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PERSPECTIVE

The great solar boom: a global perspective into the far reaching impact of an unexpected energy revolution

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Abstract

This study offers a unified perspective into the unexpected solar energy photovoltaic revolution, and its far reaching impact onto both energy generation and electricity markets. Practically relevant aspects, such as those related to the value of solar PV electricity, land consumption, energy return on energy invested, reliability of the technology, the structure of the global PV industry, the cost of Li ion batteries and related market trends are clarified. We identify the main barriers to overcome for solar PV to expand beyond a niche market (say, <10% of a country's power generation), and the related societal benefits with electrification of energy end uses.

Introduction

Solar photovoltaic energy has been of crucial applicative relevance since its very inception, in the mid 1950s, when scientists in the United States built the first solar cells based on *p–n* junctions in single Si crystals with efficiencies of 5–6% [1]. As put it by Varadi, co-founder in 1973 of a pioneering solar company which 5 years later became the largest solar producer of silicon-based photovoltaic (PV) modules in the world (0.5 MW of nominal power, in 1978), "few people realize that without the invention of solar power many things we are using today such as cell phones, TV, internet, global weather service, the GPS system, and manned space stations would not be possible" [2].

Indeed, no communication satellite could function without solar cells as batteries in the space simply do not work; while perhaps even less people, to quote Varadi again, today are aware that the satellite powered by a nuclear reactor launched in 1964 in the United States broke apart during the launch, releasing all radioactive uranium that was scattered across the globe [2].

However, due to high cost and consequent limited demand, for decades "terrestrial" photovoltaic modules were mainly sold to customers in the oil, telecommunication and naval regulation sectors [1]. All changed starting in year 2000 with the introduction, in Germany, of the Feed-in Tariff (FiT) program conceived by Hermann Scheer [3].

This original incentive scheme, rewarding for 20 years with a high and flat tariff every kWh of a PV plant connected to the grid, overcame the financial barrier that for decades had limited solar power market penetration. Suddenly, the high-priced solar PV plants became "bankable" [4].

Demand surged and, with it, mass production and technological advances, stimulating investment and forcing competition among suppliers of different modules based on a wide spectrum of technologies. For example, the first CdTe modules commercialized by the leading supplier in 2002 had 7% nominal efficiency, while those sold as of early 2015 had 16.3% certified efficiency [5]. The owners of newly installed PV plants, furthermore, were forced to undertake active maintenance of their systems, as without real and prolonged production of clean energy, no financial incentive was going to be gained.

For about 4 years (2003–2007), following the deployment of the FiT incentives also in Spain and in Italy, the price of the solar modules remained high ($5–6/W). When, however, silicon prices dramatically decreased as a consequence of massive investment in polysilicon production plants by "vertically integrated" PV module manufacturers in China and in Taiwan the price of solar modules started to fall at unprecedented rate.

Unexpectedly, the sale price of photovoltaic modules, once thought to be "physically limited" by the cost of crystalline silicon (until recently a cost price of $1.00/W was referred to as a "tipping point" for the solar industry) [6], decreased to such a low level (<$0.5/W, as of May 2015) that, rather than "grid parity" [7], a true "generation parity" with the cheapest energy source, namely coal, is now being approached. We remind here that coal continues to be massively used to produce electricity in the world's largest economies (the United States, China, Germany, and India).

Huge PV plants are rapidly built in many countries across the world and connected to the grid, giving solar PV energy the status of a true utility-scale energy resource, with dramatic consequences on the electricity price formation in countries with significant market penetration [8]. In Germany, for example, where the largest PV power capacity in a single country is installed, on April 15, 2015 the PV power reached the record value of 27.7 GW pushing wholesale electricity price into negative territory. In detail, between 1 PM and 2 PM of that day German electricity was retailing for –€1/MWh, and that tariff further decreased to –€1.1/MWh between 2 PM and 3 PM [9].

Finally, and opposite to what had been observed in the past, growth in the installation of PV plants is going on at very high rate, despite the price of oil having halved from around $100/barrel to about $55/barrel in <1 year since July, 2014.

In 2015, reputed market analysts predict the deployment of further PV power by 61 GW, namely a 30% growth over the previous year, equivalent to one-third of the cumulated global PV power installed worldwide at the end of 2014 [10]. These facts may justify the use of a frequently abused word such as "revolution" in power generation.

Aimed to energy scholars as well as to policy makers, this perspective study provides a unified overview of the global solar photovoltaic boom, taking into consideration technical, economic and energy aspects. By doing so, this study aims to address a gap in current energy and scientific literature. After clarifying a few aspects concerning the PV technology for both decentralized and utility scale electricity generation, the study identifies the barriers to overcome towards massive, global adoption of solar PV power replacing electricity obtained by burning fossil fuels or through Uranium nuclear fission. Within two decades, we argument in the conclusions, massive adoption of solar PV energy across the world will have resulted in long awaited end-use energy electrification affording the economic and environmental benefits that will solve the current energy and environmental crises, opening the route to a true solar-based economy.

A Reliable, Convenient Technology

Photovoltaics is an inherently reliable industrial technology delivering a product, the solar module, that since the early days of its commercialization needed to reliably provide power in the demanding environment in which the first "terrestrial" PV modules were used by customers (telecommunication and oil companies, and naval authorities), namely remote power generating stations, remote pipelines, offshore platforms, and buoys [1].

Crucially important quality and testing programs were then financed by the United States and other European governments right around those years. For example, the first quality control program started by the Jet Propulsion Laboratory in Pasadena, lowered the failure rate of existing solar cells from 45 to 0.1%, namely achieving the quality levels of advanced industrial productions [2].

A PV system consists of the PV module and the balance of system (BoS) components encompassing support racks, the wiring, transformer to raise the voltage, inverter to convert direct current to alternating current, and switches for connecting to the electric grid. All are reliable and long lasting.

For example, the long-term reliability of the PV technology since its early days is exemplified by the 80 kW system array installed in the island of Vulcano (a volcanic island north of Sicily's sea) in 1984 (Fig. 1). Comprised

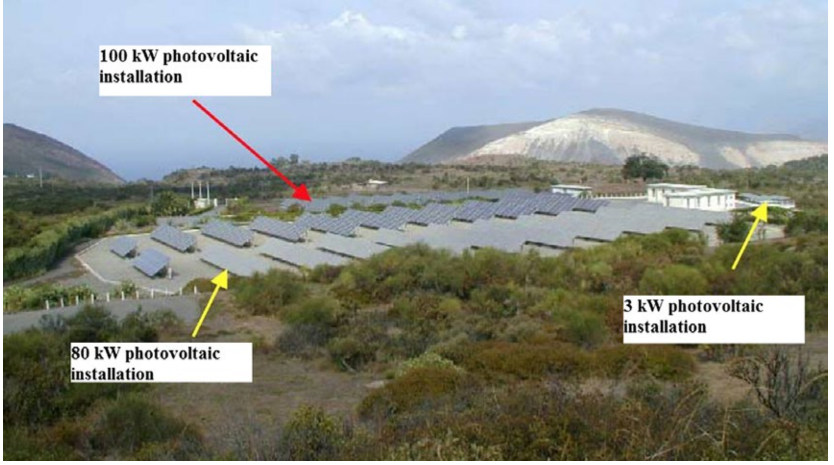

Figure 1. The PV plants, comprised of different silicon-based solar modules, installed in the island of Vulcano, Sicily, in 1984. After more than 30 years, the plant has recorded a modest performance deterioration [Reproduced from Ref 11, with kind permission].

of 9% efficient PV modules in monocrystalline silicon manufactured in Italy in 1983, after 21 years the solar PV plant had lost only 6% of its original production capacity [11], namely about one half of the expected reduction (10%) based on the 0.5%/year degradation rate median value obtained from field testing throughout the last 40 years [12].

Another issue, heavily debated until recent times, has been the energy payback time (EPBT) of the PV technology, and the related energy return on energy invested (EROI) values of the various technologies based on different semiconductors employed to make solar cells.

Most recently, Apul et al. conducted a thorough study based on a systematic review of the EPBT and EROI metrics for the two main crystalline Si and the three main thin film PV technologies taking into account scientific articles published in 2000–2013 [13]. The team harmonized several parameters (performance ratio: 0.75; system lifetime: 30 years; insolation: 1700 kWh m^{-2} yr^{-1}; module efficiency: 13% mono-Si; 12.3% poly-Si; 6.3% a:Si; 10.9% CdTe; 11.5% CIGS. The mean harmonized EROI varied from 8.7 to 34.2 (Fig. 2), whereas the EPBT values vary from 1 to 4.1 years in the following order (from lowest to highest): cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), amorphous silicon (a:Si), poly-crystalline silicon (poly-Si), and monocrystalline silicon (mono-Si).

The economic convenience of utility scale PV generation, briefly discussed above with electricity prices having reached negative values in Germany on April 2015, is evident even in the case of relatively small, ~ 1 MW plants. For example, in Israel-Palestine the recent opening of a 710 kW plant (Fig. 3) which transmits to Jerusalem the energy produced near Jericho, 278 m below the sea level, has resulted in an immediate, significant drop in electricity prices for households that were formerly dependent on high utility rates [14].

A Scalable Technology for Decentralized and Utility Scale Electricity Generation

In 2001, solar electricity provided less than 0.1% of the world's electricity consumption (13,000 TWh). In 2014, the figure had grown by one order of magnitude to reach 1% of the global demand, which in the meanwhile increased so much to exceed 20,000 TWh [15].

Moreover, the PV technology is easily scalable with minimal land consumption. For example, covering 0.6% of the EU territory with 10% efficient PV modules would

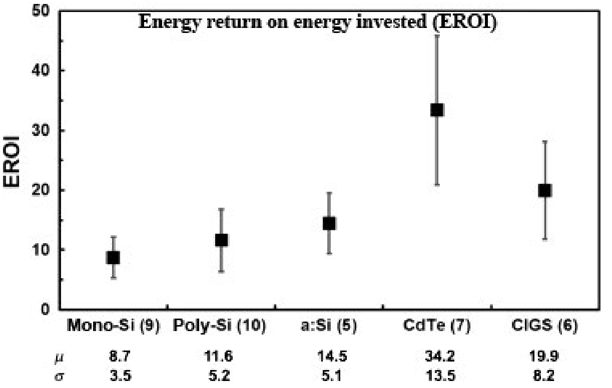

Figure 2. Mean harmonized EROI of the main five PV technologies. The number of values for each module type is included in parentheses. Mean (μ) and standard deviation (σ) are shown at the bottom of the graph [Reproduced from Ref 13, with kind permission].

Figure 3. The Dead Sea Photovoltaic Generating Plant, near Jericho, since late 2014 produces electricity dispatched to Jerusalem. Low-cost solar electricity has significantly reduced the cost of the kWh paid by households [Reproduced from Ref 14, with kind permission].

theoretically meet its electricity consumption [16]. Today's modules, however, approach and even exceed 20% efficiency (e.g.,, the silicon modules of Sun Power with no front contacts; or Panasonic–Sanyo's using the HIT technology) [17], so that the amount of required land will actually be much lower.

In this respect, Fthenakis et al. have shown that in most cases, ground-mounted PV systems in areas of high insolation (Fig. 4A) transform *less* land than the coal-fuel cycle coupled with surface mining (Fig. 4B) [18]. Obviously, the land-use requirements for wide-scale deployment of PV are further lowered by taking into account the huge built surfaces already existing, namely the roofs of all sort of buildings and of other constructions such as parking lots, highway and bridge walls, which once integrated with PV modules could supply a large fraction of industrial society's energy needs.

This aspect leads to the well-known unique advantage of solar photovoltaics, namely the decentralized power generation capable to locally produce power at low cost that is currently reshaping the electricity market in countries with significant PV penetration.

As emphasized by Varadi [19], after years of conflict and delayed interconnection to the grid, all four main Germany's utilities now offer new storage systems to the owners (over a million) of homes and farms equipped with PV systems. In this way, the utilities do not sell electricity any longer, becoming instead "PV + storage systems" installing and maintenance companies (for 20 or 30 years through a dedicated contract specifying the terms of the new business). It should be emphasized that such distributed storage approach enhances the value of PV generated electricity while dwarfing the negative impact of its increasing penetration.

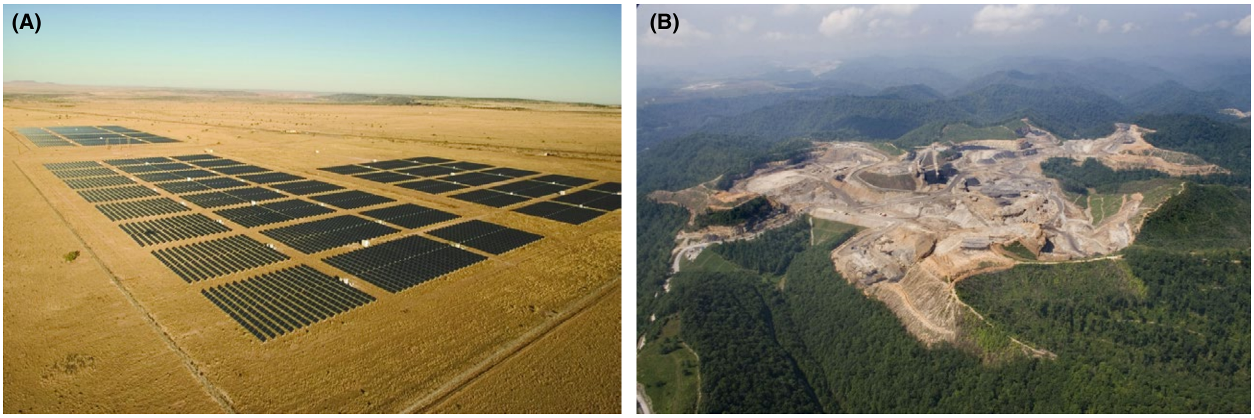

Figure 4. Difference in land impact between (A) a solar photovoltaic plant (in Springerville, Arizona: land requirement for PV: 310 m^2/GWh) and (B) a mountaintop removal coal mining site (in Rawl West, Virginia: Land requirement for surface coal mining: 320 m^2/GWh) [Reproduced from Ref 18, with kind permission].

The Global Solar Boom

Today's low-cost PV technology is experiencing unprecedented growth on a truly global scale. At the end of 2014, the global installed capacity reached 185 gigawatts (GW) [20].

Driven by the ultralow cost of the technology, photovoltaic modules are now used in the vast majority of the world's countries, including remote islands in the Pacific Ocean, such as in the case of Tokelau island chain (comprising the three atolls of Atafu, Nukunonu and Fakaofo), between New Zealand and Hawaii, that in 2012 became the world's first territory able to meet all of its electricity needs with solar PV power (Fig. 5), coupled to a battery storage system to supply power at all times [21].

Followed by China, Germany is currently the world's largest producer of PV energy, while Italy is the country with the largest fraction (7.5% in 2014 and still growing) [22] of national electricity demand met by PV energy. Table 1 shows the rank of top ten countries for installed PV power capacity at the end of 2014.

In India, where some 80% of 2014 electricity demand was met by coal, the cumulated PV power hosted at the end of 2014 slightly exceeded 3 GW. The government, however, in early 2015 announced an ambitious 100 GW installation target for 2020 that, if met, will bring the country among those with the largest fraction of solar PV power in their energy mix [23].

In China, where almost two-thirds of the overall electricity demand is met by coal, in 2010 there was almost no PV power installed, out of an overall total installed capacity of 1360 GW. At the end of 2014, the country had an installed solar capacity exceeding 28 GW (ground-mounted capacity, 23.38 GW and distributed generation, 4.67 GW).

Figure 5. The PV plant in the Atafu atoll of Tokelau island chain in the Pacific Ocean. The world's first territory to become energy-independent with solar PV coupled to storage via lithium ion batteries [Reproduced from Ref 21, with kind permission].

Table 1. Top ten countries for installed PV power capacity at the end of 2014 [Sources: China's National Energy Administration, EurObserver, US Solar Energy Industries Association].

Rank	Country	Installed power (GW)
1	Germany	36.34
2	China	28.05
3	Japan	23.3
4	Italy	18.42
5	United States	18.3
6	Spain	4.74
7	France	4.61
8	Australia	3.3
9	Belgium	3.04
10	United Kingdom	2.78

In 2014, 10.6 GW of new capacity was connected to the country's grid, whereas total electricity generated by PV reached 25 billion kWh, an year-to-year increase exceeding 200% [24]. Only in the first 3 months of 2015, China added another 5 GW, with the government aiming to add further 17.8 GW only in the course of 2015.

In Japan, PV energy capacity has rapidly grown to more than 23 GW, from slightly more than 3 GW in 2011 when all 43 nuclear reactors were shut down following an earthquake and a tsunami that caused meltdown at the Fukushima power plant [25]. By March 2016, Japan plans to shut down nearly 2.4 GW of expensive and polluting oil-fired energy plants, replacing them with solar and wind power.

In Germany, after the 2011 Fukushima accident, the government decided to immediately close eight nuclear power reactors, and all the remaining reactors by 2022. The government reinforced its option for renewable energy (mostly wind power and PV) to replace nuclear and coal energy [26]. In February 2012, a winter month, during several days the country was exporting 4.5 GW of clean electricity to France [27].

The latter country relies on 58 nuclear power plants for most of its electricity needs. Yet, new energy companies in France understood the economic impact of low-cost PV generation, and France already hosts a number of utility scale PV plants including the 300 MW plant in Cestas (Fig. 6), the largest in Europe.

This plant, built in <12 months, will profitably sell electricity at €105/MWh, namely below the price of the electricity generated by the nuclear power plant that France's largest utility (EDF) is currently building in United Kingdom's Somerset under a minimum price of €117/MWh for a period of 35 years guaranteed by the government [28].

In Italy, the deployment of the FiT incentive scheme between 2006 and 2013 caused an impressive surge in the PV installed power that in 2 years (between 2011 and 2013) grew from few hundreds of MW to 18.42 GW at the end

Figure 6. The 300 MW plant in construction in Cestas, near Bordeaux. The modules have a East-West orientation to exploit the sun radiation from early morning to late evening [Reproduced from Ref 28, with kind permission].

of 2013. As a result of a concomitant vigorous increase in wind power, in 2014 Italy met 43.3% of its large electricity production (268 TWh) with renewable energy sources [21], without either significant or specific upgrades of the grid.

The United States closes the list of the >10 GW countries, where the installed PV power grew from slightly more than 100 MW in 2006 to over 18 GW as of late 2014; more than 6 GW were erected only in the course of 2014 [29].

Numerous other countries are emerging in the global PV rush, well beyond Europe, China, Japan and the United States. South Africa has already reached the milestone of 1 GW of installed capacity. Chile will cross the threshold in 2015.

As the price and availability of the PV technology keep falling, there are no reasons why most other large countries or regions such as Brazil, Jordan, the Philippines, Thailand, Malaysia, or Mexico should not adopt clean solar energy as a convenient option to lower the cost of the electricity, and meet rapidly increasing daily energy demand.

Indeed, large (>100 MW) solar PV plants are currently being built in few Brazilian states, while the whole Latin America is becoming a significant PV market with a forecasted 350% annual growth in 2015 (from 600 MW in 2014 to > 2.2 GW of installed power in 2015 along with 34 GW in the pipeline: 6.8 GW contracted, 1.9 under construction and 25 announced) [30].

As it happens in India and in all unsubsidized solar markets, all this energy will be produced and sold either to the state-owned grid or to large utilities, following auctions aimed to select the solar company capable to sell solar power at the lowest cost. In one of these auctions, in early 2015, the Dubai Electricity & Water Authority signed a contract with a company that will now build and undertake maintenance of a 200 MW solar PV plant (using thin film solar modules) selling electricity at $5.98 cents per kWh, which at that time was the lowest tariff quoted for any solar power project in the world [31].

The PV Industry

Originally small and concentrated in Japan and in the United States, the PV industry has undergone a full reshaping in the first decade of the 2000s [32], first by new German manufacturers and then by the massive market entrance of Chinese PV companies [33]. Today, seven out of the top ten largest manufacturers are based in China (Table 2) [34].

From a technical viewpoint, nine out of the top ten companies utilize silicon as photoactive materials, with only one (First Solar) relying on a different semiconductor (cadmium telluride). The largest companies are vertically integrated, namely they manufacture polysilicon, solar cells, and PV modules.

The industry is rapidly consolidating. For example, in 2014 the top 20 PV module suppliers reached out an overall market share of 68%, up from 60% in 2011 [35].

A quick review of the figures of the 2014 leading PV module manufacturer, which shipped 3.66 GW of solar modules recording total net revenues of $2.29 billion, allows to conclude that the industry is now profitable (a 16.9% margin, in this case), despite an average sale price of $0.62/W [36].

Such a low sale price, compared to the $7–6/W price of 2003, explains why the PV industry in Europe, largely based in Germany, was practically wiped out in less than a decade [37]. Almost all Europe's manufacturers of solar cells and PV modules indeed either closed, or were sold to foreign investors. However, hyper-competition affects also China's manufacturers. Indeed, the former two largest module makers (LDK Solar and Suntech) suffering from high debt and low profit margins, became insolvent in 2013–2014, before lately restarting production either under new ownership or following debt restructuring.

The industry, though, is entering financial and technology maturity as shown by its 13% average profitability estimated in 2015 ($5 billion profits out of $38 billion revenues from

Table 2. Top 10 PV manufacturers in 2014, technologies and location of production sites [Source: EurObserv'ER, 2015].

Company	Modules delivered in 2014 (in GW)	Country	Location of the production sites	Technologies
Trina solar	3.660	China	China	Silicon wafers, solar cells, modules
Yingli green energy	3.361	China	China	Silicon wafers, solar cells, modules
Canadian solar	3.105	China, Canada	China, Canada	Silicon wafers, cells, modules
Jinko solar	2.944	China	China	Silicon wafers, cells, modules
JA solar	2.407	China	China	Silicon wafers, cells, modules
Renesola	1.970	China	China, Japan, Malaysia, South Africa, Poland, South Korea	Silicon wafers, cells, modules
Sharp	1.900	Japan	Japan, USA	Silicon modules, thin film (a-Si, mc-Si)
Motech	1.632	Taiwan	Taiwan, China, Japan, USA	Silicon solar cells, modules
First solar	1.500	USA	Malaysia, USA	Thin film modules (CdTe)
Sun power	1.254	USA	USA, Philippines	Silicon solar cells, modules

module sales). In 2015, global shipments of modules will reach 61 GW, up 27% from 48 GW in 2014, with growth expected in at least 89 countries, and profits increasing 117% from $2.3 million in 2014 to $5 billion in 2015 [38].

Accordingly, companies are currently expanding their capacity at fast pace. For example, the world's largest manufacturer (Trina Solar) is currently building a plant in Thailand, whereas the third (Canadian Solar) and fifth global producer (Jinko Solar) are building new factories in China and in Malaysia, respectively. Almost all other manufacturers are similarly boosting their solar module production with new production lines, or by running existing production lines at full capacity.

Numerous manufacturers of excellent solar modules exist beyond the top ten ranked in Table 2. On a global scale, there are hundreds of PV module suppliers even though only 3% of them is vertically integrated and uses robotic lines to manufacture high quality solar modules (Tier 1 manufacturers, Fig. 7; even though clear quality differences exist among the modules of different Tier 1 suppliers) [39], with some using a business model integrating upwards the value chain so as to become supplier of energy, rather than of a product (the solar panel).

For example, Enel Green Power manufactures in Sicily (Italy) about 200 MW of thin film (mc-Si) solar modules, which are not sold to customers in the marketplace but rather used by the same company to realize utility scale PV plants across the globe, with which the company is able to win bids in Brazil for profitably supplying energy for 20 years at a tariff as low as $8.7 cent per kWh [41].

Similarly, First Solar not only manufactures and sells the most widely adopted thin film solar modules, but it also builds large PV plants scattered throughout the world and selling solar energy to widely different energy buyers.

Nor one should think that scientifically advanced, huge countries such as India or Russia will not develop their own PV industry while photovoltaic energy is becoming a strategic energy resource.

Indeed, Russia in early 2015 witnessed the debut of its first large PV manufacturer (Hevel, manufacturing thin film modules using the silicon-based micromorph technology at a new plant with 130 MW per year capacity) [42].

In India, where a relatively large PV industry was present (15 companies with cell manufacturing equipment and 48 with module equipment, even though capacity is far from being fully exploited: Table 3) [43], foreign PV companies currently installing large PV plants in the country are as well establishing advanced manufacturing facilities based upon Chinese technology in order to lower the production cost.

The overall picture arising from PV industry trend shows that business maturity has been largely achieved,

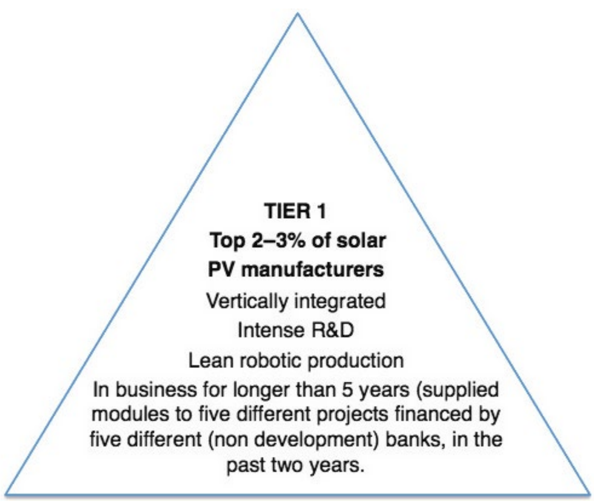

Figure 7. Common differentiation among manufacturers of PV modules uses the Tier 1 nomenclature [Adapted from Ref 40, with kind permission].

Table 3. India PV manufacturing capacity and actual production in 2014 [Source: India: PV Manufacturing Survey 2014].

Solar cell capacity (MW)	1386
Solar cell production (MW)	297
PV module capacity (MW)	2756
PV module production (MW)	1305

in terms both of size and location of the top manufacturing facilities.

Barriers to Overcome

The main barrier to further penetration of PV generation in electricity markets relates to the value of generated electricity, which is declining with increasing penetration, because PV power is intermittent, and electricity in most industrialized countries is traded on energy-only markets. This can be clearly observed, for example, in Germany where, as mentioned in Section 1, the spot market price turns negative on days with very high PV penetration.

While noting that such prices can be only nominally negative, because customers' power bills are still charged with PV subsidies, undoubtedly – if this trend continues and electricity markets in these countries is not reformed fundamentally – PV energy will barely become economically self-sufficient. For instance, in markets where PV electricity provides a significant part of the electricity supply, such as in Italy or in Germany, the need for increased self-consumption to maximize the value of the PV electricity during the sunny spring and summer days when market prices are very low or even negative becomes self-evident.

The technical solutions available that are technically and economically feasible on a large scale, include distributed storage (with batteries capable of absorbing and delivering power with sub-second response times) [44], centralized storage [45], geographical distribution [46], and demand-side management [47]. All are developing quickly with the cost of lithium-ion battery packs having fallen 8% annually between 2007 and 2014 to reach the unprecedented low value of $300 per kWh for battery packs used by leading electric vehicle manufacturers [48], a much lower cost than previously reported that will shortly translate into massive deployment of electric vehicles, a market in its turn growing at almost exponential rate since 2011 [49].

Turning to the regulatory solutions, Hildmann et al. have lately shown that energy-only power markets seem to work even for high renewable energy sources (RES) penetration scenarios (» 25%) if the day-ahead market's share of overall load demand is increased and the true marginal costs of RES units in the merit-order is used (negative prices disappear in most days, and the RES production volume settled) [50].

In order to achieve genuine parity with power generation via combustion of fossil fuels, an energy source should be functionally equivalent. Natural gas, coal, and uranium fossil fuels effectively store chemical or nuclear energy that is released exactly when needed.

This need will lead to the second innovation wave of the solar energy revolution, namely the need to overcome the difficulty of storing electricity in the huge amounts required to meet electricity demand 24 h a day, 7 days a week, 365 days a year. The development of cost-effective storage technologies, in other words, is the last significant technical hurdle to solve the heavy intra-daily intermittence and seasonal cycle of solar energy. For example, 80% of the energy output of a typical PV plant installed in Europe is concentrated in 4–5 months [16].

Both solar hydrogen [51] produced by water electrolysis, and newly developed batteries [52], will be massively used to store and release the electricity produced in large excess during the sunny months of the year.

The cost of hydrogen, indeed, is up to 97% defined by the cost of the PV component, while the material selection for the electrolysis components has vanishingly low effect [53]. Now that is available at low cost, thus, solar hydrogen can be massively used either to power fuel cell cars and trucks, or burned to generate power as it happens since years at Italy's Porto Marghera (Venice) hydrogen-fueled thermoelectric power unit [54].

A thorough net energy analysis [45] referring to the best and most widely installed battery (Li-ion) and hydrogen technology (alkaline water electrolyzer and a PEM fuel cell) for grid storage suggests that the round-trip efficiency of PEM fuel cells must improve dramatically before they can offer the same overall energy efficiency as batteries, which have round-trip efficiencies of 75–90% vs. 30% for PEM cells. From such a net energy analysis, batteries are preferable a PEM fuel cell to store photovoltaic over-generation.

On the other hand, the latter technology is perfectly suited to store over-generation from wind turbines, because its high electrical energy stored on invested (ESOI) ratio and the high energy return on invested (EROI) of wind generation offset the low round-trip efficiency.

In general, a similar dynamic net energy analysis [55] applied to the main PV technologies (mono-, poly-crystalline, amorphous and ribbon silicon Si, CdTe, and CIGS) reveals that energetically expensive solar PV can afford about 24 h of storage before the industry operates at an energy deficit. Said another way, PV systems could be deployed with enough storage to back up the natural day-night cycle and the PV industry could still operate at a surplus, supplying a net electricity yield to society even after taking into account the electricity to deploy new generation and storage capacity.

Outlook and Conclusions

The niche-size photovoltaic industry relying until the late 1990s on waste semiconductor-grade silicon used to manufacture integrated circuits (2100 tons of rejected material, or 10% of silicon used by the integrated circuit industry, in 1997) [56] has evolved into a 40 billion industry growing at >25% annual rate, supplying low-cost solar modules to customers across the world either for decentralized electricity generation, or for utility scale generation via several hundreds of MW (or even >1000 MW) large solar PV plants.

The consequences of this dramatic growth are that the price of solar modules as well as of the inverters [57] has decreased to a such low levels that in early 2015 the price of the solar kWh has reached and gone below the $6c threshold, namely around the cost of electricity produced by burning coal. The largest solar PV plants are no longer supported by generous subsidies, but sell power at low cost for 20 or 25 years in unsubsidized markets according to power purchase agreement (PPA) contracts.

Similarly, residential PV systems for decentralized electricity generation are now a global reality, both in economically developed and in developing countries [58].

This study clarifies in a single report several practically relevant aspects, and identifies the main barriers to the transition of the global economy from fossil fuels to solar electricity generated by low-cost photovoltaic technology. The role of low-cost PV solar energy in solving the world's energy and environmental concomitant crises appears likely to be significant.

For the entire economy running on solar PV (and wind) electricity within the next three decades, three main barriers – namely the rapidly decreasing value of PV electricity with increasing penetration due to intermittency and electricity trading in most industrialized countries on energy-only markets, along with accelerated electrification of transport and heating – must be overcome.

Eventually, along with rapidly increasing installation of PV power, the two central energy technologies of the 19th and 20th century, namely the internal combustion engine and the fuel-powered heater, will be replaced by electric motors and electricity-driven heat pumps. Such ongoing end-use energy electrification [59] will afford the prolonged economic and environmental benefits that will solve the current energy and environmental crises, opening the route to the solar-based economy: the helionomics.

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Conflict of Interest

None declared.

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