26. **A** - Albiasa Corporation, Arizona, USA; **B** - Liddell power station, Australia; **C** - Tessera Corporation, California, USA; **D** - PS10 & PS20 solar towers, Abengoa, Spain.
Photo sources: Wikimedia; AlbiasaSolar; Tessera Solar;

Solar Towers are not such a mature technology as Parabolic Trough's but have thermal cycle efficiency advantages, (a measure of the use to which the generated heat is put) as these systems can heat air to over 1000ºC. A gas turbine (which has high efficiency) can then be included in the generation phase before the steam turbine stage to garner more power output from the thermal energy (Fig. 27).

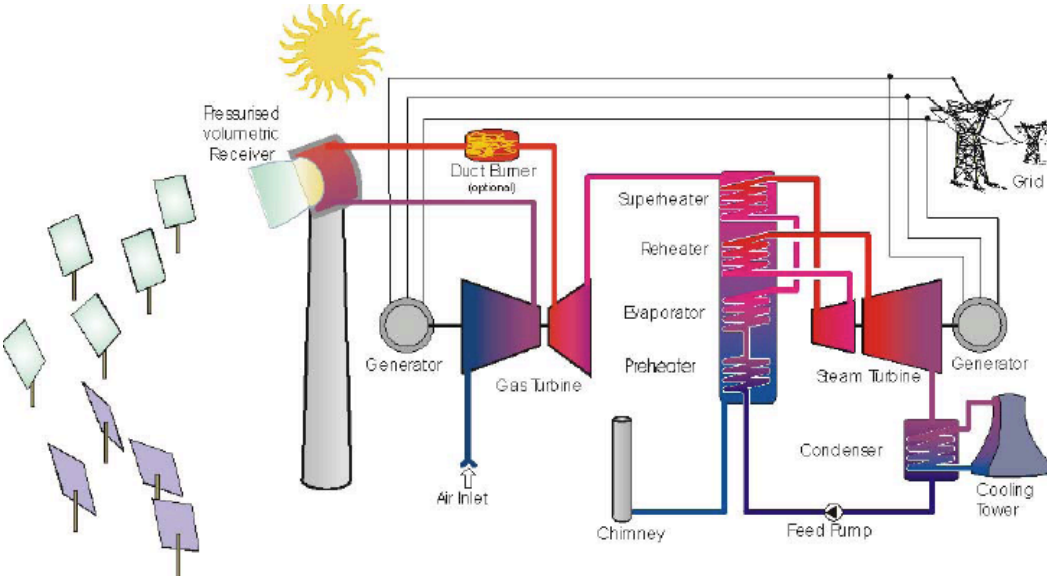


Fig. 27. Schematic of an integrated combined cycle thermal tower generation system showing the two stages of generation. Trieb (DLR, 2007) projects thermal cycle efficiencies up to 55% from this configuration, which is now operating at the PS10 & PS20 sites in Spain.
Source: DLR, 2007.

Concentrating Photovoltaic Power

CPV describes a system using an optical device (commonly a Fresnel lens although dish and parabolic mirror devices are also employed) for directing concentrated solar radiation onto a photovoltaic cell which converts this light directly into electricity (Fig. 28).

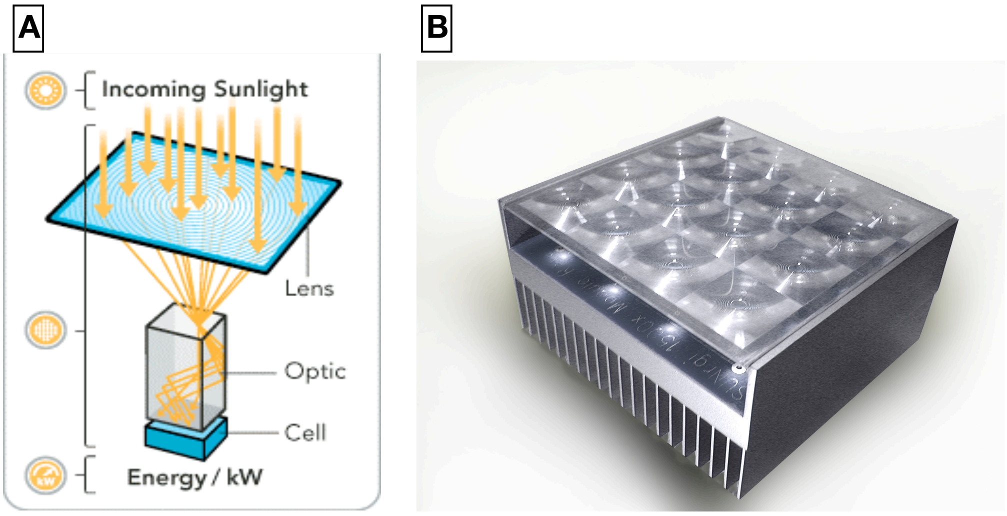


Fig. 28. **A** - Schematic showing a typical layout of a CPV cell system using a Fresnel lens to concentrate sunlight. Units with concentration factors up to x 2000 are currently under development. **B** - A unit of CPV cells under Fresnel lenses showing the cooling fins attached to the heat sink upon which the cells are mounted to dissipate the considerable amount of heat generated after high magnification of incoming solar radiation. Large numbers of these units make up the solar modules used to build the arrays of solar collectors for CPV power stations. Photo sources: A - Pyron Solar; B - Sunrgi;

Examples of CPV power station configurations which are currently in use in Spain, USA, Germany and Australia, can be seen in Fig. 29.

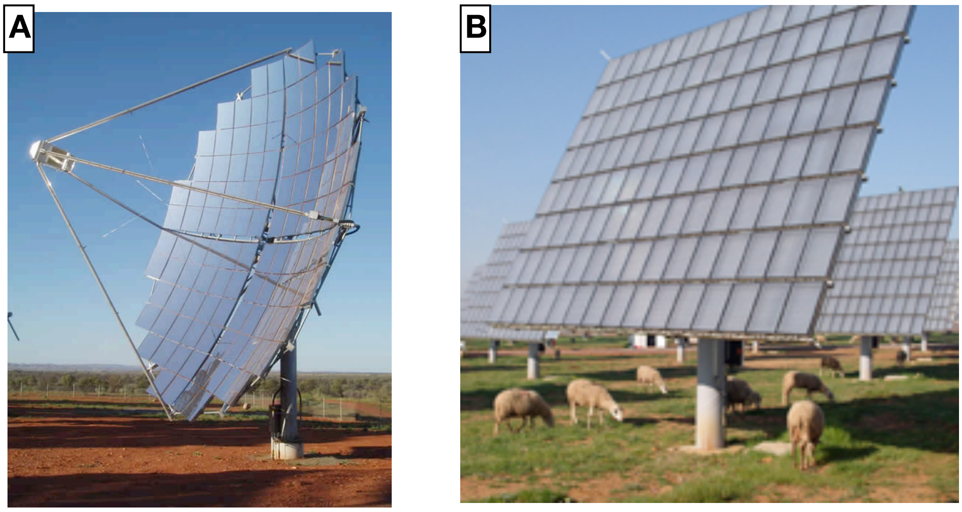


Fig. 29. Examples of CPV configurations. **A** - Dish-mounted CPV system made by SolarSystems. **B** - Fresnel concentrator system made by Concentrix. Photo sources: A - SolarSystems; B - Concentrix;

In contrast to most conventional ‘single-junction’ PV cells, those suitable for power station development currently utilise triple-junction cells with different band-gaps sensitive to the electromagnetic spectrum of solar radiation. This technology extends the potential for conversion of solar radiation into electricity beyond the *Shockley-Queisser Limit* of 30% for single junction cells (Shockley & Queisser, 1961), to about 49% for triple-junction cells, by capturing more energy from the different wavelengths of in-coming solar radiation spectrum (Fig. 30). Concentrating the radiation can increase cell efficiencies further as well. The theoretical limit of conversion efficiency under the maximum possible concentration of x 45900, for a tandem cell with an infinite number of junctions is 86.8% and 63.8% for a three-junction cell according to Vos (1980). Increasing the concentration of incident light upon the layers of cells can increase their conversion efficiency due electroluminescence of the other cells in the set, adding to the solar irradiance. The current maximum conversion efficiency achieved by a *champion cell* reported anywhere is 42.8% at only x 20 magnification (UD, 2007), although other sources claim records over 40% efficiency as well (NREL, 2008; Fraunhofer, 2009).

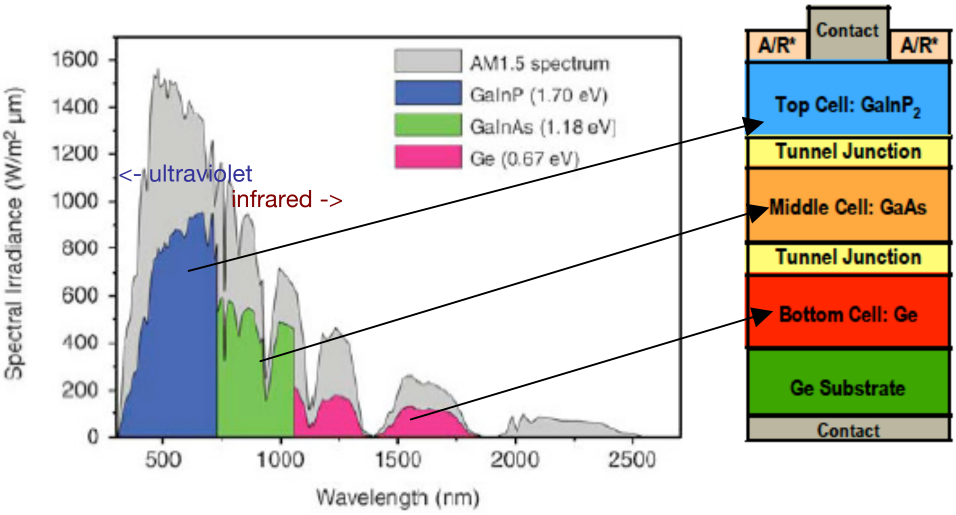


Fig. 30. **A** - Spectral energy reaching the ground ranges from ultraviolet to near infrared radiation with its peak between 400 ~ 700nm (visible light). It’s theoretical intensity is denoted by a standard reference spectrum (AM1.5) for the purpose of testing the performance of solar cells as they usually operate under more than one atmosphere’s thickness due to the angle of the sun to the earth. Multi-junction cells are designed such that their bandgaps convert different sections of the spectrum at their optimum efficiency to derive the best overall efficiency. The longer, lower energy wavelengths are converted in the lower cell layers.
B - Multiple-junction tandem cell structure showing the different combinations of elements making up each cell in the tandem and offering different bandgap sensitivity.
Sources: A - Yastrebova, 2007; B - Spectrolab, 2009.

The highest record above, is held by a cell structure which receives split wavelengths of light to specialist junctions spatially arranged. But the tandem cell design shown in Fig. 30, is commoner and relies upon light penetrating the entire cell stack to function effectively (Fig. 31).

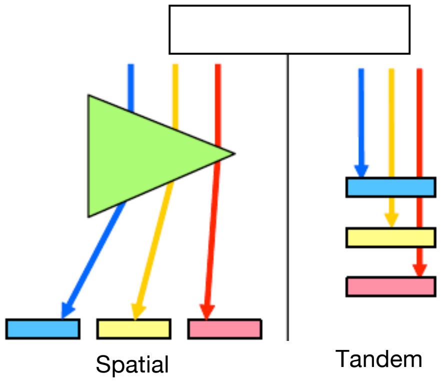


Fig. 31. Schematics of approaches to spectral radiation splitting in multi-junction cell designs. The tandem design resembles the function of a leaf structure when receiving solar radiation.

The resemblance to photosynthetic mechanisms found in plants of the tandem spectral splitting method is notable. Chlorophylls and carotenes act as spectral filters to capture different wavelengths of light in plant photosynthesis. As chlorophyll, found in the upper layer of leaves, is extremely sensitive to red and blue light, it may explain why the underside of leaves can appear red in order to ‘mop-up’ green light rejected by upper surfaces. Photosynthesis has also been biomimetically applied in a two-step, dye-solar cell (DSC) technology to generate energy from photoelectrochemical cells (Fig. 32).

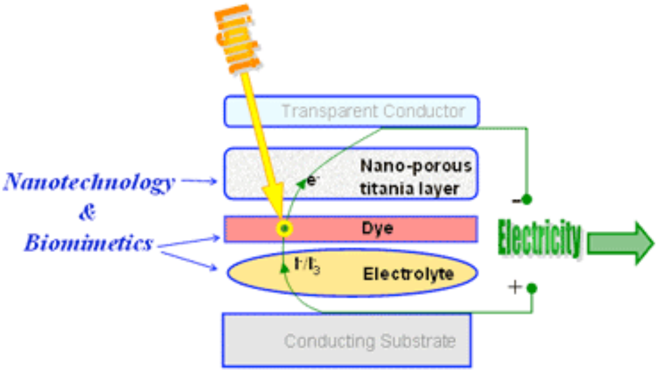
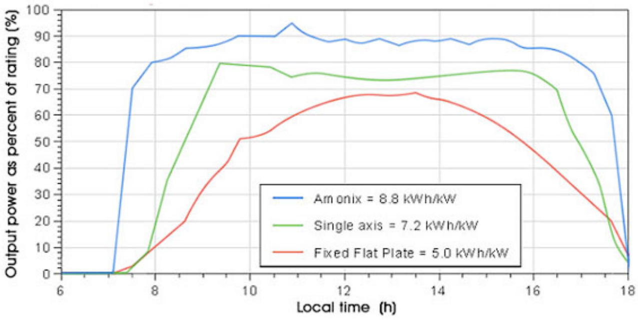


Fig. 32. Artificial photosynthesis as part of a biomimetic solar energy generator cell. The dye and electrolyte work analagously to the electron flux from chlorophyll in the complex photosynthetic reactions of plants. This phase of the plant’s photosystem 2 (PSII) is reportedly about 30% efficient.
Source: Everts, 2009; Youngblood *et al.,* 2009.
Schematic: Dyesol.

Another biomimetic factor used by CPV, and some CSP configurations, to maintain a concentrated beam of solar radiation upon the cell is heliotropism. It is essential to achieve the high performance characteristics of multi-junction cells that accurate tracking of the sun is maintained, which is not possible in single axis or static installations (Fig. 33).



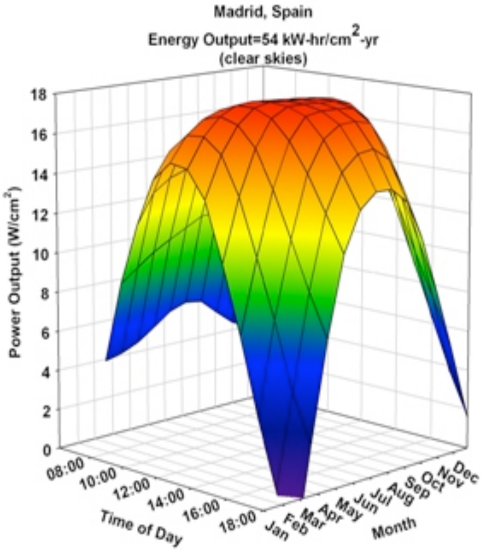


Fig. 33. **A** - Output profiles as a percentage of rated output. The power density advantage of a dual-axis CPV tracking system over single-axis and fixed systems may be of the order of 50%. **B** - Integrated energy output of a Spectrolab C1MJ cell at the latitude of Madrid.
Source: A - Amonix, 2009; B - Spectrolab, 2009; Kinsley *et al.*, 2009.

Comparisons between CSP and CPV from a sustainability perspective

The wider environmental impacts from toxic waste and pollutants identified by LCA will not be addressed in these comparisons as this information although important from a sustainability point of view, is not the focus of this work, which primarily concerns GHG mitigation in the production of energy. Voss (2006), says that the relative sustainability of technologies requires comparison of the overall consumption of resources in the production of a functional unit - in this case, a kWh of electricity. While this is a useful metric, other considerations such as the conservation of ES's and GHG mitigation are relevant. *GHG Return on Investment* (GROI), for example, the amount of GHG's saved relative to the life cycle GHG's invested compared to BAU, is a useful metric for solar power (Reich-Weiser *et al.,* 2008).

$$\mathrm{GROI} = \frac{\mathrm{GHG}_{\mathrm{BAU}} - \mathrm{GHG}_{\mathrm{Investment}}}{\mathrm{GHG}_{\mathrm{Investment}}}$$

A positive value for GROI would indicate the technology is a net GHG saver.
Equation: Fthenakis *et al.*, 2008.

In times of growing water scarcity, water usage in electricity generation is also an important sustainability consideration and its conservation is a special attribute of solar energy. CPV contrasts with CSP in this respect as in most current configurations the heat generated is rejected by air cooling of cell heat sinks and therefore wasted. CSP rejects heat by water cooling and therefore wastes water as well as heat. Quaschning (2004), mentions that PV systems can also out-perform solar thermal systems in lower insolation conditions due to the inefficiency of running steam turbines at part capacity. But different configurations of CSP offer the chance to use thermal energy to desalinate water as well as generate electricity thus reducing system life-cycle waste while adding to ES inventories. Mittleman *et al.,* (2008), describe a novel combination of CPV-Thermal (CPVT), using the rejected heat from CPV to drive a multi-effect desalination process to offer an even more cost effective approach to desalination than conventional means. Conveniently, the decrease in cell efficiency as cell temperature increases is over-compensated for by power output from increasing concentration ratios (Nishioka, *et al.,* 2005), which would benefit a CPV system incorporating the use of rejected heat.

Sustainable solar electricity is unlikely to give rise to a ‘one technology fits all’ solution therefore, and appropriateness, or how ‘fit for purpose’ a technology is, should be considered in siting the equipment.

Assessment - CSP

Life cycle and sustainability data for CSP was gathered mainly from sources, which referred to working projects in Spain, California and MENA countries. The different average solar insolation at these locations impacts upon the relative performance of systems studied, making comparisons difficult. In the case of combined cycle cogeneration, specific CO_2 emissions are relatively higher than for solar-only generation due to the emissions from burning fossil fuel in operation (Fig. 34). CO_2 emissions could be further reduced if electricity to operate the plant is taken from that ‘self-generated’ rather than from the grid which, in Spain for example, relies on coal fired power stations with high CO_2 emissions.

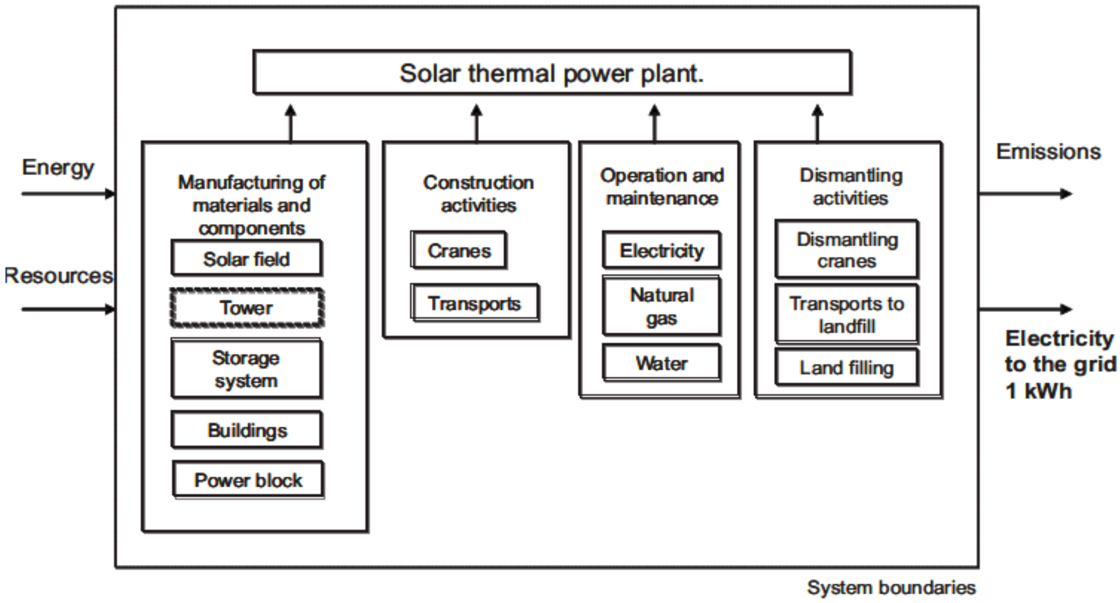


Fig. 34. Schematic of LCA System boundaries of a Spanish combined cycle cogeneration CSP power plant.
Source: Lechon *et al.*, 2008

In cases where desalination is a secondary thermal function of the power plant the environmental burden may be higher due to the added energy and discharge of concentrated brine. Different desalination processes are available but Reverse Osmosis and Multi-Effect Desalination are better suited to CSP.

Assessment - CPV

Several manufacturers of CPV systems and multi-junction cells were approached (see Appendix 1), with requests for performance and life cycle data but these were 82% unfulfilled, leaving only commercial data on company web pages. An extensive literature search for life cycle information was also conducted but this only highlighted the data gap. Two papers by Mohr *et al.,* (2007), and Raugei & Frankl (2009) partially addressed the subject however, concluding that CPV has a strong role to play in GHG mitigation with an environmentally cleaner character than conventional generating technologies and silicon-based PV. Key factors in it's favour are:-

- High conversion efficiency and suitability in areas of high solar insolation
- Very small cell size (1-5mm^2) takes away majority of cell environmental impacts due to small amount of material involved
- Concentrating equipment is relatively cheap and environmentally benign
- Very short energy payback time and high GROI
- Opportunity to use heat for desalination

Referring to Si-PV system manufacture, Fthenakis *et al.,* (2008), say GHG life cycle emissions may be reduced by up to 50%, if 100% of electricity used to build PV systems was supplied by PV generators - a *solar breeder* effect. This will further lessen the environmental impact of CPV systems as well as add to the theoretical probability that parity with fossil power cost per kWh will soon be achieved from development of large scale plant.

Results of comparisons

Data collected from various sources were collated into critical sustainability and performance metrics relating to the assessment approach directed by the sustainability model. Not all criteria were able to be filled as the corresponding data was unavailable (Table 6). As far as possible data were standardised but this was limited by lack of information relating to the conditions under which it was collected and some conflicting information. For example, not all performance information is related to the same Direct Normal Irradiance (DNI). Other information relates to field conditions at different geographic locations and some to idealised laboratory conditions.

Key sustainability criteria for CPV and CSP (power is AC)	**Triple junction CPV**		**CSP**			
	Fresnel	Parabolic dish	Fresnel	Stirling dish	Power Tower*	Parabolic Trough*
System LCA GHG Emissions gCO$_2$e/kWh power is AC (DC after inversion)					203[7], 23-48[12]	185[7], 10-80[12] 8.5-11.3[2],10-15[9]
Net Efficiency power out electricity/power in solar %	1.4[11], 23[13]	24[16]		31.25[15]	17[7]	10-21[1], 16[7]
Power Output/Land Use W/m^2	41-62[3] 2[14]	28.6[16], 9.6[18], >14[19]	19-28[1]	9-14[1] 9.65[15]	9-14[1], 11[7]	14-19[1], 25[7]
GROI %					139[7]	162[7]
Cooling litres water lost/ kWh output * Does not include water lost cleaning collectors.	N/A*	N/A*		2.4[15]	2.8[2]	2.8[2], 4.4[14]
Energy payback time months	<8[8], 6.7[7]				12[7]	12[7], 4.5[10] 5-6.72, 6[9]
Scalability range of power outputs MW	>0.006[13]			>25[14], >1k[15]		>14[6]
Concentration x Suns	500[3], 476[14]	500[16],	25-100[1]	1k-3k[1], 1300[15]	300-1k[1]	70-80[1]
System efficiency (system net efficiency x capacity factor) %	13-20[4] 22[5], 20[13]			27[15]	12[7]	10-14[6], 7[7]
Module efficiency (CPV only) %= Optical efficiency x cell efficiency	30[13], 24[14]	37[16], 28[19]				
Specific power output W/m^2 = power output/concentrating aperture	300[3], 180[13]	265.8[17]		71[15]	38[7]	36[7]

Table 6. Key sustainability criteria for CPV and CSP technologies. Sources and Notes:

1. DLR, 2007.
2. Jacobson, 2008.
3. Amonix, 2009. For the 7700 Solar Power Generator.
4. Single junction cells. Fthenakis & Kim, 2008.
5. Single junction cells. For a trough collector. Yongfeng *et al.*, 2009
6. Quaschning, 2004.
7. Lechon *et al.,* 2008. Studies conducted in Spain refer to total natural gas cogeneration CSP plant life cycles. See Appendix 1 for GROI calculations.
8. Mohr *et al.,* 2007. 8-10 months were given for solar insolation level in Spain (~1700kWh/m^2/yr) at x500 concentration.
9. Trieb *et al.,* 2002. Indication of which CSP technology being referred to was not given.
10. In Lechon *et al.,* 2008. Refers to SEGS plant
11. Amonix, 2009. For the NPC installation, Las Vegas. Information from Amonix website. See Appendix 2 for calculations.
12. In Lechon *et al.,* 2008, various authors, referring to solar-only electric power generation.
13. Concentrix Solar, 2009. System tested at 850W/m^2.
14. Sol3g, 2009. HCPV M40 S1 Modules data sheet. Flix press release, 2008.
15. Tessera Solar, 2009. Power output/land usage based on company EPC data.
16. Solar Systems, private communication, 2009.
17. Solar Systems, company literature, 2009. The reflective area of the solar dish was considered a circle fully comitted to concentration.
18. Coolearth, 2009. Calculation based upon claim that a Coolearth array measuring 150 miles x 150 miles would be enough to supply US electricity demand until 2030. US electricity demand expected to be 4902 billion KWh by 2030, according to EIA, 2008.
19. GreenVolts, 2009. This technology is not a single parabolic dish configuration but does use an array of mirrors.

5 - Discussion of Case Study Results

The results of the case studies identify a data gap for the sustainability metrics of LCA and GROI, particularly for CPV technologies, which are still emerging from development into commercialisation. Despite this the GROI's calculated from the CSP case studies conducted by Lechon *et al.,* 2008, show promising results for this approach to decarbonisation when compared to other technologies (Table 7). This is all the more remarkable as the power plants under consideration were augmented by natural-gas fired turbines. Responsible for up to 15% of the total power output this shows that state of the art solar thermal technology currently depends on fossil fuels to improve energy continuity, despite a thermal storage quotient up to 16 hours. If these systems were designed around larger solar multiples and larger heat storage capacity, and deployed further south than Spain, in the North African deserts, then the need for fossil fuel augmentation could possibly be removed, which would improve life cycle emissions significantly.

Life Cycle emissions for other technologies	gCO_2e/kWh
Wind	2.8-7.4[1]
Tidal	14
Geothermal	15.1-55
Hydroelectric	17-22
PV- single junction, non-concentrating	19-45[2]
Wave	21.7
Nuclear	9-70
Coal with CCS	255-442
Coal without CCS	790-1020
Steam/coal combined cycle	900[3]

Table 7. Comparison of life cycle emissions for other electricity generation technologies.
Source: All data from Jacobson, 2008, apart from (3).
Notes:

1. At windspeeds 8.5-7m/s
2. At 1700kWh/m^2/yr
3. Trieb *et al.,* 2002

Efficiencies for CPV technologies appear to be higher than CSP technologies in several categories, but this is not necessarily a major consideration for specific solar to electricity conversion, as land in desertified areas tends to be plentiful and under utilised. Obviously there would be a cost advantage from high efficiency of solar conversion however, as well as a smaller impact upon the environment in the plant build phase. It is also clear that CPV is more scaleable than CSP and therefore may have deployment advantages where suitable land is less available.

By using a model framework for sustainability to assess diverse technologies it was possible to orientate upon the critical aspects of LCA and ES, but comment upon system design from a Biomimetic point of view would require a more in-depth study than this work can offer, however useful that may be in terms of enhancing design criteria along natural lines. Therefore the inclusion of biomimicry in the sustainability model is not considered essential to it’s use in making comparative assessments, but rather more useful as a guide within a sustainable technology design and development model.

6 - Conclusions

There is an urgent need to totally decarbonise global energy supply with about 20 years of BAU. This 'window of opportunity' should be used to invest in the development of our future energy systems in which electricity will play a bigger role than currently. The solar resource found in deserts was shown to be clearly the most sustainable energy source available, but current policies by the British and European governments suggest that insufficient attention is being given to the sustainability of future energy options, tending instead to be 'locked-in' to unsustainable, traditional approaches as well as relying upon inadequate emissions trading schemes to mitigate carbon emissions. The funds which are required to develop carbon capture and sequestration technology could otherwise be diverted to developing a sustainable solar electricity supply for example. By not taking account of the availability of global ES's (and their energy density) to fuel sustainable energy technologies, and the environmental and social impacts of carbon fuels, we are literally risking the lives of future generations. In fact more than half of currently identified fossil carbon fuels resources should be left un-burnt in the ground. This matter is of critical importance now as time is very short to have a good (>75%) chance of limiting global stabilisation temperatures to the target of +2°C by 2100. Sustainability should therefore be central to energy policy because it offers the best approach to development, environmental conservation, security and satisfaction of demand.

Sustainable electricity needs to mitigate GHG emissions (from an LCA perspective) and conserve ES's as a priority, amongst the wider environmental and social considerations. Concentrating solar technologies offer the best means to satisfy these criteria if they are situated in desert regions around the world where high solar insolation and open land offer the optimum conditions to make this realistic. The UK and other European countries need to embrace the fact that renewable energy deployment is best suited to ES's of high energy density (in this respect solar energy is considered an ES which may be used for generating electricity in a similar way that wind or wave energy may be considered as fuels) and that the solar resource found in the deserts of

North Africa, would satisfy European electricity needs better than local resources of a lower density.

Power output can be efficiently linked to population centres and other renewable energy sources through the use of long-distance HVDC networks on a scale similar to conventional oil and gas networks, but with added security and less environmental impact. Superconducting HVDC cables pose an opportunity to store large amounts of energy and with smart grid systems (as well as other conventional storage technologies) would address concerns about continuity of supply from renewables.

The utility of CPV and CSP to contribute to water desalination is an obvious advantage in deserts. However, large scale desalination requires the plant to be located close to the coast which in the Mediterranean region does not receive the highest levels of solar insolation. Therefore there is a trade-off between the purpose of the plant in conserving ES's and it's efficiency in generating electricity, as high DNI is desirable for both processes. Both pathways offer technologies which must be deployed where they are best 'fit for purpose', which in general could mean CPV being located in arid regions with high concentration and duration of radiation, and CSP nearer to the coast. That should not limit CSP to coastal regions only, as it is also important to maximise plant capacity factor. In terms of comparison to other technologies the use of CPV and CSP solar pathways still offer favourable results when key ES's such as land, fuel type and water conservation are considered.

From a biomimetic point of view, the results of the case studies do not offer any clear indications, apart from the scalability of CPV and 2-axis tracking heliostats, as to how these principles have been included in their design. Solar power does incorporate several of the natural characteristics noted by Benyus (1997) in Chapter 1 however, which would be reinforced on a grand scale by a project of the order specified by Desertec. It may also benefit in future from dye-solar techniques mimicking photosynthetic processes and HVDC network design could benefit from 'social-insect' modelling to aid in smart network design for example (Niknam, 2008; Blum, 2005; Bonabeau *et al.,* 2000).

The attempt to test a sustainability model by making a comparison between CSP an CPV technologies was made but was weakened by the data gap in LCA and other sustainability metrics for multi-junction CPV systems in particular. Thus, for this approach to be an effective tool in policy generation, data of a suitable nature addressing life cycle and ecosystem service accounts is called for. Qualitative assessment revealed that both technologies offered opportunities to generate large scale electricity, mitigate GHG's and conserve water - a specific attribute of solar technologies. It was useful to orientate this comparison upon the principles of the model which provide a holistic approach to sustainability, but a full evaluation of its utility may only be gained when a fuller data set (such as LCA for CPV) is available.

References

Airtricity, 2006. European Offshore Supergrid Proposal. London, UK. www.airtricity.com/wind_farms/supergrid/?region=england

AlbiasaSolar, 2009. http://www.albiasasolar.com/english

Allen, M. R., Frame, D.F., Huntingford, C., Jones, C. D., Lowe, J. A., Meinshausen, M., Meinshausen, N., (2009). Warming caused by cumulative carbon emissions towards the trillionth tonne. Letter, Nature, 458, 1163-1166.

Amonix, 2009. http://www.amonix.com/technology_description.html

Battaglini, A., Lilliestam, J., Haas, A., Patt, A., 2009. Development of SuperSmart Grids for a more efficient utilisation of electricity from renewable sources. Journal of Cleaner Production, Vol. 17 (10), 911-918.

Benyus, J. M., 2002. Biomimicry: Innovation inspired by nature. Harper Perennial, New York, USA.

Beyond Petroleum (BP), 2009. Statistical Review of World Energy. http://www.bp.com/multipleimagesection.do?categoryId=9023754&contentId=7044554

Blum, C., 2005. Ant colony optimization: Introduction and recent trends. Physics of Life Reviews, 2(4), 353-373.

Bonabeau, E., Dorigo, M., Theraulaz, G., 2000. Inspiration for optimazation from social insect behaviour. Nature, 406 (6791), 39-42.

Boyle, G., Everett., Ramage., Energy Systems and Sustainability: Power for a sustainable future. Oxford University Press in association with The Open University, UK.

Brakmann, G., Aringhoff, R., Geyer, M., Teske, S., 2005. Concentrated Solar Thermal Power - Now! European Solar-Thermal Industry Association (ESTIA), Brussels, Belgium.

Broesamle, H., Mannstein, H., Schillings, C. and Trieb, F., 2000. Assessment of solar electricity potentials in North Africa based on satellite data and a geographic information system. Solar Energy, 70(1), 1-12.

Brundtland, G. H., 1987. Our Common Future. Oxford University Press, UK.

Caillon, N., Severinghaus, J.P., Jouzel, J., Barnola, JM., Kang, J., Lipenkov, V.Y., 2003. Timing of Atmospheric CO_2 and Antartic Temperature Change Across Termination III. Science, 299 (5613), 1728 - 1731.

Carbon Dioxide Information Analysis Center (CDIAC), 2009. Conversion Tables.

http://cdiac.ornl.gov/pns/convert.html#3.

Cassidy, E.S., 2000. Prospects for Sustainable Energy: A Critical Assessment. Cambridge University Press, UK.

Chambers Twentieth Century dictionary, 1980. W& R Chambers Ltd., Edinburgh, UK. p 1360.

Chapin, D.M., Fuller, C.S., Pearson, G.L., 1954. A new Silicon *p-n* Junction Photocell for Converting Solar Radiation into Electrical Power. Journal Applied Physics, 25, 676.

Chebbo, M., 2007. EU SmartGrids Framework "Electricity Networks of the future 2020 and beyond". Ieee Power Engineering Society General Meeting, Volumes 1-10*,* 4927-4934.

Concentrix Solar, 2009. http://www.concentrix-solar.de

Coolearth, 2009. http://www.coolearthsolar.com/faq

Crossley, P., 2009. Joule Centre comment on The UK Low Carbon Transition Plan.
http://www.joulecentre.org/news-centre/index.php?option=com_content&view=article&id=117:joule-centre-director-comments-on-the-low-carbon-transition-plan&catid=26:joule-news&Itemid=66

Czisch G, Giebel G. Realisable scenarios for a future electricity supply based 100% on renewable energies. Kassel, Roskilde: Working Paper, Universitat Kassel, Risø National Laboratory. 2007.

Department for Business, Enterprise and Regulatory Reform (BERR), 2007. Digest of United Kingdom Energy Statistics. National Statistics Office, London, UK.

Department of Energy & Climate Change (DECC), (1), 2009. UK Low Carbon Transition Plan Emissions Projections. URN 09D/678, HM Government publication, London, UK.

Department of Energy & Climate Change (DECC), (2), 2009. UK Energy Sector Indicators. URN 09D/193, HM Government publication, London, UK.

Desertec Foundation, 2009. Clean Power From Deserts. 4th Edition
Protext Verlag, Bonn.

Deutsches Zentrum für Luft und Raumfahrt e.V. (DLR), 2005. Concentrating Solar Power for the Mediterranean Region. German Aerospace Centre (DLR), Stuttgart, Germany.

Deutsches Zentrum für Luft und Raumfahrt e.V. (DLR), 2007. Concentrating Solar Power for Seawater Desalination. German Aerospace Centre (DLR), Stuttgart, Germany.

Dyesol, 2009. http://www.dyesol.com/index.php?page=HowItWorks

Earth Policy Institute (EPI), 2008. Carbon Emissions from Fossil Fuels Burning in Top Ten Countries, 2006.
http://www.earthpolicy.org/Indicators/CO2/2008_data.htm#fig1

Electricity Networks Strategy Group (ENSG), 2009[1]. Our Electricity Transmission Network: A vision for 2020. DECC, London, UK. URN/09/752

Electricity Networks Strategy Group (ENSG), 2009[2]. Our Electricity Transmission Network: A vision for 2020, Further Analysis - 2030 Generation and demand Scenarios. DECC, London, UK. URN/09D/715

Energy Information Administration (EIA), Press Release, 2008.
www.eia.doe.gov/neic/press/press312.html

Energie-Atlas GmbH, 2007. Meteonorm: Global Meterological Database.
www.energie-atlas.ch

European Commission (EC), 2006. SmartGrids: Vision and Strategy for Europe's Electricity Networks for the Future. European Comission, EUR 22040, Directorate-General for Research Sustainable Energy Systems, Brussels, Belgium.

euobserver.com, 2008. Russia invaded Georgia to teach the West a lesson.
http://euobserver.com/13/26611

European Council (EU), 2005; Climate Change Strategies.
http://register.consilium.europa.eu/pdf/en/05/st07/st07242.en05.pdf

Europa, 2009. The Climate action and renewable energy package, europe's climate action opportunity.
http://ec.europa.eu/environment/climat/climate_action.htm

Eurostat, 2009. Panorama of energy: Energy statistics to support EU policies and solutions. Eurostat Statistical Books, European Union, Luxembourg.

Eurostat, 2008. News Releales: Energy consumption and production. 98/2008.
http://ec.europa.eu/eurostat/

Everts, S., 2009. Attempts to Mimic a Plant's Light-Harvesting and Water-Splitting Megamachinery. C&EN, Vol 87, (15).
http://pubs.acs.org/cen/science/87/8715sci1a.html

Fthenakis, V.M., Kim, H.C., Alsema, E., 2008. Emissions from Photovoltaic Life Cycles. Environmental Science & Technology, 42 (6), 2168-2174.

Fthenakis, V.M., Kim, H.C., 2008. Land use and electricity generation: A life cycle analysis. Renewable and Sustainable Energy Reviews, 13, 1465-1474.

Fraunhofer, 2009. World Record: 41.1% efficiency reached for multi-junction solar cells at Frauenhofer ISE. http://www.ise.fraunhofer.de/news-1/world-record-41.1-efficiency-reached-for-multi-junction-solar-cells-at-fraunhofer-ise

Gerling, P., Rempel, H., Schwarz-Schampera, U., 2005. Reserves, Resources and Availability of Energy Resources 2005. Federal Institute for Geosciences and Natural Resources, Hannover, Germany.

Goswami, D.Y., 2007, in World Energy Council (WEC). Survey of Energy Resources: Solar Energy. WEC, London, UK., 381-392.

GreenVolts, 2009. http://www.greenvolts.com/solutions/advantages/

Haas, P.M., 2004. When does power listen to truth? A constructivist approach to the policy process. Journal of European Public Policy, 11(4), 569-592.

Hansen, J. E., Sato, M., Kharecha, P., Beerling, D., Masson-Delmotte, V., Pagani, M., Raymo, M., Royer, D.L., Zachos, C.J., 2009. Target atmospheric CO2: Where should humanity aim? Open Atmospheric Science Journal. (2), 217–231.

Hansen, J. E., Sato, M., Kharecha, P., Russell, G., Lea, D. W., Siddall, M., 2007. Climate change and trace gases. Phil. Transcripts of Royal Society. A 365, 1925-1954.

Hays, J.D., Imbrie, J., Shackleton, N.J., 1976. Variations in the Earth's Orbit: Pacemaker of the Ice Ages. Science 194(4270), 1121-1132.

Hennicke, P., Fischedick, M., 2006. Towards sustainable energy systems: The related role of hydrogen. Energy Policy, 34(11), 1260-1270.

Higgins, P., 2008. Electricity: levelling the renewables playing field. Renewable Energy Focus, Vol. 9 (5), 42-46.

HM Government, 2009. The UK Low Carbon Transition Plan: National strategy for climate and energy. Office of Public Sector Information, Richmond, UK. ISBN 9780108508394.

International Energy Agency[1] (IEA), 2008. World Energy Outlook 2008. Paris, France.

International Energy Agency[2] (IEA), 2008. World Energy Outlook 2008 Fact Sheet. Paris, France.

Intergovernmental Panel on Climate Change (IPCC), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the

Fourth Assessment Report of the Intergovernmental Panel on Climate Change Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L., (eds.)]. Cambridge University Press,
Cambridge, United Kingdom and New York, NY, USA, 996 pp.

ISO 14040, 2006. Environmental management - Life cycle assessment - Principles and framework. International Standards Organisation, Switzerland.

ISO 14044, 2006. Environmental management - Life cycle assessment - Requirements and guidelines. International Standards Organisation, Switzerland.

Jacobson, M., 2008. Review of solutions to global warming, air pollution and energy security. Energy & Environmental Science, 2. 148-173.

Kates, R.W., Clark, W.C., Corell, R., Hall, J.M., Jaeger, C.C., Lowe, I., Mccarthy, J.J., Schellnhuber, H.J., Bolin, B., Dickson, N.M., Faucheux, S., Gallopin, G.C., Grubler, A., Huntley, B., Jager, J., Jodha, N.S., Kasperson, R.E., Mabogunje, A., Matson, P., Mooney, H., Moore, B., O'riordan, T., Svedin, U., 2001. Environment and development - Sustainability science. Science, 292(5517), 641-642.

Kinsey, G.S., Pien, P., Hebert, P., Sherif., R.A., 2008. Operating characteristics of multijunction solar cells. Solar Energy Materials and Solar Cells, 93(6-7), 950-951.

Kintisch, E., 2005. Climate change - Panel urges unified action, sets 2 degrees target. Science, 307(5709), 496-496.

Kurtz, S., 2008. Opportunities and Challenges for Development of a Mature Concentrating Photovoltaic Power Industry. National Renewable Energy Laboratory, NREL/TP_520_43208, Colarado, USA.

Lechon, Y., De La Rua, C. and Saez, R., 2008. Life cycle environmental impacts of electricity production by solarthermal power plants in Spain. Journal of Solar Energy Engineering-Transactions of the Asme, 130(2)

MacKay, D.J.C., 2009. Sustainable Energy - without the hot air. UIT Cambridge Ltd., UK.

Meadows, D. H., Meadows, D. I., Randers, J., Behrens, W. W., 1972. The Limits of Growth: A report to The Club of Rome, www.clubofrome.org/docs/limits.rtf

Meinshausen, M., Meinshausen, N., Hare, W., Raper, S.C.B, Frieler, K., Knutti, R., Frame, D.J., Allen, M.R., 2009. Greenhouse-gas emission targets for limiting global warming to 2 °C. Nature, 458, Letter, 1158-1162

Mills, D. and Morgan, R., 2008. Solar Thermal Electricity as the Primary Replacement for Coal and Oil in U.S. Generation and Transportation. Ausra, Inc. Available online: http://www.ausra.com/pdfs/ausra_usgridsupply.pdf

Mittleman, G., Kribus, A., Mouchtar, O., Dayan, A., 2009. Water desalination with concentrating photovoltaic/thermal (CPVT) systems. Solar Energy 83, 1322-1334.

Mohr, N.J., Schermer, J.J., Huijbregts, M.A.J., Meijer, A. and Reijnders, L., 2007. Life cycle assessment of thin-film GaAs and GaInP/GaAs solar modules. Progress in Photovoltaics, 15(2), 163-179.

National Academy of Sciences (NAS), 1979. Carbon Dioxide and Climate: A Scientific Assessment, (Report of an Ad Hoc Study Group on Carbon Dioxide and Climate to the Climate Research Board), Woods Hole, USA.

National Aeronautics and Space Administration (NASA), 2009. Global Climate Change, Key Indicators.
http://climate.nasa.gov/keyIndicators/

National Renewable Energy Laboratory (NREL), 2008. NREL Solar Cell Sets World Efficiency Record at 40.8 Percent.
http://www.nrel.gov/news/press/2008/625.html

National Oceanic & Atmospheric Administration (NOAA), 2009. Trends in Atmospheric Carbon Dioxide.
http://www.esrl.noaa.gov/gmd/ccgg/trends/index.html#global

Negra, N.B., Todorovic, J., Ackermann, T., 2006. Loss evaluation of HVAC and HVDC transmission solutions for large offshore wind farms. Electric Power Systems Research 76, 916-927.

NIKNAM, T., 2008. A new approach based on ant colony optimization for daily Volt/Var control in distribution networks considering distributed generators. Energy Conversion and Management, 49(12), 3417-3424.

Nishioka, K., Takamoto, T., Agui, T., Kaneiwa, M., Uraoka, Y. and Fuyuki, T., 2006. Annual output estimation of concentrator photovoltaic systems using high-efficiency InGaP/InGaAs/Ge triple-junction solar cells based on experimental solar cell's characteristics and field-test meteorological data. Solar Energy Materials and Solar Cells, 90(1), 57-67.

Nitsch. F., 2007. Technologische und energiewirtschaftliche Perspektiven erneuerbarer Energien. Institut für Technische Thermodynamik, Stutgart, Germany.

Parliamentary Office of Science and Technology (POST), 2007. Electricity in the UK. Postnote number 280. London, UK.

Pepper, D., Perkins, J., Young, M., 1984. The roots of modern environmentalism. Croom Helm, London, UK, 242 pp,
Land Use Policy, Volume 2, Issue 3, July 1985, pp. 258-259

Pyron Solar, 2009. http://www.pyronsolar.com

Quaschning, V., 2004. Technical and economical system comparison of photovoltaic and concentrating solar thermal power systems depending on annual global irradiation. Solar Energy 77, 171-178.

Raupach, M.R., Marland, G., Ciais, P., Le Quere, C., Canadell, J.G., Klepper, G., Field, C.B., 2007. Global and regional drivers of accelerating CO_2 emissions. PNAS, 104(24), 10288-10293.

Reddy, C.C., 2009. Theoretical Maximum Limits on Power-Handling Capacity of HVDC Cables. IEEE Transactions on Power Delivery, 24(3), 980-987.

Reich-Weiser, C., Dornfeld, D., Horne S., 2008. Greenhouse
Gas Return on Investment: A New Metric for Energy Technology. 15th International CIRP Conference on Life Cycle Engineering, Sydney, Australia.

Rijsberman, F.R., Swart, R.J., (Eds), 1990. Targets and indicators of climate change: Report of Working Group II of the Advisory Group on Greenhouse Gases. Stockholm Environment Institute.

Royal Academy of Engineering, 2006. Developing a sustainable energy strategy: Report on a programme of energy seminars. London, UK.

Raugei, M., Frankl., P., 2009. Life cycle impacts and costs of photovoltaic systems: Current state of the art and future outlooks. Energy 34, 392-399.

Ravemark, D., Normark, B., 2005. Light and invisible: Underground transmission with HVDC Light. ABB Review, ABB Corporate Research, Vasterås, Sweden.

Rudervall, R., Charpentier, J.P., Sharma, R., 2000. High Voltage Direct Current (HVDC) Transmissions Systems Technology Review Paper. Energy Week, Washington, USA.

Scheer, H., 2007. Renewable Energy is the Future, in Surviving the Century: Facing Climate Chaos and Other Global Challenges. Earthscan, London, UK., 35-55.

Schmidt, G., Archer, D., 2009. Climate change: Too much of a bad thing. Nature, 458, 1117-1118

Shelton, D., Cork, S., Binning, C., Parry, R., Hairsine, P., Vertessy, R., Stauffacher, M., 2001. Application of an ecosystem services inventory approach to the Goulburn Broken Catchment. Third Australian Management Conference, Brisbane, 157-162.

Shockley, W., Quisser, H.J., 1961. Detailed balance limit of efficiency of *p-n* junction solar cells. Journal of Applied Physics, 32 (3), 510-519.

Sol3g, 2009. www.sol3g.com

SolarSystems. http://solarsystems.com.au

Solomon, S., Plattner, G., Knutti, R. and Friedlingstein, P., 2009. Irreversible climate change due to carbon dioxide emissions. Proceedings of the National Academy of Sciences of the United States of America, 106(6), 1704-1709.

Spectrolab, 2009. Photovoltaic products: Next generation (XTJ) Solar Cells. www.spectrolab.com

Strahan, D., 2009. From AC to DC: Going green with supergrids. New Scientist, Vol. 201 (2699). Reed Business Information, UK., 42-45.

Sunrgi, 2009. http://www.sunrgi.com.

Swartz, S.E., 2008. Uncertainty in climate sensitivity: Causes, consequences, challenges. Energy & Environmental Science. 1, 430-453.

Tessera Solar. http://www.tesserasolar.com/international/how-it-works.htm

Trieb, F., Nitsch, J., Kronshage, S., Schillings, C., Brischke, L.A., Knies, G. and Czisch, G., 2002. Combined solar power and desalination plants for the Mediterranean region - sustainable energy supply using large-scale solar thermal power plants. Desalination*,* 153(1-3), 39-46.

University of Delaware (UD), 2007. UD-led team sets solar record, joins DuPont on $100 million project. http://www.udel.edu/PR/UDaily/2008/jul/solar072307.html

UK Energy Research Centre, 2009. Decarbonising the UK energy System: Accelerated Development of Low Carbon Energy Supply Technologies. Version 2, Draft Report. London, UK.

United Nations Development Programme (UNDP), 2007. Human Development Report 2007/2008. Fighting Climate Change: Human solidarity in a divided world. UNDP, New York, USA.

United Nations Environmental Programme (UNEP), 2006. Global Deserts Outlook. ed. Ezcurra, E. DEW/0839/NA. Nairobi, Kenya.

United States Department of Energy (USDoE), 2008. Solar Energy Technologies Program: Concentrating Soalr Power. http://www1.eere.energy.gov/solar/csp.html

Victor, D. G., (2009). Global warming: Why the 2°C goal is a political delusion. Nature, 459, 909.

http://www.nature.com/nature/journal/v459/n7249/full/459909a.html

Vos, A, De., 1980. Detailed balance limit of the efficiency of tandem solar cells. Journal of Physics D: Applied Physics, 13 (1980), 839-46.

Voss, A., 2006. Energy and Sustainability - An Outlook. Institute for Energy Economics and Rational Use of Energy, University of Stuttgart. International Materials Forum 2006, Bayreuth, Germany.

World Energy Council (WEC), 2007. Survey of Energy Resources. London, UK.

Wikimedia. http://wapedia.mobi/en/PS10_solar_power_tower.

Yamaguchi, S., Hamabe, M., Yamamoto, I., Famakinwa, T., Sasaki, A., Iiyoshi, A., Schultz, J., Minervini, J., Hoshino, T., Ishiguro, Y., Kawamura, K., 2008. Research activities of DC Superconducting Power Transmission Line in Chubu University. Journal of Physics: Conference Series 97, 012290.

Yastrebova, N.V., 2007. High Efficiency multi-junction solar cells: Current status and future potential. Centre for Research in Photonics, University of Ottawa, Canada.

Yongfeng, X., Ming, L., Liuling, W., Wenxian, L., Ming, X., Xinghua, Z., Yunfeng, W., Shengxian W., 2009. Performance analysis of solar cell arrays in concentrating light intensity. Journal of Semiconductors, 30 084011 (6pp)

Youngblood, WJ., Lee, S.H., Kobayashi, Y., Hernandez-Pagan, E.A., Hoertz, P.G., Moore, T.A., Moore, A.L., Gust, D., Mallouk., 2009. Journal of American Chemical Society, 131 (3), 926-7.

Zachos, J., Pagani, M., Sloan, L., Thomas, E., Billups, K., 2001. Trends, Rhythms, and Aberrations in Global Climate 65 Ma to Present. Science, 292, 686 - 693.

Appendices

Appendix 1. Sample of proforma data request sent to companies building CPV systems and cells. Companies approached include: Tessera Solar, Sunrgi, Coolearth, Cyrium Technologies, Solar Systems, Concentrix Solar, Sol3g, Spectrolab, IQE, GreenVolts, Pyron Solar.

To whom it may concern -
Please could you provide the information requested in the table below to help in my research with making a comparison between varyious concentrating solar thermal and concentrating photovoltaic power systems.
Many thanks for your help,

Nigel Hargreaves
(Masters Programme, Institute for the Environment, Brunel University, UK).
Please return this document to: nigelbh@ymail.com, or, el08nbh@brunel.ac.uk

Key sustainability criteria	**1**	**2**	**3**	**4**	**5**	**6**	**7**
	System LCA GHG Emissions $kgCO_2e/kWh$	**Net Efficiency** power out electricity/ solar power in	**Land use** W/m^2 output	**Cooling losses** litres water used / kWh output	**Desalination** litres water out/ kWh solar input	**Solar efficiency** of collector or modules	**Scalability** range of power outputs
Company name							

Notes:
1 - Ideally the LCA system boundaries are set include as wide a range of inputs and outputs as possible to construct, operate and de-commission the CSP/CPV system concerned in the process of generating 1kWh of electricity at a solar insolation of more than 2100W/m^2 This would include GHG emissions from materials production, fabrication and erection as well as operational losses and receipts from recycling and recovery of components on decommissioning.

2 - This is an overall input:output calculation to give a performance benchmark expressed as a percentage for the technology.

3 - Related to (2) the power output per m^2 under more than 2100W/m^2 insolation, based on the physical footprint of the technology.

4 - The ecosystem service deficit in terms of water consumption to reject heat in the operation of the equipment to produce 1kWh electricity.

5 - The ecosystem service credit in terms of drinking water delivered per kWh solar insolation as a by-product of electricity generation. This may not apply in some system configurations.

6 - The ratio of power at equipment solar receiver (kW/m^2) to incident solar power (kW/m^2).

7 - A measure of the range of power outputs of this technology to be scaled-up or down, ie. smallest unit operating power to largest unit operating power.

Appendix 2. GROI calculations for Spanish case studies. Data from Lechon *et al.*, 2008.

$$\text{GROI \%} = \frac{\text{GHG}_{\text{BAU}} - \text{GHG}_{\text{Investment}}}{\text{GHG}_{\text{Investment}}} \text{ x } 100$$

Power Tower

= {{(104014000 x 0.485) - (104014000 x 0.203)}/ (104014000 x 0.203)} x 100

= **139%**

Parabolic Trough

= {{(187581000 x 0.485) - (187581000 x 0.185)}/ (187581000 x 0.185)} x 100

= **162%**

Appendix 3. Net efficiency calculations for Amonix/NPC installation. Data from Amonix, 2009.

Net efficiency % = power out electricity/power in solar x 100

= (annual power generated/area of facility)/(annual solar insolation) x 100
= (145242/4046.85)/(7.1 x 345) x 100

= **1.4%**