Future of Energy: Powered by Solar

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Abstract. Solar energy, radiant light and heat from the sun, is ubiquitous. It exists everywhere and is available for any one of us to use. Global, sustainable growth could be supported and environmental impacts, caused by the production of electricity, limited by an increased use of solar energy. The daily and yearly solar irradiation is especially high close to the equator and in areas of our globe affected by desertification. However, countries excelling in the areas of investments made in and the use of solar power are high-technology countries located at less optimal latitudes. This paper presents a state-of-art study and discussion of the opportunities and barriers to accelerate the use of solar power. Three interlinked visions are discussed: (1) the 100% scenario assuming that the total global electricity demand could be covered with solar energy only, (2) the global-electricity-grid scenario suggesting a global electricity market supplied by large-scale photovoltaic plants, and (3) the energy-for-all scenario presenting wide-scale adoption of solar technologies as a means to tackle climate injustice and change by entering current nonconsumer markets.

Keywords: solar energy, photovoltaics, electricity, climate change, future

1 *Introduction*

Solar energy is ubiquitous. It exists everywhere on the globe. Germany made the headlines in early June 2014 by being able, for the first time, to cover more than 50% of the country's electricity demand with energy collected via photovoltaic panels [1]. From a global perspective, the equivalent percentages are very low. Why is the market share for solar energy not bigger? What are the current barriers and opportunities? How would a substantial increase in the use of solar power impact our future?

Solar energy can be defined as radiant light and heat from the sun. The concept of the use of solar power in this paper refers to the direct collection, use, and distribution of solar energy by implementing active solar technologies, such as photovoltaic (PV) panels, for electricity production. This paper presents a state-of-the-art study and discussion of the feasibility of accelerating the use of solar power. The discussion is based on a literature review, interviews, and data collection.

2 *State of the Art*

2.1 Solar-Powered Technologies for Electricity Production

The generation of electricity from solar power is based on the photovoltaic effect: the capacity of materials (semiconductors) to generate electricity when exposed to solar radiation. When exposed to sunlight, electrons are emitted from the materials, and the electrons remaining in the materials create positive and negative bands that can be employed by electrical circuits. Until 2014, crystalline silicon (Si) was the most prevalent material for the production of PV cells, accounting for 62% of all modules produced (Figure 1 [2]). Currently, thin-film technology and other emerging technologies are gradually taking up more market share.

With the progress of PV technology, the production of solar cells is increasing yearly, with Asian Pacific areas as the leaders. The majority of PV cell installations are still located in European countries (see Figure 2) [3]. However, it is predicted that by 2020 installations in the regions of Asia Pacific and Europe will reach equal levels.

2.1.1 Materials and Manufacturing

Silicon is the leading material in producing solar cells due to its high efficiency and abundance in earth's crust. Monocrystalline silicon panels are manufactured from single-crystal silicon cells connected with each other. Polycrystalline silicon panels are made up of multiple-crystal cells that largely decrease the efficiency of absorbing solar radiation. The cheap price and easy installation of polycrystalline panels may contribute to their growing market share; however, they are not as efficient panels made of monocrystalline silicon. Figure 3 [4] shows a comparison of the structures of both types of cells.

Two technological strategies have been suggested to increase the module efficiency of crystalline silicon solar cells: (a) decreasing the impurity level of silicon feedstock to reduce the energy payback time and eco-toxicity associated with silicon production [5] and (b) eliminating the use of wafer sawing to help avoid the 50% loss of silicon as sawdust [6].

Numerous alternatives for producing solar cells are being investigated, with a focus on thin-film material (Figure 4 [7]), organic/polymer material, dye-sensitised material, and carbon nanotubes. These are listed and compared in Table 1. To some extent, thin-film material can be considered as a substitution for silicon because of three technological benefits: (1) it employs solar radiation efficiently; (2) it possesses lower temperature coefficients—that is, its power output does not drop quickly when it accumulates lots of heat; and (3), thin-film modules may be manufactured in a continuous production process [8].

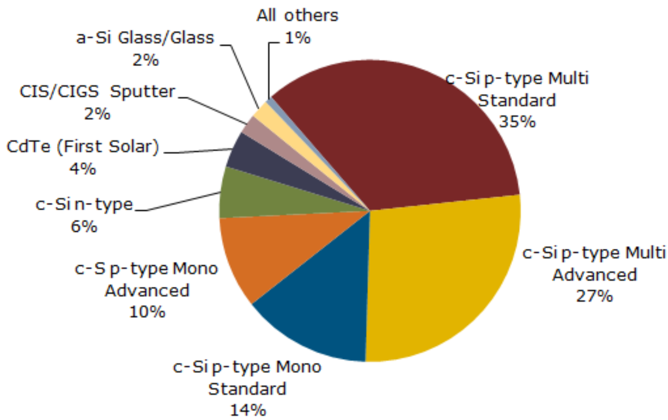

Fig. 1. ***Solar PV module production by technology, 2014 [2]***

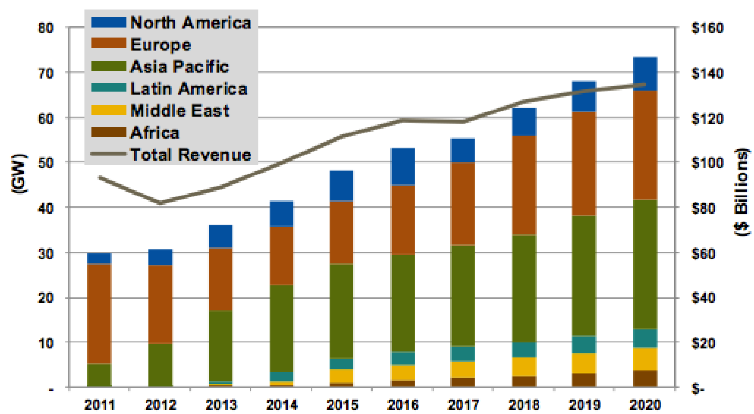

Fig. 2. ***Annual solar PV installation by region, 2011–2020 [3]***

Cadmium telluride (CdTe)-based panels employ a superstrate configuration: Production begins with a glass substrate followed by the deposition of the transparent conducting oxide (TCO, SnO_2: F), the n-type window layer (CdS), the p-type CdTe absorber, and finally the back contact (ZnTe/Cu/C). In terms of large-scale CdTe manufacturing, the issues of cadmium toxicity and telluride availability must be solved. Silicon layers are deposited by plasma-enhanced chemical vapor deposition using mixtures of H_2 and SiH_4 to form amorphous silicon. Despite the advantages of low temperature and low weight during manufacturing, the low cell efficiency and lack of advancements in research largely confine the development of CdTe-based cells [6].

Research on copper indium gallium selenide/copper indium selenide (CIGS) has continued to steadily advance, and this material crossed the 20% efficiency threshold, making it the clear efficiency leader among thin-film technologies [9]. A long-term concern is the availability and price of indium. The recycling of indium will alleviate constraints on CIGS production, but research is needed to develop technologies for efficient and low-cost recycling of all the elements from CIGS modules [6].

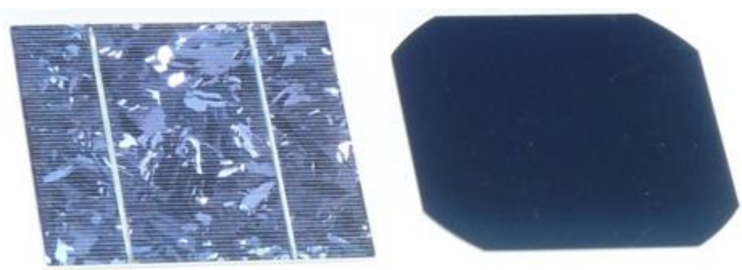

Fig. 3. ***Comparison of solar cells: poly-Si [4]***

Fig. 4. Sample of thin-film solar cell [7]

Concurrently, great attention has been paid to organic/polymer material, dye-sensitised material, and carbon nanotube material. It is easy to prepare dye-sensitised solar cells at a low cost. These cells are semi-transparent, flexible, and durable. What attracts attention is that they perform better than other PV technologies in conditions of low sun radiation and indirect light. Future development should be focused on increasing the efficiency of these cells so that they are competitive with other PV technologies in the commercial market. Sharing similar characteristics with dye-sensitised solar cells, organic and polymer solar cells are easily fabricated into flexible shapes and work in low-sunlight conditions. They can be produced at very low cost in comparison to other PV technologies because they can take advantage of roll-to-roll production techniques in which the organic photovoltaic system is 'printed' onto a continuous sheet of substrate material [10]. Their application in charging electronic devices, for example, backups, laptop cases, tents, and jackets, is promising. Finally, multi-junction cells are able to achieve high conversion efficiency due to their capability to capture electrons within multiple wavelengths of light, yet they are limited to unique applications in aerospace due to the complex fabrication process and high expense [7].

Table 1. ***List of materials utilised in the production of solar cells.***

Materials		**Advantages**	**Challenges**
Crystalline	Monocrystalline Polycrystalline	High quality, low defect, high efficiency	High consumption of active material (Si)
Thin film	Cadmium telluride (CdTe) Amorphous silicon Copper indium gallium selenide/ copper indium selenide	High material utilisation, lower cost	Scarcity or toxicity of some materials
Organic and polymer	Polymers and large molecules with repeating structural units	Non-toxic, abundant, low cost, short payback, transparent	Optimisation of lifetime-efficiency-cost tradeoff
Dye sensitised		Environmentally friendly	Low efficiency
Carbon nanotubes			
Multi-junction	One, two, three or more junctions; gallium arsenide (GaAs)	High efficiency	Complex fabrication process, narrow application range

2.1.2 Concentrated PV and Thermal (PVT) Integrated System

Known by a variety of names, such as concentrated photovoltaic thermal (CPVT), combined heat and power solar (CHAPS), or most simply combined heat and power (CHP), these integrated systems capture the wasted heat energy from the photovoltaic system and store it in a heat transfer fluid, such as water, for direct use. CHP systems

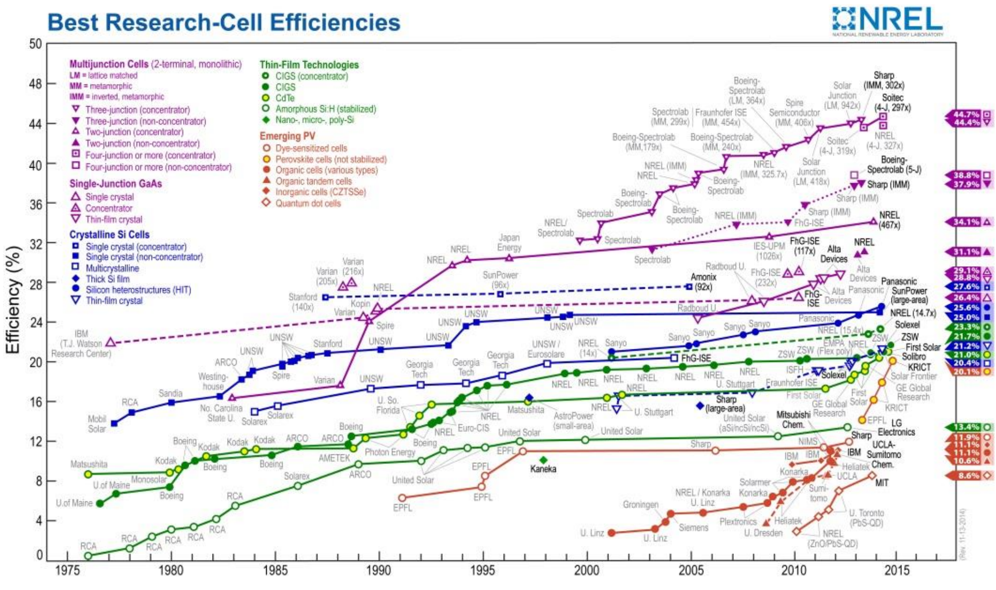

Fig. 5. ***Current PV research efficiencies, as reported by the National Renewable Energy Laboratory [11]***

help to cool the operating temperature of the PV cell, which increases its efficiency in conversion to electrical power while also providing hot water for domestic consumption at temperatures of approximately 80°C. [10].

2.1.3 Efficiency

The efficiency of solar cells is one of the key factors in determining the establishment of technologies in commercial markets. Extensive research is concentrated on efficiency improvement, which is predicted to reach 44% through year 2015 by employing multi-junction technology (Figure 5) [11]. However, large differences in efficiency can be found between lab results and commercial applications, mainly for three reasons. First, the surface areas of cells to be considered vary greatly in terms of the efficiency of a single cell and a module; second, the wires suffer from a great loss of energy when it comes to the transfer of electricity among different modules; and, last, the efficiency in commercialisation lies in the average scale during sorting of solar cells in production, whereas the best results are reported in laboratory circumstances.

The future aim of photovoltaic technologies is to achieve cells with a cost per Watt lower than 1 USD and a commercial efficiency higher than 10%. Currently, only solar cells made of crystalline silicon settle in this target zone. The future development of PV technology is about the tradeoff between cost and efficiency. Products with a high commercial efficiency offered at a low cost are bound to take up larger market shares.

2.2 Sustainability of Photovoltaic Panels

In this section, we look at the sustainability of solar PV panels from two viewpoints: economic and environmental. We analyse these attributes by looking at the life-cycle stages of solar PV panels. Because this type of analysis depends on contesting parameters, we present a simplistic analysis assuming an average irradiation of 1,500 kWh/m^2/yr and crystalline silicon and thin-film PV panels with approximately 10% efficiency.

2.2.1 Economics

Three major factors contribute to the economics of solar power technologies:

1. initial investment cost and return on investment,
2. maintenance costs, and
3. land use.

The current low penetration of utility-scale solar power is primarily attributed to the high investment costs. The estimated average investment for a simple home-based solar panel for an average-sized home is around 20,000 USD. The payback time is typically around 15 to 20 years. In terms of cost per kWh, conservative estimates place current solar power at 28 to 42 cents/kWh, which is many times higher than the 5 cents/kWh cost for power from a typical natural gas plant. The high investment costs can be attributed to the high manufacturing costs. It is estimated that mass production of PV panels will bring down the cost. New technologies have played an important role in this progress: The expenditure required to produce thin-film solar cells is lower by a factor of two than that for multi-crystalline silicon-based modules, currently the dominant technology in the market.

Some companies have made use of this barrier of high initial investment and tried to reduce the burden on end customers by creating innovative leasing plans. Examples of such companies include the Solarcity [12] and construction companies like Lennar Homes [13]. Governmental subsidies exemplify another approach playing an important role in making these numbers feasible. Even though utility-scale solar installations are not yet cost effective, commercial-scale installations have almost attained cost parity with fossil fuel–based electricity generation [14].

The costs of maintenance are usually not considered when talking about solar panels. It is a known fact that solar panels have a reduced output if not cleaned regularly. The main categories of related costs generally referred to as ‘business costs’ are (1) maintenance and cleaning costs, (2) installation labour costs, and (3) other hardware costs, such as wiring, batteries, and other components. These items constitute about 20–30% of a typical PV system’s price [15].

Many studies prove that the availability of land is not an issue. There is no limit to where solar can be placed, and solar panels consume much less land than a typical coal plant [16].

2.2.2 Environmental Impact

It has been established by research that solar electricity production is much more environmentally friendly than that based on fossil fuels. In this section, we analyse the two major solar panel types currently dominating the market and their environmental impacts.

Silicon-based PV panels release pollutants such as sulfur dioxide (SO_2) and nitrogen oxide (NO_X). During the life cycle of silicon-based panels these comprise, like their greenhouse gas (GHG) emissions, only 2–4% of those from fossil-fuel plants. Some facilities producing tandem a-Si/mc-Si use potent greenhouse gases, like sulfur hexafluoride (SF_6) or nitrogen trifluoride (NF_3), as reactor cleaning agents, but they can be replaced or their emissions abated. Replacing grid electricity with silicon-based PV systems would result in 89–98% reductions in the emissions of GHGs, criteria pollutants, heavy metals, and radioactive species [17].

CdTe thin-film panels use cadmium (Cd) and tellurium (Te), both of which are by-products of copper and zinc production. There are currently no technologies or production pipelines to efficiently extract these from copper ore, mostly because it is not profitable enough. Thus the availability and cost of these panels will depend on the usage of copper. These panels are easily recyclable at the end of their life cycle, making their end-of-life cost negligible. Direct Cd emissions from the life cycle of CdTe modules are estimated to be 90 to 300 times lower than those from coal power plants. Indirect Cd emissions include those from using fossil fuels, such as natural gas or coal, for the processing, manufacture, and transportation of these materials throughout the life cycle of the PV modules. The dominant sources of such indirect Cd emissions were found to be the use of coal during steel-making processes and the use of natural gas during glass-making processes. The direct emissions of Cd during the life cycle of CdTe PV are 10 times lower than the indirect emissions due to the electricity and fuel use in the same life cycle, and about 30 times lower than those indirect emissions in the life cycle of crystalline photovoltaics [18].

2.3 Distribution of Electricity

The transmission and storage of electricity are obstacles to increasing the use of solar power. The fact that the earth rotates around the sun and thus, consequently, half of the globe's surface is deprived of solar radiation at any given time, as well as the interrelated distribution and storage issues, challenge the solar power ecosystem.

Two important barriers need to be overcome:

1. Availability: The availability of solar radiation only at certain times of day makes it difficult to generate and supply electricity throughout all 24 hours. Either additional electricity must be generated during daytime and stored for use later (e.g., during dark nights), or electricity needs to be generated and transmitted from one place to another (i.e., where the sun currently shines to the other side of the globe). As

shown in Figure 6 [19], solar radiation is, in any given location, unavailable for a large portion of the day and typically at times when the demand is high.

2. Variability: The impact of intermittent sources (e.g., solar and wind) is highly detrimental to the traditional electricity grid if their contribution becomes significant compared to conventional electricity. Renewables like solar energy pose new problems to the planning and efficient utilisation of the transmission infrastructure.

Variability causes stress on the energy grid. Traditional grids are not designed to support intermittent sources of energy. The traditional grid can handle large power plants, sized 200 MW or more, and regulate vertically integrated utilities [20]. As a result, it cannot cope if the percentage of intermittent generation hits a significant percentage of total supply. Grids need to be upgraded to a so-called smart grid, where both the bidirectional energy flow and related information flow are utilised for the operation and management of the grid [21].

2.3.1 Decentralised or Centralised Electricity Production?

The traditional mode of electricity production and distribution relies on the existence of centralised power plants delivering energy to the end user. This constellation is now changing, with the end-user role developing from being a passive consumer to an active co-provider [22]. Today electricity can be supplied by distributed power plants.

The first peer-to-peer electricity sales between consumers have also been activated [22]. For example, Oulun Sähkömyynti in Finland offers micro-generated electricity produced by local farmers [23].

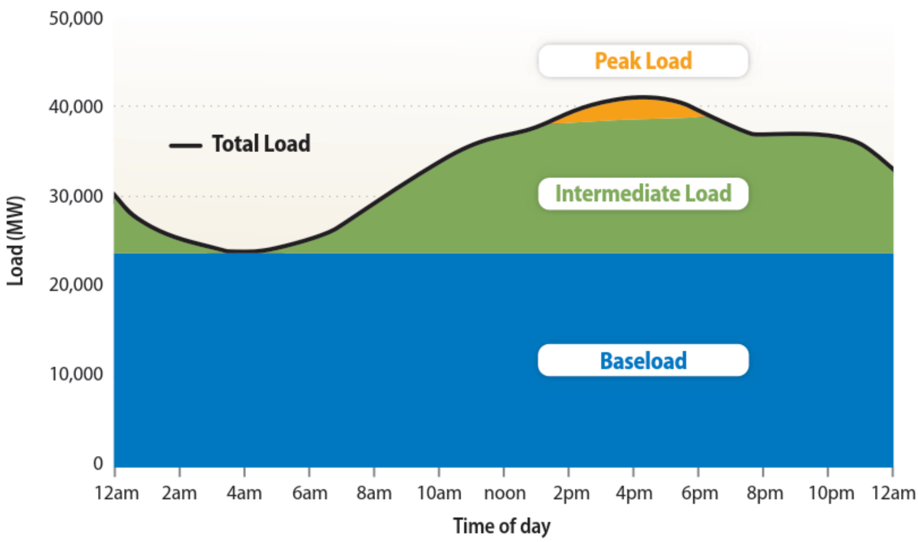

Fig. 6. ***Day electricity load curve in California, summer 2009 [19]***

Another approach to decentralisation is to centralise the power production but distribute the ownership. One recent example utilising this approach is the biggest Finnish solar power plant to be built so far: the Suvilahti plant, which has 1,200 solar panels and an estimated annual production volume of about 260 MWh and an output efficiency of 300 kWh. Power production began January 3, 2015. [24] The actual plant was built with centralised funds, but consumers have the opportunity to rent one to five solar panels for a fee of 5.50 USD per month per panel. The rent is reimbursed against the actual electricity production of the plant [25].

Both centralised and distributed systems have advantages and disadvantages. A centralised system gives the potential to produce huge amounts of energy in a suitable location. However, such a centralised system has its risks. For example, around 25% of energy is wasted in traditional systems due to transmission losses. Other challenges include reliability-related issues such as political instability and bureaucracy when use and transmission cross borders.

A distributed system seems natural for solar-powered electricity production: A solar energy electricity production system is highly modular and can be implemented for any capacity. Additionally, it can be deployed anywhere (e.g., as a building-integrated solution) [26].

3 Policies, Development, and Current Research

Recent best-practice examples regarding general energy policy were identified by the International Energy Agency (IEA) in 2013. Among the members of the IEA are those employed by Canada, the Czech Republic, Germany, the Netherlands, Sweden, and the United States, among others. Increased energy efficiency and the use of renewables, in accordance with, for example, the European 2020 targets [27] and international goals for reduced GHG emissions [28], are characteristics common among the highlighted policies. Increased competition in the electricity market is another focus in several countries [29]. Austria, Denmark, the Netherlands, Norway, Sweden, and Spain are highlighted as best-practice examples for actions aiming at an increased use of renewables. For example, Denmark aims at a full conversion to renewable energy by 2050, with wind energy covering 50% of the Danish electricity consumption by 2020 [30].

The need for grid development was identified in 2010 in the IEA technology roadmap for photovoltaics, which suggests a scenario of grid parity by 2020 through the implementation of effective policies. The vision is that 'utility-scale PV could become competitive in the sunniest regions by 2030 and provide 5% of global electricity by 2050' [31]. Currently in the United States, half of all new electricity production derives from PV panels. [32]

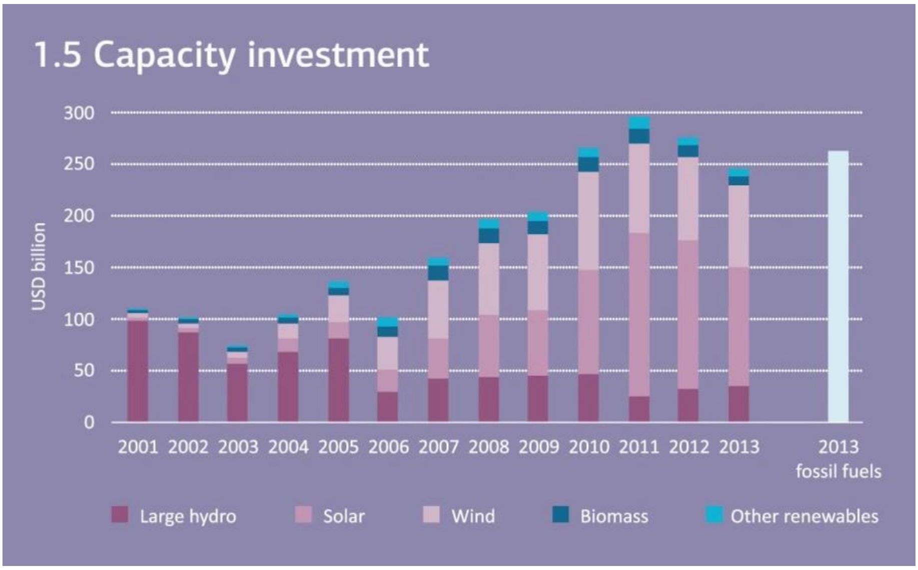

Fig. 7. ***Capacity investments in renewable energy, 2013. Investments in solar technology have increased most during the past 10 years. Asia, especially Japan and China, accounted for more than half of the global increase in photovoltaics in 2013. [33]***

On a global scale, China is currently in second place regarding amounts of installed PV panels, with 20 GW. Germany takes the lead with 37.5 GW [32]. Similar steps have been taken by the Indian government with respect to the use of solar power as a backup during power outages. Global capacity investments in renewables are illustrated in Figure 7 and development targets for 2020 in Figure 8.

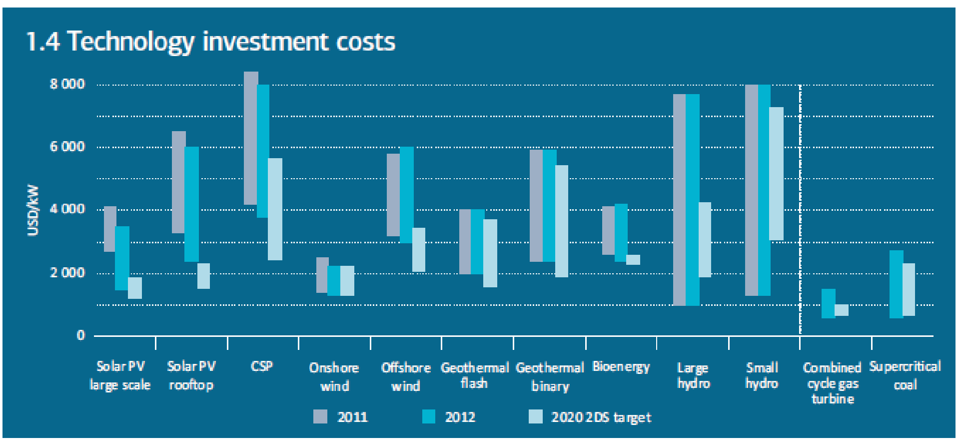

Fig. 8. ***Development of technology investment costs and targets for 2020 [39]***

3.1 Steps Forward

An incrased use of PV-based electricity requires new and innovative energy policies.

The current Dutch policy is a forerunner example of a technology-neutral approach where different renewable technologies compete for subsidies to cover extra costs for producing renewable energy—the least expensive technologies are allowed to apply first [34]. Competition is utilised for the benefit of sustainable development, acting as an incentive to lower the costs of technologies.

The Spanish situation illustrates the need for international collaboration. Spain has more than 2,000 facilities producing electricity from renewable energy sources, mainly wind and hydro power but also solar. However, the border situation with France highlights the importance of the international exchange capacity of electricity to even out fluctuations in production from renewable energy sources [35].

To accelerate the global deployment of solar-powered technologies, the IEA has identified the following four main areas for policy interventions:

1. long-term targets/policies including incentives to accelerate market competitiveness;
2. improved products and components, financing models especially for rural electrification, training and education;
3. continued technology development and increased research and development (R&D) efforts to improve the cost-efficiency ratio and ensure PV readiness for rapid deployment; and
4. improved international collaboration aimed to advance knowledge transfer to emerging and developing countries. [36]

Investments in research are another step to further the use of developed technologies and bridge the gap from innovation to market for technologies using renewable and solar energy. Exemplary programmes have been initiated in France, Italy, and Korea [37]. The IEA has identified the following roadmap for advancements in PV-related R&D:

1. Increase public R&D funding, 2010–2020.
2. Ensure sustained R&D funding in the long term, 2020–2040.
3. Develop and implement smart grids and grid management tools, 2010–2030.
4. Develop and implement enhanced storage technologies from 2030 onward. [38]

4 Future of Energy: Visions for an Increased Use of Solar Power

In this section we present three interlinked visions and suggest measures supporting an increased use of solar energy for electricity production. First we discuss the scenarios using 100% solar electricity, including prerequisites and opportunities for using solar energy as a single source for global electricity. However, as described earlier, this vision is dependent on developed transmission, distribution, and storage systems. Possible solutions are presented as the next scenario, the global electricity grid. As we discussed, the current investors in solar power are not the regions that receive the highest amount of irradiation. To change this, the scenario of 'energy for all' presents a vision of how solar-powered technologies could be used for the benefit of an environmentally, economically, and socially sustainable global future by empowering the current nonconsumer markets, such as countries in Africa.

4.1 Solar Energy as Single Source for Global Electricity: The 100% Scenario

Here we discuss the vision of covering 100% of the world electricity demand with solar power. Given the right circumstances, this could be made possible as early as 2030 [40]. Although we focus mainly on energy supply, we acknowledge and indeed emphasise the importance of demand-side energy conservation measures to reduce the requirements and impacts of energy supply.

4.1.1 Resources Needed and Available

The 100% scenario is based on the use of existing and commercially available technology. The production of energy in this scenario is mainly based on PV and concentrated solar power (CSP). Proposed storage technologies, which are already being used on a commercial scale, are compressed-air energy storage (CAES) and pumped hydroelectric (PHE). The distribution of the electricity from remote plant locations to the grid takes place through high-voltage DC lines, which are currently used [41].

The power required today to satisfy all end uses worldwide is about 12.5 trillion watts (TW) [42]. To satisfy this requirement, about 180,000 PV and CSP plants, averaging 300 MW per plant, would be required. In this scenario, solar PV is divided into 30% rooftop and 70% power plant. Rooftop PV has three major advantages over power-plant PV: (1) rooftop PV does not require an electricity transmission and distribution network; (2) it can be integrated into a hybrid solar system that produces heat, light, and electricity for use on site; and (3) it does not require new land area.

4.1.2 Feasibility in Terms of Raw Material Availability

Solar PVs use amorphous silicon, polycrystalline silicon, micro-crystalline silicon, cadmium telluride, copper indium selenide/sulfide, and other materials. According to a recent review of material issues for terawatt-level development of photovoltaics, the power production of silicon PV technologies is limited not by crystalline silicon (because silicon is widely abundant) but by the reserves of silver, used as an electrode [43]. The research also notes that if the use of silver as top electrode can be reduced in the future, there are no other significant limitations for c-Si solar cells. Other research [44] has studied the current availability and anticipated use of raw materials for 23 different types of PV technologies and concluded that with current technologies, there are still a few bottlenecks that might prevent terawatt-scale installations.

4.1.3 Economic Feasibility

In terms of economic feasibility, we look at a variety of factors, including annualised total capital and land costs, operating and maintenance costs, storage costs, and transmission costs. [45]

Table 2 compares the current and future costs of solar PV and CSP in the United States in USD. These costs include generation and distribution using only currently existing channels.

Transmission costs involving long-distance transmissions have not been considered in Table 2. As stated earlier, long-distance connections are required to alleviate the problem of the variability of solar power. Technology, in the form of high-voltage DC lines, is available to accommodate such a transfer. The best estimate known from current research for all new infrastructure enabling long-distance transmission is about $0.10/kWh. Storage costs, including batteries, CSP, and hydro-powered plants are estimated to be about $0.10/kWh, at the most. From all of these calculations, it can be concluded that the end-user cost of using only solar-powered electricity is not likely to exceed $0.30/kWh. Although this is almost double the price of the current fossil fuel–powered systems, with the increasing pressure on fossil fuels, the predicted increase in energy generation costs is also bound to increase (not factored in Table 2). Effects of policies and subsidies also are not included in the final cost.

Table 2. ***Current and future generation costs for solar power (compared with current USD price based mostly on fossil fuels). Social cost includes cost of pollution and climate damage costs.***

Energy technology	Present cost	Cost after 2020
Solar PV	> $0.20	$0.10
CSP	$0.11–0.15	$0.08
U.S. traditional	$0.07 (social cost: $0.12)	$0.08 (social cost: $0.14)

4.1.4 Policy Issues

Because solar PV-based electricity is a completely new form of electricity and requires us to redefine the way we currently generate and consume electricity, it is crucial to define new policies and modify existing policies to encourage this change on a wide scale.

The most common type of policy currently adopted to stimulate the production of renewable energy is to cover the difference between generation costs and current grid price [46, 47]. These subsidies have to be gradually reduced to promote innovation and make renewable energy competent. One major economic policy that can make a difference is to reduce and ultimately remove subsidies on fossil-fuel energy systems and taxing fossil-fuel production using carbon taxes. But even more important than subsidies or carbon taxes is the support for the development of necessary infrastructure. Another policy issue is to encourage and educate people about the importance of green energy. Municipal financing for residential energy-efficiency retrofits or solar installations can help end users overcome the financial barrier of the high upfront cost of these systems.

Overall, in order for the vision of a world with 100% solar-based electricity to be possible, the main barriers are (1) current raw materials being used, and (2) policies. With proper measures to overcome these issues, the scenario can be easily achieved.

4.2 The Global Electricity Grid: Transforming the Electricity Markets

'The sun is the spring that drives all. The sun maintains all human life and supplies all human energy. To increase the force accelerating human movement means to turn to the uses of man more of the sun's energy.' —Nikola Tesla [48]

The sun is always available in some part of the world and simultaneously unavailable in the other parts (see Figure 9). However, energy is needed 24 hours a day at any location. In order to utilise sunlight to meet the global electricity need 365/24 around the globe, it is necessary to produce and collect electricity wherever the sun is available and transmit that to other parts of the world where the sun is not present. In order to do that it is necessary to have solar energy plants in different parts of the world. However, the plants alone won't serve this purpose without a global-level grid.

4.2.1 Why Do We Need a Global Grid Now?

It has been 120 years since Tesla powered Buffalo, New York, with 25-mile-long transmission lines from the first large-scale hydro-electric power plant at Niagara Falls. The World Wide Web and globe-wide cellular networks have enabled humankind with the means to establish real-time communication between any two parts of the world. The first machine age has flourished at its peak and has given the platform for the next [49, 50]. An important observation is that the technological evolution is happening at an exponential rate. As a result, the basic requirement to support the upcoming pace of technological advancements—that is, uninterrupted, ubiquitous, and unlimited power—calls for grand planning at the present time. Significant barriers

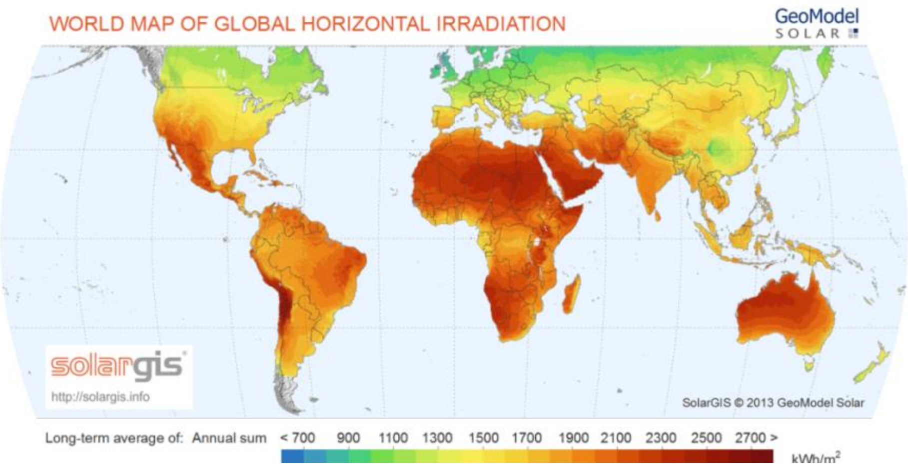

Fig. 9. ***Global solar irradiation map. Solar energy is available everywhere, and especially in the developing countries. Solar power could be an opportunity for a sustainable and equal growth. [59]***

and opportunities for a global-level energy grid are as follows.

4.2.2 Technology

Two different methods are under consideration for long-distance bulk transmission of electricity: high-voltage direct current (HVDC) and the flexible AC transmission system (FACTS). HVDC may be less expensive and have less loss for high long-distance and underwater transmission. One example is the Rio Madeira transmission link in Brazil, which has an overhead length of 2,385 km and uses 600-kV HVDC. However, the challenges resulting from the mesh of many grids need to be overcome. FACTS is a power electronics–based system that is composed of static equipment that provides control of the network and increases the power transfer capability. [51]

4.2.3 Variability

One of the major issues with solar power and also the suggested global grid is the inherent variability of solar power, discussed earlier.

The problem can be overcome by: (1) distributing solar power plants across various regions and interconnecting them; (2) using 'smart' demand-response management to shift flexible loads to match the availability of solar energy; (3) storing electric power for later use; (4) utilising oversized Wind, Water, Solar (WWS) peak generation capacity to minimise the times when available WWS power is less than the demand and to provide spare power to produce hydrogen for flexible transportation and heat uses; and (5) utilising a nonvariable energy source, such as hydroelectric power, to fill temporary gaps between demand and wind or solar generation [52].

All these solutions form a backbone for covering 100% of the electricity demand with solar power. Studies in smaller geographic regions showed how it is possible to reduce variability using dispersed PV sites [46]. One study concluded that with enough geographic diversity, the sub-hourly variability due to passing clouds can be reduced to the point that it is negligible. Oversizing the peak generation capacity is not an economically viable solution, as this requires a lot of additional investment. Research on and creation of new storage technologies are key factors in our scenarios.

4.2.4 Socioeconomic

Europe's dependence on imported energy has risen from 20% in Monnet's time to its present level of 50% and is forecast to reach 70% by 2025 [53]. This need serves as a catalyst to undertake the project of developing a global grid. The current economic recession is an important barrier for the project. However, history dictates that a grand project of this level impacts the economy significantly in a positive way (e.g., the economic boom following the massive transportation investment in the United States) [54].

A global grid will also need to deal with efficient long-term planning procedures, the generation of market-oriented pricing policies, a comprehensive cost-benefit analysis to identify economic solutions, and administration and regulatory issues. Studies suggest that obstacles such as technology per se can be overcome, whereas the real challenge for the implementation of a global grid lies in how to reach consensus among a very large group of stakeholders including generators, system owners, Transmission system operators (TSOs), consumers, and the decision-making entities at all levels of government [55].

4.2.5 Geographic Feasibility and Geopolitical Stability

Globally, 6,500 TWs of solar energy is available over the world's land plus ocean surfaces if all sunlight is used to generate electricity. However, the deliverable solar power over land in locations where solar PV could practically be developed is about 340 TW [57]. CSP could provide about 240 TW of the world's power output. It is less than PV because the land area required for CSP without storage is about one-third greater than that for PV. For implementing the proposed plan, setting up 180,000 solar plants would require only 0.6% of the global land area.

Where to place the solar plants is an issue that encounters various political problems. Putting those aside, according to the Desertec foundation [41], '90 percent of the world's population lives within 3,000 km of deserts', and we have the technology (using HVDC transmission) to transmit power to a populated area with just 3% loss. New transmission technologies are being researched and make this a feasible solution.

However, geopolitical stability is an important factor for such a global-level initiative. If nations are not harmonised internally and externally, no nation will be interested to invest in a project whose safety is a national-level risk. Interestingly, the major reason for geopolitical instability arises from the dependency on and control of fossil fuel.

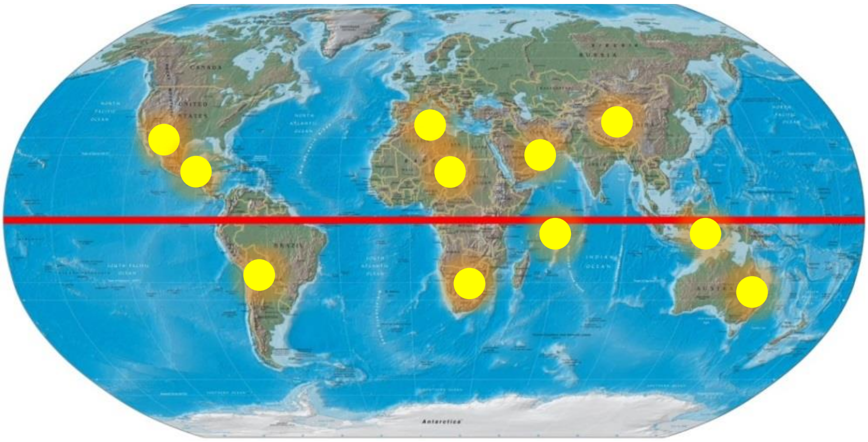

Fig. 10. ***The global electricity grid: utilising areas with most solar radiation for global electricity production [56]***

If the dependency on fossil fuel becomes insignificant through investments in clean energy and a global grid, it could contribute to improving the deteriorating world peace.

The global grid is illustrated in Figure 10.

4.3 Energy for All: Making the World Better by Entering Nonconsumer Markets with Solar-Powered Technologies

Solar power could also support the development of increased global sustainability and equality by entering new energy markets. Globally, 1.3 billion people—18% of the global population—lack electricity [58], and 95% of this population is located in developing areas of Asia or Africa. These areas also receive the highest amounts of solar irradiation (Figure 10 [59]) on the globe. However, solar energy is mostly used in existing energy markets as a replacement for other products. Research and development efforts are also mainly directed toward large-scale solar power unit applications, high-tech solutions such as smart grids and buildings, in the same markets.

Current measures to tackle climate change are also inefficient. The implications are drastic. For example, NASA has listed probable near-future scenarios including decreased precipitation in subtropical areas and decreased water resources in semi-arid areas; for example, in Africa, between 75 and 220 million people are predicted to suffer from a lack of water and a 50% drop in agricultural production by 2020 [60].

Deserts and other dry areas currently cover about 40–41% of the earth's land area; the total area affected by desertification is estimated to between 6 and 12 billion square metres [60]. If all this would be covered by dense greenery we would see an increase of 67% from today—an action tackling both climate change and climate injustice.

Small-scale solutions already exist for solar-powered irrigation pumps (Figures 11 and 12 [62]). However, with large-scale implementation, all areas suffering from or affected

Figs. 11 and 12. ***Solar-driven irrigation pumps, Bangladesh [62]***

by desertification, including the Sahara Desert, could be irrigated starting today. If all deserts would start growing greenery today—food, forests, and biomass—what would this lead to and on what time scale? Food production would start immediately, the growth of biomass with fast-growing species might take 5 years, and the development of dense forests might take a few decades.

What would be the economic consequences if the emphasis of solar technology development would be shifted toward low-cost solutions for everyday needs such as lightning, cooking, and irrigation pumps? IKEA is an example of a business that has proven the concept of gaining and constantly increasing market share by selling increasingly cheaper products for everyday use. Additionally, IKEA has proven the possibility for truly global market leadership with 338 physical stores in 40 countries [63], including, for example, India. Solar energy has the potential to act as a basis for a range of new products and services directed toward current nonconsumers of energy, supporting a sustainable growth based on economic, social, and environmental benefits.

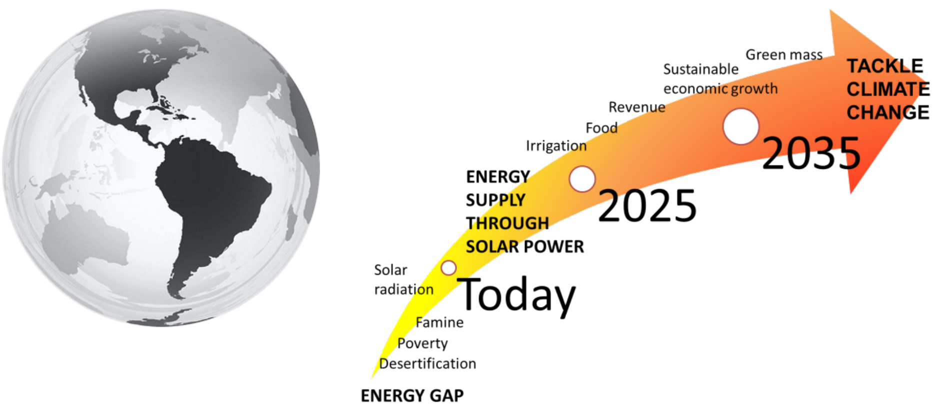

Fig. 14. Vision: solar power as a means to make the world a better place

From this perspective, solar energy could be a resource for future economic growth through capitalizing on social and environmental responsibility. Solar power has the potential for making the world become a more equal, better place (Figure 14). This power could be harnessed for furthering sustainable growth on all levels.

5 Conclusions

Solar power is ubiquitous; it is a renewable resource available for everyone and hence a global opportunity. In this paper, we discuss why solar energy is not currently the leading source of energy in the world. We first analysed current barriers, which include (1) high investment cost, (2) low efficiency, (3) variability, and (4) a lack of political will. We also discussed simple solutions to problems that are currently slowing progress, such as, for example, how variability can be addressed using storage technologies such as compressed air.

We then presented our visions for a future in which (1) 100% of the electricity needs are met using solar power, (2) a global solar-powered grid delivers uninterrupted power to all areas of the globe, and (3) the use of solar innovations in the current nonconsumer markets is increased significantly and subsequently helps to tackle global issues such as climate change.

Our conclusion from the study is that long-term political foresight is currently lacking and is the main barrier to enabling a solar-powered future. Short-term barriers such as a lack of infrastructure or high investment costs can be easily addressed given a strong political will for a greener future. In any case, we strongly believe that solar is the near future.

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