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Solar energy for heat and electricity: the potential for mitigating climate change

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Executive summary

Why are we interested in using solar energy?

Sunlight provides the energy source that powers the Earth's climate and ecosystem. Harnessing this energy for hot water and electrical power could provide a renewable, low carbon energy source, and presents an attractive way of mitigating climate change. In developing countries, solar technologies are already in use to enhance the standard of living. They are a natural choice where solar influx is high and grid services are unavailable or limited. In developed countries, solar energy can seem less attractive than conventional sources due to its intermittent nature, but with the right technology it can have considerable benefits in terms of reduced carbon emissions and improved energy security. In developed countries, most forms of solar energy are currently more expensive than conventional alternatives. At this pre-competitive stage, incentives are needed to encourage their uptake.

How can we use solar energy?

We can use solar energy either to provide heat or to generate electricity.

Solar hot water systems could be used to supply up to 70% of household hot water in the UK; in sunnier climates, virtually all domestic hot water could be provided for. The main cost for solar hot water systems is the installation itself, although they can be incorporated into new buildings with minimal overhead cost. The largest installed capacity is found in China, where solar hot water collectors are a cost-effective means for easing the rising demand placed upon conventional energy generation. The use of solar heat in commercial and industrial environments is also feasible but much less widespread.

Solar electricity can be generated directly using photovoltaic (PV) panels. These panels are suitable for use on roofs and are now manufactured in sufficient quantity that the electricity generated in some favourable locations has almost reached grid parity (the point where the cost of photovol-

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taic electricity matches the residential grid price). The growth in photovoltaic manufacturing has been driven by government incentives that subsidise the cost of electricity and drive technological innovation.

First generation PV panels are made from silicon wafers at relatively high cost. They represent the industry standard, delivering efficiencies between 12-20% and are particularly durable.

Second generation PV devices are made by depositing a thin film of semiconductor directly onto glass, metal foil or plastic, reducing the cost of materials but resulting in a loss in efficiency (usually to 10% or less) when manufactured over large areas. All plastic, flexible solar cells have the possibility of very low manufacturing cost, but the efficiency (4%) and lifetime (typically one year of operation) need to be improved.

Third generation PV devices, currently under development, aim to improve the efficiency of solar conversion towards the thermodynamic efficiency limit of 86.8%. Currently, the highest efficiencies achieved are around 40%, with very high costs. Nevertheless, these technologies are used in terrestrial concentrator solar power plants and used to power modern communication satellites.

With almost one third of the world's population living without electricity, solar energy offers great promise to improve living standards and reduce greenhouse gas emissions.

On the **domestic scale**, the quantity of electricity that PV panels can provide depends upon their efficiency, size and local level of solar illumination. PV panels suitable for use on roofs are now manufactured in sufficient quantity that the electricity generated in favourable locations has almost reached grid parity. Where a grid connection is available, it may be possible to sell surplus electricity back to the grid if a 'feed-in tariff' is in place.

On a **larger scale**, solar electricity can be generated by concentrating the sun's rays using lenses or mirrors. These **concentrator photovoltaic** (CPV) power plants focus light onto high-efficiency third-generation PV cells to generate electricity directly.

Concentrator solar thermal (CST) power plants work indirectly by focusing light onto a collector which is then used to heat a fluid, generating steam to drive a turbine. They have the advantage of being able to store energy in the form of heat and thus smooth out some of the fluctuations due to intermittent solar influx. An alternative approach is to replace the steam turbine with a dish-mounted Stirling engine, which is up to 31% more efficient.

How much can solar energy contribute to climate mitigation goals?

In terms of greenhouse gas emissions, solar energy systems rank alongside other low carbon energy technologies such as wind and nuclear. The energy required to make any solar collector is typically equivalent to one to four years of operation so, as panels typically last for 30 years, there is a significant carbon saving overall. To make significant reductions in carbon dioxide emissions, we need to install very large numbers of solar collectors in the next few years. The International Energy Agency suggests that solar energy could provide up to 11% of global needs by 2050, but this will require early and sustained investment in existing and future solar technologies. The prospect of harnessing intermittent solar energy generation on a large scale provides a strong motivation to implement demand-side management.

How can we reach these goals?

Different approaches are possible. A mix of subsidies, obligations and support through a carbon price and trading scheme may be appropriate until the market for solar devices becomes self-sustaining.

Feed-in tariffs make small-scale electricity production viable by guaranteeing a minimum price for sale of energy back to the grid. These are appropriate while the technology is in early stages, until the price of electricity generated is comparable to consumer retail prices. **Installation grants** may overcome obstacles such as unwillingness to invest money upfront and also provide training to improve installation procedures. **Obligations** requiring suppliers and consumers to source a certain percentage of electricity from renewable sources, combined with a clean energy market, could provide financial incentives for renewable sourcing while allowing the costs to be met in the most efficient manner. **Carbon pricing** would work in a similar way, increasing the cost of grid electricity in line with its carbon intensity and so providing incentives for developing and using cleaner technologies including solar energy, both for heating and electricity.

Introduction

The sun supplies the majority of the energy available on the Earth; wind power, hydropower, biomass and all fossil fuels can trace their energy source back to the sun. These indirect routes for deriving solar energy have certain advantages: storage of energy in the case of fossil fuels and hydropower, and transportation of energy in the case of wind. However, the challenges involved in harnessing solar energy directly and on a large scale are such that it remains an elusive but still fundamentally attractive way of mitigating climate change. This paper describes the present status of solar energy worldwide, and outlines the competing technologies, the magnitude of energy they could produce, and the extent to which they could be used.

Human use of solar energy spans natural lighting and agriculture, from simple technologies such as the outdoor clothesline through to centralised electrical power plants equipped with storage. It is almost impossible to quantify this habitual use, as most uses of solar energy, such as passive heating, are classed as energy efficiency measures. While these simple solar approaches are important, this paper is primarily concerned with active solar power conversion that can displace conventional power generation and contribute towards a truly sustainable energy supply.

The solar radiation continuously available to the Earth [162,000 terawatts (TW, 10^{12}W)] greatly exceeds the average worldwide primary power consumption in 2004 (16TW), 86.5% of which came from fossil fuels[1]. The combined output of active solar energy systems currently meets only 0.1% of the world's primary energy consumption.

The efficiency of solar energy systems is rated according to their performance under a standard test irradiance of 1000 W/m^2, which corresponds to the maximum irradiance expected on a clear day in summer at moderate latitudes. The actual level of solar irradiance will depend on the latitude and local climatic conditions, but the annual average solar energy density lies in a range from 100-250 W/m^2 for most locations, as shown in Figure 1. The capacity factor for solar collectors (actual output power / rated output power) therefore lies at 10-25% depending on location. This fluctuation is significant in determining the broad economic suitability of solar energy technologies[2]. However, the extent to which solar energy can help mitigate climate change depends on the carbon intensity of the local energy supply being displaced and the matching between supply and demand.

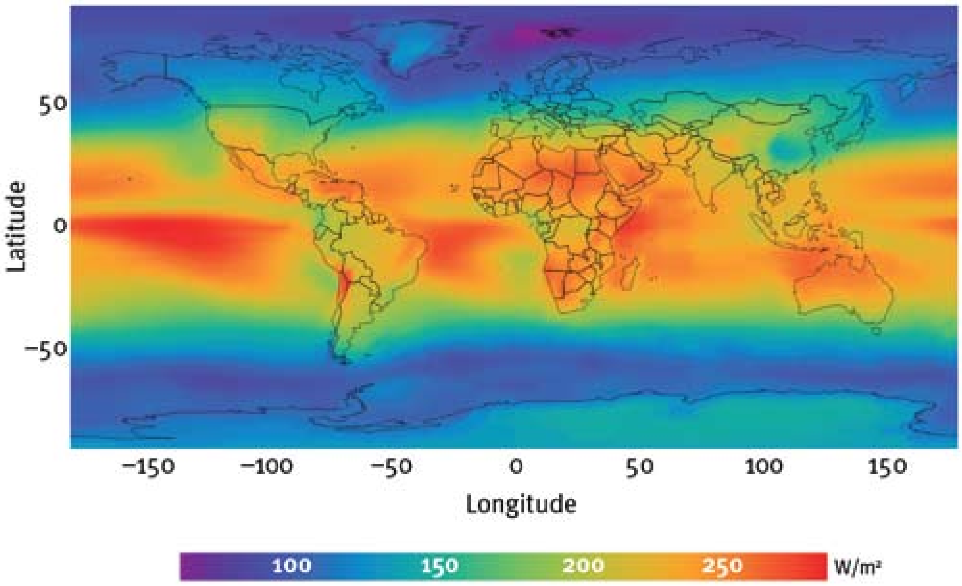


Figure 1. Worldwide variation in mean annual solar irradiance. Data re-plotted from NASA International Satellite Cloud Climatology Project (ISCCP)[3].

Were climate change of no concern, a natural, gradual shift to solar energy technologies might be envisaged as conventional energy sources become depleted and housing stock over the next century is replaced and upgraded. However, to make a significant contribution to the problem of climate change, an accelerated adoption of solar energy technologies is required. Appropriately designed feed-in-tariffs have proven to be effective in achieving this with photovoltaics, driving both technological development and market expansion and providing the motivation to overcome non-technical barriers such as limited training and local installation expertise. Solar electricity technologies require roughly another decade of government support to achieve sufficient cost reduction with present technologies to enable them to become self-sustaining.

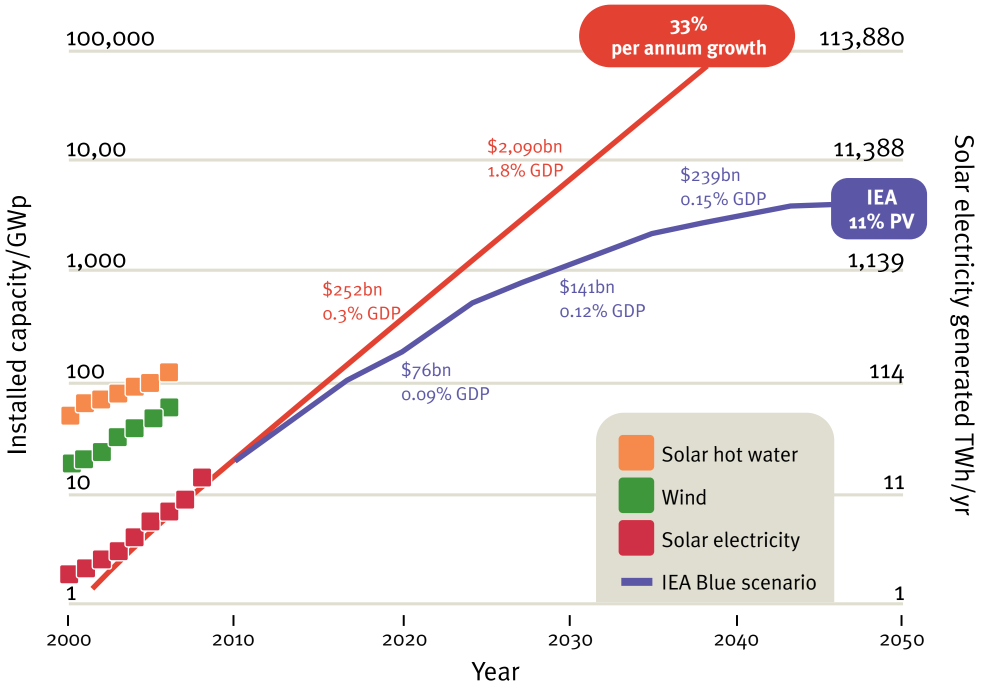


Figure 2. Chart showing growth in capacity of solar hot water, wind, solar electricity and the IEA Blue scenario for solar electricity[5]. A capacity factor of 13% is assumed for translating from peak capacity (GWp) and energy delivery (TWh/year). $1bn=$10 [9].

The International Energy Agency (IEA) predicts that approximately one quarter of renewable power, or 11% of worldwide electricity, could be supplied from solar energy in 2050[4] (Figure 2). The IEA projections indicate that it is both technically and economically feasible to be generating terawatts of solar energy within the timescales required to limit global temperature rise to around 2 °C. The speed of transition from fossil fuel combustion to a portfolio of low carbon technologies is constrained by manufacturing capacity and ultimately cost. Figure 2 shows the annual costs of maintaining compound 33% per annum growth and those incurred in the IEA scenario. For technologies such as solar energy, early and sustained investment is required to reduce costs and ensure that the necessary manufacturing and installation infrastructure is built.

The 2,000 million people in developing countries without access to grid electricity represent important potential consumers of solar energy. People living in isolated areas could enjoy improved standards of living with relatively simple solar-powered devices. With the recent advent of low-cost PV panels and efficient LED lighting, the technology could now displace traditional kerosene lamps as a cost-effective and safer alternative. In many developing countries, there is a surprisingly high level of mobile phone usage, despite a limited infrastructure for recharging the battery. With almost one third of the world's population living without electricity, solar energy offers great promise to improve living standards and reduce typically associated greenhouse gas emissions.

Technical review

This section presents the main technological options for using solar energy on domestic and utility scales, for providing heat and generating electricity. Table 1 compares currently available technologies.

Small-scale heating systems

Current technology. Solar hot water is the simplest and most technologically mature way of collecting solar energy. It is cost effective for many applications and accounts for more than 90% of installed solar energy capacity worldwide[6]. Apart from providing hot water for sanitary purposes and swimming pools, it is also used for heating/cooling spaces, and some industrial processes. The most widespread technology is the evacuated tube collector where a specially engineered energy absorber is deposited on the inside of an evacuated tube. Flat plate collectors have a similarly engineered absorber, but do not employ a vacuum for insulation. Both are used for heating hot water for domestic and commercial purposes. Unglazed energy collectors are less energy-efficient and are used to heat swimming pools, where a large area of collectors can be installed. This type of installation is the dominant application for solar hot water systems in the US and Australia. In some locations, such as China, solar hot water has a self-sustaining market position. Figure 3 shows the installed capacity and per capita capacity for leading countries.

In 2006, the installed capacity for solar hot water systems was 127 gigawatts of thermal power (GWth), almost ten times the present solar electricity capacity. Despite this level of installed capacity, solar thermal power does not usually feature in official energy statistics because until 2004, the industry quoted installed area capacity rather than power capacity.

Potential capacity and cost implications. In the UK domestic sector, hot water amounts to 22% of the domestic primary energy usage[7], so there is a large potential for cost and carbon-efficiency improvements. A recent case study in the UK showed that even in a northern, maritime climate, a solar hot water system can provide 50-70% of the hot water used by a household over a year[8]. Typical panel costs for a domestic home in the UK are around £1,440 and installation costs push this figure up to £4,000. For new buildings, the installation costs can of course be subsumed into the overall construction costs with minimal impact to the overall budget.

Usage	Small scale	Large scale
Solar thermal energy	**Solar thermal collector** » direct use to heat water » installed on building roof » mature technology » partially replaces grid gas and/or electricity » used in China, US and Israel	**Concentrating solar thermal** » light concentrated to heat water; steam production drives turbine to generate electricity » plants located in sunny regions » 20 years of operation in California » 60-400 MW plant capacity »energy storage as heat, on grid » used in US and Spain
Photovoltaic electricity	**PV panels** » direct use of ambient sunlight » installed on building roof » cost and efficiency improving » kW to MW scale installation, both on and off grid » used in Japan, Germany and Spain	**Concentrating PV** » light concentrated on PV cells » plants located in sunny, arid regions » uses highly efficient solar cells » does not consume water for cooling » 0.1-200MW plant capacity, both on and off grid » used in California, Spain and Australia

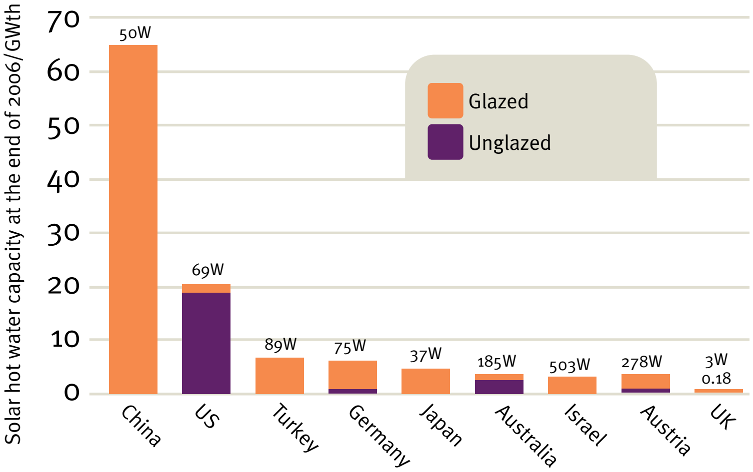
Table 1. Overview of the main technologies for small- and large-scale provision of heat and electricity.

More sophisticated applications of solar heat are possible in larger buildings and industrial environments. Standard solar hot water collectors provide water temperatures of 60-100 °C, which is sufficient for applications such as food processing and desalination. It is also possible to use solar heat for local cooling, using an absorption/refrigeration cycle or a desiccant system[9]. In general, heat-driven refrigeration cycles are less efficient than mechanically-driven systems, but they represent a useful application for excess solar heat in times of oversupply during the summer months.

Small-scale electricity production

Current technology. PV panels convert sunlight into electricity directly using semiconductor materials. These panels were initially used in remote off-grid locations where their reliability suited them to critical applications such as telecommunication relay stations and satellites. Since the late 1990s, a significant shift has occurred and now the majority of PV installations are connected to the grid. This transition began first through the Japanese 'New Sunshine' subsidies and subsequently through feed-in tariffs in key European countries, most notably Germany[10]. As a result, manufacturing output leapt to over 5GW in 2008, leading to a cumulative worldwide installed capacity of 14.8GW[11]. Figure 4 shows installed photovoltaic generating capacity and demonstrates the effect of domestic incentives. Spain overtook Germany

Figure 3. Total installed capacity of solar hot water collectors for the leading eight countries and the UK[5]. The installed thermal capacity per capita is stated above each bar.



as the largest market for photovoltaic panels due to a generous support scheme that has since been capped at 500MW. Germany is a surprising market for photovoltaics as it has a modest solar resource, but the largest installed capacity. The UK has similar sunshine levels to Germany yet has only 0.3% of its installed PV capacity.

Potential capacity and cost implications. The rapid growth of photovoltaics has resulted in dramatic cost reduction of the technology. Figure 5 shows the actual and projected system cost per watt installed over time. The two areas of the chart correspond to the cost of the photovoltaic panel (module) and the other systems costs incurred during installation, the so-called Balance of Systems costs (BOS), and include cabling, AC-DC inverters and mounting structures. The BOS costs vary considerably depending upon location, installation type and size, so an annual average estimate has been collated from data available [13,4,14]. Savings in module cost are achieved through mass production and the introduction of extremely cost-effective thin-film technologies, discussed on page 7.

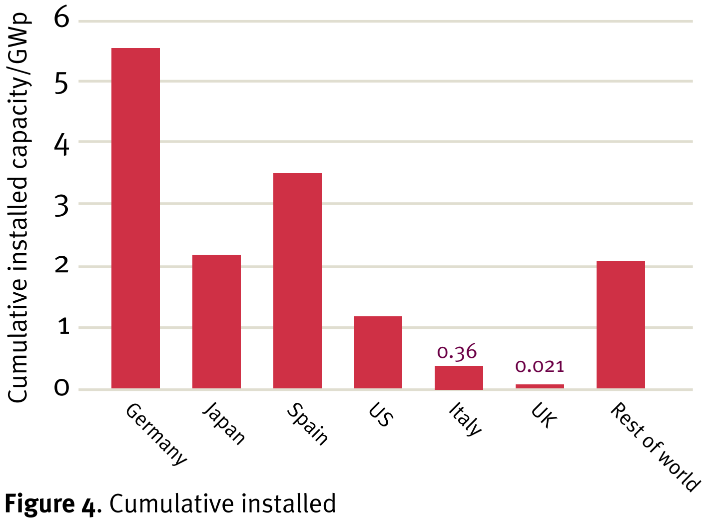


Figure 4. Cumulative installed photovoltaic capacity in 2008 for the five largest contributors; UK and rest of world shown for comparison[12].

If panels are installed as part of a solar photovoltaic farm, the electricity generated has to compete with wholesale electricity prices, which is presently difficult to achieve without subsidy. However, when installed on a domestic roof, the electricity generated by PV panels offsets grid electricity, which is supplied at much higher consumer prices. For example, in Italy the cost of electricity to the consumer is high (€0.2 per kilowatt-hour, kWh). With favourable levels of sunshine PV panels are projected to reach consumer grid parity around 2010 if the cost of residential grid electricity is extrapolated at a fixed, historical rate. Grid parity in Germany is predicted around 2016 and in the UK around 2020; levels of sunshine and consumer electricity price both dictate the parity point.

In the long-term, module costs of $0.4/W are considered attainable through development of some present technologies. Even today, some highly profitable companies are already manufacturing their product at $0.98/W, with clear technological routes to further cost reduction in the future. It is worth noting that BOS costs play a significant component in the cost of PV electricity and are projected to become dominant around 2015. As with solar hot water systems, the cost of retrofitting is inevitably high, demonstrating again the opportunity that exists for new buildings and the need for a well-trained workforce to install solar collectors efficiently.

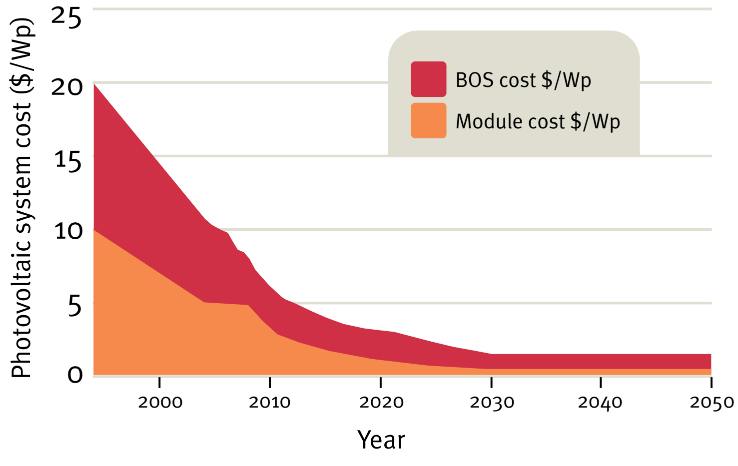


Figure 5. Reduction in PV system costs. Data pre-2007 are historical; post-2007 are projected from industry estimates[4,13,14].

Generations of PV technology. Three broad classes of photovoltaic technology can be identified with different operating characteristics, cost and efficiency; these are plotted as generations I, II and III in Figure 6.

First Generation: high cost, <20% efficiency. Of the 14.8 GW cumulative PV capacity installed in 2008, 86% is composed of cells made from silicon wafers, using processes inherited from the microelectronics industry[16]. This first generation technology has led to some high performance solar panels with up to 20% efficiency, but the cost of manufacturing remains high. This is due to the large volume of silicon used and inefficiencies in the manufacturing process, giving a cost per square metre in the range of $200-500. However, when coupled with panel efficiencies of 12-20%

and process improvements, module manufacturing prices of \$1.4/W are considered feasible[17]. Life-cycle analyses of crystalline silicon modules indicate they generate 40g CO_2 equiv./kWh[18].

Thanks to the sustained growth of the PV panel manufacturing industry (over 30% per annum over the past decade), the industry now uses more silicon feedstock than the microelectronics industry, resulting in a supply bottleneck for polysilicon. This has led to an expansion of polysilicon capacity, using both the conventional Siemens method in China and potentially less expensive solar grade silicon production routes elsewhere. From a climate change perspective, the expansion of the Siemens process in China is regrettable, as it is an electrically intensive process, which takes place in a country that already has high carbon intensity. Some reduction in the PV green house gas emissions in the future will be achieved through much more efficient crystallisation processes using fluidised bed reactors[19] or through direct upgraded metallurgical routes. The polysilicon supply shortage is expected to ease by 2010, resulting in the anticipated drop in the module price shown in Figure 5[20].

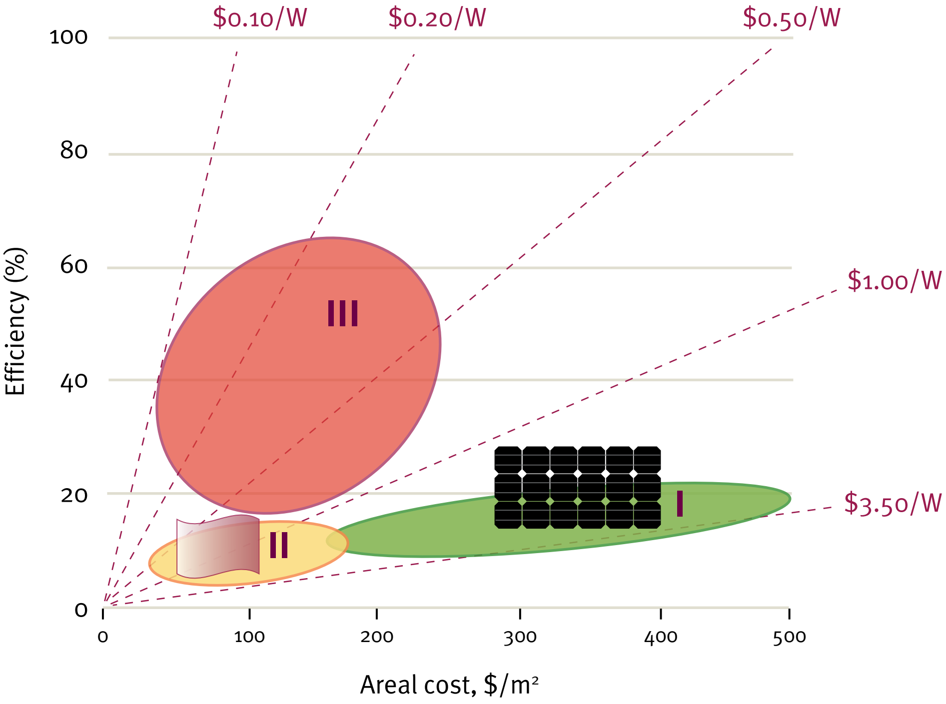


Figure 6: Three generations of PV technology: I crystalline silicon, II thin-film PV and III high performance technologies[22]. Broken lines indicate contours of constant price per watt capacity (\$/W). For reference, some roofing products exceed \$100/W and decorative facades can reach \$400/W[15].

Second Generation: low cost, 10% efficiency. Very significant cost reduction can be achieved by moving to second generation, thin-film technologies, in which the semiconductor is deposited directly onto glass, plastic or metal foil[21], minimising the amount of semiconductor material required and increasing the size of the manufacturing units – up to 6 m² in some cases. These savings result in technologies in region II of Figure 6, with low cost per unit area, but also with low efficiency. Small area devices can achieve efficiencies between 16-18%, but this efficiency drops when large area panels are manufactured. Leading thin-film manufacturers currently manufacture cadmium-tellurium (CdTe) modules at \$0.98/W with an efficiency of 10%. Other companies pursuing silicon-based approaches anticipate similar results, but to date First Solar remains the only company to have achieved this cost breakthrough. Life-cycle analyses of thin-film CdTe modules indicate they produce 20g CO_2 equiv/kWh[18].

All plastic ‘organic' photovoltaics represent the ultimate second generation technology, where large areas of flexible plastic substrate are coated very rapidly. This has clear advantages over processing glass in cost, weight and shock-resistance. At present the relatively low efficiency and short working lifetime of cells made from these materials has moved them towards applications in consumer electronics where flexibility, physical strength and low weight are more desirable than high power output. The dye-sensitised solar cell represents the principle commercially available organic PV technology.

Third Generation: low cost, high efficiency. As with any energy conversion engine, the laws of thermodynamics determine the maximum efficiency at which the process can operate. Fundamental losses arise from the broad solar spectrum and irreversible absorption of sunlight, placing an upper thermodynamic efficiency limit for solar energy conversion at 86.8%[22]. Most conventional solar cells that use a single absorber are limited to an efficiency below 31%, but a couple of approaches exist that can exceed this limit[22]. The very highest efficiencies of up to 41.1% have been attained using multi-junction solar cells[23], but these have very high manufacturing costs of around \$140,000/m^2. These technologies are routinely used to power satellites in space, but are increasingly finding application in terrestrial concentrator power systems, discussed in the next section.

Even in the UK, a solar hot water system can provide 50–70% of the annual hot water used by a household.

Large-scale electricity production

Concentrator photovoltaic technology. CPV systems use mirrors or lenses to focus sunlight onto small, high-performance photovoltaic solar cells. Their appeal is that large areas of semiconductor material are replaced with large areas of glass and steel that can be manufactured at existing foundries, at relatively low cost[24]. High solar cell efficiency is the key to reducing costs with this technology, so the development of third generation solar cells with efficiencies of more than 40% has led to renewed enthusiasm for CPV. The Australian company Solar Systems has successfully powered several remote communities in the Outback and is now building a large 154 megawatt (MW, 10^6 W) plant in North West Victoria, Australia. The cost per unit area is approximately \$200/m^2, but at a system efficiency of more than 30%, CPV can become competitive with other low-cost PV technologies in areas of high isolation. In terms of greenhouse gas emissions, the high efficiency offsets the large quantity of steel required to fabricate the collectors resulting in life-cycle figures ranging from 30-40g CO_2 equiv/kWh[25,26] – broadly comparable to the figures quoted for flat-plate PV.

Concentrator solar thermal technology. CST systems again employ mirrors to focus light, but in this case it is used to heat a fluid, generating steam to drive a conventional turbine. The Solar Electric Generating Systems (SEGS) with a combined capacity of 354MW electrical power (MWe) have been in operation in California since the late 1980s and cost \$3.9/W with 3L/kWh of water used for cooling[27]. These costs remain typical of modern installations[28]. Efficiencies of 14%[27] are attained for systems based on steam turbines, but efficiencies of 31% have been demonstrated using a dish-mounted Stirling engine. Life-cycle analyses estimate the greenhouse gas emissions for these concentrating solar thermal technologies to be 30-150g CO_2 equiv./kWh[29]. One key advantage that CST holds over all photovoltaic technologies is that it is relatively easy to store thermal energy compared to electrical energy, offering the potential to increase significantly the capacity factor of the plant and better match electrical demand patterns[30]. To date storage has been demonstrated on the timescale of hours and attempts are underway to store steam for days[31]. This advantage alone makes CST attractive for large desert-based installation. 390GWe of CST is estimated to be feasible by 2050 from the Mediterranean region desert[32]; roughly one third of the present European capacity for electrical generation.

Technical aspects of managing intermittent supply. With any intermittent energy technology, matching supply and demand is important. Once sufficient capacity is installed that periods of surplus energy arise, storage becomes desirable. Several contenders exist, namely battery storage, hydrogen fuel or compressed air, but all must be efficient and durable to be cost-effective. At present, storage of electricity using batteries is fairly efficient (>80%) but expensive (adding \$0.2/kWh[33]) as their lifetime is limited to ten years or less. The round trip electrical efficiency of hydrogen storage is currently less efficient (40%) but represents a possible long-term storage opportunity. In the absence of integrated storage capacity, direct solar electricity generation can be combined with another complementary energy supply, such as a biofuel combined heat and power plant[34]. Finally it should be noted that long-term thermal storage of solar energy can be achieved in subterranean reservoirs.

In terms of integrating intermittent energy sources in the UK, the grid can accommodate around 20% intermittent electricity generation at the additional cost of 0.5p/kWh[35]. Further market penetration by intermittent sources pushes these costs up significantly and makes dynamic management of the electrical demand an attractive option, for example varying the load placed upon the grid by switching off non-essential loads in order to balance supply and demand.

Policy and international context

Installation incentives

In developing countries, solar energy has an immediate and desirable impact on the standard of living at a local level, enabling lighting, water pumping and telecommunication. When considering the costs of establishing an electrical grid, the installation of solar energy technologies often compares favourably. For example, most solar hot-water systems in China have been installed to relieve some of the burden on the rapidly growing energy generating capacity. In general, solar hot-water systems are installed without subsidy.

The situation is different in developed countries, where solar energy provides the same services as well-established energy utilities, but with the disadvantage of intermittency. The incentive for installing solar energy then becomes a combination of energy security or self-sufficiency and a desire to reduce carbon dioxide emissions. These factors have prompted countries such as Germany and Japan to introduce financial incentive programmes to encourage the adoption of solar energy, thereby diversifying their energy supply, generating clean energy, and investing in their domestic industries.

Feed-in tariffs. Germany has adopted a feed-in tariff to accelerate the installation of both solar electricity and wind power[36]. The tariff is a pricing structure that pays producers of solar electricity a pre-determined, premium rate for each kWh supplied over a twenty year time period, starting from the moment the system is connected to the grid. This simultaneously gives investment security and encourages early adoption, as the tariff is reduced each year in line with anticipated improvements in the technology. The tariff is funded by a levy paid by electricity consumers (€0.20 per person per month in 2006, €192M per year)[37].

Grants and obligations. By contrast, Japan has used a mixture of investment grants covering some fraction of the installation and a quota obligation scheme that requires suppliers and consumers to source a certain percentage of their electricity from renewable energy. Under the quota obligation scheme, a party producing a surplus of clean energy can profit by selling credits to another party in deficit. This establishes a market, providing financial incentives for generating clean electricity and passing on the costs to those who are unable or unwilling to meet their renewable energy quota[38].

For either scheme to be effective, remuneration must be high enough for the investment to be paid off in a couple of years, leaving several decades of profitable operation. In practice, feed-in tariffs have provided the most effective means for accelerating the installation of PV panels. The pre-determined pricing gives high investment security, enabling consumers to obtain bank loans for their installation. By contrast, the value of credits in a quota scheme fluctuates, leading to uncertainty in the return on the investment[37,39]. The added complexity of the scheme also becomes a barrier for small investors.

Feed-in tariffs simultaneously give investment security and encourage early adoption.

However, simply introducing a feed-in tariff is not a guarantee of success. Several European countries, most notably France and Italy, operate seemingly attractive feed-in tariffs that have not yet stimulated the demand witnessed in Germany. This highlights the need to eliminate regulatory barriers that stall applications and hinder access to the grid[38]. Overgenerous subsidies should also be avoided or demand can be so high that the subsidy scheme has to be capped, leading to uncertainty for investors, manufacturers and installers, as witnessed in Spain in 2007-08. Only under the conditions of stable and long-term investment will a well-trained, local workforce emerge to carry out installation efficiently and effectively. Finally, it is important to note that feed-in tariffs are only a temporary measure, to stimulate growth of industries during their pre-competitive phase. Once grid parity is surpassed, the market should become increasingly self-sustaining, although loans to assist consumers to pay the up-front cost of electricity for 30 years will still be desirable.

Policy aspects of managing intermittent supply

As long as the electrical transmission grid can match an intermittent supply with fluctuating demand, then effective electrical storage technologies are not critical (either in terms of cost or carbon emissions) to the successful deployment of solar electricity in its early stages. Instead, modern computer networks can enable smart electrical grids to play an active role in balancing consumer demand with intermittent supply. Research is required on the fundamental operation of such networks and their practical and cost-effective deployment.

Unlike flat-plate PV installed on domestic roofs, which only needs to match the consumer grid electricity price, large-scale solar energy plants must compete with wholesale electricity prices that are typically three times lower than the consumer retail price. It is important to recognise that in some areas, the intermittent nature of solar electricity can be well matched to urban electricity demand, especially where air conditioning forms a significant fraction of the load. Instances of major stress to electricity grids often occur during exceptional heat waves; conditions in which solar electricity is usually available[40]. The financial advantage for solar electricity on the wholesale market is that solar power often matches the peaks in demand and can take advantage of the correspondingly higher spot prices[15]. Nevertheless, solar electricity sold on the wholesale market makes grid parity hard to achieve without carbon emission trading, or other adjustment to energy pricing.

Intermittent solar electricity can match urban electricity demand from air conditioning.

Research agenda

Heating

Solar hot water. Low temperature (< 100 °C) solar hot water collector technologies are well established: they operate close to their thermodynamic limit and can be manufactured fairly cheaply. The key short-term research opportunity with this technology is integrating it into efficient and intelligent heat control systems within buildings or industrial plants. For higher temperatures (150-250 °C), for example to supply industrial process heat, further development of medium temperature collectors is necessary. In all cases, if solar hot water is to contribute effectively to any climate change mitigation strategy, it is essential that there is sufficient professional experience and working knowledge with these technologies to deploy them in a timely and efficient manner. The low penetration of solar hot water systems in most countries suggests that effective policies for deployment of this technology are lacking.

Electricity

Concentrating solar thermal. New 50 MWe steam turbine demonstration plants are under construction in the Mediterranean[41] and US. Schemes for raising the conversion efficiency through higher operating temperatures are under development, alongside air-cooled, low-temperature designs that promise low cost and eliminate the need for cooling water towers.

Photovoltaics. First generation photovoltaics are nearing maturity, with much of the research and development taking place within companies or in close co-operation with universities. Apart from general process optimisation and associated incremental improvements in cell efficiency, there are three key areas where research is necessary[17]:

- reducing the quantity of silicon used through thinner wafers and more efficient ingot sawing;
- developing new high-volume, energy-efficient routes for purifying silicon to provide low-cost solar grade silicon;
- optimising cell processing to achieve production efficiencies approaching 20% for standard crystalline silicon cells and up to 16% for cells made from low-purity upgraded metallurgical grade silicon.

Second generation, thin-film PV research based on inorganic semiconductors has recently shifted from university laboratories and small pilot lines to large-scale manufacturing. However, the fact that small area devices can achieve almost double the efficiency of large area panels, highlights the opportunity to improve the deposition conditions and uniformity to enable high efficiency operation over a large area. To make significant contributions to tackling the problem of climate change and to compete effectively with first generation crystalline silicon panels, all thin-film technologies should aim for efficiencies greater than 10% and be fabricated from sufficiently abundant materials.

In particular, this demands:

- » indium-free transparent conducting glass integrated into all thin-film solar panels (indium is a scarce element);
- » module efficiency of all thin-film panels improved at manufacturing level to at least 10-15%;
- » plastic organic PV solar cells with longer operating lifetimes.

Third generation photovoltaics will become necessary to sustain significant annual growth in installed capacity on the terawatt scale, probably from 2020 onwards. At present, much of the work takes place in academic research groups and the main commercial work in this area is in the development of highly efficient concentrator solar cells. Near term, achievable research goals in this area are:

- » Demonstration of a 50% concentrator solar cell using multiple semiconductor junctions.
- » Reduction in concentrator solar cell manufacturing cost to below \$60,000/m^2, achieved via automated manufacturing and either a lift-off and substrate reuse technique or direct growth on silicon substrates.
- » Development of efficient (>80%) optical concentration schemes that are practical to manufacture, as well as lightweight module and tracking designs.

In the long term, possibilities remain for achieving the ultimate goal of a low-cost, high-efficiency flat-plate third generation photovoltaic panel[22]. The ability of some materials to manipulate the spectral distribution of light suggests that the efficiency of conventional solar cells could be enhanced without requiring a completely new manufacturing infrastructure. Conceptual photovoltaic schemes such as hot carrier solar cells and intermediate band solar cells hold great promise, if suitable materials can be found.

Conclusion

Harnessing solar energy directly and on a large scale is an attractive, long-term means for reducing carbon dioxide emissions associated with electricity generation. However, to have a significant impact in overall emissions by 2050 the industry must continue to expand rapidly. Existing technologies are beginning to become cost effective in favourable locations and with continued investment, likely to become cost effective in more marginal locations by 2020. Thereafter compound growth will depend upon the ability of new technologies to attain high power conversion efficiency at low cost and to manage intermittent supply. They must go hand in hand with policy incentives to overcome the barriers to adoption. With sustained effort, solar energy has the potential to play a pivotal role in mitigating climate change.

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