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Photovoltaics advancements for transition from renewable to clean energy

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Abstract

Moving from fossil fuels toward renewable resources of energy has a worldwide consensus. Solar energy alone can satisfy all our energy requirements since the earth receives 725 ZJ of energy from the sun each year while total human energy consumption in 2019 was 0.584 ZJ. The 2010s are highlighted as a transitional decade when the photovoltaic conversion industry transformed from a subsidized to a profitable energy sector. While photovoltaic energy conversion is a clean process, technologies for producing photovoltaic materials and solar panels affect the environment. The utilization of photovoltaic materials with low impact on the environment during the entire life cycle will mark the beginning of the sustainable transition toward 100% clean renewable energy sources in a sustainable manner. Thus far, only perovskite compounds have the potential to satisfy these requirements because of their theoretical conversion efficiencies, ease of synthesis, production scalability, adaptability, and comparability to existing photovoltaic systems. In this article, the rise of the photovoltaic industry in the last decade is shown and requirements in further transition from renewable to clean sources of renewable energy are foreseen

Keywords: Photovoltaics, renewable resources, clean energy, solar cells, sustainable transition, energy consumption

1. Introduction

One of the most intriguing questions among early experts in sustainable development was is it possible to satisfy all energy needs from renewable resources. Nowadays, a question is how and when the transition from renewable to clean energy will occur. Renewable energy implies that energy is converted from renewable resources such as solar, wind, biomass, or hydropower, while clean energy requires no environmentally affecting processes through an entire life cycle of energy converting components. Wind farms and hydropower stations affect their environments, leaving solar energy as only one viable source of clean energy in the future.

Since the beginning of the 21st century, no other scientific branch has experienced an influx of new materials and technologies like the photovoltaic field. The share of primary energy consumption originated from renewable sources had a steep increase, rising from 26.7 in 1999 to 66.9 EJ in 2019 [1]. Photovoltaic conversion processes contributing about 26% in power generated by all renewable sources and have by far the highest potential for further utilization among all renewable resources [2]. The yearly potential of the renewable, proven exploitable reserves of the nonrenewable resources, and the world's energy consumption in 2019 is visualized in Figure 1 and envisions the potential of solar energy compared to the other sources of energy. Among renewables, only solar and wind exceeds 0.584 ZJ per year convertible capacity corresponding to annual energy consumption. The solar with 725 ZJ per year exceeds all other resources by orders of magnitude, and therefore, the future economically and environmentally sustainable energy consumption will be based on photovoltaic conversion technologies. Further assuming 20% conversion efficiency of the current commercial photovoltaic materials gives a potential of 125 ZJ per year for conversion into electricity, although the highest conversion efficiency of the photovoltaic components reported at 47% would double that potential.

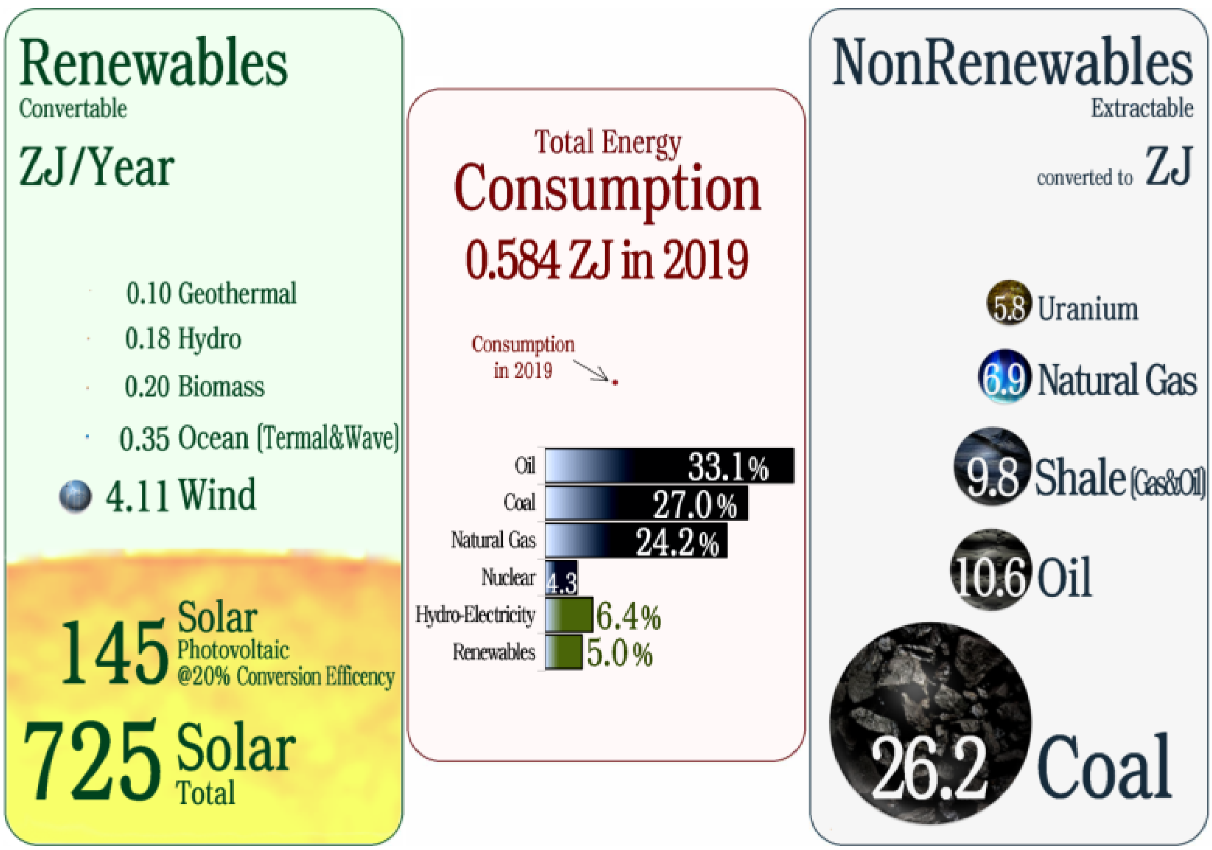

Figure 1. Availability of the primary energy resources. Spheres' volumes are visually comparable illustrations of currently consumed and available energies. Renewable energy resources are expressed in ZJ per year and values correspond to the amount of energy available every year [3]. Extractable nonrenewable resource capacities are normalized to ZJ and these values correspond to the final amount of energy [4]. Whereas metadata were in TWh are normalized to zettajoules (ZJ) by a conversion factor of 0.277778. Availability of shale oil, shale gas, and uranium are expected to expand in near future because of advancements in extraction technologies.

In the first quarter of 2020, only increase in energy demand is registered from solar and wind sources, about three percent relative to the first quarter of 2019, although total demand for electricity and transportation fell by 3.8% and 14.4%, mostly to Covid-19 reverberation [5]. These early analyses showing that photovoltaic processes are likely the most suitable kind of energy conversion in conditions of the global pandemics or during periods of adjourned social contacts, that may become our reality in near future. Another noteworthy remark is the recognition that the sun's radiation roots terrestrial temperature changes, water flows, and biomass replenishment but the harvesting energy from the sun has no impact on climate change, in contrast to nonrenewable resources or biomass and geothermal [6]. The rise of the photovoltaic industry in the 2010s, the availability of solar energy, advanced human knowledge regarding photovoltaic processes, low environmental impact, and social acceptability make photovoltaic conversion processes the leading candidates to make exploitation of the nonrenewable sources of energy obsolete.

2. The rise of photovoltaic industry in the 2010s

Solar energy experienced tremendous progress throughout the 2010s. Global annual solar installations already grew over sevenfold in less than one decade and keep growing, from 16 GW in 2010 to 121 GW of added power in 2019 with further addition between 121 and 154 GW in 2020, with many projects now being executed without direct subsidy. The transition from small manufacturers to today's independent and fully automated 627 GW capacity industry is one of the key factors that contributed to the exponential growth of the global solar cell market [7]. Entering the Far East companies into the silicon solar cell market further diminished the effect of the highest contributor to the price of solar cells that was the feedstock solar grade silicon [8]. Nowadays, an almost exclusive global producer of silicon wafers for the photovoltaic industry are Chinese companies, also featuring top four suppliers of the finished solar cell systems, contributing over 80% in photovoltaic products, and covering more than 50% of the worldwide market [9]. No other electricity generating technology has kept up with the pace of cost reduction of photovoltaic solar systems. In conjunction with installed capacity, the price for commercial solar cells fell from over $2.00 in 2010 to $0.16, $0.11, and $0.06 per kWh for residential, commercial, and utility photovoltaic solar systems, respectively [10]. Besides significant cost decline, the quality of the commercial silicon solar cells improved significantly over the last ten years period. The output of a commercialized multi-silicon module was below 250 watts in the early 2010s while today, in the early 2020s consumers would receive over 350 watts at one-tenth of the 2010 price. Increased power for the same amount of photovoltaic material further leads to a lower dollar-per-watt ratio for new photovoltaic systems.

Figure 2 illustrates the historical linkage between installed system capacity and the dollar-per-watt ratio for the photovoltaic modules. The long-term decline in installed system prices results from multiple factors such as reductions in photovoltaic materials' price and price of other components, governmental subsidies, and regulations. The photovoltaic module costs may have represented over 50 percent of the total system installed price in the 1990s while that percentage in the 2020s is below twenty. The further downward trend in the cost of photovoltaic systems during the last two decades is also attributed to increased social awareness of the necessity to transition toward renewable resources that consequently allowed positive political and policymaking measures.

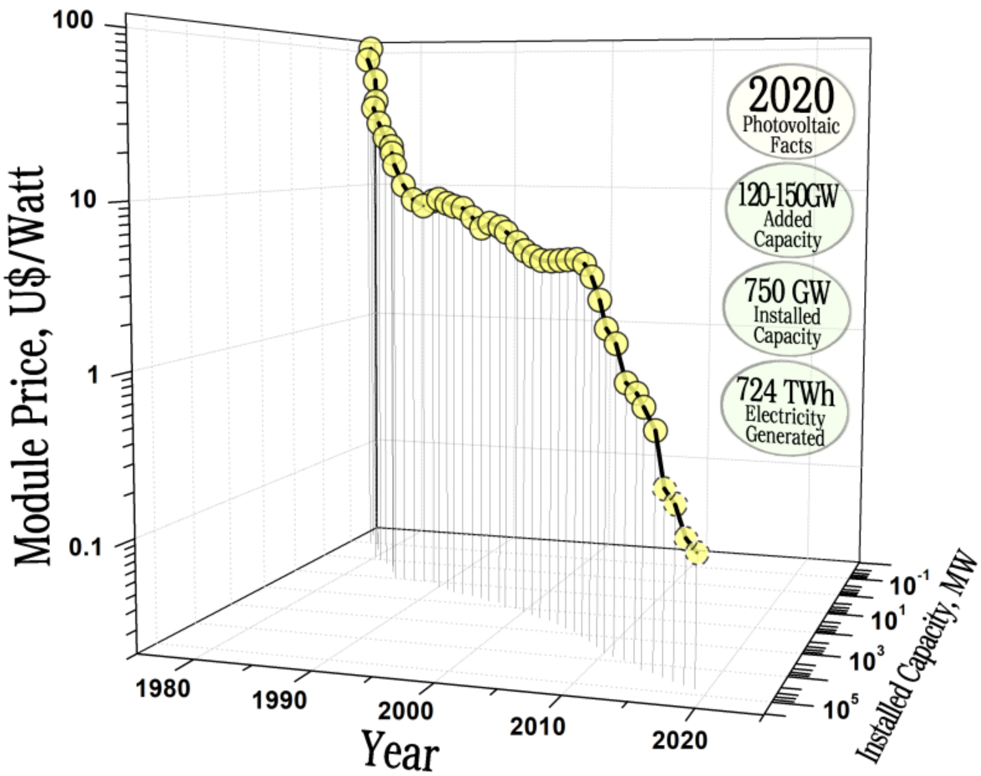

Figure 2. Photovoltaic module price slide and 2020 photovoltaic facts. The values of historic module price are informative rather than exact since data are retrieved from LaFond's diagram where sources beyond 2016 are extrapolated [11].

While the other photovoltaic technologies did not experience a tenfold price drop like silicon-based solar cells, in some cases, the researchers working on emerging photovoltaic materials and technologies achieved an increase in conversion efficiencies well over ten times. Regardless of the photovoltaic material or manufacturing technology, current innovations will increase both, the solar systems' installed capacity and overall power output without significantly increasing the manufacturing costs. Improvements in conversion efficiencies allow for more electricity generation per square area of photovoltaic material that reduces the need for wires, junction boxes, and other components while frees space for the installation of more solar panels. Technological advancements in all segments of photovoltaic energy conversion gave us the tools to satisfy all our energy needs from renewable sources. Further social acceptance of the new technologies allows the photovoltaic industry to become an independent and profitable part of the energy sector.

3. Socio-political acceptance

The process of the renewable energy transition in the 2010s is an example of great scientific success but new advancements in the energy sector have socio-political implications where efforts to shift from fossil fuels and decarbonize societies inevitably lead toward an opposition with careers of the dominant systems of energy supply [12]. Among many positive examples worldwide regarding policy adjustments is the state of California, the world's sixth-largest economy, with its 100% by 2045 renewable target and proposed US. House Resolution HR540, US Senate Resolution SR 632, and US Senate Bill S.987 calling for the United States to go to 100% clean renewable energy by 2050. By 2020, another 14 US states passed into the law targets toward at least 100% renewable energy. Along with policy enabling steps and socio-political acceptance, also local community acceptance for specific renewable projects and enabling infrastructure is one of the exampling requirements facilitating the expansion of the photovoltaic industry to the renewable energy sector. Developed countries such as the US, Germany, or Italy were the leaders in transforming the photovoltaics into profitable industry whereby transferring the power to the local governments resulted in faster improvement of the energy efficiency and switch towards more sustainable sources of energy [13], an example that policymakers in other countries may follow.

4. A transition from subsidized to a profitable industry

Each new industry branch has to forgo a period when requires more investment than the net value generated from its production to grow to an independent self-sustainable entity. Figure 3 depicts the road of the photovoltaic industry that started about 50 years ago, in the 1970s, and recently moved in positive net power output, marking one of the most important turning points in a future expansion of the photovoltaic industry among others in the energy sector. In recent years, many authors properly recognized a reduction in governmental subsidies all over the world for projects related to renewable energies but with a steady growth of the photovoltaic market, this is a sign that generating energy from renewable resources became independent, stable, and sustainable industry in the energy sector.

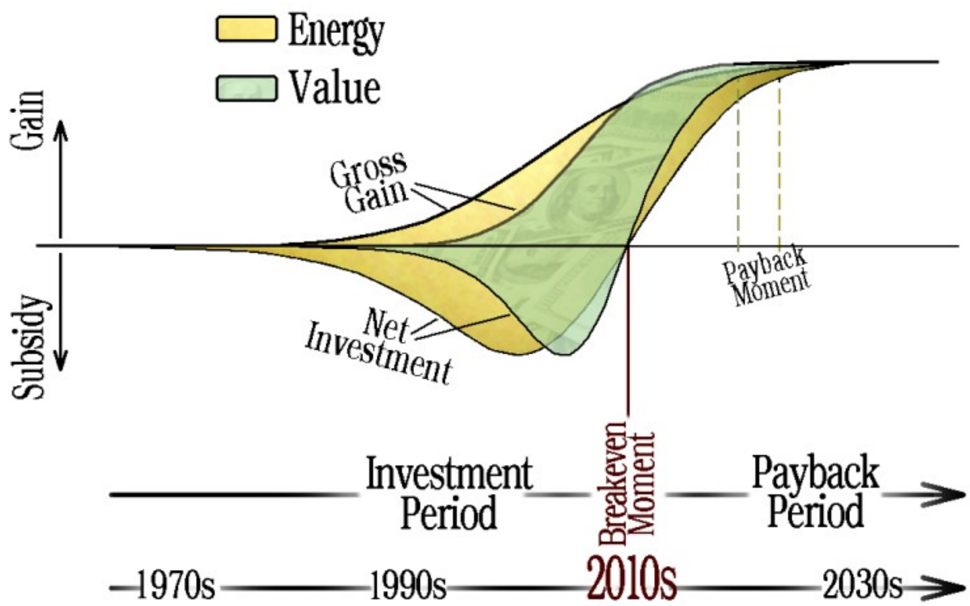

Figure 3. The evolution of the photovoltaic industry from the subsidized branch to independent profitable energy sector.

Current commercial solar cells are installed with ever-increasing efficiency with a small or no increase in manufacturing costs that consequently reduces watts per dollar ratio [14]. Each small lip in improving efficiency and longevity or decreasing the size of the solar cells is an important and strengthens photovoltaic industry. However, fundamental improvement of photovoltaic systems rests on new materials for the next generation of solar cells that must be resistant to surrounding influences and at least efficient as the first-generation silicon photovoltaic materials while utilizing the manufacturing technologies of the thin-film second-generation solar cells. With a set goal toward clean energy, an important feature of the new materials should be non-toxicity and wide availability, which would ensure widespread applications without affecting environment.

5. From renewable to clean energy

Worldwide consensus refers that developing renewable energy technologies are critical to addressing concerns about climate change and environmental issues. For example, The U.S. Department of Energy Photovoltaics Program estimated that an average U.S. household producing 1000 kWh of electricity with solar power reduces emissions by nearly four kilograms of sulfur dioxide, three kilograms of nitrogen oxides, and over 700 kilograms of carbon dioxide. During its projected 28 years of clean energy production, a rooftop system with two years' payback time and meeting a household's electricity use would avoid conventional electrical plant emissions of over one ton of sulfur dioxide, almost one ton of nitrogen oxides, and 200 tons of carbon dioxide. However, even in the case of utilizing only renewable energy sources that would not eliminate all environmental concerns since these systems for energy conversion and delivery to the consumers already consumed energy in its production cycle. Most 'top-down' estimates related to energy payback time properly taking into consideration the energy demands for producing feedstock photovoltaic materials but a closer look in ‘bottom up’ estimates unveils environmental impacts of mining, manufacturing, transport, construction, operations, and disposal processes of the same materials. For example, silicon for photovoltaic application is reduced from silica sand by a carbothermic process, a process that requires over one GJ of energy for one kilogram of silicon and its byproducts are large quantities of carbon dioxide and sulphuric gases. The next step in silicon purification creates toxic trichlorosilane by combining hydrochloric acid with metallurgical grade silicon. Finally, trichlorosilane reacts with added hydrogen and produces satisfactory purity polysilicon along with silicon tetrachloride in a ratio of three tons of silicon tetrachloride for every ton of polysilicon.

Regardless high energy demand for producing silicon-based solar cells their energy payback time approaching two years line. However, the trade-off in producing solar panels is an environmental concern due to generated toxic and very corrosive gases. The greatest potential in reducing environmental impact during the production of solar silicon rests in replacing the conventional Siemens process with a direct metallurgical route [15]. Silicon treatment by a direct metallurgical route for the production of Solar Grade Silicon can be five times more energy-efficient than the conventional/commercial processes that use over 200 kWh for one kilogram silicon produced [16]. Although silicon as photovoltaic material reached its maturity, the advancements in refining processes and efficiency increase will continue, and consequently, energy payback time and environmental impact will reduce. A viable solution for further price decrease where photovoltaic material reached its inherited limits is the concept of overbuilding solar system capacity and forward surplus energy to the grid rather than converting solar to chemical energy.

The strategy of building relatively low price solar systems and connecting to the large grid could theoretically lower the cost of electricity by as much as 75% [17]. Although the suggested strategy does not address the shift from conventional photovoltaic materials toward clean energy, the concept of overbuilding capacity applies to any kind of photovoltaic system.

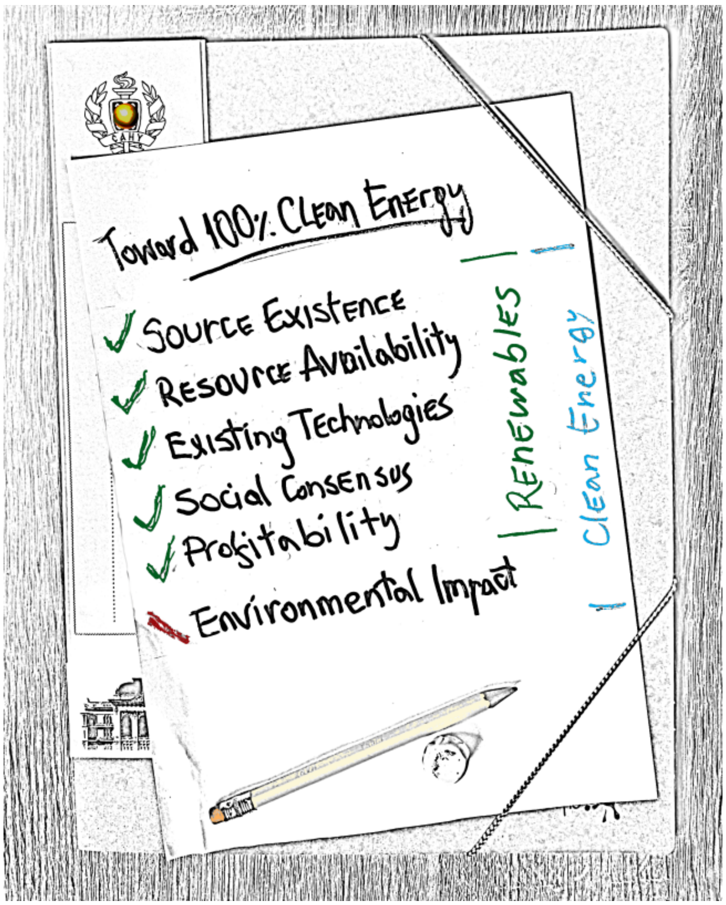

Figure 4. Status of the renewable energy in the 2010s. We set all requirements for transition from nonrenewable to renewable sources of energy. Further transition to clean energy requires new photovoltaic materials and technologies harmless to the environment throughout the entire life cycle.

Because of strong atomic bonds between silicon and oxygen in silica sands and inherited conversion efficiency of 29%, silicon is hardly suitable photovoltaic material for harvesting clean energy. New materials have to entirely replace silicon to leap forward in endeavor toward 100% environmentally sound clean renewable energy conversion. Where new industry rapidly emerging number of patents and scientific reports are a valuable tool in estimating future development of a particular industry. In the US, a number of patents related to photovoltaic materials and technologies raised from less than 200 in 1999 to over 2,000 in 2019 [18]. Among photovoltaic materials, a major indicator could be the fact that in the 2010s over 25,000 scientific publications are addressing perovskite materials, with a popularity that is an order of magnitude higher than any other photovoltaic material. Perovskite solar cells achieved higher conversion efficiencies than silicon, production cost and scalability are superior compared to silicon, and the availability of raw materials is limitless. Projecting further in the future, the photovoltaic industry will ultimately become the primary source of energy that means the size of today's photovoltaic systems requires a tremendous capacity increase in a brief time [19]. Perovskite materials sit in a remarkably strong position, not only compared to other emerging materials but also compared to silicon. For example, to reach one TW electricity generation, GaAs PV cells would require 40 years of today's gallium production capacity, thin-film CdTe modules would require 80 years of today's tellurium, and thin-film copper indium gallium selenide (CIGS) would require 32 years to achieve the same goal. In contrast, due to the simplicity of the synthesis, it would only take a few days to scale up perovskites' production capacity to the one TW level. The only commercial photovoltaic technology that can scale to this level is silicon, which for one TW electricity generation capacity would require around 80 days of our current silicon production [20]. New technologies allow for the synthesis of perovskite material on silicon that results in the utilization of tandem solar cells with the increased conversion efficiencies on already existing silicon-based photovoltaic networks. The key scientific challenge in perovskite solar cells is understanding the complexity of mixed ionic-electronic conduction in complex hybrid molecules [21]. The lead-halide perovskites reached a mature research stage and approaching the commercialization [22] with current status either in the proof-of-concept phase [23] or in hands of start-up companies that are in the process of delivering the first commercial products [24].

6. Perspective

The beginning of the 21st century is sometimes referred to as the renewable energy renaissance. In one decade, the global annual photovoltaics installation grew from 16 GW in 2010 to 154 GW in 2020, increasing the share of primary energy consumption originated from renewables from 26.7 EJ in 1999 to 66.9 EJ in 2019. The power output of commercially available solar cells increased from 250 W in 2010 to 350 W in 2020 while the price of the commercial solar cells fell from two dollars in 2010 to bellow two cents for residential, commercial, and utility photovoltaic systems. With such stark improvement in parameters related to the utilization of renewable energies, renewables will eventually replace fossil fuels. Among all renewable resources, photovoltaic materials have the steepest growth in each step, from the idea, through research and development, and all away to commercialization. Compared to the previous decades when silicon was almost only commercial photovoltaic material, a significant number of new photovoltaic materials found their markets in the 2010s. Increasing the market share of new photovoltaic materials inevitably leads to further improvement in all segments of the photovoltaic field. So many positive indicators in the R&D would not happen without firm support from governments of the leading countries followed by less resourceful regions. Considering increased awareness regarding our natural habitat and global consensus regarding replacing fossil fuels with renewable sources of energy, further advancement will continue.

Photovoltaic energy conversion crossed over critical steps and now is a self-sustainable and profitable industry. These signs are encouraging, but much more work needs to be done to transition the world to 100% clean renewable energy. We have consensus regarding the necessity to become independent from finite sources of energy, we have the technology to satisfy global energy needs, we put tremendous efforts into advancements regarding energy conversion from renewables, only that we are missing is widely available photovoltaic material with high efficiency, longevity, but low impact on the environment (Figure 4). The utilization of the material with low impact on the environment not only during its service time but also during the entire life cycle will mark the beginning of the sustainable transition toward 100% clean renewable energy sources in a sustainable manner.

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