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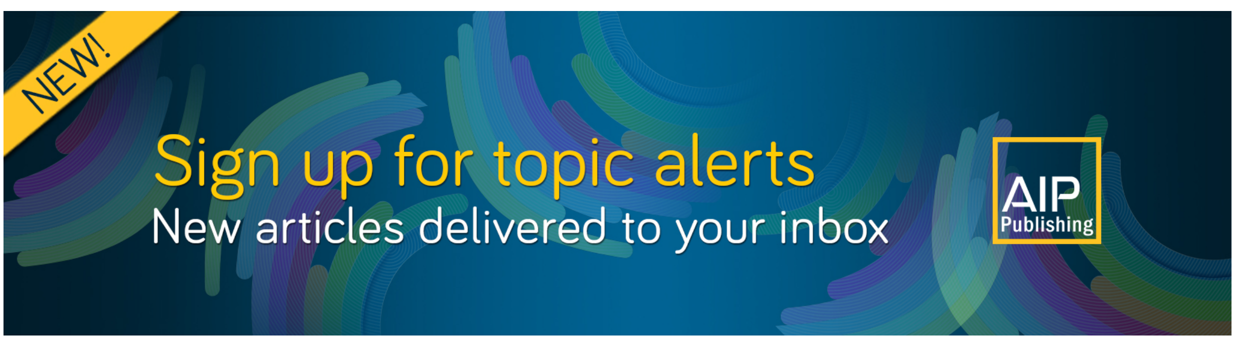

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ABSTRACT

To meet the target set by the Paris agreement in 2015 to keep the Earth average temperature rise to less than 2 °C (or even 1.5 °C), the best choice is to transition the energy economy to 100% renewable energy using solar photovoltaic energy (PV), playing a central role along with wind, hydro, geothermal, and biomass energy, to power directly or indirectly all sectors of the economy. The development of a large global energy storage capacity and the production of green hydrogen or other synthetic fuels by renewable energy will be critical. The estimated needed global PV generating capacity will be about 70 TW by 2050. The PV industry needs to rapidly grow its production capacity to about 3 TW p.a. to reach this objective. The industry has demonstrated that it is capable to grow at a very high rate and to continuously reduce the cost of manufacturing. There are no challenges related to the technology, manufacturing cost, or sustainability, except for the consumption of silver, which needs to be reduced by at least a factor of 4, and the recycling of material used in the PV system, which needs to be dramatically improved. The deployment of PV systems must be accelerated to reach a fast growth (>25%) until at least 2032 to avoid a major market downturn in 2050.

INTRODUCTION

The geologic history of the Earth is divided into eras, which are in turn divided into periods, epochs, and ages. Officially, since the last glacial period, about 11 650 years ago, we are living in the Holocene epoch. The Anthropocene is proposed by many people to be the new current geological epoch, dating from the commencement of significant human impact on Earth's geology and ecosystems, including, but not limited to, anthropogenic climate change. One proposal, based on atmospheric evidence, is to fix the start of the Anthropocene and the end of the Holocene, with the Industrial Revolution, ca. 1780, with the invention of the steam engine. Although the Anthropocene was proposed as the new geological epoch since 2000, it has not yet been approved by the International Commission on Stratigraphy (ICS) nor the International Union of Geological Sciences (IUGS).[1]

Annually, the human activity on Earth emits over 36×10^9 tons of CO_2 per year, increasing in average since 1950 by about 0.45×10^9 tons every year. Since the Industrial Revolution, humans have cumulatively emitted more than 1.5×10^{12} tons of CO_2. The concentration of CO_2 in the Earth atmosphere has increased to more than 410 ppm and is thought to be the main responsible for a remarkable increase in the average Earth temperature, in the range of 1–1.2 °C so far.[2] Experts have calculated that, to reach our climate goal of limiting the average temperature rise to less than 2 °C, as agreed in 2015 at the COP-21 international meeting on climate change in Paris, the residual emission of CO_2 that we would be allowed to emit is only 800×10^9 tons, which corresponds to about 20 years at the current emission rate. To keep the rise in average temperature to 1.5 °C, our residual emission is about 400×10^9 tons (11 years). After reducing the emissions of CO_2 to zero by mid-century, we need to keep removing CO_2 from the atmosphere.[3] If we do not dramatically cut the CO_2 emissions to zero, the consequences will be dramatic. The world is probably on a path of a temperature rise greater than 4 °C by the end of the century. We are approaching a tipping point when it will be too late to act. At that point, the increase in average temperature will make many parts of the world inhabitable, and we will observe significant desertification, ocean acidification, rise of the sea water level, and extreme climate-related disasters (floods, wild fires, hurricanes, and tornadoes). Some experts have predicted that a "+4 °C World" might only support

1×10^9 people, maybe half a billion.[4] For our grandchildren, it means that one person out of 10 will survive. We believe that the only solution and our only target should be for the world economy to be 100% powered by renewable energy. Our vision is that photovoltaic (PV) solar energy will play a central role in a new transformed economy. With wind energy, hydroelectricity, geothermal energy, and biomass, PV will power directly or indirectly all segments of the economy (Fig. 1). "Indirectly" means via the production of electricity by renewables and storage of the energy with hydrogen, ammonia, or other synthetic fuels to be used in the sectors of the energy economy that cannot be electrified, such as long-distance transportation, petrochemical industry, steel industry, and agriculture (fertilizers, for example). Several studies have shown that, to achieve this goal, a cumulative deployment of about 70 Terawatts of PV, corresponding to 6–10 kW of PV per capita, and an annual production of PV systems of 3–4 TW p.a. will be necessary by 2050.[5,6]

ACHIEVEMENTS OF THE PV INDUSTRY: COST, EFFICIENCY, AND SUSTAINABILITY

Over the last five decades, the PV industry has demonstrated that it is capable to grow very fast, some years with a growth rate greater than 50%, and to significantly reduce the cost of manufacturing. On average, over the last 50 years, the annual production rate and the cumulative installation have doubled every 3 years, to reach in 2019 more than 100 GW/year and cumulatively more than 600 GW. During the same period, the cost of PV panels has been reduced by more than two orders of magnitude. In the last 10 years only, the spot price of PV panels has decreased by about 90% to reach less than US$0.20/W.[7] Different countries have provided, at different times, significant contributions to the PV industry: first, the USA with its large PV market for satellites and the first large-scale PV plants, then Japan with the first significant residential PV market, and Australia with a large remote PV-powered telecommunication market, followed by Germany and the rest of Europe with an innovative feed-in tariff, and finally China where great financial support from investors drove low-cost mass industrialization. These regions have significantly contributed, each in their own way and with large R&D efforts, to the current status of the PV industry.

Like any manufacturing industry, the cost of manufacturing of PV panels follows a "learning curve model," predicting that the manufacturing industry is learning "by doing" over an extended period of time to make things better, cheaper, and more reliable. The theory predicts that the cost of manufacturing goods decreases as the cumulative production increases, following the formula

$$C_t = C_0 \left(\frac{q_t}{q_0}\right)^{-b},$$

where C_0 and C_t are manufacturing costs at reference time 0 and at time t and q_0 and q_t are cumulative production volumes at the same

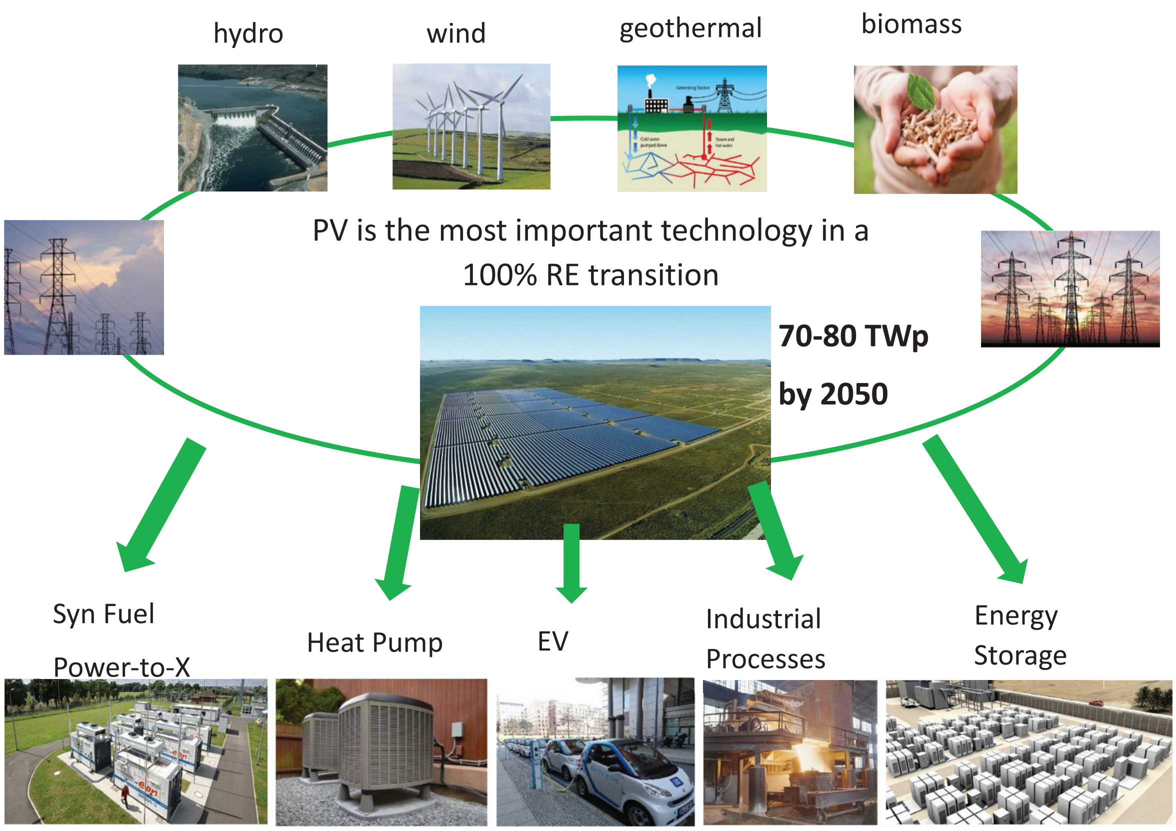

FIG. 1. Vision of the world economy 100% powered by renewable energy.

times. The parameter b is <1 and typically in the range 0.2–0.75. The learning rate (LR) is the reduction in manufacturing cost for every doubling of the cumulative production,

$$LR = \left(1 - 2^{-b}\right).$$

Since 1970, the PV industry has presented a LR of about 22%, i.e., representing a decrease in the manufacturing cost of 22% for every doubling of the cumulative production, which appears on average every 3 years. There is, of course, every year a possible slowdown or acceleration of the decrease in manufacturing cost due to temporary variations of the cost of supplies, and it is difficult to extract a short-term LR. However, over the last decade, the LR seems to have accelerated to about 25% to 40% due to the concentration of manufacturing in China and a strong alignment of the entire supply chain on a standardized and commoditized product.[8] It is expected that the cost of PV panels will reach US$0.10/W when the cumulative production reaches about 3 TW, around the year 2030. If the concentration of PV manufacturing in China has been an important factor in the cost reduction, it is not thinkable that it would stay like that. With increasing automation, labor cost is becoming an insignificant component, whereas shipping cost is proportionally increasing. The manufacturing of photovoltaic components, at an annual rate of several TW p.a., will become a strategic industry and a global affair with more localized manufacturing centers closer to the final customers.

Hundreds of small improvements are responsible for the historical reduction in manufacturing cost. We can mention, among many other factors and improvements, standardization of the entire supply chain and strong competition between suppliers, an increase in silicon wafer size (from 100 mm to 210 mm) and reduction in wafer thickness (down to about 150 μm), diamond wire sawing and reduction of kerf loss (from 200 μm down to less than 60 μm), reduction in silver consumption (from 50 mg/W down to less than 19 mg/W), automation, acceleration of Takt time and an increase in throughput per tool (from 1000 UPH to more than 10 000 UPH for some tools), and major reduction in manufacturing tool cost. Solar cell efficiency improvement has had a significant role in the overall PV cost reduction because cell efficiency impacts the cost in terms of $/W of every other component. As the concept of 100% renewable energy is being more and more accepted, higher PV efficiency has never been more important than it is today. The cost of other components in PV systems, such as inverters, racks, and trackers, has followed and experienced a similar impressive reduction over the last four decades, bringing the levelized cost of electricity (LCOE) to be lower than US$20/MWh for very large utility-scale solar farm in sunny regions and less than US$50/MWh in more temperate climates.[5]

The roadmap of silicon PV technologies is well documented and was established a long time ago (Fig. 2). The current standard product of the PV industry is the silicon Passivated Emitter and Rear Cell with local aluminum doping (PERC or PERL). The supply chain is well aligned to produce a low-cost reliable product that is bankable, i.e., well accepted by financial institutions for large scale PV power plants. The typical efficiency of industrial PERC solar cells in 2020 is between 21.5% and 23%, whereas the typical module efficiency is between 19% and 20%, compared to about 14% in 2010. The difference in efficiency between cells and modules comes in great part from the difference between the cell and module area due to the gap between cells. Other power losses from the cell to the module are due to the electrical resistance in interconnections between cells and optical losses. Recently, the PV industry has embarked in a series of rapid changes in the cell and module design, pushing toward larger cells (up to 210 mm), cutting cells in half or smaller pieces to reduce electrical losses due to the interconnections, reducing gaps between cells, and even sometimes overlapping adjacent cells. The result of these changes is a smaller gap between the cell efficiency and the module efficiency, which now can reach levels as high as 21.6% with standard PERC solar cells.

A laboratory champion PERC cell efficiency of 25% has been demonstrated in laboratory more than 20 years ago,[8] but this type of small laboratory cell made with an expensive photolithography

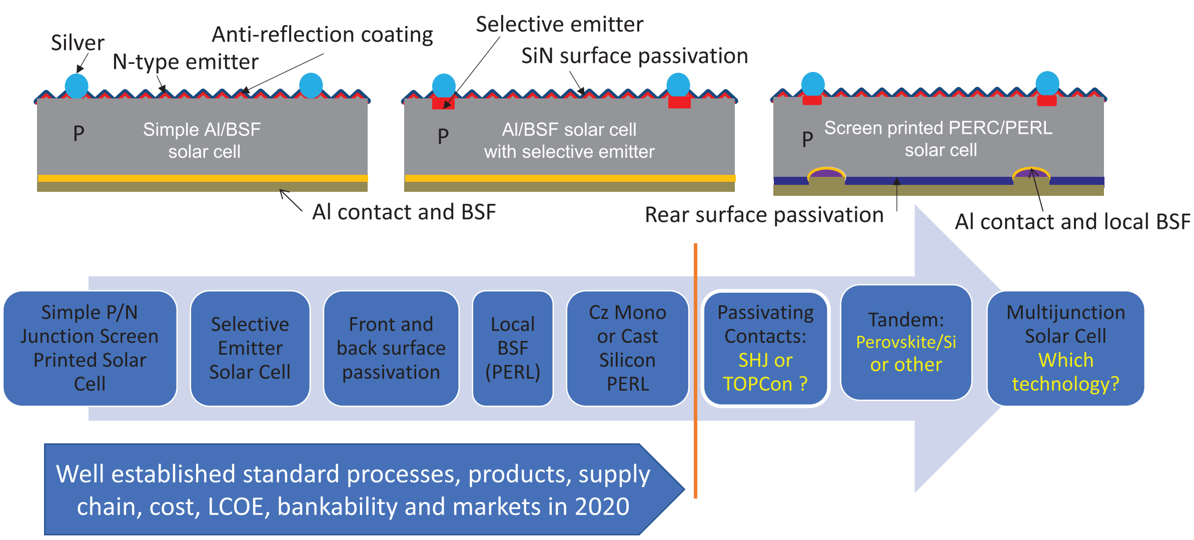

FIG. 2. The PV technology roadmap has been well known for many years. The remaining questions are related to defining the best way to cost-effectively integrate the latest improvements, such as passivating contacts, tandem structures, and multijunction cells.

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technology does not have much in common with the current low-cost large-area industrial cell. Nevertheless, an efficiency of 25% is a good target for a solar cell manufacturer to aim for. The main power loss within a silicon solar cell, which prevents reaching the theoretical efficiency of 29.4%, is due to the recombination of the generated carriers at the metallic electrical contacts. The current solution to this source of efficiency loss is to develop new electric contacts with good conductivity and that are passivating, i.e., that do not cause significant carrier recombination. The solar cell can have passivating contacts on one side or two sides (or two polarities). Another advanced technology in development is to stack two solar cells made of two semiconductor materials with different bandgaps. This is called a Tandem structure or a multijunction if more solar cells are stacked. Laboratory cell efficiencies up to 26.7% using passivating contacts and up to 29% with a perovskite/silicon tandem structure have been demonstrated.[9] These technologies are either still in development or are reserved for niche applications. It is, however, very clear that the market demands PV components with higher efficiency, providing significant savings for storage, transport, handling, balance of systems (BOS), and land. Currently, the market accepts a US$0.01/W price increase for 3.5% relative increase in power performance (typ. +10 W). It is also clear that the entire supply chain of the PV industry will soon be aligned to provide PV panels with passivating contacts, either with silicon heterojunction (SHJ) or with tunnel oxide and polysilicon (TOPCon) at a competitive cost. The winner between these two technologies will be determined by the cost of manufacturing.

Tandem solar cells are part of the next generation of PV technologies that will allow us to fabricate PV modules with efficiencies above 30%. Currently, several technologies are considered, with different semiconductor materials and different configurations (two terminals, three terminals, or four terminals). The most advanced technology toward high-efficiency low-cost PV modules uses a two-terminal monolithic structure with silicon as the bottom solar cell and a new hybrid organic–inorganic material, such as methylammonium lead iodide, called perovskite, as the top solar cell.[12] Potential issues to the future commercialization of perovskite/silicon tandem cells are the stability of the cells under exposure to UV, temperature, and air, the toxicity of lead if it would happen to leak from a sealed module, and the cost of integration with silicon. Considering the recent exceptional progress in this technology, it is expected that perovskite/silicon tandem modules with efficiency above 25% will be commercially available after 2022.

There are many different ways to look at the sustainability of the PV industry. One can evaluate the sustainability of the industry in terms of energy, emissions, effluents, waste, material, recyclability, or financial stability. A silicon PV system built today has a typical Energy Payback Time (EPBT) of 1.7 years and a Greenhouse Gas (GHG) emission of 28 g of CO_2 eq. per kWh of produced electricity over its lifetime.[10] These numbers continue to improve years after years, as the industry grows and learns to manufacture these products with higher efficiency, cleaner manufacturing, and greater economies of scale.

The PV industry is now, better than ever, capable of growing and building new production lines with the cash it generates from the sales of products, thanks to a significant reduction in cost of capital manufacturing equipment. The typical cost of capital equipment is steadily reducing at a rate of about −18% per year over the last 10 years (Fig. 3). The current costs of production lines per GW of annual production are as follows:

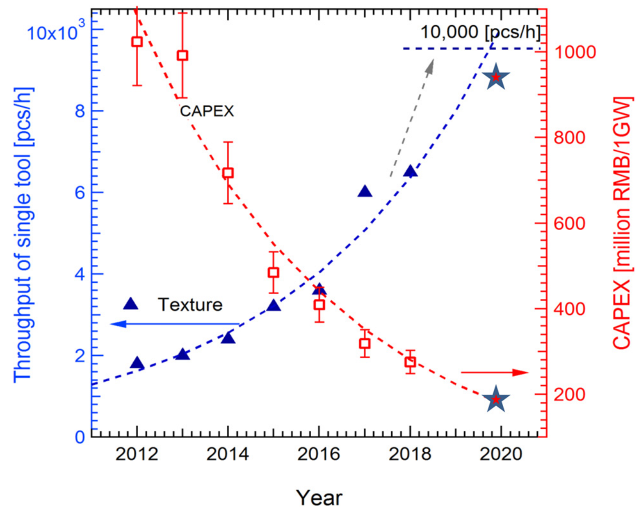

FIG. 3. Cost (in Chinese renminbi, or RMB) of a new silicon solar cell production line (1 GW) in China and, for example, throughput of a single chemical production tool (texturization step) in wafers per hour (Courtesy of Dr. Chen Yifeng, Trina Solar[11]).

- purification and polysilicon production: US$64 millions,
- monocrystalline ingot production: US$41 millions,
- wafer slicing: US$8.3 millions,
- mono PERC cell production: US$56.8 millions, and
- module assembly: US$11.8 millions.

This level of capital investment allows the industry to grow sustainably and reasonably fast (∼25%/year) with the gross margin that it generates from sales.

CHALLENGES

To meet the target of 70 TW of cumulative installed PV capacity by 2050, the industry has to grow its annual production by a factor of about 30. Based on its 60-year history and experience, the industry has demonstrated its capability to grow (doubling its capacity every 3 years on average) and to reduce cost with a LR of 25%–40%. The technology exists and is continually improved. The cost of PV manufacturing is reducing by about 10%–16% per year. The cost of capital equipment is reducing by about 18% per year. The EPBT of a typical rooftop-installed silicon PV system is 1.7 years under Southern European insolation (1700 kWh/m^2/year), and its GHG emissions are 27–35 times less than a traditional fossil-fuel power plant.[10] For a fixed tilt ground-mounted utility scale, the typical EPBT is reduced to 1.3 years in US South-West locations. It does not seem that there is any major problem to rapidly grow this industry to a level of 30 times the current production rate. There are, however, a few challenges.

The first challenge is that the time constants of climate change are so long, much longer than most human preoccupations, such as the re-election of politicians, the typical time for calculating the return on investments, or even a person's life expectancy. The most important barriers for solving environmental problems are selfishness, greed, trade barriers, return on investment, the accounting of stranded assets (old fossil-fuel plants that are closed down), wrong scale of values, populism, apathy, no sense of urgency, and slow response of grid operators, resulting in a slow growth of demand for renewable energy systems. Government supports for e-mobility, large-scale or residential energy storage, long-distance high voltage direct current (HVDC) transmission lines, hydrogen production, power-to-X, and general incentives for complete electrification of the economy are urgently needed.

The second most important challenge is related to the rate of growth of the industry. One would have thought that, when the PV technology reaches grid parity, either on the customer side of the meter for residential applications or on the utility side of the meter for large scale applications, there would be a fast growth of the demand for solar PV generation. It is interesting to note that the annual growth of the PV market has slowed down since 2018 to about 10%–11% p.a., even when PV has reached grid-parity in many parts of the world. With this level of annual growth, it will not be possible to reach a cumulative capacity of 70 TW by 2050, and the world will be forced to accelerate the growth of PV deployment in the last few years to 2050 to reach the objective to reduce the CO_2 emissions to zero. At that stage, after installing all the necessary PV system to power the world, the remaining PV market will be the normal growth of the electricity demand (∼2% p.a.) and the replacement of the old PV components, scaling back the annual production level to where it was 25 or 30 years earlier, which would create serious damages to the PV industry and many large ripples in the market in the second part of the century (Fig. 4). It is critical that the market maintains an annual growth in demand of about 25% p.a. until around 2032, to reach a stabilized annual production level of 3 TW p.a. from around 2032 to 2055 (Fig. 4). In such a way, the industry will not suffer any significant downturn.

The final important challenge for terawatt-scale PV manufacturing concerns the availability of material and recycling. Most materials used in silicon PV manufacturing are abundant elements in the Earth crust. Only silver (Ag) used for the metallization of solar cells, and being about 10^7 times less abundant than silicon, is an issue. Currently, Ag is used as the principal metal in a screen-printing paste to contact silicon and to provide a solderable metal for interconnection. The Ag-content in the screen-printing paste is currently about

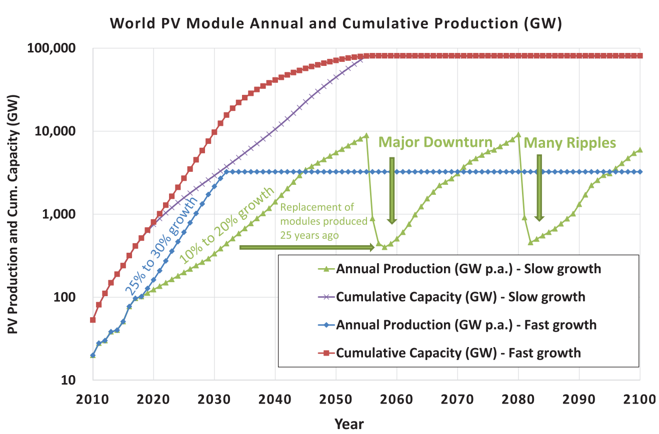

FIG. 4. Slow growth scenario of the PV industry would require increasing the annual production volume to almost 10 GW p.a. with a risk of a major downturn in 2055 and several ripples every 25 years, compared to a fast growth scenario of 25% p.a. minimum, bringing the annual production to a stabilized level of about 3 GW p.a.

80%. On a 156 mm wafer, typically 120 mg–130 mg of paste is used, corresponding to 96–104 mg of Ag or about 20 mg/W. The PV industry currently uses about 20 tons of silver per GW of production (2400 tons of silver in 2019) or a bit more than 10% of the global production of silver. If nothing changes in the consumption of Ag in PV production, at the 1 TW level of production (around 2028), the PV industry will use 100% of the global production of silver. To reach material sustainability, the PV industry needs to reduce the consumption of Ag to less than 5 mg/W, for example, by replacing Ag screen-printing by copper plating.

Recycling should also be improved, not only on volume but also in developing cost-effective technologies to recycle valuable materials like silver, copper, aluminum, tin, lead, glass, and silicon. Currently, the industry recycles about 100 MW of PV modules, i.e., about 400 000 modules or 0.1% of the current annual production. In 10 years from now, the volume will be 10 times larger or about 150 000 tons of recyclable materials.

CONCLUSIONS

Facing the global climate change challenge, the world has very few options. The most obvious choice would be to power the world economy with 100% renewable energy, from PV, wind, hydroelectricity, geothermal energy, and biomass. Green electricity would become the primary energy, which can be transformed to synthetic fuel or gas (power-to-X) for particular applications where electricity is not suitable, for example, long-distance transportation, or for long-term storage.

The PV industry would play a central role and would have to grow about 30 times in production capacity, to about 3 TW per year. The cumulative global PV capacity would have to reach 70 TW. The industry has demonstrated a great ability to grow, doubling every 3 years on average, and to lower the cost of manufacturing at a rate of −20% (long term average) to −40% (recent learning rate) for every doubling of the cumulative production. The technology to achieve this goal exists. Currently, the standard product is a monocrystalline PERC photovoltaic module. New technologies (SHJ, TOPCon, and perovskite/silicon Tandem) are in development and will most probably be cost-effective in the next few years to be commercially produced as well. The challenges that the PV industry is facing are not about efficiency, cost, energy or emission sustainability, or even financial sustainability.

The important challenges to this transition of the energy economy to 100% renewable energy are as follows:

- the slow growth in demand for the PV system due to greed, apathy, and lack of sense of urgency. Government supports for e-mobility, large-scale or residential energy storage, long-distance HVDC transmission lines, hydrogen production, power-to-X, and general incentives for complete electrification of the economy are needed;
- the current low growth rate in the PV market, resulting in the growing of the annual PV production to unsustainable levels in 2040–2050, which will create a major downturn or important future ripples in the PV market in the second half of the Century. A fast growth of about 25% p.a. is needed right now until 2032 to mitigate this risk;
- the consumption of silver as the principal metal for making the electrical contacts onto the semiconductor, resulting in a

consumption equal to three times the global annual production of silver in 2035–2050 when the PV market reaches 3 TW p.a. Technologies like Cu plating have to be developed to mitigate this risk.

ACKNOWLEDGMENTS

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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