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Solar power for CO_2 mitigation

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Executive summary

SOLAR POWER REPRESENTS A VAST RESOURCE WHICH COULD, IN PRINCIPLE, meet the world's needs for low-carbon power generation many times over. The technology to generate solar power by conversion of light to electricity (PV) and conversion of light to power via heat (solar thermal) is already proven and widely deployed. The cost reductions in solar PV over the last ten years now make it competitive with conventional, fossil fuel based grid power in some locations, and it will soon be competitive in others, including the UK. Solar power is particularly relevant to the developing world where solar resource is high and solar power with storage is likely soon to become a more cost-effective option than diesel generators.

Recent growth in the use of photovoltaic (PV) technology (of around 40% per year) and rapid reduction in its cost (20% per doubling of capacity) has demonstrated the potential of solar power to deliver on a large scale. The International Energy Agency (IEA) projects that solar power could generate 22% of the world's electricity by 2050. This would remove a significant fraction of the growing global carbon dioxide (CO_2) emissions from fossil generation. Such a target is ambitious but achievable: the rate of growth of installed capacity needed to meet this target is much lower than the actual average growth rate over the last 20 years.

In a low-carbon world where balancing generation from fossil fuels may be limited, the main challenge in achieving these high penetration levels will be the capacity of energy systems to manage the consequent variability in supply. In energy systems with extensive electricity grids, flexibility can be provided in a number of ways enabling solar PV to provide a large percentage of energy demand. Energy storage and large scale power distribution networks therefore become critical complementary technologies to solar power generation.

The costs of solar panels made from the dominant PV technology, crystalline silicon (c-Si), have tumbled in the last few years so that the panels make up only a minor part of the cost of the electricity. Meanwhile, research continues into alternative PV materials which may reduce costs and expand capacity even further. Concentrated solar thermal power is currently more expensive than c-Si panels, but its built-in storage capabilities allow it to be integrated more easily into the electric grid at a large scale. Solar hot water is a mature technology that could provide the majority of hot water globally.

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The contribution of solar power to energy supply and therefore to emissions reductions could be increased, beyond the IEA projections, through continuing technological innovation, improvements in manufacture and new applications. For example, printed flexible photovoltaic panels, alternative product forms that can be integrated into buildings, large area ground mounted systems and concentrated PV technologies all offer the prospect of reduced costs and embedded energy. In terms of public policy support, market expansion policies can drive down the costs of existing technologies but there is also a need for investment in programmes to accelerate technology innovation and development.

Introduction

This Briefing Paper explores the potential for existing and emerging solar photovoltaic (PV) technologies to deliver rapid transformation of our energy systems to limit the scale of future climate risks from fossil fuel use. In particular, we examine the potential for cost reductions and scalability of manufacture and the new science needed in order to accelerate the uptake of solar power technologies.

The Sun's radiation provides on average 1.73 x 10^{17}J of energy to the Earth every second[1]. Figure 1 shows the annual average intensity of radiation over the Earth's surface, which varies between around 100 and 250 W/m² due to variations in latitude and climate. Over a year, the solar energy falling on the Earth amounts to almost four million ExaJoules (1 EJ = 10^{18}J). Of this perhaps 5x10^4 EJ could be readily harvested, which massively exceeds existing and projected human primary energy demand of around 533 EJ in 2010 and 782 EJ in 2035, based on current policies.[2]

Despite this vast potential, only 0.3% of global primary energy demand and 0.5% of global electricity demand is currently met by solar energy. Low carbon development pathways forecast that by 2050 some 14%[3] to 22%[4] or more[5] of electric power should be supplied by solar conversion. In such pathways, solar, along with other low-carbon technologies, plays a vital role in decarbonising the power sector.

Solar energy is also particularly appropriate in enabling low carbon development in developing countries, where nearly 1.3 billion people lack access to electricity[2]. In general, poorer countries tend to enjoy a relatively high level of solar resource: Figure 2 shows a scatter plot of the correlation between solar irradiance and GDP per capita. Technical advances and cost reductions suggest that solar PV, with appropriate energy storage, creates the potential for many communities to leapfrog traditional (fossil based) power generation technologies, similar to the widespread take-up of mobile telecommunications. (See Box 2)

Solar Energy Conversion

The Sun supplies the overwhelming majority of the energy resources harnessed on the Earth, including wind, wave and tidal power, hydropower, biomass, all fossil fuels (which derive from biomass laid down in the past) and direct solar energy conversion into heat, electricity or fuel. Solar energy is also exploited in a passive sense in natural lighting, heating and cooling, and in agriculture. Here, we are concerned only with the direct and active routes to solar energy conversion.

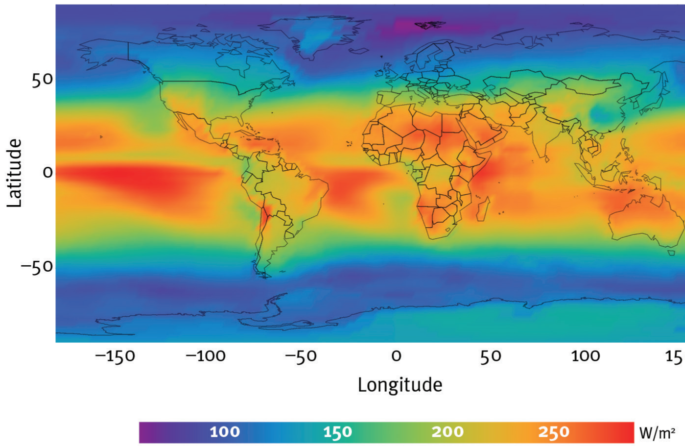


Figure 1: Distribution of annual average solar irradiance over the Earth's surface.[6]

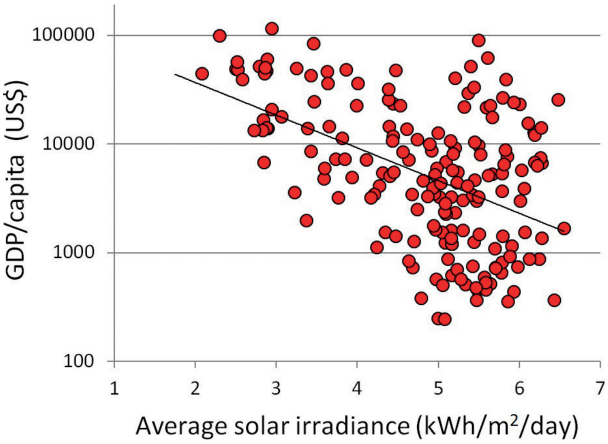


Figure 2: Intensity of mean solar irradiance for individual countries plotted on a logrithmic scale of GDP per capita measured in US$ per person. Calculated using World Bank and NASA data with exponential trend line.

Box 1: Solar energy conversion

Solar energy is received as packets of radiant energy, called photons, of different energy. When the solar photons are absorbed in a material they give up their energy to excite electrons, which are involved in bonds between the atoms that make up the material, to a state with higher energy. That energy can be captured and converted into heat, fuel or electric power.

We may distinguish three different varieties of solar energy conversion: **solar thermal** (light energy is converted to heat), **solar photovoltaic** (light energy converted to electrical work), and **solar chemical** (light energy converted to stored chemical potential energy).

In solar thermal conversion, the electron relaxes back to its original state, giving up its energy in small packets, generating heat. Solar thermal conversion is used when water is heated in solar hot water systems, and is also used to generate electric power in large concentrated solar power (CSP) systems where sunlight is focussed to heat a fluid that generates power via a heat engine.

In solar photovoltaics, light is absorbed in a semiconductor to liberate electrical charges which can then travel through the material towards a contact with an external circuit, where they are able to do electrical work through the photovoltaic effect. In some cases the sunlight is first concentrated on the panel using lenses and mirrors. This photovoltaic (PV) energy conversion is the only process to convert radiant light energy directly into electricity.

In solar photochemical energy conversion, the excited electron takes part in a chemical reaction and gives up its energy to form a new chemical bond. This solar driven chemical reaction is one means to generate synthetic 'solar' fuels, which store chemical energy until it is released again in combustion. Solar chemical conversion is much less well developed than solar thermal or photovoltaic, and will not be discussed further here, but may become significant in future.

Mitigation of carbon emissions using solar energy

The impact of an energy technology on the climate can be characterised by its carbon emission intensity, a measure of the amount of CO_2 or CO_2 equivalent emitted per unit of energy generated. Here, 'CO_2 equivalent' (CO_2eq) refers to non-CO_2 greenhouse gases, notably methane and nitrous oxide, which are released from a number of human activities such as fossil fuel extraction and agriculture. Existing fossil fuel technologies possess high carbon emission intensity through the combustion of carbon rich fuels, whilst renewable technologies such as solar produce little or no emissions during operation, but may incur emissions during manufacture (Figure 3). Solar energy thus can help to mitigate carbon emissions by replacing more carbon intensive sources of heat and power. The amount of emissions mitigated depends on the amount of conventional heat or power that is displaced, the carbon intensity of the displaced energy sources, and the amount and type of energy that is consumed in manufacturing, installing and operating the solar energy system.

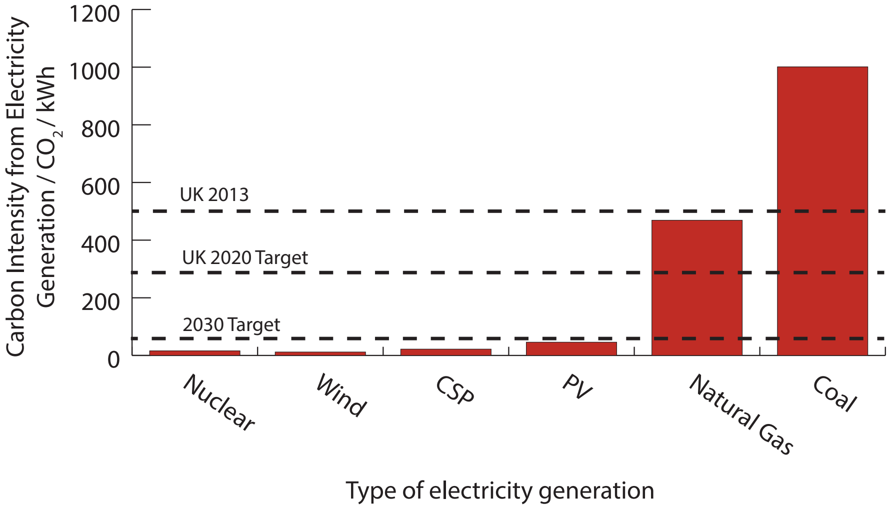


Figure 3: Carbon intensity of some key electricity generation technologies; the value for PV refers to manufacture in Europe. UK Climate Change Committee targets for carbon intensity of electric power are shown for comparison.[7]

The International Energy Agency (IEA) has published a number of future energy scenarios including the two degree scenario (2DS) in which the global temperature rise is limited to around 2°C and the 2DS-hiRen scenario, in which renewable generation plays a major role. The 2DS-hiRen scenario projects that approximately one third of renewable power, or 22% of worldwide electricity, could be supplied from solar energy by 2050, of which 11.3% is provided by PV and 10.4% by solar thermal.[8] In the 2DS, where the renewable contribution is smaller, solar is anticipated to provide 14% of global power. The projected growth for the 2DS scenario is shown in Figure 4 in comparison with historical trends. Moreover the IEA estimates that the use of solar photovoltaic and concentrated thermal power would contribute 12% of the 258 Gt of CO_2 emissions that would need to be mitigated globally by 2050 in the 2DS scenario relative to the baseline 4DS case[8]. The projected 2050 deployment level represents a growth in capacity of some 12-14% per annum on average, much slower than current and historical growth rates. These rapid growth rates appear to be both technically and economically feasible on the basis of recent experience. Thus, solar photovoltaic and solar thermal energy represent a vitally important capability to achieve significant emissions reductions.

The low level of solar energy utilisation so far is the result of a number of factors. Historically, a major hindrance was the high cost of solar photovoltaic technologies but dramatic price reductions have meant that solar PV technology is now cheap, with cost limited by other components of the system. The low private cost of fossil fuels (i.e. ignoring atmospheric pollution and climate costs) relative to lower-carbon alternatives has led to the current dominant position of fossil fuels in the energy system. Investment in and development of associated generation and distribution technologies and infrastructure have entrenched this advantage. The limited large scale and commercial experience with low-carbon alternatives and their variable nature have also made it challenging to scale up their adoption and attract the investment needed to drive down costs and to drive innovation in the absence of significant policy incentives or regulations. Even with such measures, additional energy storage or power management measures will be needed if solar energy is to meet a much larger proportion of energy demand.

A number of factors, economic, technical and policy related, influence the contribution that solar energy actually makes in a given situation:

- *Technical and economic considerations* include: the available solar resource; the power conversion efficiency; the cost per unit capacity; the operational (as opposed to capital) costs; the lifetime of the system; the carbon intensity of the system and its operation; the carbon intensity and cost of competing technologies; the match between resource availability and demand; and the availability of complementary technologies to improve this match;
- *Policy measures* can influence solar technology deployment through subsidies and incentives, regulatory measures, measures to facilitate sufficient manufacturing and installation infrastructure, demand management, awareness raising and other means.

Achieving the anticipated level of solar energy generation will require some combination of performance improvement, further reductions in the cost of manufacture and cost of systems, and implementation and policy measures.

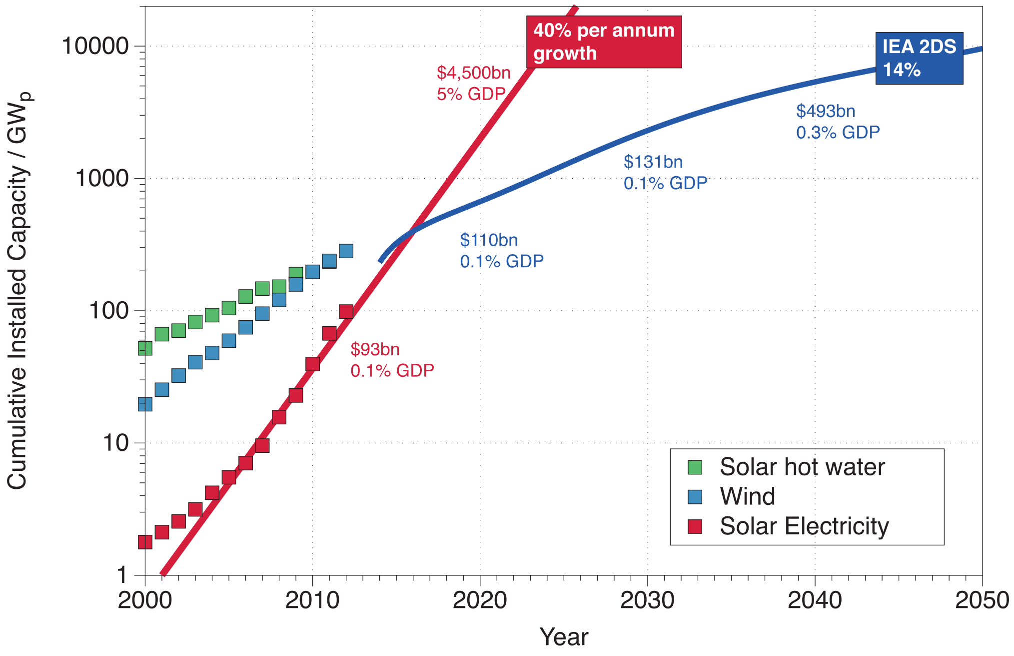


Figure 4: Historical growth of solar hot water, wind, solar electricity (symbols). The solid blue line shows the IEA 2DS scenario for solar electricity, whilst the solid red line indicates the much higher growth suggested by experience with solar[8]. The annual investment in solar technology is marked for 2013, 2020, 2030 and 2040 for each scenario stated in US dollars and as a fraction of global GDP.

Solar energy technology and current status

Solar hot water systems

Current status and technology

Solar hot water is the simplest way of harnessing solar energy and is a mature technology. Apart from providing hot water for sanitary purposes and swimming pools, it can also be used for heating and cooling spaces, and some industrial processes. The most widely used technology is the evacuated tube, glazed collector where a specially engineered energy absorber is deposited on the inside of an evacuated tube. Such collectors can heat water to 60-100°C and can convert 20-70% of the incident solar energy into heat, depending on the temperature of the water, the environment and the solar irradiance level. Flat plate glazed 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. A third variety, unglazed solar collectors are less efficient and are used to heat swimming pools, where a large area of collectors can be deployed. Such systems are widely used in the USA and Australia.

Solar hot water accounted for 235 gigawatts of thermal power (GW_{th}), that is, the great majority of the global installed solar energy capacity, by the end of 2011.[9] Figure 5 shows the installed capacity for leading countries. Solar hot water is already cost effective for many applications and in some locations, such as China, it has a self-sustaining market position.

The majority of domestic hot water globally could be provided by solar heating systems. A 2010 study showed that solar hot water systems can provide 50-70% of the annual domestic hot water use even in the UK.[10] Since hot water amounts to 18% of domestic energy usage in the UK,[11] solar hot water could make a large contribution to domestic energy use.

Mitigation potential

In practical domestic solar hot water systems, the solar hot water system is usually run in conjunction with, rather than instead of, a backup conventional boiler and as a result the carbon intensity of the combined system is high relative to other renewables, at some 100-200 gCO_2/kWh_{th}.[12] Moreover the high efficiency of modern condensing gas boilers, which can convert over 90% of the calorific value of the fuel into useful heat, means that the carbon intensity of these heat sources is relatively low at 200-300 gCO_2/kWh_{th}.[13] As a result domestic solar water heating systems are a relatively expensive way of mitigating carbon emissions when they replace heat from efficient modern boilers. The abatement cost would be lower if the solar hot water system were compared against an electrical immersion heater powered by high-carbon generation. Abatement costs are also helped when the solar systems are installed in new buildings rather than retrofitted to existing ones.

In addition, solar heating of water and other fluids can be exploited for industrial applications such as food processing and desalination, and, in principle, for space cooling using an absorption/refrigeration cycle or a desiccant system.[14] Although heat-driven refrigeration cycles are less efficient than mechanically-driven systems, they may be an appropriate solution when cooling demand coincides with oversupply of solar heat during summer.

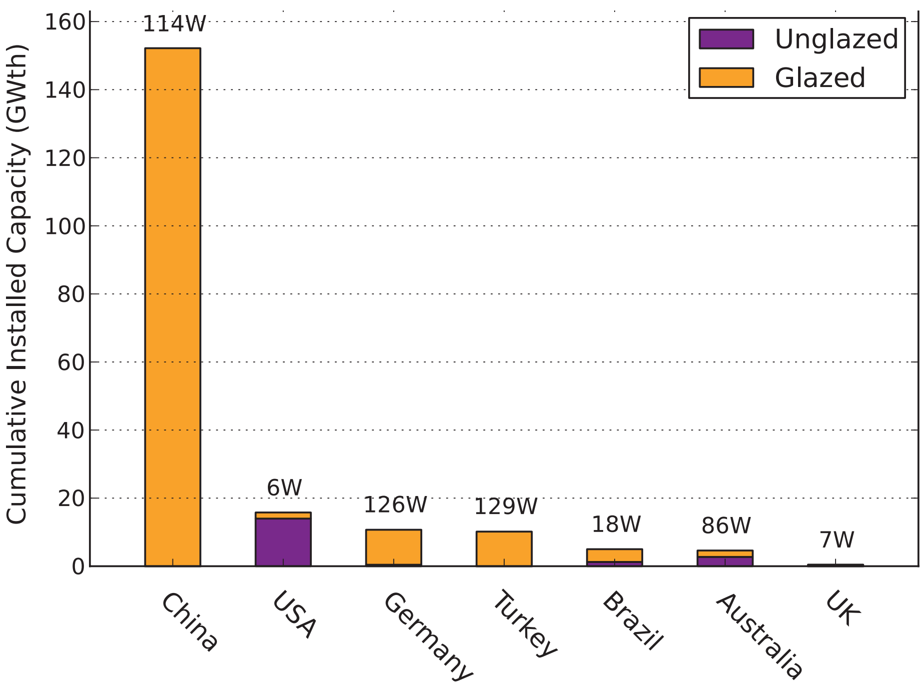


Figure 5: Total installed capacity of solar hot water collectors for six leading counties and the UK[9]. The installed thermal capacity per capita is stated above each bar.

Solar photovoltaics

Current status and technology

In solar photovoltaic energy conversion, light is absorbed by a semiconductor to generate electric current which can be used directly, fed into the electricity grid or used to charge a battery. The PV system usually consists of a set of PV modules, typically 0.5-1 m^2 in area, electronics to control the output, mounting structures, electrical cables, and commonly, an inverter to convert the direct current generated by the panels into alternating current. The modules are made from a semiconductor, most often silicon, and the remaining components are grouped as the 'balance of Systems' (BoS). In a system which is not connected to the grid, batteries are also needed but the AC/DC converter may not be. The capacity of a PV system is stated in peak Watts (Wp), where the panel rating in Wp refers to the power output by a module, or system, measured under standard testing conditions where the solar intensity is set at 1000 Wm^{-2}, typical of a clear, sunny summer day.[15] The power production by a PV system is given in units of Watt hours (Wh) per annum, and depends on the capacity and the annually averaged irradiance at the location. The average power output of any system is much less than its rating in Wp, because of the variability in sunshine and periods of darkness.

The capacity of PV power installed globally exceeded 100 MWp in 1992, 1 GWp (1 GW = 10^9 W) in 2002 and 100 GWp early in 2013, as shown in Figure 4, resulting in an average growth of around 40% per annum. This sustained growth followed a series of incentive schemes including early German and Japanese incentive schemes and feed-in tariff (FiT) schemes in several key European countries. Figure 6 shows installed photovoltaic generating capacity and demonstrates the effect of domestic incentives. In 2012 Germany was the largest PV market, installing 7.6 GWp, followed by China with 3.5 GWp, and Italy and the United States with 3.3 GWp each. In 2013, China has taken the lead followed by Japan. Since the introduction of a feed-in-tariff, PV installations in the UK have increased to reach 1.8 GWp by 2013. The continuing growth globally in spite of reducing incentives reflects the economic competitiveness of PV.

The majority of the approximately 100 GWp of installed systems are grid connected and of these, most are mounted on or integrated into buildings. Building mounted PV systems are typically less than a few 100 kWp in capacity. However the fraction of generation in utility scale installations is growing rapidly, with the fraction of capacity installed in Germany as large (>500 kWp) units increasing from 3% in 2008 to 45% in 2012.[16] Less than 10% of capacity is currently deployed in off-grid systems.

The PV module is made from one or more layers of a semiconductor material, placed between two contact materials that collect the electric current. The most commonly used semiconductor material is crystalline or multi-crystalline silicon: Crystalline silicon (c-Si) accounted for 88% of the market in 2011[17] and the vast majority of installed capacity to date. c-Si has dominated the development of PV thanks to experience in manufacture and processing from the microelectronics industry. The best commercial modules can convert sunlight to electricity with an efficiency of 21% but the average efficiency is close to 16%[16]. In the mid 2000s, the demand for silicon for PV module manufacture outstripped that for microelectronic components and caused a temporary shortage in silicon feedstock (as reflected in module prices in Figure 7). The trend in PV module prices mainly reflect c-Si module prices and have fallen with the growth of installed capacity through economies of scale in manufacture, reduced silicon usage, and innovations in device design and processing. As a result, the price has fallen with a 'learning ratio' of around 20%,[18] that is, prices have fallen by 20% for every doubling of capacity. Silicon module prices have tumbled from around $16/Wp in 1989 to below $1/Wp[59]. As a result, an increasing share of the cost of the PV system, and the resulting electricity, arises from the balance of systems and not the solar module (Figure 7).

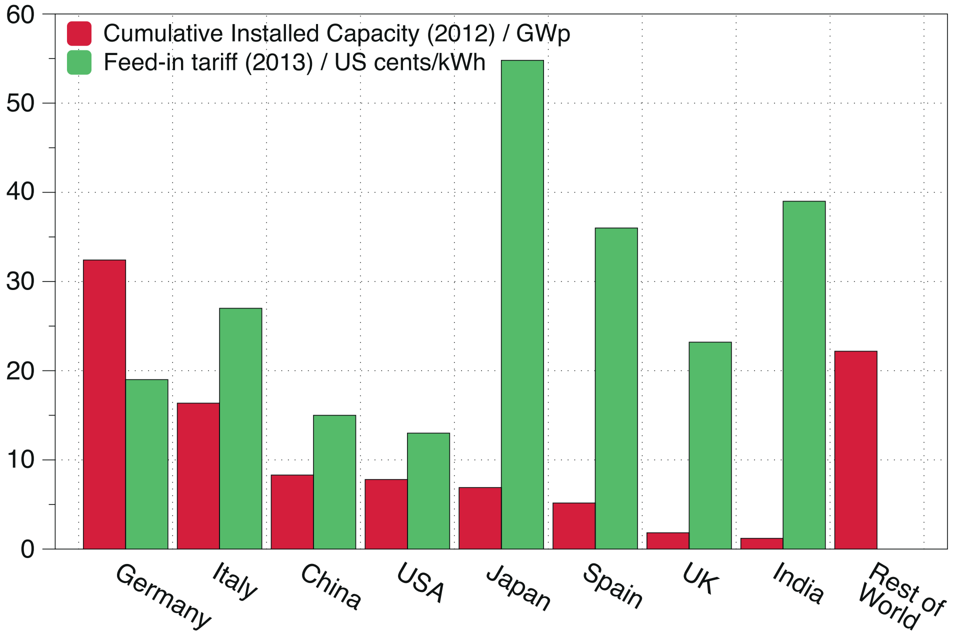


Figure 6: Cumulative photovoltaic capacity installed by the end of 2012 and Feed-in tariff as of December 2013.[33] The tariff for USA varies between states, the value shown pertains to California where the majority of solar capacity is installed.

A second important class of PV materials are thin films, most commonly the inorganic compound semiconductors cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS). Relative to c-Si, thin film PV modules require less semiconductor material because of better light absorption and because they can be deposited directly onto glass, plastic or metal foil,[19] avoiding several of the processing stages needed for Si cell manufacture, and also increasing the size of the manufacturing units. They were introduced as a lower cost alternative to c-Si, on the grounds that a lower efficiency (commercial thin film modules offer 10-14% efficiency[16]) could be tolerated if the cost per unit capacity was reduced. In practice, thin films such as CdTe offer superior generation under high temperatures or cloudy conditions than a similarly rated capacity of c-Si. The leading CdTe manufacturer reached a module cost of $0.65/Wp in 2012[20] but the advantage was soon threatened by the aggressive development of c-Si. In this context it should be noted that the falling costs of PV modules mean that the module comprises a minority of the system, and therefore the electricity cost, so the advantage of a cheaper module technology is small. Thin films comprise around 12% of the current installed capacity and market.[21] The potential for widespread growth of thin film PV is questioned on the grounds of scarcity of the rare elements indium (used in CIGS) and tellurium (used in CdTe), and the toxicity of cadmium (used in CdTe and also in CIGS).

Alternative thin film designs, in which the semiconductor can be processed from solution on to a flexible plastic or foil, include dye-sensitised,[22] organic,[23] and solution processed inorganic designs based, for example, on semiconductor nanoparticles[24] or semiconducting organometal compounds called perovskites.[25] Low materials costs and fast throughput offer the possibility of reducing module cost significantly to just that of the substrate and encapsulation layers. Light weight, mechanical flexibility, semi transparency and low capital investment in manufacturing plant may expand the range of PV applications beyond those available to flat plate modules. Currently, apart from some demonstration projects and consumer products mainly made using dye sensitised technology, these technologies are still pre-commercial. Growth of a market will depend on the impact of the module properties on BoS costs, product form and ability to scale up manufacturing capacity.

A third group of PV technologies are high efficiency devices based on multiple layers of different semiconductors chosen in order to harness the different wavelengths in the solar spectrum more efficiently than a single semiconductor material. The best solar cells of this type have achieved efficiencies of over 44% in laboratory,[26] and commercial modules up to 32% efficiency, although these efficiencies only apply to the direct beam component of sunlight. Because of the expensive manufacturing routes required to make these multijunction solar cells, they are not economic for power generation when most of the sun's energy received is diffuse. They become more economic when used together with mirrors or lenses that focus the sunlight onto small, high-performance solar cells in concentrator PV (CPV) systems. In this configuration most of the light harvesting surface areas is provided by glass and steel that can be manufactured relatively cheaply.[27] To ensure the optical system is always facing the sun, the light collecting surfaces are rotated with time of day and season in order to capture the direct part of the sun's radiation. CPV technology is well suited to large, ground based solar power plants in sunny locations but smaller modules containing miniature cells and focussing optics are also available. By the end of 2012, CPV provided a global capacity of around 80 MWp[16], well under 1% of global PV capacity, with new plant sizes of up to 30 megawatts (MW, 10^6W)[28]. Practical module efficiencies are 25-31%[16] and capacity costs stood at around $4/Wp.

Mitigation potential

The carbon intensity of PV power varies between these technologies according to the materials and processes used and module efficiency. According to Ref. 21 power generation by PV systems manufactured in Europe and deployed in southern Europe using c-Si, multi crystalline silicon and CdTe systems incur 38 gCO_2/kWh, 27 gCO_2/kWh and 15 gCO_2/kWh, respectively. Around 5 gCO_2/kWh of this is embedded in the BoS. These values may double for manufacture using a grid mix typical of China rather than Europe.[29,30] In the case of concentrating PV systems, where a large quantity of steel is required to fabricate the collectors along with a small device area, the resulting carbon intensities are similar to silicon at 20-40 g CO_2/kWh for deployment in ideal locations.[31,32] In all cases the carbon intensity is very much less than the carbon intensity of the grid electricity that is being displaced in any fossil fuel reliant countries; carbon intensity of grid power is around 500 gCO_2/kWh in the UK, for example. The carbon intensity of the displaced generation will also be affected by the variability in supply and variations in the local demand.

The performance, availability, costs and carbon intensity of photovoltaic power all indicate that this technology can make a very substantial contribution to reducing carbon emissions, as discussed below.

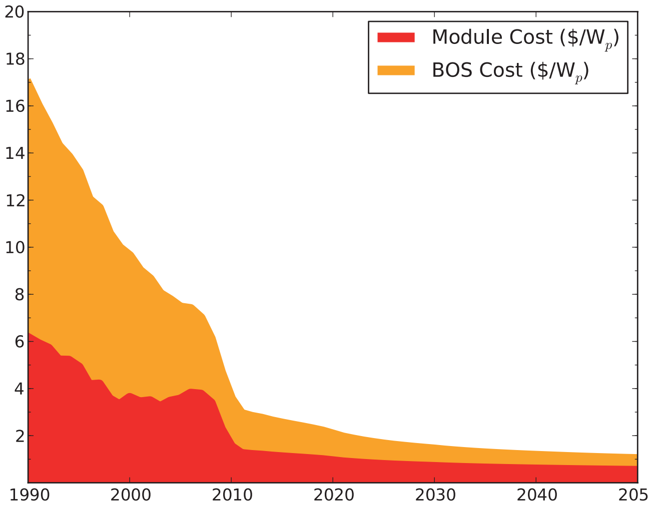


Figure 7: Reduction in total PV system costs. Data pre-2012 is historical; post-2012 are projected from industry estimates.[34,35]

Concentrating solar thermal power

Current status and technology

In the case of concentrating solar thermal power (CSP) systems, concentrated sunlight is used to efficiently heat a fluid to a high temperature at which it can drive a steam turbine or a heat engine to generate electric power. Whereas unconcentrated sunlight is sufficient to heat water in solar water systems, high concentration levels are needed to collect heat with a thermal fluid at the level at which it can drive a heat engine efficiently. In the most widely used solar thermal systems, sunlight is concentrated by a factor of 70 using a reflective linear parabolic trough that collects sunlight and focuses it on to a tube, resulting in working fluid temperatures of 390°C. Concentration in two axes using a parabolic dish with a receiver at its focus, or an array of mirrors focussed on to a solar tower leads to higher concentration ratios of several hundreds, fluid temperatures of 500-1000°C and solar to electric power conversion efficiencies of over 30%. Because, as with CPV, only direct sunlight can be concentrated in this way, CSP systems are sited preferentially in cloudless, sunny locations. CSP is well suited to large scale power generation, because of economies of scale in plant manufacture and operation. By 2012 over 2.5 GWp of CSP capacity was installed globally, the majority in Spain and USA, mainly in plants of 50 MW using parabolic trough systems. 390 GWe of CSP is estimated to be feasible by 2050 from the Mediterranean region desert.[36] Costs of modern installations stand at around $4/Wp.[37] One key advantage that CSP holds over all photovoltaic technologies is that it is easier to store thermal energy than electrical energy, so that by storing the heated fluid, electricity can be generated hours after the sunlight has been absorbed, enabling power generation over a longer period than daytime and a better match of generated solar power to demand. For example, 60% of the CSP capacity in Spain has six-hour sensible heat storage in molten salts: i.e. the plant can run at full power for six hours using only stored energy. Steam storage is less efficient and lasts less than an hour, but attempts are underway to extend steam storage to days.[38]

Mitigation potential

Life-cycle analyses place the carbon intensity of CSP derived power at 20-50 gCO_2/kWh.[39] When integrated into energy systems the uniformity of power output and built-in thermal storage mean that the requirement for associated storage or flexible capacity is less than for PV and the need for curtailment is less. Indeed the flexible nature of CSP could help in integrating more variable capacity, such as PV, into electricity grids.

Integration of solar photovoltaic electricity

The costs and carbon intensities given for the technologies above are calculated for power delivered to a grid, rather than matched to a particular demand profile. In practice the power generated from a variable source such as solar radiation is provided at a different time, and possibly place, than the demand for this power. The mismatch between supply and demand is met by feeding the power into an electric grid and using other sources to provide power when the solar resource is low, or by storing the generated power in large or small storage systems, or by managing the demand through regulation and incentive. A common practical route to accommodate such variable power generation is to incorporate flexible capacity such as open cycle or combined cycle gas turbines into the grid, which can be turned on and off at short notice[41]. A renewable alternative would be a biofuel combined heat and power plant.[40] This incurs cost through the investment in flexible capacity.

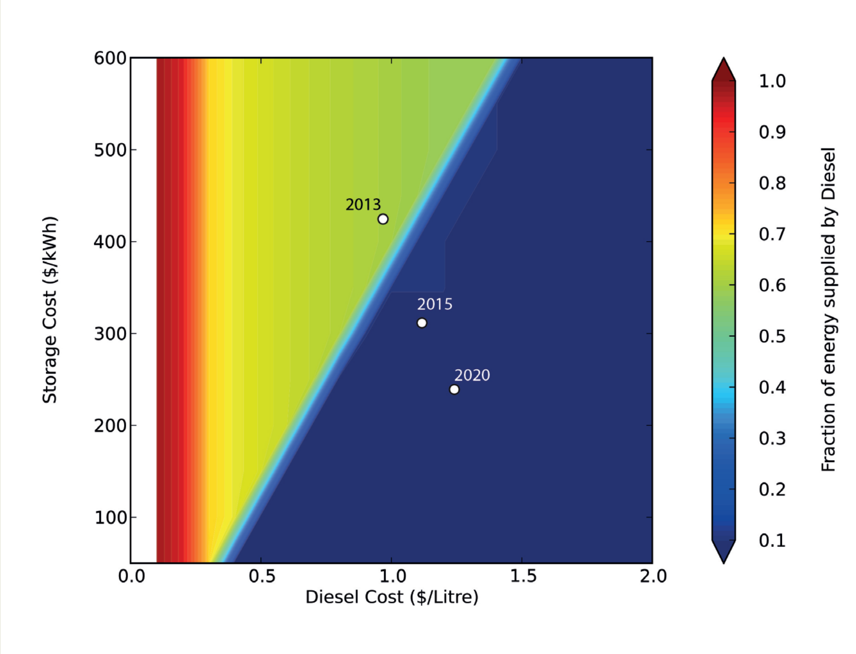
In the UK, it is estimated that the grid can accommodate 20% of generation from variable sources in this way, at an additional cost of 0.5p/kWh.[41] At higher levels of penetration the integration of variable sources becomes more challenging, placing demands on power redistribution, grid storage and dynamic response of back-up power sources.[42] Renewable penetration may also increase costs by a few per cent through impact of rapid cycling on backup fossil plant lifetime.[43] At high penetration levels dynamic management of the electrical demand, by switching off non-essential loads in order to balance supply and demand, becomes a more attractive option.

When other renewable sources, such as wind power, are included the complementary supply profiles reduce the burden on conventional capacity. In Germany, where generation from renewables (both wind and solar) can amount to 20-30% of demand, experience has shown that wind and solar generation complement each other on a daily and seasonal basis[16]. A study undertaken by Poyry[44] for the UK CCC demonstrated that, also in the UK, a more diverse renewables mix helps the electricity system to accommodate variability. Fluctuations in supply can be managed partly with the help of short term (minutes to hours) power storage technologies such as flywheels and longer term (daily and weekly) large capacity storage involving compressed air (CAES) or pump-storage plants (PSP). Since CAES and PSP are the cheapest and incur the least emissions per unit capacity[45] they tend to be preferred to electrochemical storage (batteries) or hydrogen fuel conversion. However developments in battery technology may make domestic scale batteries cost effective in the medium term in some contexts.

In off-grid applications, such as solar power in the developing world, battery storage is essential to enable electricity demand (principally for lighting, communications, refrigeration and small-scale industry or commerce) to be met using solar power – with some exceptions such as water-pumping for agriculture. PV capacity may be deployed as individual solar home systems consisting of module and battery, or as centralised PV and storage facilities with a local power distribution network.

From the perspective of the whole energy system, replacing conventional coal or gas generation with renewables together with electricity storage or possible increases in flexible capacity raises the cost and the carbon embedded in the renewable system. At present, storage of electricity using batteries is fairly efficient (>80%) but expensive (adding $0.2/kWh)[46] with a lifetime of ten years or less. In the case of off-grid generation, the relatively high cost of battery storage can double the overall cost of the electricity and the carbon intensity.[47]

Box 2: Competitiveness of solar PV with diesel power in developing countries



In off-grid locations in developing countries, solar power together with energy storage typically must compete with diesel generators. While the variable nature of solar generation and the high cost of storage mean that it is usually cheaper to meet demand using diesel power, this balance is changing. The figure above shows the fraction that diesel generation contributes to the total energy demand in the cost-optimal hybrid system consisting of PV generator, battery and diesel generator, as a function of the cost of diesel and the cost of battery storage in rural India.[47] For each combination of diesel and storage costs, the diesel generator, PV panel and battery are sized to minimise the cost of electricity generated. Typically, it is cheaper to generate daytime power with solar and night-time power with diesel. According to current and projected storage and diesel costs in India for 2013, 2015 and 2020 the lowest cost system is currently dominated by diesel (60% diesel generation in 2013) but is likely to be dominated by PV within a few years (10% diesel generation in 2015). This imminent crossover is enabled by the anticipated development of lithium ion storage as a load shifting technology and by the expected phasing out of diesel subsidies in India. Even at current prices it is economical to use solar PV in conjunction with a diesel generator to benefit from cheap solar electricity when supply overlaps demand. This shows that technology choices based on present day costs alone could be misguided, and that hybrid systems enable flexibility.

Achieving carbon emissions mitigation using solar energy

Factors influencing carbon emissions mitigation

The amount of carbon dioxide emissions that can be mitigated by a renewable energy technology such as solar power in a given period (usually, a year) depends on a number of factors. The scale of emissions savings is set by the amount of useful energy generated by the solar technology over the relevant period. The actual level of mitigation is then determined by multiplying this by the difference between the carbon intensity per kWh of the power source that is displaced by solar and the carbon intensity of the replacement solar technology. Calculating the carbon intensity of a given solar technology is not as straightforward as it sounds, since it depends not just on the technology but also where and how it is produced.

The mitigation potential of solar power will thus be greatest when the maximum useful solar power capacity is deployed, when the carbon emitted per unit of electrical energy produced is minimised and when solar displaces the most carbon intensive generation technologies, e.g. currently coal or diesel generation. In Box 3 we consider these factors in more detail. The discussion is focussed on PV power but many of the issues are relevant for CSP.

Box 3: Factors influencing emissions mitigation

Carbon intensity of solar electrical energy. Carbon is spent in the manufacture of solar panels and balance of systems, through the energy used in manufacture and transport and the embedded energy in the materials used. This leads to a carbon intensity per unit capacity of between 600 kg CO_2/kWp for practical CdTe systems and around 1500-2500 kg CO_2/kWp for practical c-Si systems, reflecting the more energy intensive manufacture process for silicon modules. This number also depends on the carbon intensity of the energy used in manufacture, hence on manufacturing location. The carbon intensity per kWh of power generated is then found by dividing the carbon intensity per unit capacity by the power generated per peak Watt over the system lifetime. This quantity is influenced by the solar resource (typically 1000-2000 kWh/Wp/year, depending on location) and the system lifetime (typically 25 years). The resulting values are in the range 20 to 40 gCO_2/kWh for manufacture and deployment in Europe, rising to 80 gCO_2/kWh for manufacture in a coal dominated economy, such as China[21]. This number is reduced by increasing module power conversion efficiency (which reduces area related costs), extending system lifetime, by deploying the systems in sunnier areas or by using less carbon intensive materials and fabrication processes in module manufacture.

Note that the relevant quantity is the carbon intensity of solar electricity used to meet demand rather than that of the electricity *generated*. Resource variability and the resulting mismatch of supply and demand mean that some solar power has to be stored, dumped or, possibly, complemented by additional conventional power capacity in excess of that needed to generate the displaced power. These factors increase the carbon intensity and cost of the useful solar electricity. In off-grid situations the dumping of generated power because of limited storage capacity can double the carbon intensity of solar power.[47]

Carbon intensity of displaced power. The carbon intensity of grid power varies between locations, from around 900 gCO_2eq/kWh in India to around 500 gCO_2eq/kWh in the UK and less in countries such as Norway and France. Given that solar resource also varies between locations, the mitigation potential can vary by a factor of 3 or 4 solely through location of the PV system. When solar power is used in off-grid situations, then the carbon intensity of the displaced fuel and any related plant should be used. For example, the high embedded energy in kerosene lamps makes it effective to replace kerosene with solar lighting despite the relatively high carbon intensity of off-grid solar systems that include battery storage.[48,49] In more detailed analyses the marginal carbon intensity, which may vary with time of day, needs to be considered.

The amount of solar capacity deployed depends on:

(i) the cost of the PV electricity relative to alternatives, which in turn depends upon the module cost and efficiency, cost of the balance of systems, solar irradiance level and the cost of the locally available alternatives;

(ii) availability of the PV technology, which depends on availability of modules and system components (such as inverters and batteries), and hence on manufacturing capacity and raw materials such as the rare elements tellurium or indium, as well as on the infrastructure and skills to install and maintain systems; and on the available area;

(iii) the fraction of renewable power that can readily be accommodated in the electric grid, which depends on the cost, capacity and flexibility of back-up generation, the integration of complementary renewables in the grid mix, measures to control demand, and large scale grid optimisation; and

(iv) regulatory issues, such as building and planning regulations, and policy measures such as incentives to stimulate the market and/or obligations on suppliers to provide solar generation.

Historically the volume deployed was restricted by the high cost of modules which led to high solar electricity costs relative to grid power, but since 2012 grid-connected PV electricity has reached price parity with the electrical grid in countries where retail electricity prices are high, such as Denmark, Germany and Italy, and other European countries are soon to follow.[50] Therefore the other factors become important in influencing deployment levels.

Achieving proposed carbon emissions mitigation

According to the 2012 IEA Energy Technology Perspectives scenario 2DS, PV is expected to generate over 11% and CSP over 10% of global electricity/energy demand by 2050 with a resultant saving of 30 Gt CO_2.[51] In the 2DS-hiRen scenario the CO_2 savings due to solar power, relative to the 4DS, are doubled to approximately 60 Gt CO_2.[4]

This level is viable from both a technical and an economic perspective. The cost of the dominant silicon based PV modules has come down faster than expected even compared to the IEA 2010 roadmap, so that the incumbent PV technology is already competitive with retail electricity prices in some areas and soon will be elsewhere. The rate of growth of installed capacity to meet the target of 11% in 2050, of 10-15% per annum, is much lower than the average growth rate of around 40% experienced over the last 20 years.

The main remaining challenge lies in managing the anticipated level of penetration. The projected 11% penetration level is approximately double the highest fraction of PV generated electricity experienced, so far, of 5.6-5.7%, in Germany and

Italy during 2012.[52] These levels have led to some challenges in electricity supply: it has been claimed that variability in Germany's overall electricity supply is responsible for increased risk of blackouts, and that Germany's distribution network is unable to cope with this level of solar PV without some curtailment. High PV penetration with public subsidy has also been blamed for reducing electricity spot prices and for deteriorating business models for traditional power technologies.

The German government is investing in the development of storage technology in order to address some of these issues and has imposed limits on the fraction of generation that can be provided by PV. Of the remaining factors, government policies can help to develop skills and infrastructure and foster a supportive regulatory environment. In some countries with limited land area, such as Singapore, or low insolation and high population, such as the UK, deployment is partly constrained by available land area. In these cases, more innovative PV products may become useful.

Costs of carbon emissions mitigation

The cost effectiveness of different carbon abatement approaches can be measured by evaluating the cost of implementing the carbon saving measure per unit CO_2 avoided (i.e., the *abatement cost*) against a reference or business-as-usual scenario. A number of organisations have published marginal abatement cost curves[44,45,46], with the McKinsey report highlighting the affordability of both CSP (\$18/tonne CO_2) and PV (\$19/tonne CO_2) as mitigation solutions by 2030, ahead of fossil fuel power plants equipped with Carbon Capture and Storage (CCS) technology.

For comparison, the Climate Change Committee's published value of £260/tonne CO_2 of solar PV deployed on existing UK residential buildings in 2020 illustrates the strong, regional variation of abatement costs and their sensitivity to the background assumptions, in this case high retrofit costs and low solar irradiance. Nevertheless, a relative comparison of abatement costs against a single reference mode helps inform discussion of when and where it is most effective to stimulate growth in solar technology via subsidies.

Despite widespread potential, solar water heating systems are estimated to have significantly higher abatement cost than photovoltaic systems, at over £600/tonne CO_2 as a result of the high efficiency of modern gas boilers[12,13]. They therefore hold the greatest potential in situations where gas is unavailable and later in the century, when all combustion of natural gas requires capture and sequestration to remain below the 2030 carbon intensity target shown in Figure 3.

Strategies to increase the mitigation of carbon emissions using solar energy

Assuming that the grid penetration can be managed, then solar power has the potential to have an even greater impact on carbon emissions than projected by the IEA. Based on the above, we can identify a number of routes to enhance emissions mitigation using solar energy.

Promoting PV technologies with lower embedded energy or lower cost

Innovations in module manufacture can lead to significant savings in both module cost and emissions during manufacture. For c-Si, the energy payback time of a rooftop system has halved since 2000, along with reductions in the wafer thickness and in the amount of silicon wasted in manufacture[16]. Such a trend in manufacture and in associated emissions is expected in other, less mature or emerging PV technologies such as thin film, CPV or flexible PV as the level of production grows. For example, in the case of organic photovoltaics it has been shown how a pre-commercial manufacturing process based on coating with an energy payback time of 1-2 years[53] could evolve to deliver a payback time of one day through innovations in manufacture and materials use.[54] Use of solution based manufacture offers the potential for enhanced reductions in embedded energy with production volume. However, given that the majority of the cost of the PV system is already due to the balance of systems, continuing reductions in the module cost will have a small effect on the cost of electricity, unless the new technologies also enable savings in installation, electrical connection or application.

Reducing the cost and emission of the associated system components

Figure 7 shows how the BoS dominates the overall cost of the PV system as the module costs reduce. BoS costs have also reduced but more slowly, because whilst savings can be achieved via market pressure on control electronics some elements (such as labour costs) are highly variable between applications and locations. Innovation in inverter technology has helped to bring prices down in Germany where BoS costs approximately halved between 2005 and 2012 to around \$1/Wp partly though inverter price reductions[16]. Standardisation in product form, marketing and installation are also expected to reduce system costs. A key factor influencing BoS costs is whether the PV system is retrofitted onto existing buildings. System costs are usually lower for both new-build, where installation costs are absorbed into building costs, and for ground mounted PV systems, than for retrofit on old buildings. Use of local manufacture can also reduce emissions by avoiding transport, but will compete with savings due to economies of scale.

Economies of scale in manufacturing modules have been an important factor in achieving cost reductions so far[55] as has the market size and density. Further potential exists for the reduction of costs also through the *scale* of the PV system. The form and size of PV product has barely evolved in the last 40 years. Flexible and light weight products, for example, could be implemented at lower cost over large area roofs or as part of urban and rural infrastructure provided the efficiency is high enough to be cost effective. New manufacturing technologies using high throughput printing and coating offer such product variability.

Improving integration through development of associated technologies

Provision of more than about 20% of generation from renewable sources will eventually require the development of new technologies for power distribution and storage. At the present time no single approach has been identified to solve the problem of mismatch of intermittent supply and demand, however, energy storage, power redistribution, demand management and mixing of renewable energy technologies all have the potential to increase the fraction of generation from renewables.

Energy storage is currently limited by the high cost, size and relatively high carbon intensity of batteries and the limited geographical availability of large scale storage solutions such as PSP and CAES. For solar power, the primary requirement is for storage technologies that can charge and discharge on a daily timescale, including both large capacity grid scale storage that can be integrated into the distribution network and domestic scale storage that can be integrated with local generation. R&D into developing new battery materials and reducing the costs of existing technologies may, however, reduce the costs of batteries, such as lithium ion batteries for domestic scale applications and flow batteries for mini grid or grid integrated batteries, over the next decades. These developments will benefit from knowhow and market experience developed for electric vehicles.

Regarding the electric distribution network, current R&D efforts address the development of technology to manage demand and supply using so-called smart grids, as well as higher efficiency power transmission using high voltage DC transmission networks. In addition, demand can be managed using regulatory tools and price incentives to switch non essential demand to high supply periods. The different supply profiles of wind, marine and solar energy can be exploited in order to smooth the renewable supply. Improved techniques to forecast supply from natural resources, as well as improved energy system models with temporal and spatial resolution will be necessary to optimise the mix of energy technologies.

Finally, since solar photovoltaic and solar thermal technologies each exploit only part of the solar spectrum, hybrid technologies that combine more than one function offer to extend the ways of using solar energy. Examples are hybrid systems that integrate solar PV and solar thermal technology into the same module where the different parts of the solar spectrum are preferentially harnessed by the PV and thermal converters, and hybrid PV/storage devices where solar PV is used either to deliver power or to generate a fuel, such as hydrogen, or systems where the spectrum is split between PV power and fuel generation.

Scenario dependent energy balance

Cumulative emissions savings over a period of time can be optimised through planning of deployment scenarios, selection of technologies and attention to the carbon intensity of displaced power sources. As for any low-carbon generation technology, during the growth of manufacturing capacity, carbon emissions will increase before net savings in CO_2 emissions are achieved. Figure 8 shows the time dependent cumulative emissions due to Germany's PV programme (realistic case: full line), demonstrating that net carbon savings are made only after more than a decade of experience. Moreover, net savings, for the same power generation profile, are made more quickly if a technology with lower embedded energy is used, if panels are manufactured in a less carbon rich power source (in EU rather than China) and if deployment after manufacture is accelerated. This type of analysis may help in planning for the uptake of lower carbon technologies as they become available. For example the relative impacts of incentives to stimulate market growth and R&D investment to accelerate lower carbon technologies could be evaluated.

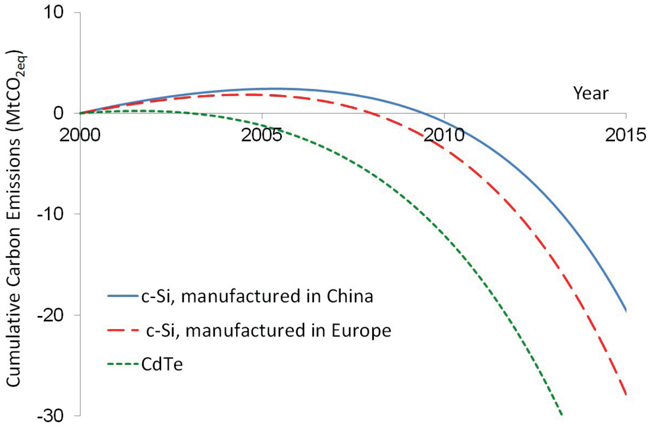


Figure 8: Cumulative emissions in Mte CO_2 due to the growth of PV in Germany from 2000 to 2015 depending on technology deployed (c-Si and CdTe PV technology), and also comparing the effect of location of c-Si panel manufacture.[56]

Policy and regulatory measures

As discussed in this paper, the costs of solar PV technologies have fallen dramatically over time. PV monocrystalline silicon cell costs were of the order $300 per Watt in the mid-1950s.[57] Recent analysis suggests that PV module production costs (again for monocrystalline silicon) in both the US and China are now below $1 per peak Watt, with predictions of around $0.5 per Watt achievable in the long-term, as a result of continued innovation and scale-up.[58] Newer technologies such as OPV are believed to be able to achieve similar or even lower costs to established PV technologies in the long-term.[59] A key question is the role that policy and regulation should play in the achievement of these cost reduction, for both established and emerging technologies.

PV module prices have been demonstrated to have a high correlation with cumulative installed capacity over the last few decades, with a "learning rate" (the % reduction in price for every doubling of cumulative installed capacity) of just over 20% when measured at the global level over the period 1976-2006.[60] Such learning curve analysis has often been invoked to argue for the role of market creation incentives in order to promote learning-by-doing and scale economies. The sustained growth in PV capacity since the 1990s followed a series of incentive schemes starting with the German '1000 roof' and '100,000 roof' programmes in 1990 and 1999, respectively, the Japanese 'New Sunshine' subsidies in 1993, the first Feed-in-Tariff (FiT) schemes in Germany in 1999, and more recently by FiTs in other key European countries, notably Italy and Spain[61] and, in 2010, the UK. FiTs achieve stability of return on investment for households, businesses and power generators installing PV systems and have become the preferred option relative to capital subsidies.

However, the overall effectiveness of FiTs remains a topic of debate and analysis, since these schemes have proven costly. The Spanish Government, in particular, implemented relatively high FiT rates in 2007, which contributed to an unexpectedly large boom in installed capacity in 2008. Although the Government responded with a reduction in FiTs and a relatively stringent cap on capacity additions in 2008, by 2009 total tariffs paid to PV generators had reached over Euro 2.5 billion, with high public expenses expected to be incurred over the next 20 years.[62] The UK Government also announced a reduction in FiT levels in 2011, first for larger installations and then for smaller, household-sized installations, in order that Government funding for the scheme was not exceeded. The German Government has so far resisted the imposition of capacity or budget caps on FiTs, instead opting for a "dynamic degression" regime in which reductions to FiTs for new installations are adjusted in light of installed capacity in previous periods.[63] This has maintained a strong rate of capacity additions in Germany.

An additional question concerns the appropriate balance between public funding towards market pull mechanisms such as FiTs, as opposed to investment in R&D and demonstration activities. PV module cost reductions have been demonstrated to result not only from cumulative capacity deployed, but also from cumulative R&D investment.[64] One assessment of five major PV markets suggests that far less public money has been spent on R&D compared to FiTs and other deployment support policies.[65] There are, however, interactions between market pull and R&D (technology push) mechanisms, with market creation driving (often private) R&D and innovation efforts[66] and in some cases vice versa.[67] But there is also anecdotal evidence that market expansion may have encouraged the uptake of mature PV technologies, through expanded manufacturing capacity and the management imperative of meeting market demand, in preference to encouraging innovation.[68] So, whilst investment in market expansion has been accompanied by support for R&D and demonstration, separating out the comparative effects of R&D, demonstration and deployment support is not a straightforward task.

If emissions are to be significantly reduced in line with a stated intent to limit the change in global mean surface temperature to 2°C above pre-industrial levels, then there are only a few decades for the world to make a transition to a much lower-carbon energy system. It therefore seems that we need both to drive down costs and expand deployment of current solar technologies while at the same time continuing to invest in R&D on the most promising new solar technologies that have the potential to deliver a significant improvement in one or both of cost and efficiency.

A key question for policy makers is therefore how to achieve the correct balance between deployment subsidies, fundamental R&D support and demonstration support, in order to achieve cost reductions in PV systems with the least impact on scarce public resources. This requires more detailed research into the way that different factors (such as market expansion, R&D support, demonstration programmes and environmental regulations) have driven cost reductions, and how these factors could affect PV costs in the future.

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About the Grantham Institute for Climate Change

The Grantham Institute is committed to driving research on climate change, and translating it into real world impact. Established in February 2007 with a £12.8 million donation over ten years from the Grantham Foundation for the Protection of the Environment, the Institute's researchers are developing both the fundamental scientific understanding of climate change, and the mitigation and adaptation responses to it. The research, policy and outreach work that the Institute carries out is based on, and backed up by, the worldleading research by academic staff at Imperial.

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Solar power for CO_2 mitigation