



# The transition to renewables: Can PV provide an answer to the peak oil and climate change challenges?

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## ABSTRACT

This paper explores energy and physical resource limitations to transitioning from fossil fuels to the large-scale generation of electricity with photovoltaic arrays. The model finds that business as usual models, which involve growth rates in world electricity demand of between 2% and 3.2% p.a., exhibit severe material difficulties before the end of this century. If the growth rate is lowered to 1% p.a., then it may be possible to reach the year 2100 before such difficulties, but it is likely that material constraints will occur early the next century. Steady state scenarios show that silicon based photovoltaic panels could, however, displace fossil fuels before the middle of the century, providing around the same order of magnitude as present (2010) world electricity demand. Scenarios also show that outcomes will be highly dependent upon the rate of improvement of photovoltaic technologies. The analysis does not contend that silicon PV technology is the only technology that will or can be adopted, but as the embodied energy content per kWh generated of this technology is similar to other renewable technologies, such as other solar technologies and wind, it can provide a baseline for examining a transition to a mixture of renewable energy sources.

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## 1. Introduction

The archeologist Joseph Tainter, in “The collapse of complex societies”, claims energy is vital for civilizations to flourish and suggests that: “*For human societies, the best key to continued socioeconomic growth and to avoiding or circumvention (or at least financing) declines in marginal productivity, is to obtain a new energy subsidy, when it becomes apparent that marginal productivity is beginning to drop*” (Tainter, 1988). As of 2010 oil production has been virtually flat for the last 5 years and world marginal productivity is showing signs of stress, with a financial collapse in late 2008 and further economic difficulties in Europe in early 2010. In terms of energy supply it is becoming clear that fossil fuels will not sustain society for very much longer and while some will contest Tainter’s suggestion of continued socioeconomic growth it is also clear, to all but vested interests in the current system, that the world urgently needs to transition to a new form of energy supply, if it is to keep its population and standards of living intact. Such a transition was mooted by the US Geologist Hubbert back in 1949. Hubbert saw 60 years ago that fossil fuels could last humanity only a few hundred years and that unless civilization was to adopt renewable energy sources from the sun and the wind, then world energy supply must decline and along

with this decline also a decline in the world population (Hubbert, 1949). Hubbert also recognized in 1949 that the world could not, even with renewable energy sources, continue to grow its energy supply and population ad infinitum and that sooner rather than later both must plateau or collapse (Hubbert, 1949). In this regard he preempted the ecological economists such as Herman Daly. Ecological economists see the economic system as a subsystem of the environment and not the other way round (Daly and Townsend, 1993). In his famous three laws of sustainability, Daly suggested that “*Renewable resources should be exploited in a manner such that: harvesting rates do not exceed regeneration rates and waste emissions do not exceed the renewable assimilative capacity of the local environment.*” For fossil fuels Daly also suggested that: “*Non renewable resources should be depleted at a rate equal to the rate of creation of renewable substitutes.*” (Daly and Townsend (1993). Whether these laws can be adhered to in terms of the creation of solar PV systems, using fossil fuels as a starting point, is the substantive subject of this paper.

### 1.1. Solar energy and EROEI

In terms of a new energy subsidy it is well known that the total amount of sunlight that continuously reaches the Earth’s surface is much larger than the current use of energy by humanity. Kreith and Goswami (2009) have suggested that if only 1% of this energy flux could be converted to electricity with an overall efficiency of

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10%, then there would be sufficient energy to satisfy the world energy demand, at least until 2050 if not further. Such a simplistic calculation would, however, mean that 1% of the earth's surface would need to be covered by a material collector of some sort. And herein lies the rub because 1% of the total earth's surface is 5 million km<sup>2</sup> or  $5 \times 10^{12}$  m<sup>2</sup>. Covering this area with just 1 mm of sheet aluminum would amount to some 14 billion tonnes or 36% of the total world reserves of aluminum (USGS, 2009). Using steel or glass would be much better in terms of the proportion of world resources but the point is that the amounts of physical resource and energy needed to manufacture that resource, to enable a transition to solar energy, are likely to come close to world limits. As the availability of free aluminum metal and other vital resources are ultimately linked to the availability of energy for their production, the crux of the matter boils down to how much energy is needed to make the energy converting devices, or the Energy Returned On Energy Invested (EROEI). The EROEI is the ratio of the energy produced by an energy converting device over its lifetime to the amount of primary energy required for the manufacture, transport, construction, operation and decommissioning of the device. Stoppato (2008) uses the term "Energy Return Factor" (ERF) which is identical to EROEI. Similarly "Energy Yield Ratio" is used by Gürzenich et al. (1999). In a review by Kubiszewski and Cutler (2009) of thirteen distinct analyses of 51 PV systems the EROEI was found to be 6.56, showing that PV systems provide more energy than required over their lifetime. There is very little, however, in the literature that talks about PV in terms of EROEI, the majority use embodied energy, gross energy, cumulative energy demand or calculate the energy payback time (EPBT). The online article mentioned above by Kubiszewski and Cutler has not yet been formally published and is part of a long term task by Cutler Cleveland, Charles Hall and other researchers to document energy systems in terms of EROEI (or Energy Returned On Invested, EROI). For comparison the EPBT is given as EPBT (years)=Consumed energy for system production/Annual energy produced by the system (Frankl et al., 1998). The EROEI is given by EROEI=the energy produced by the system over its life span/Energy consumed for system production. Thus if the system lifetime is known then the EROEI can be calculated from the EPBT thus: EROEI=system lifetime (years)/EPBT (years).

## 1.2. Limits to material and energy resources

It is not only that the resources to enable a transition to a renewable energy supply system might be close to available world limits, many researches are finding that our present

economic system is producing such a strain on the world ecosystem that the ecosystem is either close to existing limits or that we have overshoot and exceeded such limits (Meadows et al., 1972; Meadows et al., 2004; Catton, 1980; Lloyd, 2007). This situation is likely to affect our civilization in many fundamental ways, including transportation, food production, lifestyle and the cost of commodities (Lloyd and Subbarao, 2009).

In 2009 the total world commercial energy supply was about 11.2 billion tonnes of oil equivalent (460 EJ) of which fossil fuels provided approximately 88% (BP Statistics, 2010). The world electricity generation capacity in 2009 was close to 20 trillion kWh, which was produced using around 5000 GW of installed capacity (BP Statistics, 2010). Of this capacity only just under 1000 GW was from renewable resources (mainly large hydro) and 400 GW from nuclear. The average growth rate of fossil fuel generation (in kWh terms) for the last decade to 2007 was around 4% pa compared to hydro 1.8% pa and nuclear 1.5% (EIA, 2010). The average growth rate of total world electricity generation has been 3.2% over the last decade with the combined total of nuclear and hydro increasing at almost exactly half of this rate, i.e. 1.6% pa. Of the total fossil fuel contribution of 10 billion tonnes of oil equivalent in 2008 to the world energy supply, around one-third was converted into electricity. The Energy Information Agency of the US Department of Energy (EIA) gives only just over 100 GW installed capacity of total other renewables including biomass, wind geothermal and solar (PV plus solar thermal), growing at a decade long average of 8.1% (EIA, 2010). But these figures must underestimate the wind contribution, at least, as other industry sources put wind installed capacity alone in 2006 at 74 GW and in 2008 at 121 GW with an annual increase (in 2008) of 29% per annum (World Wind Energy Report 2008, 2009). Fig. 1 shows the EIA data until 2006 with the last three years extrapolated using existing growth statistics and incorporating the wind data from the world wind energy report and the PV data from the EPIA (2009a) report.

The enormous social and infrastructural change needed to shift completely to renewable energy resources is probably the greatest barrier to providing a secure future energy supply (Lloyd and Subbarao, 2009; Sovacool, 2009). Other critical factors to using large scale renewable energy may include: intermittency of supply, uneven distribution of resources and the low power density of renewable energy supplies (Smil, 2007). Another concern is that the production of renewable energy devices currently requires fossil fuels. So as fossil fuels become scarcer it will be more difficult to make the transition to renewable energy sources (Hubbert, 1949). In addition lower fossil fuel consumption will mean contracting economies and so funding will be in short supply to enable the transition.

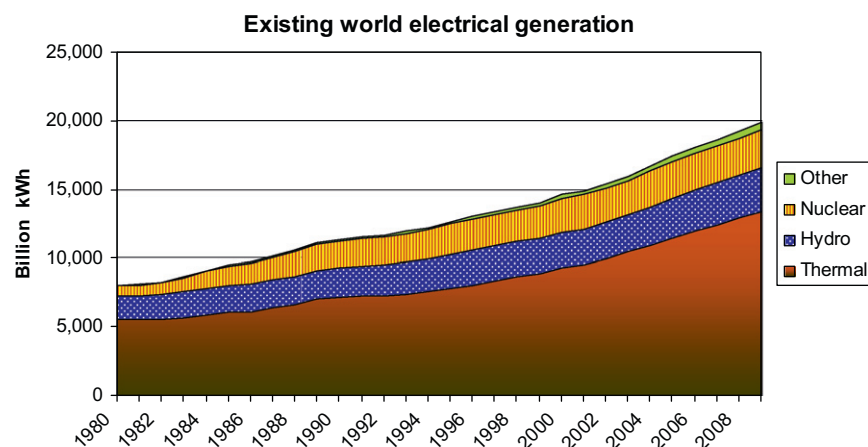


Fig. 1. Existing world electrical generation (EIA, 2009) until 2006.

Also there is a growing scientific opinion that coal fired power stations must be replaced with non-CO<sub>2</sub> emitting alternatives, possibly by as early as 2030, to prevent catastrophic climate change (Hansen et al., 2008). It seems unlikely that the energy overhead of carbon sequestration will make this technology financial viable as a solution for CO<sub>2</sub> emissions from fossil plant. Finally, unless the breeder reactor is perfected, it is unlikely that nuclear energy will become a major player over the long term, as the uranium fuel is again a finite resource.

## 2. The technology: large scale deployment of PV

There is a surprising dearth of critical modelling studies in the literature investigating large scale deployment of PV, with some that exist having clear vested interest either in actively promoting the technology or, alternatively, in debunking the technology.

In a study of material requirements for multicrystalline silicon (mc-Si) arrays by Wyers and Wild-Scholten (2003) it was found that changes would be required to the material inputs for solar arrays to enable them to be deployed on a large scale. Based on an installed capacity of 7 TWp by 2040, the economic and sub-economic reserves of silver would be depleted by 2023, six years earlier due to PV production, and copper by 2065, seven years earlier due to PV production. These authors suggest that such impacts could be eliminated in the future by replacing silver as a metal contact with copper or aluminum and by replacing copper interconnections with conductive adhesives. Large reductions in the requirement for aluminum would also occur; they suggest by making modules without aluminum frames.

Feltrin and Freundlich (2008) also found that silicon PV could not easily reach the terawatt range due to limited global reserves of silver, but if the requirement for silver could be reduced the authors felt that there were no other significant material limitations for silicon solar cells. The research by these author's, however, is limited as it did not include any embodied energy analysis. The authors concluded that:

*"It is shown that many existing technologies, albeit playing an important role in the present sub-gigawatt energy production levels, are affected by severe material shortages, preventing their scale-up to the terawatt range."*

The material problems were thought to be particularly severe for cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS) cells and while dye sensitized thin film technologies were not material limited their low efficiencies would cause difficulties in terms of the area needing to be covered (Green, 2006). Some authors, however, have been more optimistic with regard to thin film technologies, e.g. Fthenakis (2009) and Fthenakis et al. (2009).

A recent IEA report 'Energy Technology Perspectives' investigates strategies for decarbonising the world energy supply out to 2050 (IEA, 2008). The report looks at PV options and goes into some depth as to the economic costs but does not detail either the resource or embodied energy implications of a transition to renewables. The environmentally friendly 'Blue Map Scenario' in this report envisages an installed capacity of PV (all technologies) of 1150 GW by 2050.

A recent European Photovoltaic Industry Association report found that there were no physical or technological limitations to the growth of PV (EPIA, 2009b). The report also suggested that PV has also demonstrated a quick ramping-up capability in production volumes, currently growing faster than any other renewable energy technology.

A similar and extensive study by the IEA PVPS task 8 "Energy from the Desert" (Komoto et al., 2009) investigated what it would

take to deploy large scale PV systems in the world's deserts. This project, which started in 1999, came to the conclusion (in 2009) that there were no insurmountable financial or technical problems to large scale PV systems at multi-gigawatt levels. The challenges, the report suggested, were mainly to convince world governments to proceed with such ambitious schemes. The energy payback times for the technologies assumed in the report were modest, between 2.1 and 2.8 years (see later). A road map was proposed in this study, which saw PV installed capacity reaching 100 GWp by 2030, 2 TWp by 2050 and 133 TWp by 2100.

A survey by Groenendaal et al. (2000) of over 300 experts in the implementation of PV technologies from the European, American and Asian continents was undertaken to study the factors influencing the success of the large scale implementation of PV. The report, however, gives no mention of the possible limitations to growth imposed by resource limitations. Again such a report might ring alarm bells as any suggestion that there are no limits to physical growth must be considered suspect.

Raugei and Frankl (2009) have investigated life cycle impacts of PV systems and posit three scenarios, pessimistic, optimistic/realistic and very optimistic, suggesting that the installed capacity of PV could reach 500, 2200 and 9000 GWp for each scenario in turn by 2050.

Trainer (2007) comes to the opposite conclusion in a general survey of various renewable technologies, including PV, to suggest that while each may play a part in a transition from fossil fuels, unless some way is found to curtail limitless consumer oriented growth then all will be lost. In particular Trainer, echoing Daly and earlier limits to growth models, emphasizes that: "there is no possibility of all people rising to anywhere near the living standards we take for granted today in rich countries" (Trainer, 2007, p. 126).

### 2.1. Current deployment of photovoltaic systems

Currently the majority of solar PV systems are deployed in Europe, followed by the OECD Pacific region and North America, see Table 1. This is diversifying rapidly to include significant further deployment in the US, major deployment in China, Korea, Africa and many other countries.

According to the European Commission's Joint Research Centre (JRC, 2009), annual global production of photovoltaic cells and modules increased by 80% over 2007 levels to 7.3 GW in 2008. This increase surpassed wind energy by a considerable margin, although coming from a much smaller base (i.e. a 29% increase in 2008 for wind energy from 94 GW in 2007 to 121 GW in 2008). The global installed capacity of PV increased by 4.8 GW in 2008 to reach a cumulative installed PV capacity of 14.7 GW. This capacity has exceeded the prediction by EPIA (2009a), which was that the 2008 growth of installed capacity would be 3.1 GW in their 'business as usual' moderate scenario and 4.2 GW in their advanced scenario. These numbers from the EPIA (2009a) suggest that over the last 6 years the growth rate in installed capacity of PV has averaged 39% p.a (see Fig. 2). It looks as if 2009 may have been a downturn, or stabilization in deployment, due to the global economic crisis, but some industry figures are suggesting a return to high growth rates by 2010. The "PV Group" in particular suggests 10 GW will be produced in 2010, PV Group (2010), and

**Table 1**  
Total installed capacity and market share of the top five countries in 2007 (EPIA, 2008).

OECD region	Germany	Japan	USA	Spain	Italy	World
Installed capacity (MW)	3800	1938	814	632	100	9162
Share of PV market (%)	42	21	9	7	1	100

Photon International predicts up to 24 GW (Boas, 2009). It is clear, however, that PV deployment is likely to be strongly linked to the world economic situation.

The EPIA gives three scenarios for the future of PV for Europe: modest growth taking penetration to 4% of the electricity market by 2020, accelerated growth taking the total to 6% by 2020 and a paradigm shift giving a total PV share of 12% of the EU electricity market by 2020 (EPIA, 2009a).

## 2.2. Choice of PV technology

While it is recognized that no one solution is being considered as the final renewable energy technology, in order to simplify the energy and material dynamics of the transition problem the present paper will consider only one PV technology, that is silicon (crystalline and polycrystalline) technology. It is likely that this particular technology will be used as a major component of a more general mix, which would certainly include other PV technologies, solar thermal, wind and possibly other contenders. The payback times and corresponding EROEI for wind, however, are similar to that for crystalline silicon PV and the material requirements, in terms of structural infrastructure, are similar for all the solar technologies, as they have to cover similar collector areas, depending of course on the efficiency of the cells.

## 2.3. PV cell efficiency

The efficiency of a PV cell affects the area of PV needed and the amount of electricity produced. Using the efficiencies of the different types of cells in mass production and the market share of each of these types, an overall efficiency of 13.2% is suggested to be typical at present (2010).

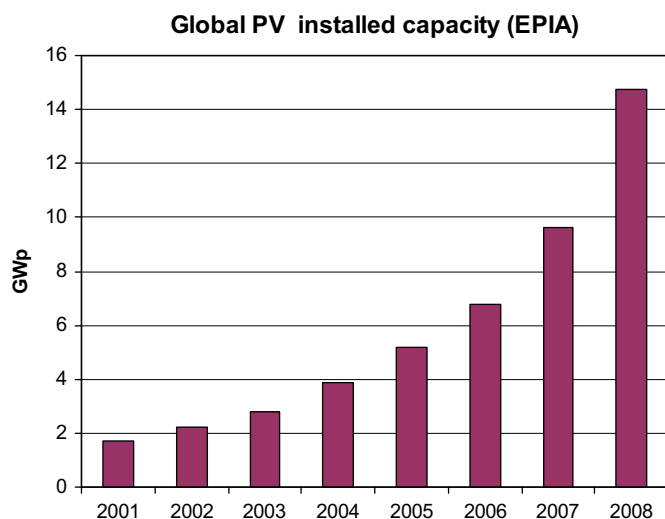


Fig. 2. Global installed PV capacity (EPIA, 2009a).

Table 2

PV silicon panel efficiency (Green et al., 2009).

Photovoltaic technology	Cell		Module		Array
	Highest confirmed	Typical	Highest confirmed	Typical	Typical
Crystalline	25.0 ± 0.5	15.3	22.9 ± 0.6	14.0	10.5
Multicrystalline (ribbon)	20.4 ± 0.5	14.4 (13.1)	15.5 ± 0.4	13.2 (12.0)	9.9(9.0)
Amorphous	9.5 ± 0.3	6.5			4.9

According to Alsema et al. (2006) the future efficiency of multicrystalline modules, based on current best practice being used by the entire industry, will be 17%. Hamakawa (2005) predicts that by 2015–2020 module efficiency will increase to 20%. Raugei and Frankl (2009) predict an increase of module efficiency to 25% in the near future. Based on these figures the efficiencies for the model used in this paper are suggested to improve from 14% now to 25% in the future (Table 2).

## 2.4. Storage

One of the major disadvantages of PV is that it is a non-dispatchable supply depending on the availability of solar radiation. Currently any electricity generated by the available relatively small scale PV systems can be put into the electricity grid without requiring additional storage. As of 2008 around 90% of existing systems were grid connected, a percentage thought to increase as grid connected systems overshadow stand-alone systems (EPIA, 2008). However, as PV deployment increases and this source generates a significant proportion of the world's electricity supply (> 15%) it is likely that new grid management methods and large scale devices for the storage of electricity will then be needed (Pearce, 2008). An alternative solution suggested is that another source of dispatchable energy will have to be commissioned as a backup supply to replace solar power during cloudy days and nights. The need for such storage or backup supply has been used to suggest the improbability of PV making substantial inroads into the world's electricity supply (Trainer, 2007). Others suggest that combinations of storage devices and power supplies that can be quickly accessed such as gas or biomass powered turbines, fuel cells and hydro power could be used. A report by the US National Renewable Energy Laboratory found that pumped hydro and compressed gas storage were the most economic options, as of 2009, but only pumped hydro has been demonstrated on a large scale (Steward et al., 2009). Plug-in hybrid vehicles, which have energy stored in their batteries, are another storage possibility (Pearce, 2008). Other intermittent sources of energy, such as wind, have been mooted to be used with solar power to provide a more consistent supply of electricity over a wider grid (Daoutis and Dialynas, 2009). Alternatively a new economic paradigm could be developed in which demand could be changed to match the availability of solar generated electrical energy (Trainer, 2007; Stodola and Modi, 2009), but this alternative would require a complete reorganisation of the way we conduct our economic activities.

## 2.5. Embodied energy

An embodied energy analysis of PV arrays is necessary to assess their viability as a long term substitute for fossil fuels. Because PV technology is not yet mature, estimates need to be made for the future embodied energy requirements extrapolated from existing technologies. As such future estimates are problematic; the methodology adopted in this paper has been to



produce a range of scenarios that incorporate embodied energies for existing technologies, to scenarios for embodied energies for possible future technologies. Energy inputs for a PV array include the energy needed for material extraction, transport, manufacturing, plant equipment, processing, installation, operation, disassembly and recycling. In addition there are energy inputs required for grid connection, transmission and possible energy storage devices. As usual with such calculations the boundaries are problematic and are open to interpretation.

Storage devices have not usually been included as an energy input in the available literature to date as most existing large scale arrays are connected to the electricity grid. This omission will be a problem once deployment rises significantly and it is clear a great deal more work needs to be done on the storage problem in terms of both materials and embodied energy requirements at the multi-GW level.

## 2.6. Review of the embodied energy of silicon cells, modules and arrays

There is a growing body of literature that either directly calculates the embodied energy of silicon solar cells or infers the values from other literature information, including materials databases. This paper will use existing literature values as scenario inputs for the embodied energy of PV cells, modules and arrays. The calculations in such papers are usually based on a set of reasonably standard assumptions (see below). This standardization has been necessary as there are many different silicon technologies that can be used in a variety of applications. The majority of the literature discusses multicrystalline modules as this technology currently (2010) has the largest market share.

The standard assumptions that have been used in the literature are a performance ratio of 0.75, an incident horizontal irradiation of either 1000 or 1700 kWh/m<sup>2</sup>/year and a system lifetime of 30 years. The performance ratio is the ratio of the real PV energy output compared to the nominal output and is a function of matching the varying current voltage (IV) characteristics of the panel to a fixed AC voltage grid supply (Alsema et al., 2009).

PV module outputs are generally given in kWh per year for a 1 kWp installed module. The unit kWp stands for kilowatt peak and is the maximum output of a PV module under standard conditions of 25 °C and 1000 W/m<sup>2</sup> of sunlight in the plane of the module. The International Energy Agency (IEA) has produced a standard set of guidelines on life cycle analysis for PV systems (Alsema et al., 2009).

Energy requirements for the production of PV modules vary with publications but are usually represented as primary energy, MJ thermal (MJth) per m<sup>2</sup> of module area, kWh/m<sup>2</sup>, or instead as a function of panel area, as the energy to make one nominal kWp. The present paper presents both the primary energy MJth/m<sup>2</sup> and the electrical equivalent kWh/m<sup>2</sup> (with a conversion of 1.0 MJ of primary energy=0.35 MJ electrical energy) and converts the /kWp notation to /m<sup>2</sup> by multiplying by the nominal panel efficiency. Note that the primary energy input may not always be 100% thermal and will of course depend on the energy mix of the specific country: see for instance IEA (2009).

The most comprehensive information on the embodied energy of photovoltaic arrays (and how to reduce this embodied energy) has been provided by Alsema and Wild-Scholten (2007a) and Jungbluth et al. (2008). These authors use the “Ecoinvent database v2.0”, which contains a standardized international life cycle inventory data on energy supplies, material supplies, resource extraction, chemicals, metal, waste management and transport in over four thousand datasets (Ecoinvent, 2009).

Jungbluth et al. (2008) suggest around 3440 MJth/m<sup>2</sup> for crystalline silicon and 2640 MJth/m<sup>2</sup> for polycrystalline silicon

modules, in reasonable agreement with Alsema and Wild-Scholten (2007a), who give 3700 MJth/m<sup>2</sup> for mono crystalline silicon and 2900 MJth/m<sup>2</sup> for polycrystalline. Glockner et al. (2008) give 2260 MJth/m<sup>2</sup> for polycrystalline modules, again in reasonable agreement with the above authors. Perpinan et al. (2009), however, give a somewhat higher value for the specific Isofoton crystalline panels investigated at 5200 MJth/m<sup>2</sup> and in addition these authors stress the uncertainty in such calculations saying that they cannot be considered more accurate than  $\pm 40\%$ .

Stoppato (2008) presents a life cycle analysis of PV Si polycrystalline modules and gives a value of 1494 MJth per 0.56 m<sup>2</sup> panel, i.e. 2300 MJth/m<sup>2</sup> of panel area, which is quite a bit lower than other researchers, as this analysis assumes the Union Carbide Corporation (UCC) process to make solar grade silicon, a process that is not yet in common use.

Deenapanray et al. (2004) report on the Australian National University researched “sliver” solar cells and suggest an embodied energy of around 1863 kWh/kWp. Converting these values to per m<sup>2</sup> of panel area at a thermal to electrical efficiency of 35% and a quoted panel efficiency of 18% suggest that the sliver cell module has an embodied energy content of 3450 MJth/m<sup>2</sup> of panel area, which is comparable to other estimates.

The IEA PVPS task 8 report ‘PV in the Desert’, Kurokawa, K. (2003), examined the total primary energy requirement of a 100 MWp PV system located in a desert area of high isolation. This report gave a range of between 3493 and 3030 GJ depending on the orientation of the panels. The corresponding values for the EPBT were between 2.3 years and 1.2 years. The primary embodied energy costs, less transmission and transport energy costs, were given as around 2600 GJ/100MWp or 26 MJ/kWp.

## 2.7. Summary of embodied energy requirements for modules

The literature thus documents a range for module embodied energy production from around 2500 MJth/m<sup>2</sup> up to a little over 5000 MJth/m<sup>2</sup>. At 35% conversion efficiency from primary (thermal) energy to electrical energy these values amount to an electrical input of between 200 and 500 kWh. Such a set of conversions would be appropriate using the conventional paradigm of using mostly fossil fuels to generate electricity but would not be appropriate of course in a purely renewable world where the majority of electricity supply comes from renewable sources.

## 2.8. Other resource requirements of panels

The amount of silicon available for the production of PV is not seriously limited, as silicon is the second most abundant element in the earth's crust and it is readily accessible in the form of silica and quartz.

In the current paper the mineral requirements for the production of PV arrays have been calculated mainly using the wafer, cell, module, cabling and inverter requirements provided by the life cycle inventory data by Wild-Scholten and Alsema (2007). Separate resource requirements have been used for roof and ground mounted structures. The minerals required annually to build the predicted amount of PV have been compared to the annual global production of minerals and the total global reserves of minerals (see Table 7) as documented by the U.S. Geological Survey, USGS (2009). The annual global production and global reserve data have been used to calculate what resources could limit the growth of PV production. In particular the frame used for a typical PV module uses a relatively large amount of aluminum, up to 4.2 kg for a 1.60 m<sup>2</sup> module. According to Alsema and Wild-Scholten (2007a) frameless modules are possible and preferable from a resources perspective.

## 2.9. Modules only

Table 3 below gives the approximate physical resource requirement for crystalline silicon based PV panels, based on the published and unpublished literature as discussed.

## 2.10. Balance of system (BOS)

### 2.10.1. Support structures

The data for support structures, maintenance, etc. is less well documented, as case studies of large scale operating PV arrays are relatively small in number. In addition the embodied energy requirements of ground mounted arrays are highly dependent on the soil structure and wind loading for the site chosen, as these parameters determine the steel and concrete needed for the foundations. An early paper by Frankl et al. (1998) gave some indication of the BOS embodied energy for ground mounted arrays at around 1800 MJth/m<sup>2</sup> and roof mounted arrays between 500 and 1400 MJth/m<sup>2</sup>. Nawaz and Tiwari (2006) give similar numbers for ground mounted (500 kWh/m<sup>2</sup>) and roof mounted (200 kWh/m<sup>2</sup>) arrays but it is not clear if these values actually originate from the Frankl et al. (1998) paper. Jungbluth et al. (2008) give around 1000 MJth/m<sup>2</sup> for BOS for roof mounted panels only.

A recent paper by Perpinan et al. (2009), looks at both fixed ground mounted panels and tracking versions, suggesting 9200 MJth/kWp for fixed panels (12.4% efficiency) and 18,300 and 11,300 MJth/KWp for double axis and single axis tracking systems, respectively. Converted to embodied energy per m<sup>2</sup> these values are 1140 MJth/m<sup>2</sup> for fixed panels, 2270 MJth/m<sup>2</sup> for two axis and 1400 MJth/m<sup>2</sup> for one axis tracking. The Frankl et al. (1998) paper suggests that roof mounted panels may have more opportunity for energy reductions (50% or more) than ground mounted panels, especially for building integrated modes, where the embodied energy of the original roofing material is displaced. However, in terms of very large scale deployment of PV the predominant rooftop mode must be retrofits as there would be little scope for new building installations on the scale envisaged. In terms of the final ratio between roof and ground mounted systems a back of the envelope calculation shows that the possible available roof area for the world is relatively small compared to the total array areas likely to be needed (1 billion houses in the world with substantial roof structures each having 30 m<sup>2</sup> (facing the right direction) gives only 30 × 10<sup>9</sup> m<sup>2</sup> or 30,000 km<sup>2</sup>).

Mason et al. (2006) give BOS embodied energy values for a well researched 8 MWp PV array, in Springerville, USA, that has largely done away with concrete foundations, as 542 MJth/m<sup>2</sup> of panel area. The IEA task force 7 report “Energy from the Deserts” compares the embodied energy consumption for earth screw installations such as at Springerville and those with concrete foundations and comes to the conclusion that the earth screw systems use slightly more embodied energy (40,862 TJ/system) than the concrete ones (39,067 TJ/system) (Komoto et al., 2009).

In summary the BOS embodied energy appears to range from around 500 MJth to 2000 MJth/m<sup>2</sup> of array area.

**Table 3**

Mineral, water and EVA requirements per square meter of photovoltaic array, not including the balance of system (unpublished spreadsheet (Wild-Scholten and Alsema, 2007).

Mineral	Al	EVA	Water	Cu	Ag	Pb	Ni	Glass
kg/m <sup>2</sup>	0.060–2.66	1.0	21.2	0.11	0.052	0.0031	0.00016	10.0

## 2.11. Embodied energy summary

For the purposes of this paper the total embodied energy for the arrays, including mounting systems inverters and transformers and array interconnections, but not storage or long distance transmission are taken to range from 3500 to 7000 MJth/m<sup>2</sup>. These estimates are presented later as the starting points for optimistic and pessimistic scenarios regarding panel parameters.

## 2.12. Materials contribution

The physical resource contributions to support structures are also quite variable, with the main difference being between ground mounted systems and roof mounted systems. For ground mounted systems Frankl et al. (1998) suggest around 20 kg steel (650 MJth/m<sup>2</sup> using an embodied energy content of steel at 32 MJth/kg) and 190 kg concrete (1150 MJth/m<sup>2</sup> using an embodied energy content of concrete at 6.06 MJth/kg), per m<sup>2</sup> of panel area, in good agreement with Perpinan et al. (2009), who gives 15 kg steel (128 kg/kWp) and 240 kg concrete (1 m<sup>3</sup>/kWp). For roof mounted systems Jungbluth et al. (2008) report a large variation in resources needed, with between 1 and 14 kg of structural materials per m<sup>2</sup> of panel area. These authors do not report the type of material but presumably it is a mixture of aluminum and steel. An unpublished spreadsheet by Wild-Scholten and Alsema gives between 0.08 and 0.72 kg steel and 0.54 and 1.71 kg aluminum for roof mounted systems per m<sup>2</sup> of panel area deployed. Wild-Scholten and Alsema (2007). Raugei et al. (2007) give 25 kg for steel supporting structures per m<sup>2</sup> of array area.

The other main contributions to an array are the requirements for cabling and inverters. The Mason et al. (2006) paper gives 9792 kg steel, 2277 kg copper and 894 kg aluminum per 1 MWp inverter and transformer. Converting these values to per m<sup>2</sup> gives 1.4 kg steel, 0.32 kg copper and 0.125 kg aluminum (for 14% average panel efficiency). The total BOS requirements (including the panel frames) given in the Mason et al. (2006) paper include 7.7 kg steel, 2.7 kg aluminum and 1.05 kg copper, which is at the low end regarding steel but as mentioned this calculation was for a low steel and low concrete installation.

The 2003 IEA report of Task 8, Kurokawa (2003) investigated a 100 MW array located in desert regions and suggested around 11 kg of support structures (steel) would be needed per m<sup>2</sup> of panel area (14% efficiency) and around 160 kg of foundations (concrete) per m<sup>2</sup> of panel area (14% efficiency), which is in good agreement with other studies.

In summary the BOS material requirements used in this paper are given in Table 4. Concrete is not considered a limiting material other than in the embodied energy needed to make the material.

Finally the module array and BOS requirements can be added to produce a final material requirement for PV silicon based technologies as shown in Table 5.

## 2.13. Future options for silicon PV

The embodied energy of the active material in solar cells has been decreasing over time (Alsema and Wild-Scholten, 2007b). This observation reflects rapid changes to the technology, leading

**Table 4**

BOS/m<sup>2</sup> panel area.

Mineral	Aluminum	Steel	Concrete	Copper
kg/m <sup>2</sup>	0–1.0	0.08–20.0	0–240	1.0

**Table 5**

Total material requirements for silicon based PV arrays.

Mineral	Al	EVA	Water	Glass	Cu	Ag	Pb	Fe	Ni	Concrete
kg/m <sup>2</sup>	0.060–3.66	1.0	21.2	10.0	0.11–1.11	0.052	0.0031	0.08–20	0.00016	0–240

to the reduction of silicon consumption and other improvements. Reduced silicon consumption has been primarily achieved by reducing the thickness of silicon in the solar cells. Consumption has also decreased (in terms of MJth/kWp) due to improved production processes.

A recent case study of the state-of-the-art Elkem SoG silicon manufacturing facility was undertaken by Glockner et al. (2008). The improved energy efficiency of this facility supports predictions by Alsema et al. (2006) that in the future the embodied energy of mc-Si based PV modules will come down to at least 1800 MJth/m<sup>2</sup>. The future values predicted by Alsema et al. (2006) were based mainly on improvements to the SoG Si process, current trends in the reduction of silicon in wafers and improved efficiencies of solar cells.

Other areas for savings in energy consumption include improving module assembly and reducing the embodied energy of other components of a PV array by using different materials and recycling. Recycling is likely to be imperative in the long term maintenance of very large solar arrays. In addition, a large scale-up in production should produce economies of scale and improved manufacturing setups. As much of the present technology for the production of PV silicon is identical to that used in the semiconductor industry, this should lead to more rapid improvements in manufacturing technology (Pearce, 2008). In terms of recycling PVcycle is now established in Germany and is being expanded to other countries (PVcycle, 2009).

The improvement process could give an optimistic possible future embodied energy of as low as 1500 MJth/m<sup>2</sup> for a PV module. For the purposes of this paper two sets of numbers will be used for a full array, with BOS including inverters and transformers, these are as follows:

- an optimistic range from an embodied energy of 3500 MJth/m<sup>2</sup> in 2010 down to a future value of half this or 1750 MJth/m<sup>2</sup> by 2050.
- A pessimistic range from 7000 MJth/m<sup>2</sup> in 2010 down to half this or 3500 MJth/m<sup>2</sup> by 2050.

No estimates are used for transmission and storage embodied energy components at this stage, as both the transmission technologies and possible location of large land based arrays are largely undecided. It might be noted, however, that the IEA PVPS task 8 (2003) report, Kurokawa (2003), suggested only around 10% of the total embodied energy for the array, including BOS, would be needed for long distance transmission.

#### 2.14. Comparison with wind energy

In terms of installed capacity, wind energy is about an order of magnitude ahead of solar PV as of 2010. In terms of embodied energy the documentation situation is similar, with various papers suggesting the embodied energy content of wind turbines is between 15 and 30 GJth per kW installed (Crawford, 2009; Lenzen and Wachsmann, 2004; Tremeac and Meunier, 2009). The corresponding values given earlier for solar PV are between 20 and 40 GJth per kWp. The differences are that wind generally has a somewhat higher utilisation factor, producing between 15% and 30% of the time whereas solar at 1000 kWh/kWp amounts to 11%

and solar at 1700 kWh/kWp amounts to 19% (Northern and Southern Europe, respectively). These values can be compared to thermal generation, which has averaged 42% over the last decade, hydro, which has averaged 37%, and nuclear with a very large 70% utilisation factor (EIA, 2009). Wind generators, however, are generally thought to have a shorter lifetime (20 years) than PV (30 years). Thus overall the EROEI for wind and PV tend to be similar. In the longer term, however, there appear to be more avenues to improve the EROEI for PV than for wind, which is further down the development path. In this paper the optimistic long term embodied energy for crystalline silicon PV has been taken as 7 GJth/kWp (that is 1750 MJth/m<sup>2</sup> at 25% cell efficiency). Thus in terms of investigating a transfer to renewable sources of energy the embodied energy requirements of PV are a reasonable proxy for wind.

### 3. Methodology

A simple model of the future growth of world PV installed capacity and the associated energy and mineral resource requirements was constructed. The input variables were adjusted to create different possible scenarios. Limits on critical inputs were imposed in the different scenarios to simulate resource and energy supply constraints.

The central aspect of the model is the calculation of new PV manufactured each year. This manufacture includes the embodied energy needed to make the materials for the arrays and the material resources required. If the calculated embodied energy is equal to or greater than a set percentage of the annual total world electricity production (typically set at 10%), the model limits the production of new PV so that the embodied energy used equals the set percentage of world energy production. The arrays are assumed to be deployed in the year after manufacture. The electricity produced by the new PV and incumbent arrays is then calculated and compared with that needed by the worldwide electricity system. If the total PV generated electricity is greater than the world supply, excluding nuclear and hydro, the renewable (PV) production is limited to 100% of that supply. The starting growth rate of new PV is entered for each decade starting from 2010 in order to make the model simpler to use. The growth rates in the years in between the decade intervals are linearly interpolated from the start rate of one decade to the start rate for the next decade in order to remove step changes. The use of discrete growth rate percentages means the growth of PV deployment can be adapted more easily to scenarios which predict distinct changes in direction (e.g. the peak oil scenario).

Installed PV capacity is programmed to stop generating electricity after the system lifetime, which is taken to be 30 years. After this time the retired PV capacity is replaced with new arrays. The electricity yield is calculated using a performance ratio of 0.75, which is based on a comparison of the rated output of modules with studies of the actual measured output of PV arrays. No allowance is made for degradation of the array output over time.

#### 3.1. World electricity demand

In terms of modelling future energy demands there is a wide range of possibilities on offer in the literature. These range from

the pessimistic collapse and regression of society to pre-industrial stages (Holmgren, 2009) to the optimistic where growth continues as usual or even accelerates (Pernick and Wilder, 2008). Some authors believe that renewable energy will not be able to sustain our current standard of living. According to Trainer (2007) for our standard of living and our energy supply to become sustainable our society will have to use a fraction of our current rate of resource use. He suggests our current economic system must change from being growth and profit driven to providing efficiency and sustainable consumption. In Holmgren's 2009 book "Future Scenarios" peak oil and climate change are used to explore four possible future scenarios for humanity.

As pointed out by Trainer (2007) the prospect for renewable energy supplying a constantly increasing world energy demand over the long term is dubious to say the least. Nevertheless the established agencies continue to predict an increasing demand for both world energy and world electricity for the "foreseeable" future (EIA, 2009). Such predictions are becoming increasingly suspect in relation to indications for the curtailment of the supply of critical fossil fuel energy resources, especially oil (Alekkett et al., 2010; Jakobsson et al., 2009; Hirsch, 2008).

In this research the EIA (2009) business as usual world electricity demand projections are used in the model as the business as usual (BAU) scenario. These projections are only until 2030 and postulate a constant increase of 2.4% per annum in world electricity production to 2030. The BAU scenario used here, rather implausibly, gives a 2.4% increase for the rest of this century, but starting in 2010 with the past decade long average rate of 3.2% per annum. A separate growth rate is used for hydro and nuclear at exactly half of the total world rate (i.e. starting at 1.6% p.a.), as per the last decade average (1996–2006) for these two sources combined (EIA, 2009). The growth rates between decades is interpolated linearly, i.e. if the 2010 rate is 3.2% per annum and the 2020 rate is 2.4% per annum the rates for the years in between will be a linear interpolation between 3.2% and 2.4% p.a.

A more modest growth rate scenario is added that suggests growth will slow down to 1% per annum by 2060. There is of course good reason why agencies such as the EIA only forecast ahead 20 years, as longer times are increasingly uncertain. Nevertheless the sort of timeframes necessary for a transition to RE are likely to be longer than this horizon and so longer timeframes need to be explored, albeit with the requisite uncertainty.

In addition a peak oil scenario is considered whereby after 2020 the growth in electricity demand is suggested to follow the decline in oil production, which is estimated to be around 4% per annum in the collapse scenario (Hirsch, 2008) and stabilize at 0% by 2020 in the recovery scenario, after a fast-track PV deployment corrects the world economy.

The electricity demand in terms of climate change impacts is quite uncertain but is likely to produce an economic downturn that will curtail world economic growth again to 0% after 2030. As the modelling for this particular scenario will only look at the possibility of entirely replacing fossil fuels by 2030, the growth

after that date is not applicable (na). A summary of the electricity demand growth scenarios is given in Table 6.

### 3.2. Material resources

As mentioned earlier the USGS (2009) data for world metal production have been used for both annual production and for total world reserves. These are reproduced in Appendix A, Table A1.

### 3.3. Scenarios for PV production growth

Four base scenarios are used to explore the limitations to large scale PV production. Each scenario is based on four different rates of postulated growth of PV demand. Each scenario can have an associated electricity demand growth or decline and each can have either optimistic or pessimistic parameters regarding PV characteristics and embodied energy. The rates given are the starting dates and are linearly interpolated throughout the decade as has been done for the electricity growth rates.

### 3.4. Moderate deployment scenario

The moderate scenario is used to explore the limits to growth with business as usual. This scenario is based on the EPIA (2008) reports' 'moderate scenario', extrapolated into the future. Note that the actual average growth rate for PV deployment has been 39% for the last five years or so; thus the moderate rate set at 32% in 2011 declining to 26% in 2020 is indeed modest.

### 3.5. Two peak oil scenarios (fast-track and collapse)

The peak oil scenario is used to explore what will happen if the global supply of energy is severely restricted. The demand for energy is assumed to decrease at about the rate of decline of world GDP or around 4% per annum (Hirsch, 2008). In addition, the availability of funding for PV production is likely to decline but it is not known if the decline in fossil fuel energy will force the world to fast-track PV production or constrain it to decline with the world economy. Thus two possibilities are suggested: a collapse condition whereby PV production declines by 4% per annum and a fast-track scenario where PV stays at previous rates or better. In the latter case it is assumed that the world economic situation improves and produces electricity growth rates, as given in Table 6, for the PV recovery scenario.

### 3.6. Climate change scenario

According to some scientists, Hansen et al. (2008), in order to avoid serious consequences from climate change all coal fired power stations in the world must be shut down by 2030. The climate change scenario explores if photovoltaic arrays can be deployed sufficiently quickly (in terms of embodied energy requirements) to replace the current supply of energy from fossil

**Table 6**  
World electricity growth scenarios.

Years	BAU (EIA, 2009) extended (%)	Modest growth (%)	Peak oil collapse (%)	Peak oil recovery (%)	Climate change
2010	3.2	3.2	3.2	3.2	3.2%
2020	2.4	2.0	0.0	0.0	0.0%
2030	2.4	1.8	−4.0	0.0	0.0%
2040	2.4	1.5	−4.0	0.0	na
2050	2.4	1.3	−4.0	0.0	na
> 2060	2.4	1.0	−4.0	0.0	na



fuel fired power stations by 2030. A summary of the PV deployment rate for each of the four scenarios is given in Appendix A, [Table A2](#).

### 3.7. PV array parameters

Various PV array characteristics have been used based on the previous discussion. The values are for the starting dates and are linearly interpolated throughout the decades in the same manner as is done for the electricity growth rates. A summary of the inputs used in each scenario is provided in Appendix A, [Table A3](#).

Tables A4–A7 in Appendix A show the EROEI for the possible array structures traverses a range (approximately an order of magnitude) from 6 to 55 depending on the choice of array yield, panel parameters, cell efficiencies and array embodied energy. Note that for the high end, the EROEI is around half of that for the 'easiest' oil available in the Middle East. The corresponding energy payback times range from 5.4 years to 0.5 years.

*Total other resources:* [Table A8](#) in Appendix A gives a summary of the total other resources used for arrays including BOS (fixtures, transformers and inverters).

### 3.8. Global limitations for each scenario

The model assumes that around 1% of the world's total land or 1,500,000 km<sup>2</sup> could be made available for PV sites. By comparison the world's arable land area is approximately 10 times this value. The model can also be made to limit embodied energy consumption in array production to a fixed percentage of the world electricity supply, up to 100%. Once this limit is reached the PV production automatically is adjusted so that the % is kept constant. In most cases this percentage is set to 10%. In addition once the PV contribution to world electricity including supplying the embodied energy for the arrays reaches a set percentage of the world production (excluding nuclear and hydro) the PV deployment is adjusted to keep the contribution at that set level (usually 100%). In the scenarios where electricity demand decreases, it has been assumed that the hydro and nuclear capacity remains constant and the thermal capacity is reduced with demand.

In terms of resources it has been assumed that the production of arrays would not be limited by the availability of a particular resource but that the date at which the set % of either 2008 annual production or 2008 world resources was reached is flagged.

### 3.9. Other inputs to the model

*Solar regime:* Two values were considered for the irradiance of PV arrays, namely 1000 and 1700 kWh/kWp per annum, roughly corresponding to generation in northern and southern Europe, respectively.

*Starting points:* The installed PV capacity to 2008, according to [EPIA \(2009a\)](#), was 14.7 GWp and the annual production in 2008 was 7.4 GWp with a sharp but not yet quantified downturn in 2009. The starting GWp was thus assumed to be 20 GW (i.e. 5.3 GWp of the 7.4 GWp produced in 2008 being actually installed) and the starting annual production was assumed to be 5 GWp per annum in 2010 (this is the same annual production as existed in 2007).

### 3.10. Module cost

Although the analysis is primarily concerned with energy and material constraints it has been easy to add in basic cost factors to see what proportion of the world GDP would be needed to effect the transition. It has been assumed that the world GDP increases

(or decreases) at the same rate as world electricity production in each of the scenarios. Two cost structures were used for the analysis: a high cost option, assuming a starting price of US\$4 per Wp of module (installed) and US\$2 per Wp for the BOS (installed), with the module cost reducing to US\$2/Wp by 2040; and a low cost option, assuming half of these costs, as shown in the table below. These costs represent a reasonable spread from expectations in the industry and in any case, if they are doubtful, the final cost is linear with PV deployment. It is certainly possible that peak oil and higher future energy costs will actually increase the cost of the BOS and possibly the arrays. [Table A9](#), in Appendix A, summarizes the cost structure used with all dollars in US\$ in constant 2010 terms.

### 3.11. Scenarios summary

Because this paper tries to cover all possibilities the options examined are complex and thus need to be summarized:

*Four World electricity growth/economic growth options* as given in [Table 6](#):

- **ebau**, business as usual
- **emod**, modest growth
- **epoc**, peak oil collapse
- **epor**, peak oil recovery (same as climate change ECC)

*Four growth options for PV deployment options* as taken from [Table A1](#):

- **pvm**, moderate growth
- **pvpoc**, peak oil collapse
- **pvpofit**, peak oil fast-track
- **pvcc**, climate change

*Two array technology options*, which define panel efficiencies and embodied energy, are given in [Table A3](#):

- **opt**, optimistic: high efficiency low embodied energy
- **pes**, pessimistic: low efficiency, high embodied energy

Two options for irradiance levels:

- **hy**, a high irradiance 1700 kWh/m<sup>2</sup> per year (roughly corresponding to southern Europe or central Asia)
- **ly**, a low irradiance 1000 kWh/m<sup>2</sup> per year (roughly corresponding to North Europe or Southern New Zealand)

In addition we have *two scenarios for panel cost* as shown in [Table A9](#):

- **hc**, the high cost option
- **lc**, the low cost option

These options will be examined in terms of the scenarios for world electricity growth and economic growth. Obviously many more options are available but of course as the number increases the complexity of the analysis goes up. It is thought that the available options would cover most eventualities and as mentioned earlier it could also cover the circumstance of mixed renewable generation with wind, biomass, other solar PV technologies and solar thermal.

## 4. Results

The model calculates the kWh produced by the various sources (PV, fossil fuel, solar and hydro and nuclear combined), the energy required by the world and the embodied energy needed as a function of time, the maximum installed capacity of PV needed in GWp, the area that this would cover (as a % of 1.0% of the world's land area) and the average and maximum (yearly) % of GDP that the array deployment would cost. In addition, the times that the specified limits are reached are calculated.

### 4.1. BAU electricity demand growth rates scenario grouping

*First the BAU electricity growth—moderate PV deployment:* These scenarios start with a 3.2% annual growth rate in electricity demand, dropping to 2.4% by 2030 and continuing at this increase until 2100. This scenario sees annual world electricity demand soar from around 20 trillion kWh in 2010 to 60 trillion kWh in 2050 and 200 trillion kWh by 2100, a total ten-fold increase. This scenario is very close to the Baseline Scenario in the IEA produced 'PV in the Deserts' report (IEA, 2008), i.e. 2.2% p.a. growth in demand up until 2050.

*Pessimistic panel parameters:* see Appendix B, Fig. B1. With PV embodied energy limited to 10% of world electricity production and under the pessimistic option for the technology, the PV supply can get to 78% of world demand by 2100, in the low yield scenario and to 90% in the high yield scenario, which would supply all world electricity demand (excluding nuclear and hydro) and the embodied energy requirements in both cases. The final installed PV capacity would need to be 209,000 GWp in the low yield case and 135,000 GWp in the high yield case (compared with 133,000 GWp in Komoto et al. (2009) report). The embodied energy requirements by 2100 in the low yield case would be around 20 trillion kWh per annum, which would still require an installed thermal capacity of around the same as in 2010, i.e. 5000 GW. In the high yield case all thermal generation could be retired by 2050. By the end of the time period (2100) 95% of the maximum land area suggested (i.e. 100% is 1% of world land surface) or 1.4 million km<sup>2</sup> would need to be covered by arrays in the low yield case and 61% or 0.92 million km<sup>2</sup> in the high yield case (allowing for 20% spacing between panels). Thermal generation would peak in 2040 in the low yield scenario using 7000 GW plant capacity to produce some 28 trillion kWh and would only need to be increased slightly above 2010 levels in the high yield case. By 2040 the embodied energy requirements of the PV would reach 10% of world electricity supply.

The material constraints for BAU growth and pessimistic array technology are very severe with silver demand for panel production reaching 10% of annual world demand by as early as in 2012, aluminum by 2025, copper by 2027 and steel by 2037. While silver could be substituted for and the demand for aluminum reduced by using frameless panels and other metals for the supports, the constraints on copper and steel would be more serious. By 2050 the annual demand for copper for panel and BOS requirements would reach 100% of 2008 production levels and by the end of the century close to the total 2008 known world copper reserves would be required. And as mentioned the model does not include transmission and storage requirements. The annual demand for steel would exceed 50% of 2008 annual production by 2082 and concrete by 2082. By 2042 the copper used for arrays and BOS would come to 10% of total world resources and if silver was used for panel contacts 100% of the world supply would be needed by as early as in 2028. The above does not include recycling of the arrays after a 30 year life but in scenarios where the panel deployment is increasing at around

14% per annum recycling could only supply about 1% of the needed embodied energy and materials.

In terms of cost, the above cases would require a relatively modest maximum of around 7% of world GDP by 2053 for the high cost option and roughly half this for the low cost option. Note that with oil at US\$100 per barrel the world energy bill for oil alone would be around 5% of world GDP (2008).

*Optimistic panel parameters:* With the optimistic panel parameters the situation improves considerably, on the energy side at least, with the PV able to substitute for all thermal generations by 2055 under the low yield scenario and before 2040 under the high yield scenario. This effort would require 72% of the 1.5 million km<sup>2</sup> under the low yield scenario and 43% under the high yield scenario. In terms of embodied energy, the improved situation would mean that for the low yield case only 7% of the world's electricity supply would be needed to make the arrays by 2054 and 5% needed for the high yield case by 2047.

Material constraints would, however, still be severe, with around 220,000 GWp of installed PV capacity being needed by 2100 in the low yield case and 132,000 GWp for the high yield case. That is between 26 and 44 times the 2010 installed total world capacity of 5000 GW. The arrays would occupy around 43% of the suggested land area under the high yield option and 72% under the low yield option. This area would be 0.043% of the world land area (i.e. 645,000 km<sup>2</sup>) or roughly twice the size of New Zealand, in the case of the high yield option and even greater under the low yield option. Assuming silver and aluminum demand could be reduced, the need for copper would reach 10% of world 2008 production by 2029 (high yield) and steel by 2041 (high yield). Copper demand would exceed the 2008 annual demand by 2073 and annual steel demand would reach 36% of world 2008 annual demand by 2100.

Finally for the high cost case the world economy would be strained as the low yield option would cost nearly 14% of world GDP and the high yield case nearly 10%. Note that these percentages for the optimistic panel parameter case are higher than those for the pessimistic panel parameter case because the installed array GWp is deployed faster in the former case when world GDP is smaller. See Appendix B, Fig. B2 for a typical model output for this set of scenarios.

### 4.2. Modest electricity demand growth rates scenario group

These scenarios see a more modest annual demand for future electricity, decreasing from 3.2% p.a. in 2010 to 1% p.a. by 2060 and thereafter at a constant 1% p.a. This situation would see world electricity demand increase from around 20 trillion kWh in 2010 to 44 trillion kWh in 2050 and to nearly 80 trillion kWh by 2100, a total fourfold increase. This demand scenario is close to both the ACT Map scenario and the Blue Map scenario in IEA (2008), which both see electricity demand to rise to around 42 trillion kWh by 2050.

*Pessimistic panel parameters:* With PV embodied energy limited to 10% of world electricity production and under the pessimistic option for the technology, PV could replace all thermal generation by 2060 in the low yield scenario and by 2050 in the high yield scenario. By the end of the century, 41% of the allowable land area would need to be devoted to PV arrays in the low yield case and 24% in the high yield case. This effort would cost a maximum of 7% of world GDP, assuming world GDP increases at the same rate as electricity demand, and would require 10% of world electricity by 2040 in both cases to manufacture the panels and BOS.

Similarly for this group of scenarios, the material constraints would be difficult. Between 90,000 GWp (low yield) and 53,000 GWp (high yield) installed PV capacity would be required needing 10% of world (2008) annual demand for silver resources

by as soon as 2012, aluminum by 2025, copper by 2027 and steel by 2038. Similarly, assuming the silver and aluminum constraints could be alleviated as before, the copper and steel demand could still remain a problem. Appendix B, Fig. B3 gives a typical model output for this group.

**Optimistic panel parameters:** With the optimistic panel parameters the situation again improves on the energy side, with the PV able to provide 100% of world demand by 2055 under the low yield scenario and by 2045 under the high yield scenario. Material constraints are still severe, however, with a very large 86,000 GWp (low yield) and 51,000 GWp (high yield) of installed PV capacity being needed by 2100. The arrays would occupy around 17% of the suggested land area under the high yield option and 28% under the low yield option. The need for copper would reach 10% of world 2008 production by 2029 (high yield) and steel by 2042 (high yield). Appendix B, Fig. B4 gives a typical model output for this group.

#### 4.3. Peak oil scenarios

As suggested, two possibilities are explored, one where PV deployment follows the economy and declines at the same rate as GDP, which is the same rate as oil supply decline, i.e. 4% per annum (collapse), and the other whereby PV deployment is given priority and proceeds at an accelerated deployment rate (fast-track).

##### 4.3.1. Peak oil collapse

Even for the high yield case with optimistic parameters for the panel efficiency and embodied energy this situation gives a predictable outcome whereby world energy demand drops to just over 1 trillion kWh by 2100 of which solar PV supplies around 17%. The peak PV deployment occurs around 2043 when 1140 GWp is deployed or 50 times the 20 GWp installed in 2010. This scenario is certainly feasible in the sense that no material or other limits are breached but it also gives a very dire future for civilization. In this situation there is not much difference between the outcomes for the pessimistic panel parameters option and the optimistic one.

##### 4.3.2. Peak oil fast-track renewables

In this scenario it is suggested that despite a downturn in world GDP and corresponding downturn in electricity demand the world acts quickly to fast-track PV deployment to alleviate world

energy shortages. If the pessimistic panel parameters are used then the PV contribution climbs to around 65% of world supply just before 2040 for the high yield case and to the same percentage just before 2050 for the low yield case. In both cases this would enable all thermal generation to be retired by about the same dates. Only 12% of the allocated land area or 180,000 km<sup>2</sup> would be needed but there are material limits other than silver and aluminum, as copper demand reaches 10% of the world annual supply by 2024 and 50% of world annual supply by 2050. Steel reaches 10% of world annual supply (2008) by 2042. Fig. B6 in Appendix B gives a typical model output for this set of scenarios

For the optimistic high yield scenario group the situation improves considerably. In this case fossil fuels could be eliminated by 2035 with PV installed capacity stabilizing at close to 14,000 GWp by the same time. This capacity would take up around 5% of the allowed land area or 68,000 km<sup>2</sup>. In this case copper would not reach 10% of world demand until 2086, by which time it could be largely obtained by recycling old systems and infrastructure. The demand for steel reaches close to 10% of world (2008) annual supply by 2093 but again this limit could be circumvented by using recycled material. Silver and aluminum remain problematic and their use would have to be worked around to allow this scenario to run out. The cost, however, may be prohibitive, reaching 13% of world GDP early in the 2020s and averaging 2.4% to 2100 in the high cost scenario and roughly half in the low cost scenario. Fig. B7 in Appendix B shows a typical output of the model for the collapse scenario.

#### 4.4. Climate change scenarios

This group of scenarios explores the same demand scenario as above but here the growth rate in panel deployment has been increased and the limit of embodied energy demand for arrays as a % of world electricity demand, relaxed, to see if the deadline set by some climate scientists of 2030 for the retirement of all fossil fuel electricity generation can actually be reached.

If pessimistic panel parameters are used, however, the world would need to devote 40% of world electricity to fabricate the arrays in order to retire all fossil fuels by 2030 if arrays are located in low yield situations and 20% of world electricity for high yield locations. For low yield locations the growth rate in PV deployment for the next two decades would need to be close to

**Table 7**  
Summary of main outputs.

Inputs				Outputs					
Electricity demand	PV deploy	Panel	Array yield	2100 installed (GWp)	2100 installed array area <sup>a</sup> (%)	Max GDP (%) <b>hc</b> <sup>b</sup>	Embodied energy (%) of world electricity demand (date)	Cu 10% limit date reached	Fe 10% limit date reached
ebau	pvm	pes	ly	210,000	95	7.0	10% (2041)	2027	2037
ebau	pvm	pes	hy	135,000	61	7.4	10% (2042)	2027	2038
ebau	pvm	opt	ly	220,000	72	13.7	7% (2054)	2029	2041
ebau	pvm	opt	hy	132,000	43	9.8	5% (2047)	2029	2061
emod	pvm	pes	ly	90,000	41	7.2	10% (2041)	2027	2038
emod	pvm	pes	hy	53,000	24	6.8	10% (2041)	2027	2066
emod	pvm	opt	ly	86,000	28	12.8	7% (2052)	2029	2067
emod	pvm	opt	hy	51,000	17	8.5	5% (2046)	2029	2095
epoc	pvpoc	pes	ly	160	≈ 0	0.3	10% (never)	never	never
epoc	pvpoc	opt	hy	160	≈ 0	0.3	10% (never)	never	never
epor	pvpof	pes	ly	26,000	12	6.5	10% (2074)	2024	2074
epor	pvpof	opt	hy	14,000	5	13.1	7% (2094)	2086	2093
epcc	pvcc	pes	ly	39,000	17	30.1	65% (2030)	2053	2088
epcc	pvcc	opt	hy	15,000	5	13.2	11% (2027)	2052	2086

<sup>a</sup> The area is a percentage of 1.5 million km<sup>2</sup>—which is 1% of the earth's land surface.

<sup>b</sup> The low cost scenarios (**lc**) are approximately half the high cost (**hc**) scenarios and so are not listed separately.

60% p.a. and for the high yield case 50% p.a. While such an increase is consistent with recent growth rates it will be harder to maintain in the next decades as materials limitations would also be severe with demands for copper reaching 10% of world annual supply by 2021 and steel by 2025, even for high yield locations. In addition, for the low yield case new fossil fuel plants would need to be built just to cope with the increase in embodied energy needed to fabricate the panels (15 trillion kWh p.a. at the peak in 2027). The cost would amount to 30% of world GDP (low yield) in 2024 in the high cost scenario and half this in the low cost scenario, meaning that these possibilities would be unlikely to play out.

For optimistic panel parameters the situation again improves considerably, indicating the crucial impact of embodied energy and panel efficiency on the outcome. Here for the high yield case, less than 10% of world electricity would be needed for the transition to allow all fossil fuel electricity generation to be retired by 2030. The equilibrium array capacity would get to nearly 15,000 GWp by the same date, taking up 5% of the specified land area or a little over 71,000 km<sup>2</sup>. Material limits would be reached, but in this case they would not be severe (except for aluminum and silver) as they would occur when panel recycling could take place. The race to remove fossil fuels would, however, cost a peak of 13% of world GDP by 2025 in the high cost scenario and 6.5% in the low cost scenario. Fig. B8 in Appendix B gives a model output for this set of scenarios.

#### 4.5. Summary of results

Table 7 summarizes the outputs for the main scenarios.

### 5. Discussion and conclusions

The first thing to be seen from the results of the modelling exercise is that the scenarios that encompass business as usual growth to 2100 all come to serious grief in terms of material limits. In this respect our analysis has more in common with that of Trainer (2007) than that of the IEA or EIA, who in general mostly posit continuous growth scenarios, at least out to 2030. The moderate growth scenarios giving an increase in supply of around four times 2010 levels may be just possible in terms of resources, if intensive recycling of materials is incorporated, but would require stabilization in demand growth soon after 2100, if limits were to be avoided in the next century. This latter scenario outlook is similar to that put forward in the IEA Blue Map (IEA, 2008). In such a case, however, avoiding the prospect of continuous economic growth (past 2030) requiring a continuous growth in energy supply and the associated environmental problems, however, will remain the more difficult of the challenges that the world would have to face (Lloyd, 2009a). And again we must remember that because storage and transmission has not been incorporated into the model, the results are only a lower bound and that additional energy and resources would be needed to smooth supply. The above conclusions suggest that expanding the world electricity supply anything beyond around 4 times its present extent would be exceedingly difficult using silicon solar PV technologies and probably difficult using any RE technologies due to the very large material requirements. On the other hand it is

highly likely that resource difficulties would arise in any case if the world electricity system is expanded beyond 2100 BAU requirements using even existing technologies.

The above growth orientated scenarios, specifically, ignore climate change and the economic problems that the limits to fossil fuel supply and environmental disruption will incur, and so are inherently improbable. The peak oil collapse scenarios do not cross any physical limits and so are certainly possible; it just remains to be seen in terms of world politics and foresight if these are probable. The peak oil fast-track scenarios have some resource limitations and the probability of eventuating would depend on large scale intervention and whether the optimistic panel parameters and low cost scenarios come into play. If so the world could stabilize its electricity supply at a level similar to the 2010 supply for between 3.5% and 6.5% of world GDP, if the panels were located appropriately. The climate change scenarios show that reaching 100% PV supply by 2030 would be clearly impossible in the case where the pessimistic predictions for panel parameters eventuate but could just come about if the optimistic predictions eventuate and panels were located in high sun regions, but at a cost of between 6.5% (lc) and 13% (hc) of world GDP depending on the deployment cost outcomes.

The bottom line is that from a materials and technology viewpoint, if the storage problem is solved or the world demand system is reconfigured to accommodate a partially intermittent supply, it is likely that silicon PV technologies, in conjunction with other renewable energy sources, including large scale hydro, other solar technologies and wind energy, could replace the current (2010) electricity supply system. There is some scope for expansion of such a supply but unless a steady state economic system is soon put in place, overshoot is thought inevitable. The political and social decision to embark on such a transition, however, is likely to be restrained by vested interests and the social inertia present in current technologies (Sovacool, 2009). Our conclusions thus concur with those of Trainer (2007) in that it is highly unlikely that the world can produce sufficient energy from renewable sources to enable the world's inhabitants to enjoy the current (2010) developed world's electricity consumption.

Finally we are also in agreement with Hubbert (1949) and Daly and Townsend (1993) that fossil fuels should be used strategically to assist the transition and not be wasted just in trying to prop up the world economy. Such a transition could in fact lead to a new world economic transformation, if completed urgently.

### Appendix A. Model inputs

#### A.1. PV array embodied energy data

Tables 10a–d show the embodied energy in terms of the PV module efficiency, PV array embodied energy (both as MJ thermal/m<sup>2</sup> and as MWh electrical/m<sup>2</sup>) the energy returned on EROEI and the energy payback time in years (EPBT) as a function of array yield and whether the pessimistic or optimistic panel parameters are chosen. The conversion from thermal (MJth) to electrical energy (MWh) assumes a conversion of 0.35 MJ electrical = 1 MJ thermal, i.e. the EU ratio. The conversion from EROEI to EPBT assumes an array lifetime of 30 years (Tables A1–A9).

**Table A1**

Global annual production and world reserves of required minerals for PV arrays: data from USGS (2009).

Mineral	Aluminum	Steel	Copper	Silver	Lead	Nickel
Global annual production (million metric tonnes)	39.7	1360	15.7	0.0209	3.8	1.61
Global reserves (million metric tonnes)	38,000	230,000	1000	0.57	170	150



**Table A2**

PV deployment rates used for the four future scenarios (note the actual rate may be reduced by the limit on the embodied energy used to make the arrays, as a % of total electricity demand).

Time period	Moderate PV growth (BAU demand) (%)	Peak oil collapse (%)	Peak oil fast-track PV growth (peak oil demand) (%)	Climate change PV growth (climate change demand) (%)
2010	32	40	40	50
2020	26	0	32	50
2030	14	−4	18	50
2040	10	−4	16	na
2050	8	−4	14	na
> 2060	6	−4	12	na

**Table A3**

Summary table of the baseline values used for each scenario for panel parameters.

Time period	Optimistic		Pessimistic	
	Module efficiency (%)	Embodied energy (MJ/m <sup>2</sup> )	Module efficiency (%)	Embodied energy (MJ/m <sup>2</sup> )
2010	14	3500	14	7000
2020	20	2700	15	5400
2030	23	2400	16	4800
2040	24	2000	17	4000
2050	25	1800	18	3600
> 2060	25	1750	18	3500

**Table A4**

Pessimistic panel parameters, low yield.

	PV cell efficiency (%)	PV array embodied energy (MJth/m <sup>2</sup> )	PV array embodied energy (MWh/m <sup>2</sup> )	EROEI	EPBT (years)
Irradiance (1000 kWh/m <sup>2</sup> /yr)	14	5800	564	6	5.4
	15	5000	486	7	4.3
	16	4000	389	9	3.2
	17	3500	340	11	2.7
	18	3000	292	14	2.2
	18	2800	272	15	2.0

**Table A5**

Pessimistic panel parameters, high yield.

	PV cell efficiency (%)	PV array embodied energy (MJth/m <sup>2</sup> )	PV array embodied energy (MWh/m <sup>2</sup> )	EROEI	EPBT (years)
Irradiance (1700 kWh/m <sup>2</sup> /yr)	14	5800	564	9	3.2
	15	5000	486	12	2.5
	16	4000	389	16	1.9
	17	3500	340	19	1.6
	18	3000	292	24	1.3
	18	2800	272	25	1.2

**Table A6**

Optimistic panel parameters low yield.

	PV cell efficiency (%)	PV array embodied energy (MJth/m <sup>2</sup> )	PV array embodied energy (MWh/m <sup>2</sup> )	EROEI	EPBT (years)
Irradiance (1000 kWh/m <sup>2</sup> /yr)	14	3700	360	9	3.4
	20	2700	263	17	1.8
	23	2000	194	27	1.1
	24	1800	175	31	1.0
	25	1800	175	32	0.9
	25	1800	175	32	0.9

**Table A7**

Optimistic panel parameters high yield.

	PV cell efficiency (%)	PV array embodied energy (MJth/m <sup>2</sup> )	PV array embodied energy (MWh/m <sup>2</sup> )	EROEI	EPBT (years)
Irradiance (1700 kWh/m <sup>2</sup> /yr)	14	3700	360	15	2.0
	20	2700	263	29	1.0
	23	2000	194	45	0.7
	24	1800	175	52	0.6
	25	1800	175	55	0.5
	25	1800	175	55	0.5

**Table A8**

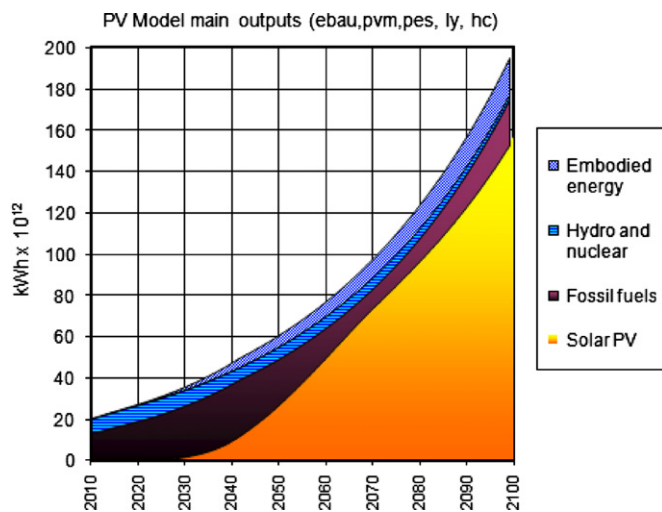
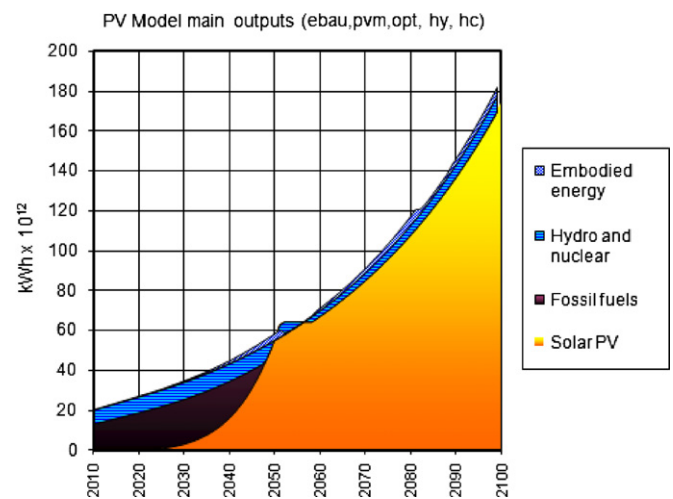
Resources summary for all scenarios.

Mineral	Aluminum	EVA	Water	Glass	Copper
kg/m <sup>2</sup>	3.66	1.0	21.2	10.0	1.0
Mineral	Silver	Lead	Concrete	Nickel	Steel
kg/m <sup>2</sup>	0.052	0.0031	100	0.00016	20

**Table A9**

Cost regimes used.

	High cost		Low cost	
	Module cost (US\$/W)	BOS cost (US\$/W)	Module cost (US\$/W)	BOS cost (US\$/W)
2010	4.0	2.0	2.0	1.0
2020	3.0	2.0	1.5	1.0
2030	2.5	2.0	1.0	1.0
2040	2.0	2.0	1.0	1.0
2050	2.0	2.0	1.0	1.0
> 2060	2.0	2.0	1.0	1.0

**Fig. B1.** Model output for BAU electricity demand, moderate PV deployment, the pessimistic panel parameters and low yield locations.**Fig. B2.** Model output for BAU electricity demand, moderate PV deployment, the optimistic panel parameters and high yield locations.

## Appendix B. Model results

*Note to all model outputs:* the “lumps” in the generation after 2040 are due to the way the model works in replacing modules after their 30 year life. The model calculations result in the embodied energy pattern being repeated every 30 years. In real life

these irregularities would be smoothed out to ensure optimum operation of array manufacturing plant. No allowance has been made for recycling panels as this option would only become viable after 30 years of deployment, but again this option could be used to reduce and smooth out embodied energy requirements after 2040 in scenarios that reach a steady state (Figs. B1–B8).

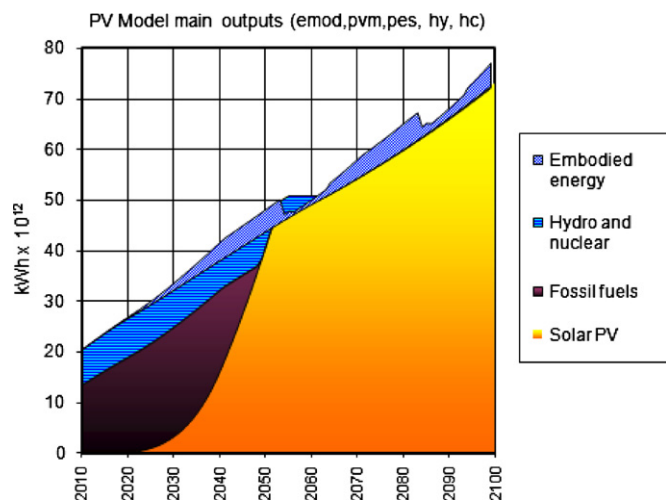


Fig. B3. Model output for moderate electricity demand growth, moderate PV deployment, the pessimistic panel parameters and high yield locations.

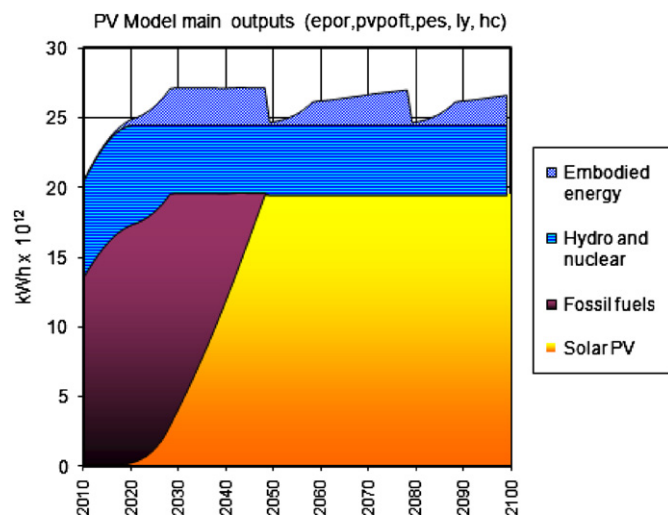


Fig. B6. Model output for peak oil recovery electricity demand, peak oil fast-track PV deployment, the pessimistic panel parameters and low yield locations.

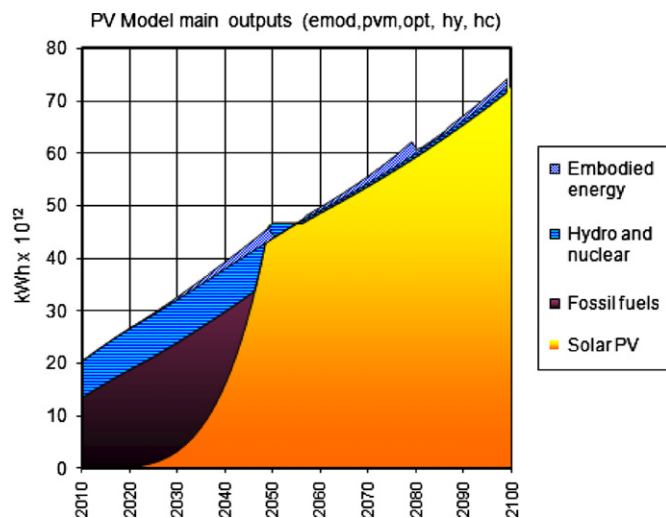


Fig. B4. Model output for moderate electricity demand growth, moderate PV deployment, the optimistic panel parameters and high yield locations.

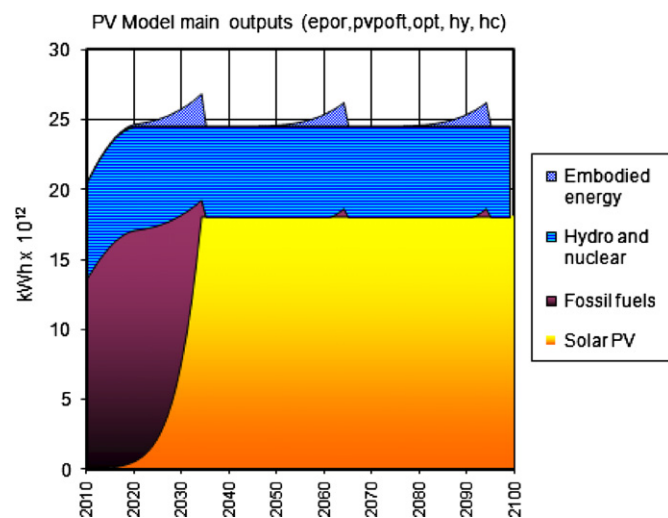


Fig. B7. Model output for peak oil recovery electricity demand, peak oil fast-track PV deployment, the optimistic panel parameters and high yield locations.

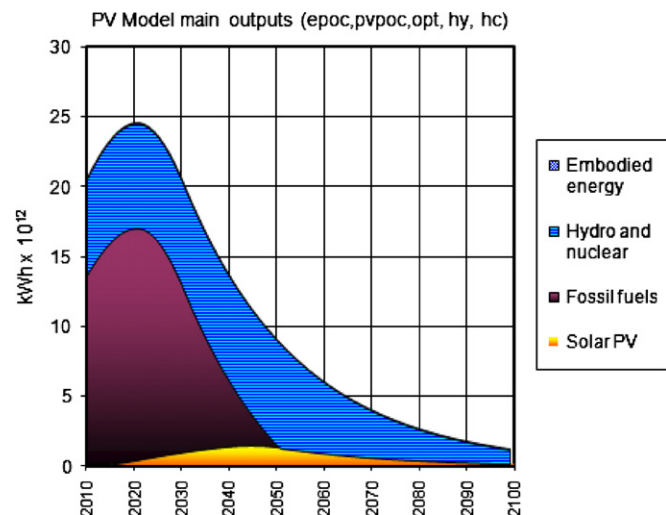


Fig. B5. Model output for peak oil collapse electricity demand, moderate peak oil collapse PV deployment, the optimistic panel parameters and high yield locations.

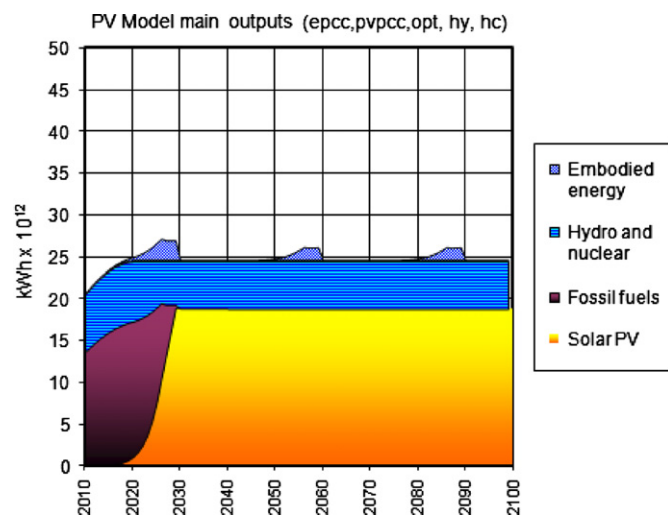


Fig. B8. Model output for climate change electricity demand, climate change PV deployment, the optimistic panel parameters and high yield locations.

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