Thin Film CdTe Photovoltaics and the U.S. Energy Transition in 2020

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TABLE OF CONTENTS

LIST OF FIGURES

List of Tables

Acknowledgments

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EXECUTIVE SUMMARY

Solar energy and the photovoltaic (PV) technologies that harvest it are rapidly transforming the world's energy systems. This transformation is being driven by two basic facts. First, solar energy is nearly carbon-free. As such, it is an ideal technology for tackling climate change. And, as the overall carbon intensity of the power grid declines, manufacturing new solar panels will eventually become carbon-neutral. Second, thanks to technology and manufacturing improvements, solar energy is extremely inexpensive. Today, a new solar power plant is one of the lowest cost strategies available for meeting the world's growing energy needs, in terms of the levelized cost of electricity. And the price keeps going down, with new world record low prices for contracts routinely announced.

Many projections of the future of energy now anticipate that, as a result of its low cost and minimal carbon footprint, solar energy may provide as much as 50% or more of future global energy demand. Part of this growth is likely to come from electric utilities, who are increasingly comfortable with high rates of penetration of solar PV on the grid. At the same time, the need for low-carbon options for the transportation sector is driving innovation in battery-electric vehicles, hydrogen fuel cell cars, and other solutions, all of which provide the potential to soak up and store large quantities of abundant, low-cost solar electrons produced when the sun is shining. Together, the electricity and transport sectors may drive the addition of multiple terawatts of solar panel manufacturing capacity and of solar panel deployment over the next several decades.

These trends highlight the importance for the field of solar energy to regularly evaluate the ongoing progress of photovoltaics in technology innovation and development, safety and environmental performance, contributions to low-carbon energy transitions, and providing value to society. This report contributes to that effort, focused on thin film cadmium telluride (CdTe) solar PV technology and the principal global manufacturer of CdTe PV modules, First Solar. Today, CdTe PV technologies comprise approximately one-third of the U.S. utility-scale PV market and over 25 GW of CdTe PV modules have been deployed globally. First Solar's capacity to manufacture CdTe PV modules is currently 6 GW per year, globally, and projected to grow to 8 GW in the next few years. With annual production capacity of 1.9 GW in its Ohio manufacturing facilities, First Solar is the largest U.S. PV module manufacturer, with over 2,750 direct jobs in the U.S., $1 billion spent annually in the U.S. supply chain, and over $1 billion spent on research and development since 2010.

Working with First Solar, we reviewed the now extensive research literature describing the performance of CdTe PV technologies and systems, both theoretically and in the field over the past two decades. We also visited First Solar facilities and spoke with First Solar technology, manufacturing, and sustainability managers. The work was carried out jointly by Arizona State University and the Massachusetts Institute of Technology, under the auspices of the Quantum Energy and Sustainable Solar Technologies Engineering Research Center.

The report describes the growing acceleration of trends towards transitioning the U.S. and global economy to a carbon-neutral future, the place of PV technologies in that transition, existing and potential future CdTe PV technologies, the historical and theoretical performance of CdTe technologies in terms of energy generation in diverse operating contexts, the environmental and safety record of CdTe PV, and the social and economic dimensions of solar energy.

Based on our review of competitiveness, safety, and life cycle environmental performance, CdTe PV technology is expected to make a valuable contribution to the U.S. energy transition. These conclusions are drawn on the basis of eco-efficiency as the driver of solar energy adoption, where eco-efficiency is the concept of creating more economic value with lower environmental impacts. The main findings include:

- *Creating economic value:* CdTe PV technology is well positioned to contribute significant economic value as part of a low-carbon energy transition. Along with wind and combined cycle natural gas, utility-scale solar energy is the most cost-competitive source of new electricity generation based on levelized cost of energy. To the extent that module prices continue to fall and module efficiencies continue to increase, these economic benefits will continue to grow. To date, CdTe PV efficiency has increased steadily with record cell efficiency of 22.1%, record module efficiency of 19.0%, and average commercial modules of 420-450W (First Solar Series 6). Innovation in module size and packaging, back contacts, and semiconductor band-gap grading have been used to improve CdTe PV device efficiency, long-term degradation rates, and cost per watt, and additional improvements in efficiency are expected in future CdTe PV technologies. In the future, synergies with battery storage and vehicle electrification are also expected to increase the demand for and integration of solar energy into the grid. Through use of advanced inverters, control systems, energy forecasting, and rapid ramping capabilities, large-scale PV power plants are also able to regulate real and reactive power output to provide grid-flexible operation and provide important grid services. CdTe PV technology is especially suited for hot and humid climates, where it has higher energy yield than crystalline silicon PV due to a lower temperature coefficient and lower spectral sensitivity to infrared light absorption by water vapor.

- *Creating environmental value:* CdTe PV technology is also well positioned to contribute significant environmental value as part of a low-carbon energy transition. Overall, CdTe PV technology has among the lowest greenhouse gas emissions and smallest environmental footprints of any energy technology. Per unit energy generated, CdTe PV creates significantly lower overall life-cycle environmental impacts than the current U.S. electricity grid. Avoidance of grid electricity greenhouse gas and air pollutant emissions with use of PV electricity amounts to environmental and public health benefits of \$20/MWh and \$14/MWh, respectively. Among commercial PV technologies, due to low energy and material use in manufacturing, CdTe PV has the lowest life cycle environmental impacts, including carbon footprint, energy payback time, water use, human health impacts, and ecosystem impacts. Properly designed and constructed solar facilities can have a positive impact on shared uses of land, including increasing agricultural productivity and enhancing biodiversity through revegetation, management of invasive and sensitive species, and preservation of land for alternative future uses. CdTe PV modules are also recyclable, reducing long-term waste from energy generation. First Solar's high-value recycling facilities have been operating commercially for over a decade and are able to recover more than 90% of a CdTe PV module for reuse in new solar modules and glass products. First Solar's global recycling facilities process 20,000-30,000 metric tons of manufacturing scrap and end-of-life PV modules annually.

- *Health, safety, and reliability:* First Solar CdTe PV modules are designed to provide 25+ years of reliable performance. CdTe is sourced as a byproduct of zinc and copper mining. All thin film PV manufacturing steps occur in a single facility, facilitating integrated quality control. Automated, enclosed equipment and air monitoring help ensure industrial hygiene, and worker biomonitoring is used to confirm occupational health. First Solar manufacturing facilities are certified to international standards for quality, environmental management, and occupational health (ISO 9001, ISO 14001, ISO 45001). Product reliability is continuously evaluated through in-line monitoring of production processes, indoor reliability testing with long-term test sequences, outdoor testing in temperate, tropical, and desert climates, and operations and maintenance programs that monitor performance in the field. The manufacturing process encapsulates and seals ~3 μm thick semiconductor layers in durable glass-glass modules. Experimental data, fate and transport models, and field data from extreme weather events have confirmed the environmental product safety of CdTe PV in case of non-routine events such as field breakage and fire. Although the goal is to recycle all PV modules, standard waste characterization testing and fate and transport modeling have confirmed the environmental product safety of CdTe PV in case of landfill disposal. Strong chemical bonding in CdTe results in high chemical and thermal stability, which are important for long-term device reliability and product safety.

I - THE PLACE OF SOLAR ENERGY IN A LOW-CARBON ENERGY TRANSITION

The U.S. and the globe are in the midst of a large-scale transformation of the energy sector. This transformation is expected to fundamentally alter the world's energy mix, shifting the energy sector from a heavy dominance on fossil fuels, today, to one in the relatively near future that is much more reliant on alternative energy sources and, especially, solar photovoltaic (PV) and other renewable energy technologies. As we detail below, current estimates anticipate that the energy sector will globally deploy multiple terawatts (TW) of solar PV technologies over the course of the next few decades. There is thus a clear need to assess the long-term performance and sustainability of PV technologies. In this report, we review thin-film, CdTe PV technologies, manufactured by First Solar, with regard to a range of technical performance, environmental, health, safety, and socio-economic considerations.

The current transformation of the energy sector is being driven by two primary factors. The first is rapid declines in the price of renewable energy generation technologies, especially solar and wind technologies. In the past decade, world record prices for unsubsidized contracts for solar energy dropped by a factor of ten from 17 cents/kWh in 2011 to less than 2 cents/kWh in 2018 and by lesser but significant amounts for wind energy (onshore from 8 to 2 cents/kWh; offshore from 17 to 5 cents per kWh) (Liebreich, 2018). In 2018, as a result, the levelized cost of energy from new solar and wind generation was lower than for all other electricity generation technologies, and in a growing fraction of the world was competitive with the marginal cost of operation of existing coal, gas, and nuclear power plants (Lazard, 2019). In May 2019, the EU spot market price for mainstream silicon solar modules was 25 cents/W (Schachinger, 2020). The second is widespread scientific, public, and policy concern about climate change and the resulting need to quickly reduce carbon emissions from energy use (IPCC, 2019). Concerns about climate change have grown markedly since 1990, escalating rapidly over the past ten years. Today, a growing number of governments and companies have committed to achieve carbon neutrality over the next few decades, including several of the world's largest oil companies, such as British Petroleum and Total S.A. (The Climate Group, 2020; CNCA, 2020).

These changes in policies and markets are, in turn, driving new patterns of energy generation and investment in new energy technologies, with renewable energy now accounting for 18% of U.S. electricity generation, while coal has dropped to 24% of U.S. electricity generation (EIA, 2020d). In 2021, the U.S. Energy Information Administration (EIA) projects electricity generation from renewable sources to surpass nuclear and coal (2020a). Worldwide, since 2016, new investments each year in solar and wind generation capacity have exceeded new investments in natural gas and coal-fired power plants (McKinsey, 2019). In 2019, global investments in wind and solar energy reached $ 284 billion (BNEF, 2019). Today, the amount of global investment in new renewable energy generation technologies for the power sector is nearly three times the amount invested in new fossil fuel generation (IEA, 2019b).

The upshot of these changes is that expectations are rapidly evolving regarding the future of the global energy industry. Annual additions to the world's capacity for solar energy generation now top 100 GW/year, and this number is anticipated to continue to increase steadily (Liebreich, 2018). Recent estimates suggest that solar and wind technologies will supply between 20% and 40% of world electricity demand by 2040 (BNEF, 2019; IEA, 2019b). While forecasts for what a future carbon-neutral energy system will ultimately look like remain uncertain, current expectations are that renewables will occupy a large share of future energy generation. Under such a scenario, it is not unreasonable that solar PV technologies may by themselves perhaps comprise up to 50% of the world's energy markets. By 2050, one estimate projects that the world will install an additional 7.7 TW of solar PV (McKinsey, 2019). This may be particularly true if electric vehicles come to dominate the transportation sector, requiring large, low-cost increases to electricity supply. Another recent study examined the scale of solar PV additions to global energy supply to meet 50% of the world's energy needs under a variety of scenarios (Kurtz et al., 2020). Their estimates range from 37 TW, in a scenario in which all final end uses of energy are electrified, to 180 TW, in a scenario in which major segments of final end uses of energy rely on chemical storage and combustion of hydrocarbons generated with renewable electricity. Their baseline scenario is 80-120 TW of solar PV in a world of 10 billion people and 3.2 kW of consumption per person.

Within this landscape of changing energy policies and technologies, the manufacturing and deployment of CdTe thin film solar PV technologies constitutes an important segment of the PV market. In the U.S., CdTe PV accounts for approximately one-third of cumulative capacity of utility-scale solar through 2018 (Bolinger et al., 2019). First Solar employs over 2,750 associates in the U.S. and with the addition of a second factory in Ohio in 2019, First Solar's U.S. annual production capacity is 1.9 GW, making it the largest PV module manufacturer in the U.S. and the Western hemisphere (First Solar, 2019c). In the past decade, over one-third of the total manufactured PV modules in the U.S. (2010-2018) were thin film CdTe PV modules (NREL, 2019). Globally, in 2017, thin film technologies represented approximately 5% of the world's solar energy markets (Fraunhofer, 2019). Within the thin film market, the largest manufacturing segment is CdTe, with First Solar currently the world's largest manufacturer of thin film PV. As of 2020, First Solar reported total sales of over 25 GW of CdTe thin film product (First Solar, 2020b). Today, First Solar's global manufacturing capacity for CdTe thin film PV modules is approximately 6.0 GW/year, with 5.5 GW/year of manufacturing capacity for its newest Series 6 modules in three facilities in Vietnam, Malaysia, and Perrysburg, OH (First Solar, 2020). The scale of CdTe thin film PV manufacturing is expected to grow. While the future scale of the PV market is uncertain, First Solar currently anticipates expanding its manufacturing capacity to ~8 GW/year by the end of 2021 (First Solar, 2020b). If thin film retains a similar market share of global solar installations over the next few decades, total cumulative installations of CdTe thin film PV could reach several hundred GW or more.

Our intention in this report is to review the most important developments in solar energy in recent years, with an emphasis on CdTe thin film technologies. Outstanding results have been achieved by many contributors and in many countries. A complete overview of existing literature (Google Scholar lists close to 3,000,000 publications on solar energy, 750,000 alone in the last four years) is beyond our scope. Our approach was to select examples that we believe illustrate and are representative of the developments and discussions currently ongoing. This selection was subjective and with a focus on the United States. The omission of studies from this report should in no way be interpreted as a comment on their quality. For example, when discussing energy transition scenarios, we briefly describe efforts in Australia and in California. Australia and California both have a long tradition in solar energy development and have recently developed exemplary integrative infrastructure concepts. Yet, equally detailed transition scenarios now exist for many regions and countries around the world. We kindly ask the reader to bear this in mind.

A - The Contribution of Photovoltaics to the Energy Transition

Between 1998 and 2015, the cumulative photovoltaics installation capacity has grown between 20% and 72% annually, with a compound growth rate of about 40%. This makes PV the fastest growing renewable energy technology. However, most projections and scenarios of PV deployment have consistently underestimated this growth (Creutzig et al., 2017). For example, the International Energy Agency (IEA) predicted annual growth rates of between 16% and 30% between 1998 and 2010. The 2012 World Energy Outlook 'new policies' scenario predicted 32% annual growth until 2015 but anticipated a too small growth rate of 12% for the following five years. Transformation scenarios by the German Advisory Council on Global Change (WBGU) estimated the growth rate to be 26%, and even the most advanced scenarios fall below reality with expected growth between 24% and 32%. The different scenarios, as well as the actual growth of PV are shown in **Figure 1**, illustrating the fact that every projection has consistently fallen short of the pace of actual solar growth.

Figure 1. PV Growth Over 20-Year Period

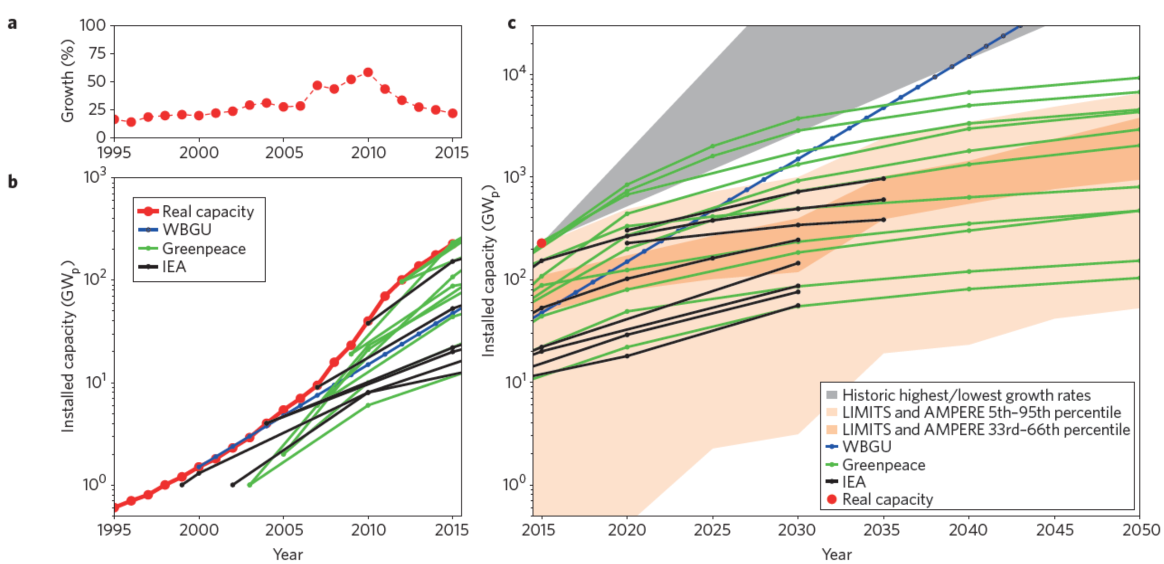


Figure 1. Top left - PV growth rate over 20 years. Lower left - real capacity over time (red) compared to various scenario projections. Shown are year to year data from past developments until 2016. Right - comparison of projections to historic growth rate (Creutzig et al., 2017).

The discrepancy between actual deployment and model-based predictions is attributed to biases in the models, with three factors being especially important: underestimates of the fast technological learning that has occurred in the PV industry, changes in policy support for PV, and increasing costs for competing technologies. PV technology has experienced exceptional technological learning. Module costs, in accordance with what is sometimes called Swanson's Law, have decreased by 22.5% for every doubling of installed capacity. Underestimating the learning rates, as well as the rapid capacity expansion, have both contributed to modelling errors. In addition, cost reductions in PV technology have helped transform it from an expensive option to one that is on par or even less expensive than traditional electricity sources, expanding the customer base. Learning curves are expected to continue in the future (Creutzig et al., 2017). By 2030, for example, projections suggest that solar energy may be the lowest cost energy source in most global markets, including being less expensive than the marginal costs of operating existing combined cycle thermal power plants (McKinsey, 2019).

Policy support has also had a significant impact on the success of PV. One example of policy is the use of feed-in tariffs, which have accelerated growth in some markets following their introduction. In Germany, feed-in tariffs contributed to a 400-fold growth in installed capacity between 2000 and 2016 (Creutzig et al., 2017). Important features of the German feed-in tariff were a streamlined permitting procedure and guaranteed remuneration over a long time period (20 years), making PV a low-risk investment. In addition, the technology enjoyed broad societal and public acceptance, with adopters willing to pay up to a 20% premium on electricity generated via PV modules. These factors are often left out of models of the electricity market, which typically minimize system cost and design the energy mix accordingly. Only stylized policies, like carbon pricing, are typically considered, and often projections are made using existing policies only. Personal preferences and technology-specific policies are typically neglected, resulting in a failure to capture these effects in growth predictions. In addition, models overestimated the impact of carbon capture and storage or nuclear power, technologies that can compete with the growth of renewables (Creutzig et al., 2017).

Creutzig et al. (2017) present their own growth model, attempting to correct for some of these discrepancies. They predict a share of 30% to 40% of PV in the electricity mix by 2050, even if sectors continue to electrify. They conclude:

> *Reaching a solar economy would require policymakers and society to overcome organizational and financial challenges in the next decades but would then offer the most-affordable clean energy solution for many. Continuing to underestimate the role of solar risks squandering this opportunity.*

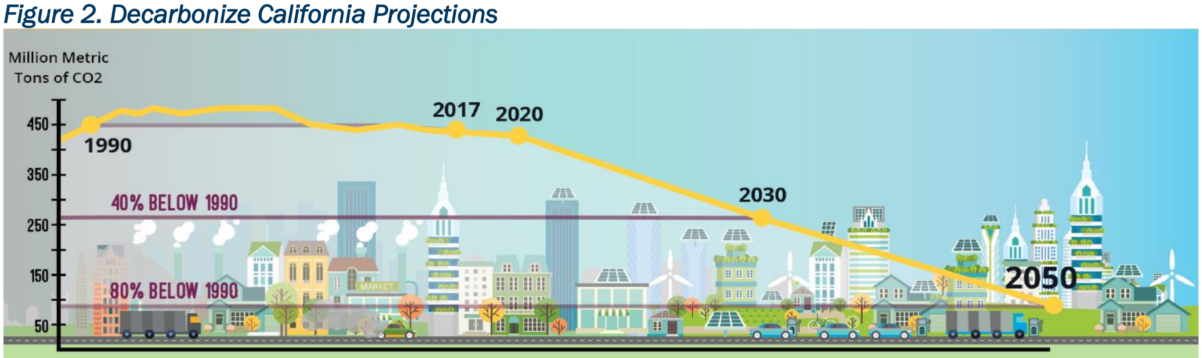
B - Transition Scenarios

As more and more regions of the world, as well as individual companies and cities, commit to carbon neutrality, a number of initiatives have begun to develop longer-term scenarios for the transition to carbon free electricity generation. Briefly, two such scenarios are discussed here. These scenarios are meant to be illustrative, only, reflecting a much larger pool of efforts currently underway to identify and develop pathways for achieving long-term energy transitions for specific localities or organizations. In both cases, as with many other similar efforts worldwide, the studies project large new additions of solar energy in the coming decades.

I.B.1 - Decarbonizing California

California is a leader in the solar energy transition in the U.S. With the passage of Senate Bill 100, California has committed to targets of 60% renewable electricity by 2030 and 100% carbon-free electricity by 2045 (2018). The California electric utility, Southern California Edison, has developed the Clean Power and Electrification Pathway as an integrated approach to reduce greenhouse gas emissions and air pollution and create a future low-carbon economy, including electricity generation, transportation and buildings (Southern California Edison 2017). They plan to further develop state policies and explore new measures to find cost-effective and practical ways to significantly reduce emissions, reach defined climate goals, and generate new jobs. Goals include the installation of increasingly energy efficient buildings with electrified space and water heaters, an electric grid that is 80% carbon free and the adoption of more than 7 million electric vehicles, all by 2030. **Figure 2** summarizes these measures and shows that the objective is to reduce the overall carbon footprint of the California economy by 40% compared to 1990 in 2030, and by 80% in 2050.

Figure 2. Decarbonize California Projections



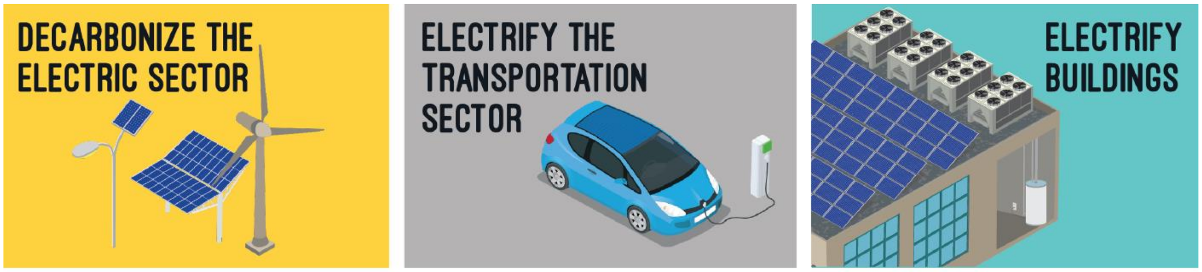


Figure 2. Illustration of California's clean power and electrification pathway (Southern California Edison, 2017).

The plan includes the future installation of an additional 30 GW of renewable energy generation capacity and 10 additional GW of storage from fixed and mobile sources. The plan is to support these resources with large hydroelectric generators. Achieving the goals set for 2030 are seen as a starting point to achieve the even deeper carbon emission goals set for 2050. While the initial period will be dominated by a shift to renewable electricity, later measures will more strongly focus on further decarbonizing the transportation sector, buildings, and industrial energy consumption.

I.B.2 - 100% Renewables in Australia

In a series of papers, A. Blakers and colleagues from the Australian National University (ANU) describe a scenario that supports 100% renewable electricity for Australia (Blakers 2017, Blakers et al. 2017). They present simulated results using an hourly energy balance model of the Australian National Electricity Market (ANEM), assuming a scenario with 100% renewable electricity. The lion's share of the generation is provided by wind and photovoltaics (about 90%), with biomass and hydroelectricity providing the balance of required energy. They assume that wind and solar generation are distributed over the Australian landmass to average out variations in weather patterns and to reduce the need for storage (see **Figure 3B**). Meeting this assumption would require a significant expansion of high-voltage interconnection power lines between regions, as well as adding electricity storage. These measures are also necessary to support grid stability. To provide storage, the study concentrates on pumped hydro, which currently accounts for 97% of the worldwide stationary installed storage capacity. The study includes estimates of the unused pumped hydro potential in Australia. The authors later extended this investigation to provide a map of potential pumped hydro sites in the world (**Figure 3A**). The additional cost to support the projected renewable energy supply is estimated at AU$25-30/MWh (corresponding to US$19-23/MWh). LCOE is estimated at AU$93/MWh (US$70/MWh) and is estimated to fall over time.

Figure 3. Australia Renewable Energy Maps

Figure 3A. Atlas of potential pumped hydro sites. More than 22000TWh of potential capacity were identified. (Stocks et al., 2019).

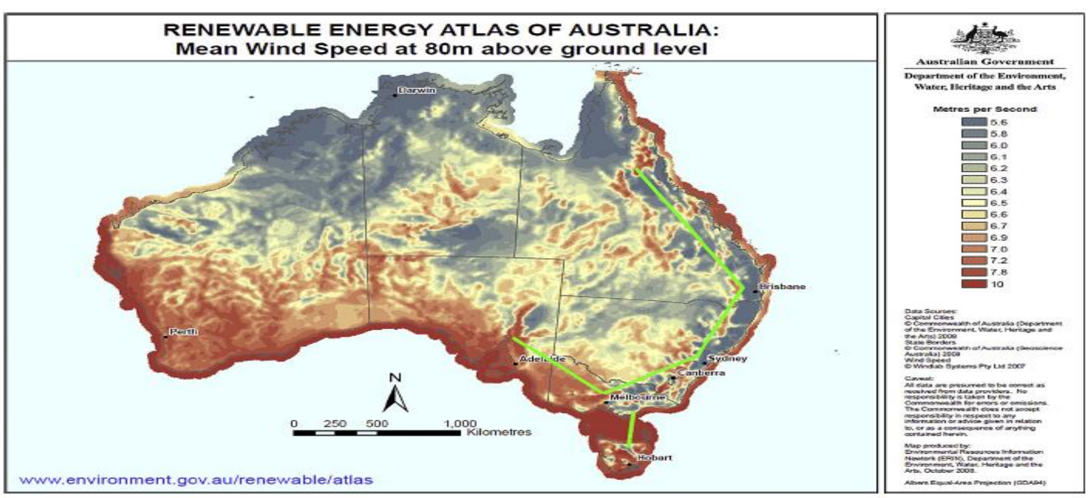


Figure 3B. Map of the wind resource in Australia. High voltage transmission lines to interconnect different regions are indicated in green (Stocks et al., 2019).

Achieving the goals set for 2030 are seen as a starting point to achieve the even deeper carbon emission goals set for 2050. While the initial period will be dominated by a shift to renewable electricity, later measures will more strongly focus on further decarbonizing the transportation sector, buildings, and industrial energy consumption.

II - PV PERFORMANCE

PV deployment is growing rapidly. To achieve the high solar PV capacities needed to reduce carbon emissions from the energy sector significantly and create a low-carbon economy, however, will require significant continued growth, as highlighted above. One of the core questions is what the conditions are for the PV industry to be able to scale sufficiently rapidly to meet global PV targets. Central to that challenge is the need to continue to advance the performance of PV technologies coming off the manufacturing line.

Needleman et al. (2016) used the Paris climate goals to estimate a PV deployment target of more than 10TW by 2030, about 20 times the total installed PV capacity at the end of 2018. To achieve this installed capacity, the study emphasizes that manufacturing capacity needs to scale accordingly and explores the requirements for achieving this goal.

The study explores multiple scenarios through which the PV industry might scale its manufacturing capacity. The scenarios explored include simply scaling current PV manufacturing, raising additional debt, and including new technological innovations (e.g., reduced variable costs and increased module efficiencies) (Needleman et al., 2016). The results for different scenarios are summarized in **Figure 4**.

Figure 4. Projected PV Installation 2016-2030

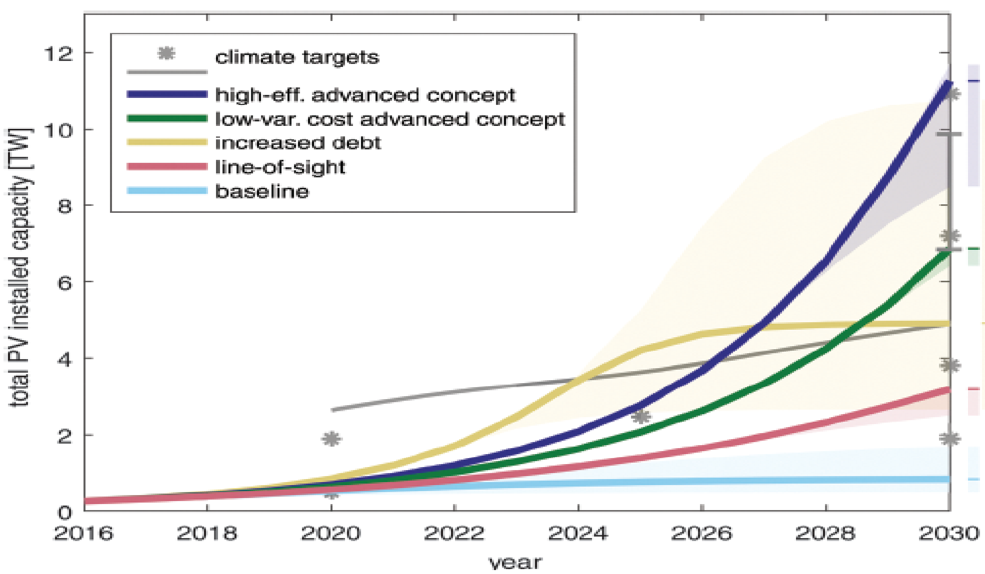


Figure 4. Projection for cumulative PV installation over time for a number of scenarios: baseline technology (light blue), line-of-sight technology innovations (red), an advanced concept with improved efficiency (16% to 24% module efficiency), an advanced concept focusing on reduced variable costs (green), and line of sight improvements with an additional increase in debt to equity ratio of 5:1 (Needleman et al., 2016).

The authors find that, currently, the PV industry is not capable of scaling fast enough on its own. With existing manufacturing capacity (light blue line), the installed PV capacity by 2030 would fall significantly below 2TW (Needleman et al., 2016). Line-of-sight innovation (red line) would improve the potential to meet the Paris goals—between 3 and 4TW PV could be installed by 2030—but this would still not suffice to reach the needed manufacturing capacity. One way to accelerate growth is to increase debt (yellow). This strategy is initially efficient and allows the fastest growth rates of any scenario. In later years, however, interest payments slow the ability of companies to grow, and growth stagnates. In the shown scenario, a debt to equity ratio of 5:1 was used, and a cumulative capacity of just above 4TW was reached. The most efficient ways to improve growth that the authors identified were technological advancements. One scenario used a reduced variable cost (green), which can be accomplished, for example, by using much thinner wafers and advanced module concepts (the scenarios were developed for silicon). This scenario achieved more than 6TW cumulative installation. A further improvement in efficiency (from 16 to 24%) resulted in the highest installation level – more than 11TW. It should be noted, though, that the models assume that innovation here benefits profit margins that are used to scale manufacturing; they do not prioritize a reduction in selling price.

The study highlights the crucial role of continuing innovation in the PV industry to create the conditions to supply enough modules to achieve the deployment targets necessary to create a low-carbon economy. Improving efficiency and reducing material and module costs, traditionally targets of PV research, are confirmed to be the right topics. The study also warns that the accumulation of debt, a practice observed with many PV companies in their battle for market shares, while helpful in the short term, may become a serious issue for the ability of companies to continue to expand manufacturing capacity in the future.

A - Technology Roadmap

PV technology has seen a tremendous increase in installations, with more than 0.5 TW of cumulative capacity installed today. The market is dominated by wafer-silicon technology (multi- and mono-crystalline silicon), which have seen extraordinary growth rates. Thin-film technologies utilize glass or other substrate materials to directly deposit compound semiconductors such as CdTe and copper indium gallium diselenide (CIGS), instead of silicon wafers. Thin-film technologies, particularly CdTe, have also benefited from rapid growth in the PV industry. Market share for thin-film technologies has decreased since 2009 (**Figure 5A**), despite overall production having ramped up significantly (**Figure 5B**). The reason for the comparably small market share is the immense scaling of silicon PV production following the embrace of this technology by Chinese solar manufacturers. In 2017, thin-film technologies garnered approximately 4.5% of the global PV market, with CdTe securing over 2%. As of 2017, annual production of CdTe was just 2.5 GW per year. In 2019, CdTe manufacturing grew significantly, to nearly 6 GW/year of CdTe PV modules, more than doubling its prior peak production capacity from 2016, and it is set to continue to grow rapidly in the next few years.

Figure 5. Thin-film PV Market Share and Production

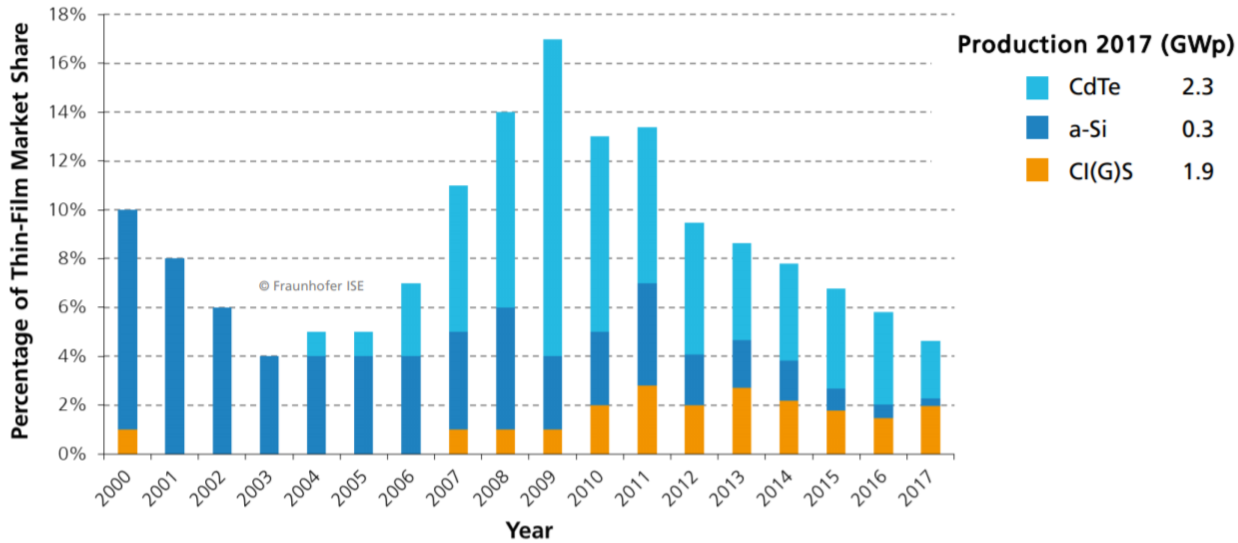


Figure 5A. Market share of thin-film PV technologies (Fraunhofer, 2019).

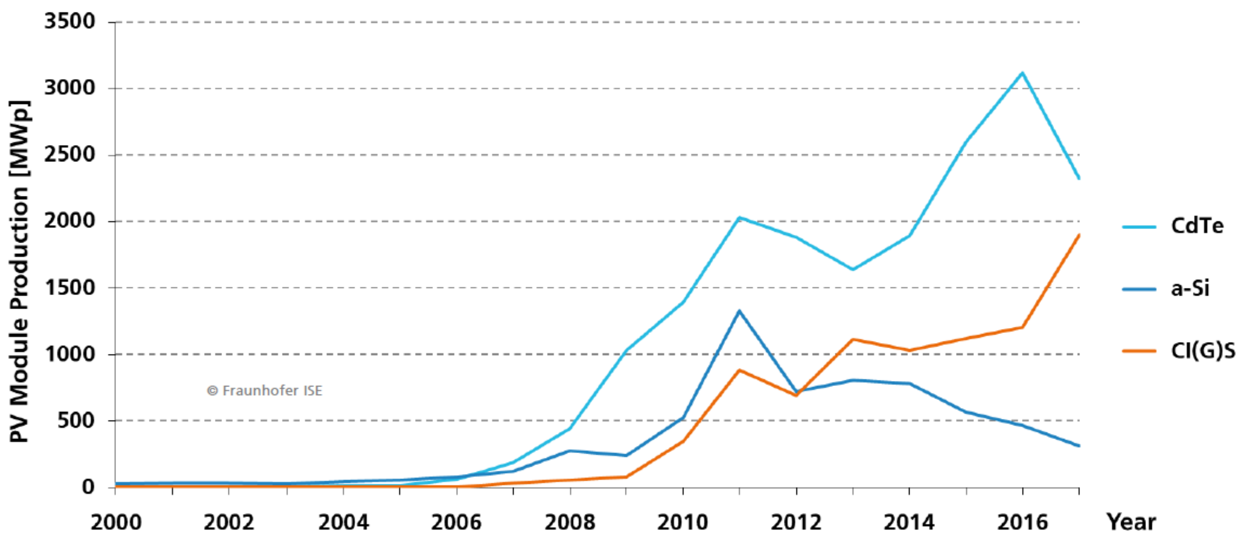


Figure 5B. Module production of thin-film PV technologies (Fraunhofer, 2019).

II.A.1 - Efficiency

The power conversion efficiency, measured under standard testing conditions, remains the most significant factor of merit for photovoltaic technologies. The significance of this factor lies in the sensitivity of most other metrics to efficiency. Improving efficiency (without increasing cost, and ideally while also decreasing cost) is the most effective technological way to reduce the costs of a module and the levelized cost of electricity (as measured in $/W) (Powell et al., 2012; Powell et al., 2013). **Figure 6** shows that improving module cost is most sensitive to gains in the efficiency of PV modules, and efficiency has the highest potential for cost savings overall. These results were derived for silicon but can be qualitatively transferred to CdTe as well.

Figure 6. Sensitivity Map for 2012 Cost Structure

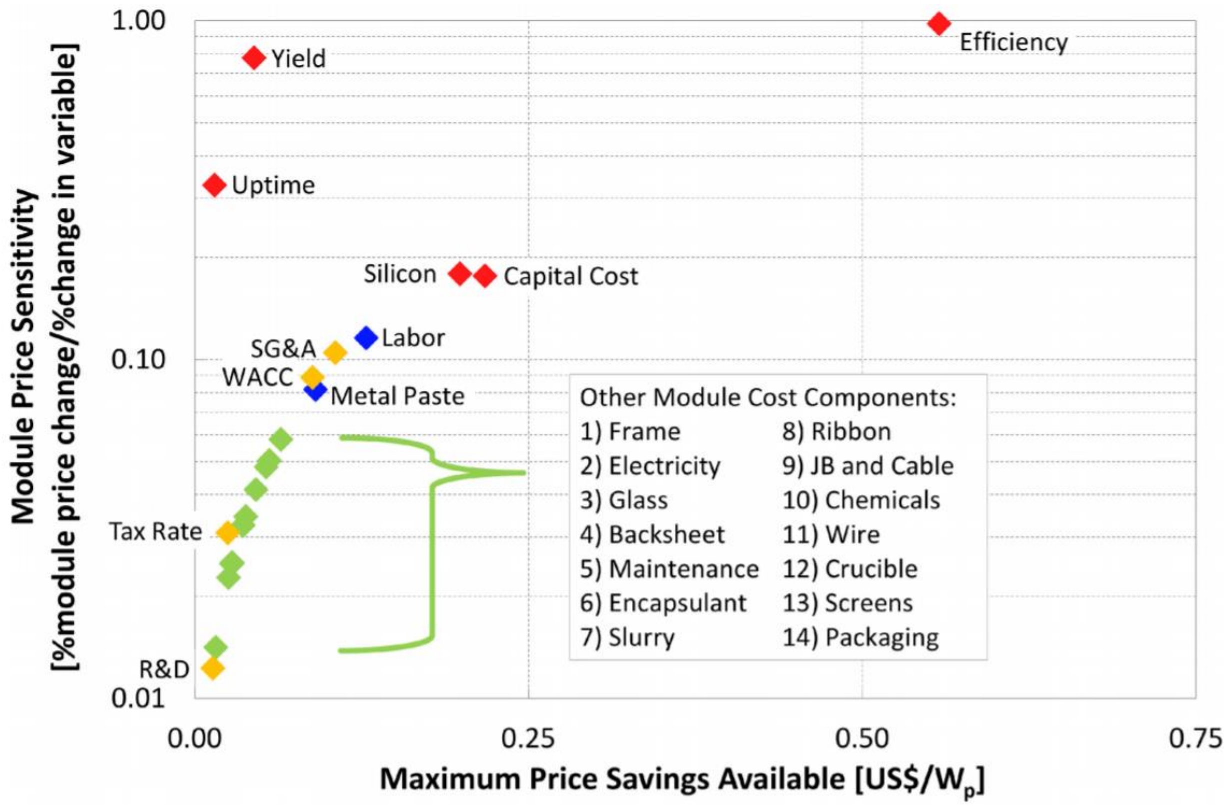


Figure 6. Sensitivity map of the cost structure for silicon solar cells. The analysis emphasizes the role of improving efficiencies in reducing costs. Module cost is most sensitive to changes in efficiency, and improving efficiency has also the overall highest potential for cost savings (Powell et al., 2013).

The state of the art for CdTe cell and module efficiencies, according to the NREL (2020) efficiency charts, is shown in **Figure 7**. The efficiency record for a lab-made solar cell (0.5 cm^2) is 22.1%. Since 2010, this number has steadily increased ~15%, with First Solar having contributed the majority of world records since then, including the most recent. Lab-based efficiencies demonstrate the potential of a technology but are not representative for what can be realized in a manufactured module. Scaling of cells to module areas induces additional loss mechanisms for all key metrics (current, voltage, and fill factor). The current world record efficiency for a CdTe module is 19.0% (Green et al., 2019) for a First Solar module with an area of 2.4 m^2. Also, this number has steadily increased from about 10% in 2010, with First Solar being the only contributor since 2012.

Figure 7. CdTe PV Efficiency Record for Solar Cells and Modules

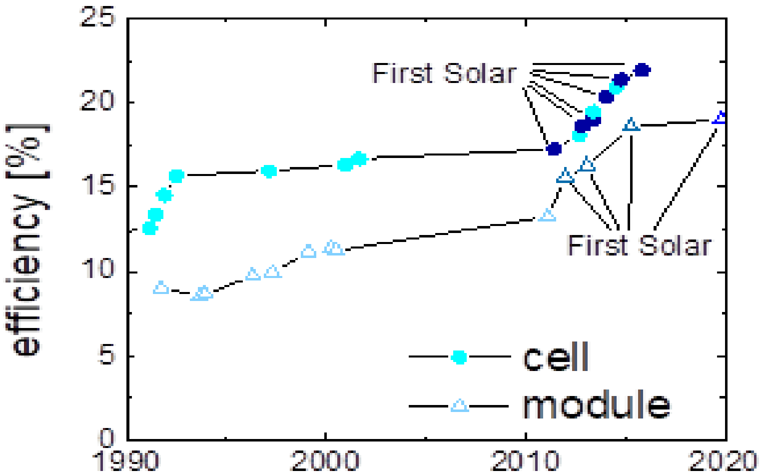


Figure 7. Development of cell (dots) and module (triangle) record CdTe PV efficiencies over the past 30 years. First Solar's contributions are marked by darker shades (National Renewable Energy Laboratory, 2019).

A comparison of efficiencies between CdTe and other technologies is shown in **Figure 8** and **Table 1** (Fraunhofer, 2019). **Table 1** was adapted for this report, using data from multiple sources (Green et al., 2019; Geisthardt & Topic, 2015). Note that **Figure 8** only considers cells with an area in excess of 1cm^2, and the highest efficiency value for a CdTe solar cell with this area is given as 21.0%, whereas the record efficiency for a smaller cell is 22.1% (both First Solar). All major technologies are included that contribute to utility and residential PV applications. These technologies are mono-crystalline silicon, multi-crystalline silicon, CIGS and CdTe. We also include one upcoming technology: perovskites. There are currently no perovskite module manufacturers selling products, and this technology is still resolving stability issues.

Figure 8. PV Efficiency Comparison

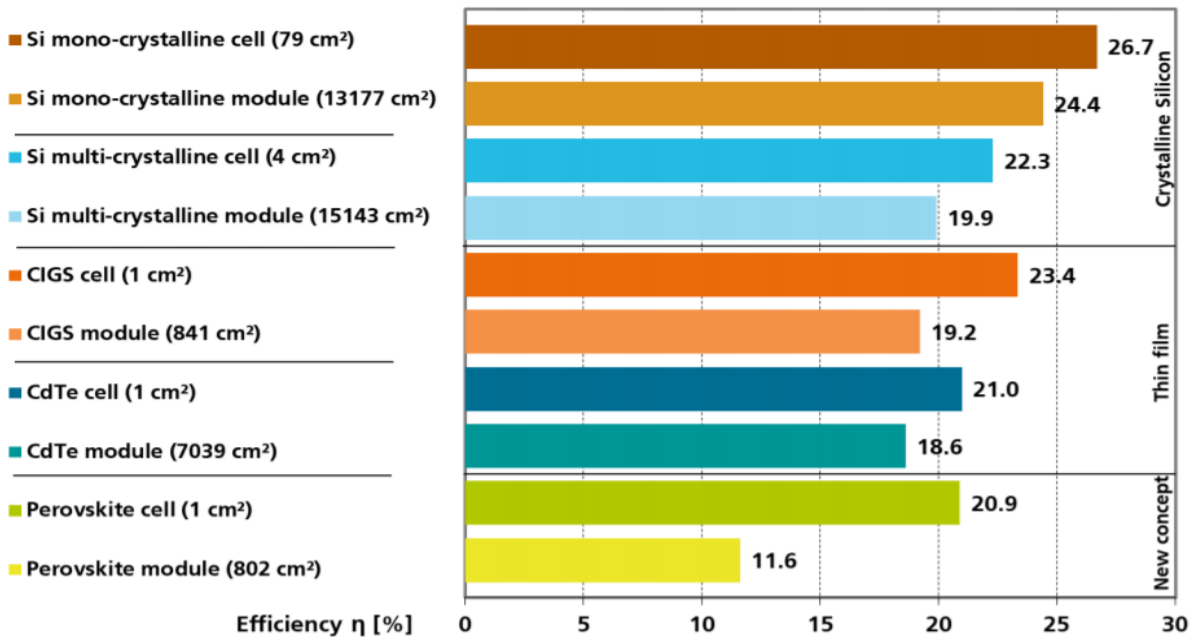


Figure 8. Comparison of state-of-the-art research cell and module efficiencies for a variety of different PV technologies (Fraunhofer, 2019).

In 2019, CdTe manufacturing grew significantly, to nearly 6 GW/year of CdTe PV modules, more than doubling its prior peak production capacity from 2016, and it is set to continue to grow rapidly in the next few years.

In a direct comparison, cell and module efficiencies for CdTe are slightly below the values achieved for the other technologies – a disadvantage that is compensated by the lower fabrication cost of CdTe modules, as will be shown later. The highest efficiency value achieved for any single-junction solar cell under non-concentrated light is 28.8% for GaAs. The most advanced silicon solar cells have achieved 26.7%, multi-crystalline silicon – the most widely installed technology – have achieved efficiencies of 22.3% and CIGS cells have achieved 22.9%. The most efficient advanced silicon PV module has achieved 24.4% efficiency, multi-crystalline silicon 19.9%, and CIGS 19.2%. CdTe has currently achieved 19.0%.

A look at some of the key solar cell characteristics reveals the future potential avenues for improving CdTe efficiency. **Table 1** shows which fraction of the potential for two metrics, open circuit voltage (V_{OC}) and fill factor (FF), have been realized for different technologies. To date, CdTe solar cells have realized the least potential, in both FF, and more significant, voltage. For Si and GaAs solar cells, more than 95% of potential in FF have already been realized; CIGS has realized more than 91% of its potential; and CdTe 88%. In V_{OC}, CdTe has only realized 77% of its potential, with GaAs going as high as 97% and Si and CIGS reaching 85%. Possibilities to realize higher values in FF and voltage will be discussed later. Considering past improvements, significant advances in CdTe efficiencies for both modules and solar cells are possible.

Table 1. Different Solar Cell Metrics

Category	Alta GaAs -28.8%	Panasonic Hit-Si - 26.7%	Solar Frontier CIGS - 22.9%	First Solar CdTe - 22.1%
FF_{ideal} (%)	89.5	87.1	87.1	89.5
FF (%)	86.5	83.3	79.7	78.5
FF/FF_{ideal} (%)	96.6	95.6	91.5	87.7
$V_{OC,ideal}$ (V)	1.163	0.879	0.879	1.156
V_{OC} (V)	1.122	0.744	0.747	0.887
$V_{OC}/V_{OC,ideal}$ (%)	96.5	84.6	85.0	76.7

Table 1. Comparison of the potential for different solar cell metrics realized by different technologies (Geisthardt & Topic, 2015).

A final remark should be made about efficiencies. While efficiencies are the basis for a first, general comparison, they are not sufficient to capture the full picture of how much energy a solar cell generates under outdoor conditions, which for most of the operational lifetime of a PV system deviate from the standard testing conditions used to determine nameplate efficiency (see section **II.B**). A significant difference between CdTe and Si, as well as CIGS, is the higher band gap of 1.54 eV (compared to around 1.1 eV for the latter two). We will discuss the implications of band gap on energy yield in detail later. Here it should just be mentioned that a higher band gap comes with an overall advantage on energy yield (see **Figure 9**). Considering median values for the electricity generation potential of solar cells around the planet, there is a penalty on energy yield or harvesting efficiency (i.e. the average efficiency of the solar cell under outdoor operation) that is roughly linear with band gap. Comparing CdTe and Si on this account, lab-measured efficiencies of Si solar cells should be reduced by 1.4% to better account for outdoor conditions, whereas CdTe solar cell efficiencies should only be reduced by 0.2% (Peters & Buonassisi, 2018). This would bring module efficiencies of CdTe, CIGS and multi-crystalline silicon very close together.

Figure 9. Band Gap Comparison

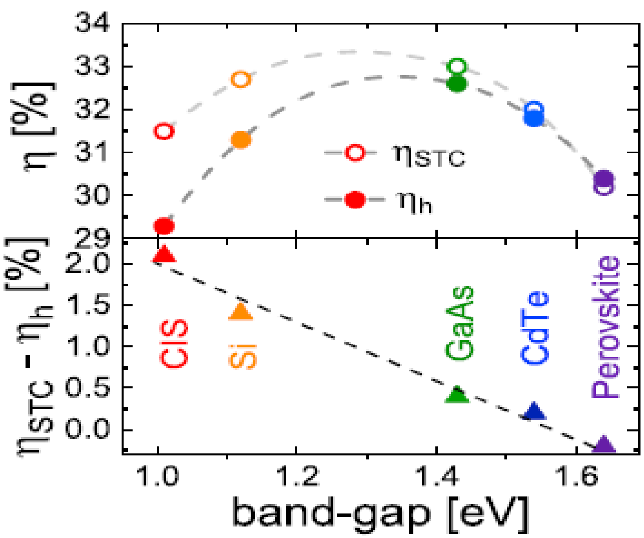


Figure 9. Upper - Comparison of standard testing condition efficiency η_{STC} and harvesting efficiency η_h for different solar cell technologies in the radiative limit as a function of band gap. Lower - The difference between the two efficiency metrics is plotted, revealing a roughly linear relation between the efficiency penalty for outdoor operation and the band gap of a solar cell. As a consequence, standard testing condition efficiencies benefit cells with a smaller band gap. In outdoor operation, performance losses for higher band gap cells are smaller than and result in a better performance ratio when compared to STC ratings (Peters & Buonassisi, 2018).

II.A.2 - Module Cost

A second important metric is the cost of the module. Typically, this cost is measured in $/W and combines the power generated by the module (W) with the cost to produce a module ($). The reduction of this metric ($/W) in PV over the past decades is unique in the history of energy technologies. A 29% reduction in cost for every doubling in installed capacity has been observed for silicon solar cells, and a 25% reduction for thin-film technologies. Reminiscent of Moore's Law for semiconductors, this development is sometimes referred to as "Swanson's Law". Module prices between 2006 and 2017 are shown in Figure 10. The total installed capacity in 2017 was 405GW for c-Si technology and 33GW in thin-film modules (about half of which are CdTe PV modules).

Figure 10. Decrease in PV Module Pricing

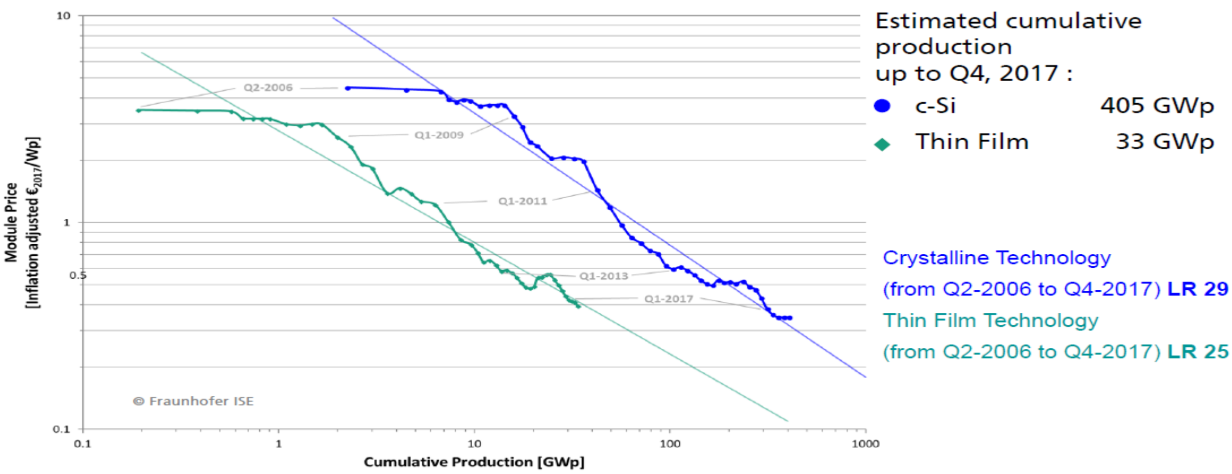


Figure 10. Learning rates for thin-film (green) and crystalline silicon technology (blue) for the time between Q2 2006 and Q1 2017 (Fraunhofer, 2019).

Traditionally, thin-film technologies have been able to produce modules at a lower $/W price than crystalline silicon technology, due to the relatively low energy and material requirements of thin film PV manufacturing. In recent years, however, strong competition among silicon PV manufacturers in China, with a focus on capturing market share, has resulted in the sale of some silicon modules at extremely low prices, especially in conventional multi-crystalline aluminum back surface field (Al-BSF) technology. The fact that the industry transitioned from BSF to passivated emitter and rear cell (PERC) and, to some extent, from multi-crystalline to mono-crystalline manufacturing may be an additional factor. Manufacturers have closed or phased out old manufacturing lines which is accelerating the transition away from this out-of-date technology (Al-BSF). **Figure 11** shows the U.S. and global average selling prices for silicon PV technologies (NREL, 2019).

Figure 11. PV Module Pricing

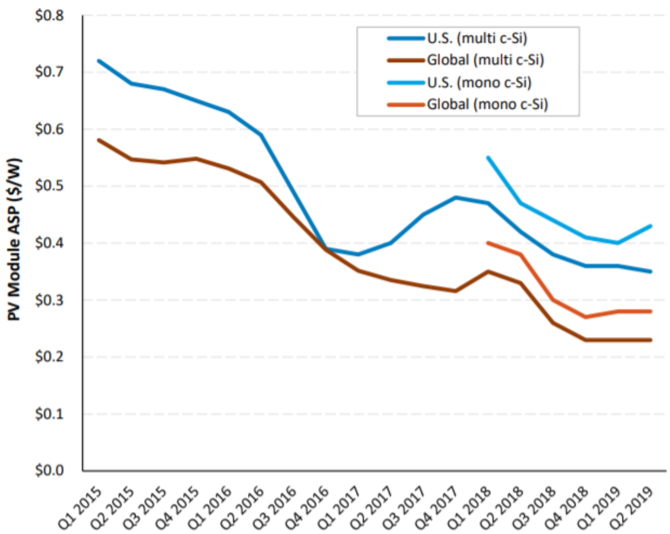


Figure 11. U.S. and global average selling prices for different crystalline silicon (c-Si) PV technologies (NREL, 2019).

II.A.3 - Levelized Cost of Energy (LCOE)

A third relevant metric is the levelized cost of electricity (LCOE). This metric describes the price at which a PV installation is able to generate electricity over its lifetime. In addition to efficiency and module cost, this metric also considers balance of system (BOS) costs, as well as costs for installation and maintenance and the impacts of module degradation on electricity generation by the module as time progresses. LCOE uses a net present value calculation to assess the average cost of electricity incorporating all occurring costs over the lifetime of the PV system.

PV electricity has undergone dramatic cost reductions that have turned it from one of the most expensive forms of electricity to one of the cheapest. An analysis by Lazard (2019) shows this development in **Figure 12** (2019).

Figure 12. Levelized Cost of Energy Comparison

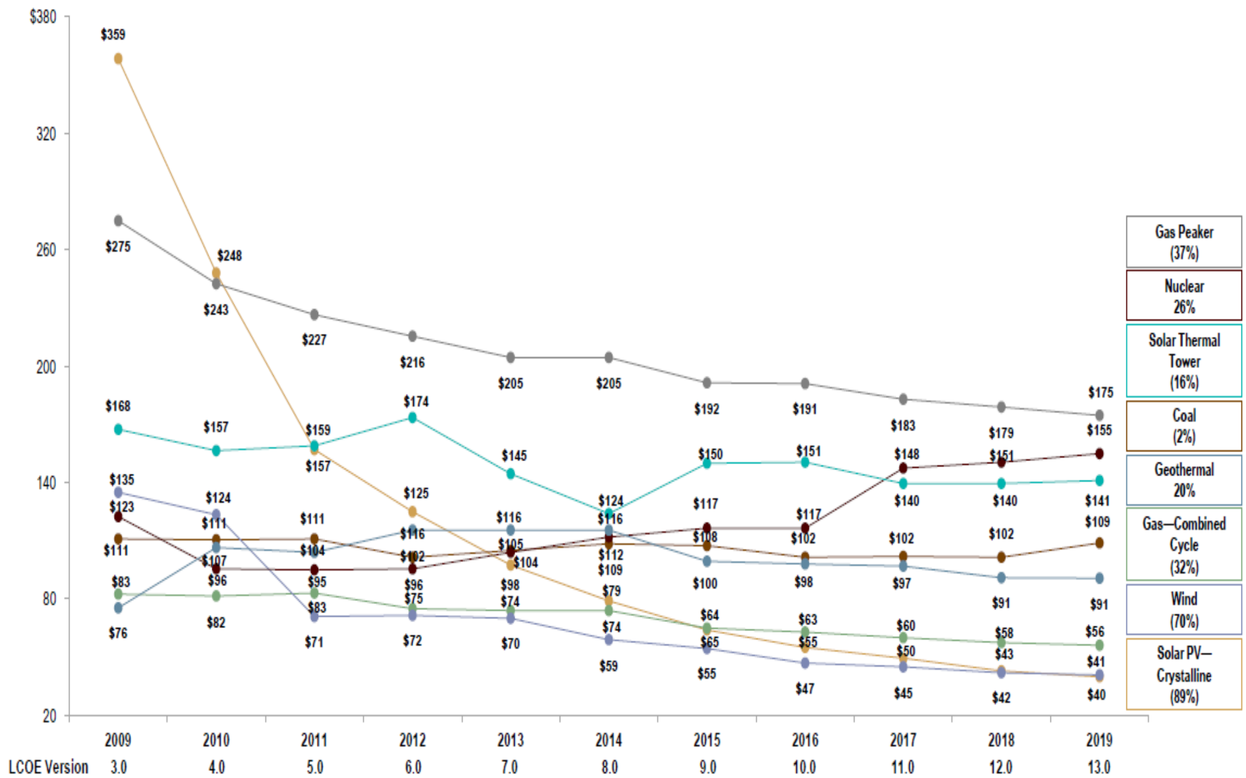


Figure 12. Unsubsidized LCOE for different electricity generators between 2009 and 2019 (Lazard, 2019).

When considering unsubsidized LCOE, solar and wind fare better than any other source of electricity. Notably, thin film solar PV with 32-42 $/MWh is slightly cheaper than crystalline silicon PV with 36-44 $/MWh in this analysis (Lazard, 2019). Wind generates the lowest value with 28-54 $/MWh, and gas combined cycle is also at a very low value with 44-68 $/MWh (**Figure 13**). A large part of the reason for the low LCOE of renewable energy technologies is their rapidly declining capital costs, in comparison to traditional energy technologies (**Figure 13**).

Figure 13. Levelized Cost and Capital Cost Comparison

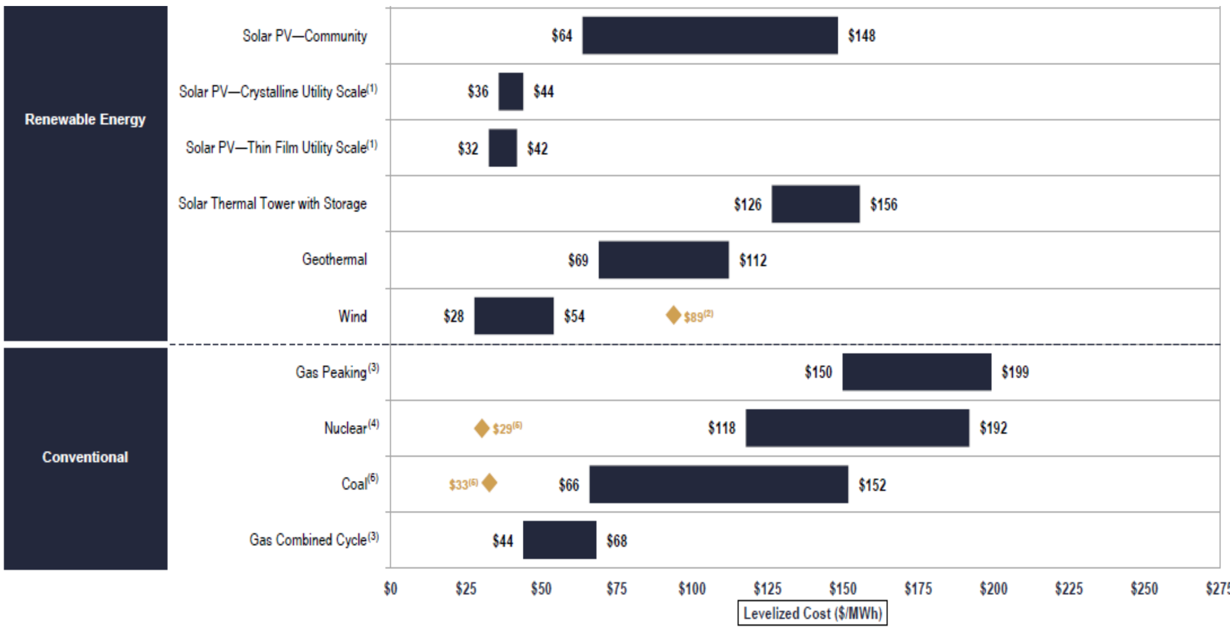


Figure 13A. Analysis of the unsubsidized LCOE for various electricity generating technologies. The analysis shows that solar PV and wind are cost-competitive with conventional generation technologies.

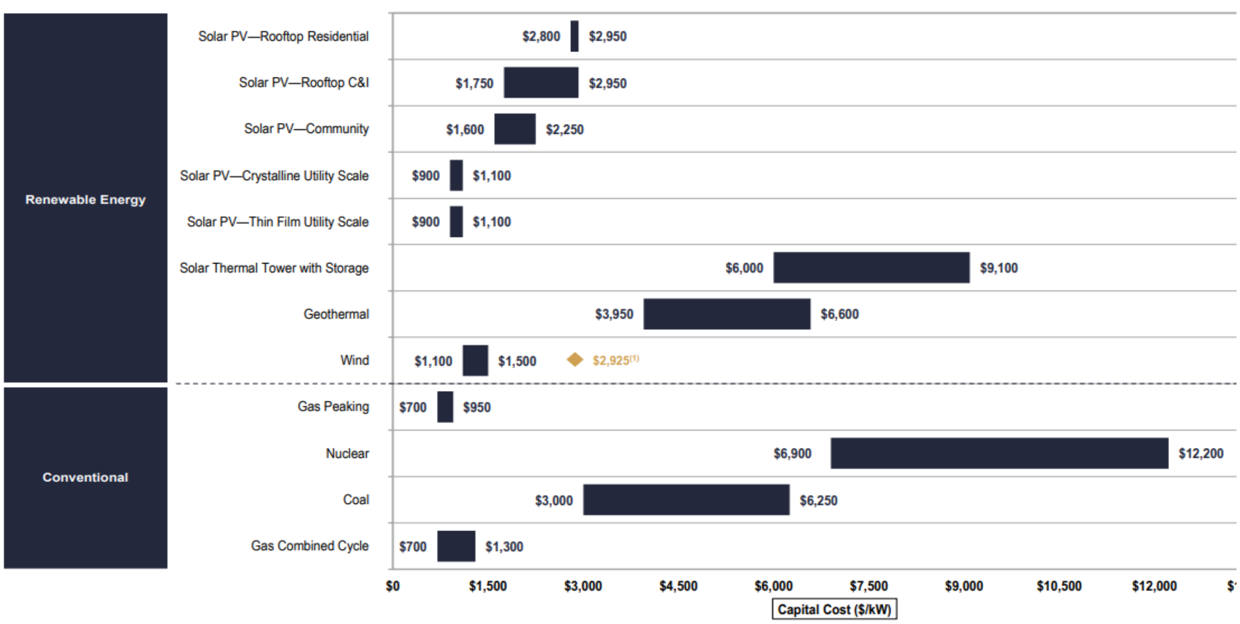


Figure 13B. In some instances, the capital costs of renewable energy generation technologies have converged with those of certain conventional generation technologies, which coupled with improvements in operational efficiency for renewable energy technologies, have led to a decrease in LCOE (Lazard, 2019).

II.A.4 - Energy Payback Time

A fourth relevant metric is energy payback time. Investigations of energy payback time generally mirror the results for the carbon footprint (see later in the report, section **IV**). The smaller energy intensity of fabricating a CdTe PV module compared to a silicon module, in combination with relatively high conversion efficiencies results in faster energy payback times. Whereas the carbon footprint critically depends on the carbon intensity of the electricity used in the fabrication process, the energy payback time is solely defined by the amount of energy required to manufacture the module and the amount of energy produced by the system. The latter varies with the solar cell resource, which is location dependent, due to, among other things, the cosine factor of solar insolation and variations in air mass.

Figure 14. Africa and Europe Energy Payback Map

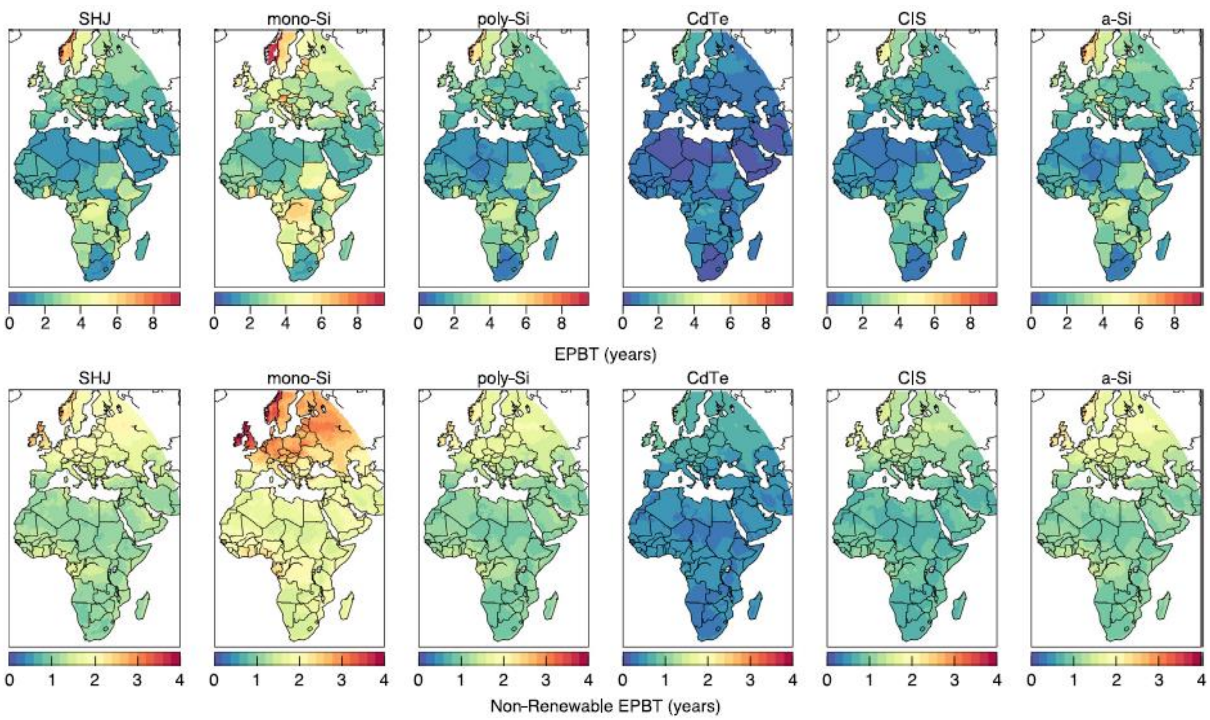


Figure 14. Standard (upper row) and non-renewable (lower row) energy payback time of different photovoltaic technologies (Louwen et al., 2017).

A study by Louwen et al. shows the energy payback time for several PV technologies as a function of location for Africa, Europe and the Middle East, **Figure 14** (2017). The authors distinguish between energy payback time (EPBT, upper row) and non-renewable EPBT (lower row). The difference between the two lies in the assumption about what type of electricity production is replaced by a newly installed PV system: the current mix of electricity, including all renewable and non-renewable sources (conventional EPBT) or just non-renewable sources (non-renewable EPBT). The difference between the total and non-renewable EPBT depends on the penetration level of renewable electricity sources. In countries with very high shares of renewable energy (mainly hydropower) like Norway, there will be a big difference between the two, while at low penetration levels of renewable electricity, the difference will be small.

In either case, CdTe has the lowest EPBT of all investigated technologies, with values below 0.5 years in many locations, especially on the African continent, but also in some southern European countries, where irradiance levels are similar to the U.S. Variations in EPBT are due to the calculation method which considers each country's average grid efficiency. Countries with high shares of renewable electricity (especially hydropower) and with high primary energy to electricity conversion efficiency show high non-renewable payback times.

Energy payback time was also considered in the review by Peng et al. (2013), using the same sources with data between the year 1998 and 2011 as indicated below. Also here and even for the quite early stage of CdTe PV module technology, CdTe PV already demonstrates its advantage compared to other module technologies. Energy payback times stated in this study vary between 0.75 years and 2.1 years with an average of about 1.4 years. The results are summarized in **Figure 15**.

Figure 15. Average PV Energy Payback Time

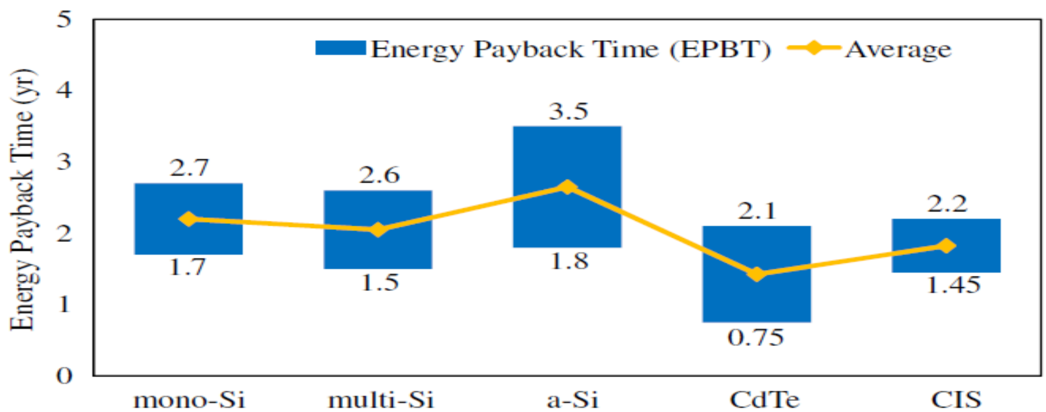


Figure 15. An overview of energy payback times from various PV technologies. Data was assembled from a number of sources (Peng et al., 2013).

The study by Leccisi et al. (2016) considers a more recent state of CdTe PV technology and distinguishes between three levels of irradiation. The study confirms EPBT values as low as 0.5 years for regions with the highest insolation and supports a difference by more than a factor of two between CdTe PV and single-crystalline silicon technology. Results for the study are summarized in **Table 2**.

Table 2. Energy Payback Comparison

GRID EFFICIENCY (η)	SC-SI PV	MC-SI PV	CDTE PV	CIGS PV
1000 KWH/(M^2 YR) (η=0.3)	2.8	2.1	1.1	1.9
1700 KWH/(M^2 YR) (η=0.3)	1.6	1.2	0.6	1.1
2300 KWH/(M^2 YR) (η=0.3)	1.2	0.9	0.5	0.8

Table 2. Energy payback time (yr) for various PV technologies and under various insolation conditions and grid efficiencies (Leccisi et al., 2016).

B - Hot and Humid Climates

Solar cells react to the environments in which they are placed, including temperature and humidity, and cells made of different materials react differently to their operating conditions and environmental contexts. These differences can have a significant impact on the amount of energy produced by different kinds of solar cells. Generally, materials with a higher band-gap are less sensitive to operating conditions, where the band gap of a semiconductor is the minimum energy required to excite an electron from its bound state into a free state where it can participate in conduction. Compared to silicon, the reduced sensitivity of CdTe to elevated temperatures or to the impact of humidity on the light available to the PV module (technically referred to as light extinction) provides CdTe thin film modules with an advantage, especially when operating in hot and humid climates. The result is an improved relative performance and higher comparable energy yield, defined as the total energy output from an installed solar module.

II.B.1 - Impact of Temperature

The impact of temperature on PV system performance is well documented (Nishioka et al., 2003; Woyte et al., 2013; Ye et al., 2013; Reich et al., 2012). The impact of temperature is also developed in predictive models (King et al., 2004; Veldhuis et al., 2015; Sandia National Laboratories, 2020). The solar-cell output voltage and current generation are affected via temperature and materials-specific factors (the kT dependence of Boltzmann statistics and materials-specific band gap narrowing or widening), as well as device-architecture specific factors (Peters et al., 2018). **Figure 16** shows how the radiative efficiency of several PV materials changes as a function of temperature. **Figure 16** directly compares the temperature dependence of performance ratios of state-of-the-art CdTe and PERC-type silicon PV modules as a function of temperature. This function is often linearly approximated, and the slope is called the power temperature coefficient.

Figure 16. Cell Efficiency at Different Band Gaps

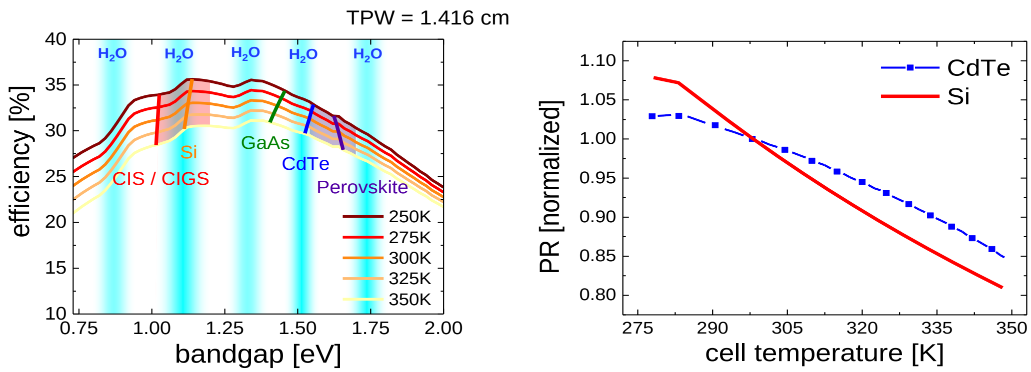


Figure 16. Left - Limiting efficiency as a function of band gap and temperature. Band gaps of various PV technologies as a function of temperature are also shown. Right - Normalized performance ratio of a CdTe PV module and PERC-type silicon solar cells. CdTe is less sensitive to changes in temperature and has a comparably higher performance ratio at high temperatures (Peters et al., 2018)

Table 3 summarizes the material properties of various solar cell materials. Temperature coefficient here is the most relevant parameter. Compared to mainstream silicon PV technology, CdTe has a significantly smaller temperature coefficient, resulting in a better performance ratio at temperatures above standard test conditions of 25 degrees Celsius (77 degrees Fahrenheit). When generating most of their power, PV modules are typically much hotter than the ambient air around them (10 degrees Celsius or more above ambient air is not atypical), hence much of the power is generated at temperatures above 40 degrees Celsius (104 degrees Fahrenheit; 313 degrees Kelvin in **Figure 16**). One example of the relationship between PV module power generation and temperature is shown in **Figure 17**, which shows that, in hot, arid climates, most of the power is generated at very high module temperatures of between 50 and 60 degrees Celsius.

Table 3. Properties of Different PV Devices

		CIS / CIGS	Si	GaAs	CdTe	Perovskite (CH_3NH_3PbI)
Band gap	E_g @ 25°C (eV)	1.010 (1.0 - 1.2)	1.125	1.431	1.540	1.639 (1.55 – 1.7)
Temperature coefficient	Dη/ dT (% K^{-1})		0.3 – 0.6		0.27	
Record cell efficiency	η_{rec} (%)	14.1 (22.8)	26.7	28.8	22.1	22.1

Table 3. – Band gap at 25deg C (Eg@25°C), power temperature coefficient (Dη/DT) and record efficiency (η_{REC}) (Peters & Buonassisi, 2018).

A smaller temperature coefficient offers a significant advantage for a PV technology in hot climates. It should be noted, though, that temperature coefficients are not only linked to materials, but also depend on the architecture of the solar cell. In general, solar cells with a higher voltage have a smaller temperature coefficient. Typical values for silicon are in the range of -0.45%/K; for CdTe values are around -0.27%/K. The very best silicon solar cells, heterojunction (or commonly called HIT cells), however, generate much higher voltages than conventional silicon solar cells (up to 750mV at open circuit) and can have temperature coefficients as low as -0.3%/K. Further improving the voltage of CdTe solar cells should also reduce the temperature coefficient.

Figure 17. PV Module Temperature Range

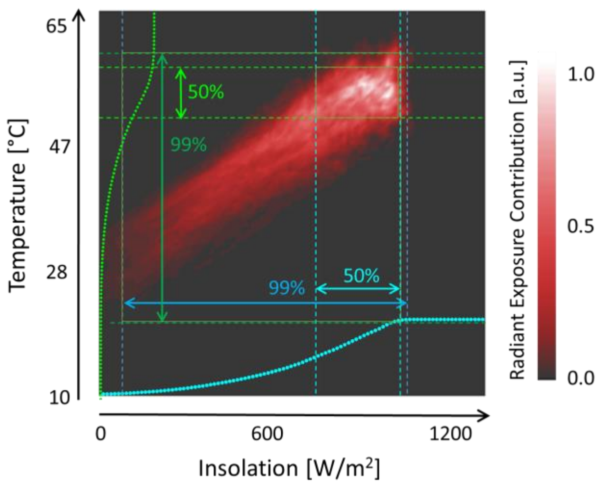


Figure 17. Insolation and module temperature in a hot and arid sub-tropical environment. The majority of the power is generated at module temperatures between 50 °C and 60 °C (Peters et al., 2018).

II.B.2 - Impact of Water Vapor

In addition to temperature effects, also the impact of spectral variation on CdTe modules, and their differences to silicon, are well documented. Spectral effects occur because different agents in the atmosphere absorb light predominantly in certain spectral ranges. Water, a main contributor to the shape of ground reaching solar radiation, is more dominantly active in the infrared, while aerosols are mostly active in the blue. These absorptions result in changes of the percentage of available photons that can be absorbed by a solar cell. A small band gap cell like silicon will see a larger relative reduction in power for high atmospheric water concentrations than a larger band gap cell like CdTe. The reverse is true for aerosols.

Higher levels of humidity or water vapor in the atmosphere, sometimes referred to as precipitable water, reduces the amount of sunlight that reaches the solar module as it passes through the atmosphere. Water blocks or extinguishes light through absorption or scattering. Water absorption is not equally distributed over all wavelengths of sunlight, but rather is concentrated in a number of discrete bands called absorption bands. These absorption bands are indicated in **Figure 17** as blue bars and marked with H_2O. **Figure 18** shows how the limiting efficiency of solar cell as a function of band gap of the solar cell material changes with increasing amounts of water in the atmosphere. It can be seen that, whenever one of the blue bars is crossed, efficiency is reduced. Because silicon has a smaller band gap (1.12 eV) than CdTe (1.54eV), silicon absorbs a wider range of photons, and light that Si can use is affected by more absorption bands. Consequently, as the water content in the atmosphere increases, the light intensity that can be used by silicon modules to create electricity is reduced more strongly than for CdTe. The greater sensitivity of silicon compared to CdTe is also shown in **Figure 18**.

Figure 18. Precipitable Water and Band Gap Effects on Efficiency

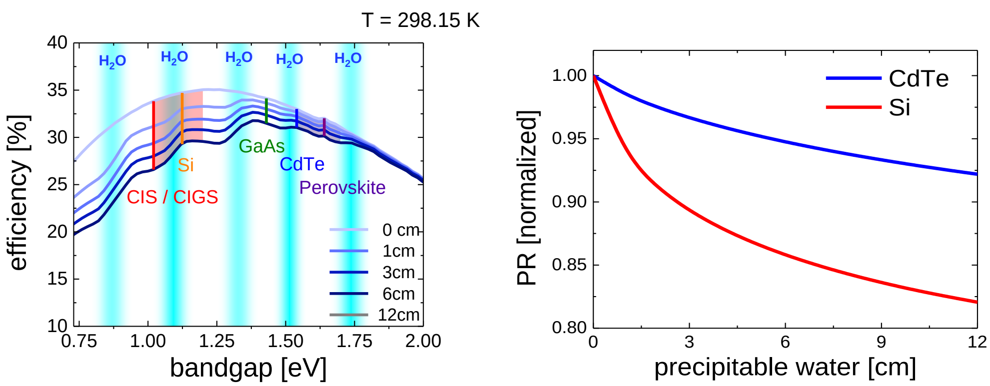


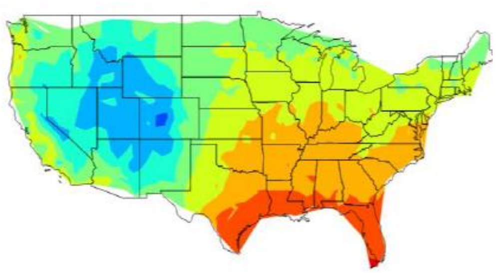
Figure 18. Left - Limiting efficiency as a function of band gap and total precipitable water. Band gaps of various PV technologies are also shown. Right - Normalized performance ratio of a CdTe PV module and a PERC type silicon solar cells as a function of total precipitable water (Peters et al., 2018)

The sensitivity to water is specific to a solar cell band gap, which is defined by its absorber material. Higher band gap materials are principally less sensitive to water vapor in the atmosphere than lower band gap materials. All higher band gap materials consequently have an advantage over silicon in areas with high humidity. Because this advantage is tied to the absorbed band gap, there are also no technological means by which lower band gap materials could compensate. In temperate climates, the total precipitable water (i.e. the total water content of the atmosphere when condensed into a column) is typically below 2cm. In the tropics, values can be as high as 12cm, and the corresponding performance difference between silicon and CdTe can exceed 10%.

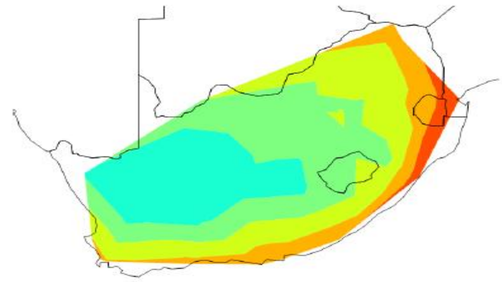
Analysis by First Solar (**Figure 19**) shows how spectral variations influence the energy yield of CdTe PV modules compared to silicon PV modules (Lee et al., 2015). Because of the generally greater atmospheric water content in parts of the tropics and subtropics, CdTe has a performance advantage in these regions. The effect was named “spectral gain” and describes the relative gain in energy yield when compared to yield based on a single, standard spectrum (typically called the AM1.5 spectrum).

Figure 19. Spectral Response Maps

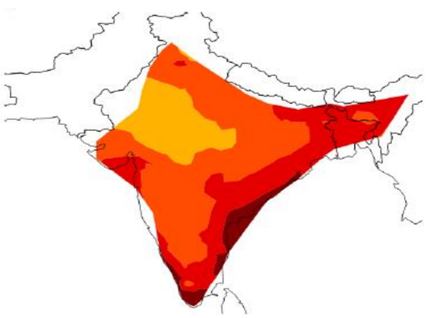
A) United States



B) South Africa



C) India



D) Japan

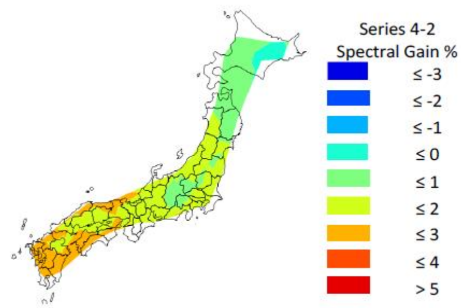


Figure 19. Irradiance rated spectral gain in energy yield for the First Solar series 4-2 module in different regions of the world (Lee et al., 2015).

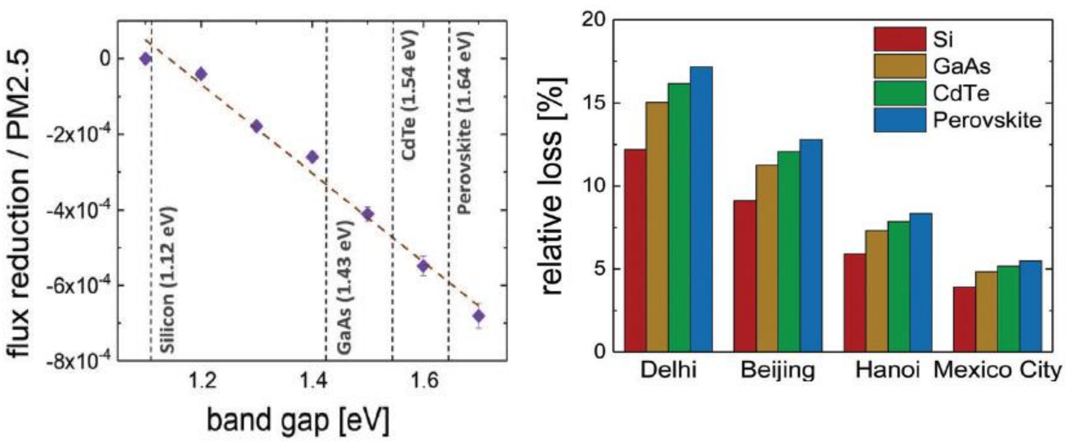
A note on PV module characterization – Testing and certification of PV modules is done under so called Standard Testing Conditions. These conditions include one particular temperature (25deg C), a specific spectrum (AM1.5g), and one specific light intensity (1000W/m^2). To account for deviations of these conditions, typically corrections are applied. The already mentioned temperature coefficient is one of these corrections, and allows projecting performance at varying temperatures. Spectral effects have long been neglected. One reason is that variations in the spectral shape alone have little consequence when only silicon solar cells are considered, and silicon PV has dominated utility installations for a long time. Yet, if two PV technologies with different band gaps are compared, spectral correction becomes necessary. For this reason, First Solar and others have introduced spectral correction factors that need to be applied to arrive at the correct energy yield for CdTe PV modules. The above shown spectral gain is a consequence of this.

II.B.3 - Impact of Aerosols

Similar to water, aerosols in the atmosphere also extinguish light through absorption and scattering. One difference between aerosols and water is the spectral range in which they are active. While water extinguishes light in bands, many of which are located in the infrared, aerosols predominately affect blue, short wavelength light. As CdTe absorption is constrained to shorter wavelengths than silicon, it is relatively more affected by aerosols. Note that this argument refers to aerosols in the atmosphere and not to soiling. The situation for soiling is different and is determined by module architecture rather than solar cell material.

A study by MIT indicates that CdTe modules are affected more strongly by atmospheric aerosols (Peters & Buonassisi, 2018). In areas with high pollution, especially cities like Delhi or Shanghai, CdTe PV modules have a disadvantage over silicon for this reason (see Figure 20).

Figure 20. Aerosol Impacts



A) Aerosol Related Flux Attenuation *B) Estimated Performance Reduction*

Figure 20. Impact of PM2.5 aerosols on a variety of PV materials. A) Estimated flux attenuation as a function of band gap. B) Projected performance reduction for four PV materials in selected cities with high levels of air pollution (Peters & Buonassisi, 2018).

II.B.4 - Performance Ratio

Performance ratio is not uniquely defined, and the meaning of the term can differ depending on who uses it. Importantly, performance ratio in research often is used differently than in industry. In general, the performance ratio describes the ratio of actual yield to the expected yield. The expected yield requires a reference value, which can be derived, for example, from the STC module efficiency, or from the nameplate capacity of the system, but can also be obtained from more rigorous calculations. The actual yield also needs to be specified and can vary, depending on whether, for example AC or DC yield is considered.

Performance ratios are a useful research metric to compare different solar cell technologies, as they eliminate efficiency differences from the comparison and integrate the impacts of temperature, humidity, and other factors on performance. Because of the lower sensitivity of CdTe to water related light absorption and temperature, compared to silicon, we'd expect to see higher performance ratios for CdTe in hot & humid climates. In reverse, in cold and dry climates, silicon solar cells should show superior performance. Various studies confirm this expectation (Gottschalga et al., 2003; Alonso-Abella et al., 2014; Nofuentes et al., 2014; Schweiger et al., 2017), with examples in **Figure 21** (Peters et al., 2018; Huld & Gracia Amillo, 2015).

Figure 21. Performance Ratio in Different Regions

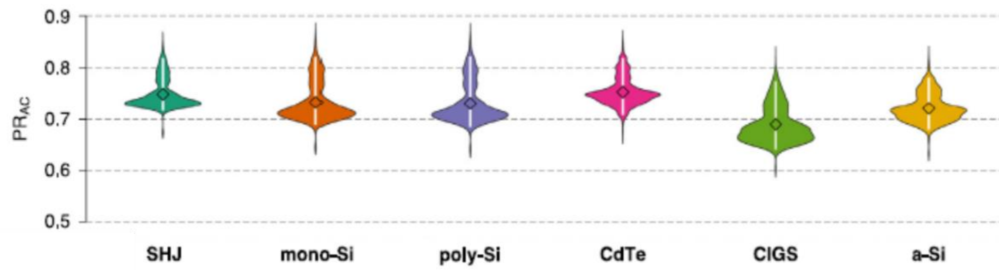


Figure 21A. Simulated performance ratios for a variety of solar cell technologies for all areas shown in B.

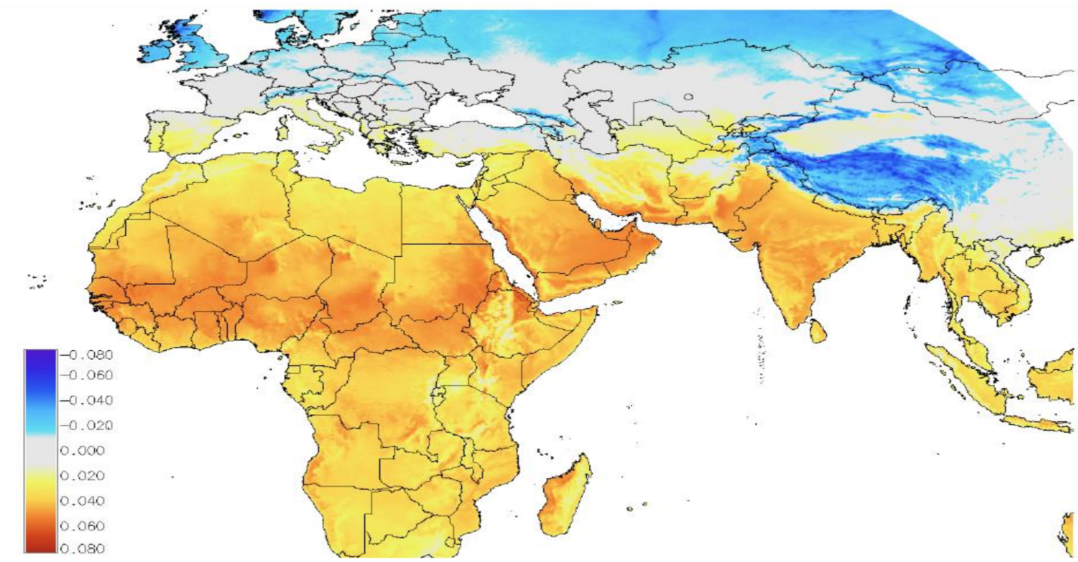


Figure 21B. Difference between the performance ratios of CdTe and mono-Si in parts of Africa, Europe and Asia (Huld & Gracia Amillo, 2015).

Huld & Gracia Amillo (2015) explored the difference in performance between CdTe and silicon solar cells in parts of Africa, Europe and Asia using satellite-based simulations (**Figure 21**). Their results confirm the expected trends: CdTe has a performance advantage in all of Africa, tropical and sub-tropical Asia (with the exception of the Himalayas), and parts of southern Europe. The magnitude of the performance advantage is up to 8%. In northern Europe and northern Asia, as well as in the high mountain ranges, silicon has a performance advantage of the same magnitude. In wide parts of Europe, Kazakhstan, and China the two technologies perform similarly.

A study by Peters et al. (2018) extends a similar comparison to the global scale with similar results. CdTe is shown to have a performance advantage in the Tropics and Subtropics with a magnitude of up to 6%. Silicon has an advantage of the same magnitude in northern North America, northern Asia and the southern tip of South America (**Figure 22**). Similar performance is found in large parts of the U.S., Europe, and Central Asia. A difference to the study by Peters et al. (2018) compared to Huld and Gracia Amillo (2015) is that CdTe also appears to have an advantage in China. This difference could be due to different data sets and years used in the two studies. It should be noted that a warming climate will likely extend the region in which CdTe has an advantage.

Figure 22. Performance Ratio Comparison

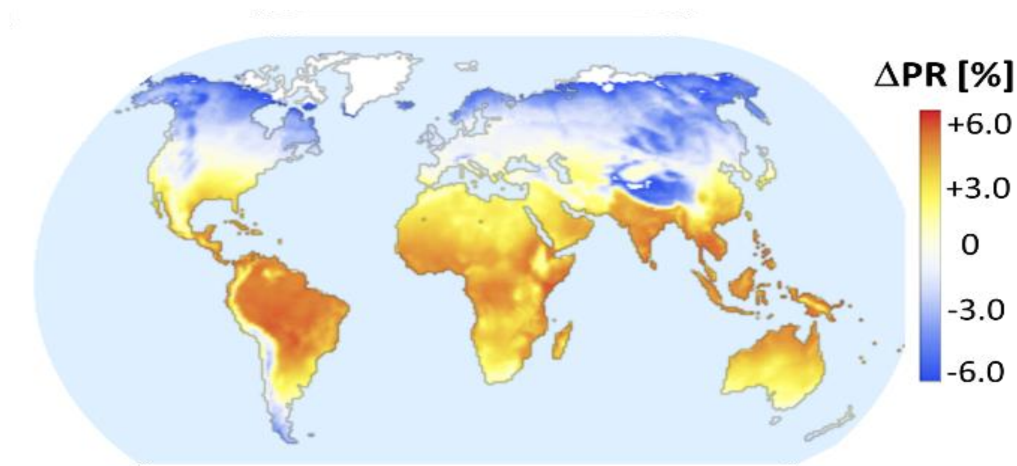


Figure 22. Calculated annual average performance ratio difference between a silicon PERC solar cell and a CdTe PV modules. Positive values, indicated by red and yellow tones, mark a performance advantage for CdTe, blue values one for Si (Peters et al., 2018).

II.B.5 - Energy Yield

A second important metric is energy yield. Energy yield describes the actual energy generated by a PV system over a certain time. This metric includes the solar cell efficiency, as well as operating conditions. Huld & Gracia Amillo (2015) also modeled the comparative energy yield (in kWh per kWp) of different PV technologies in the area they explored. Results are shown in **Figure 23**. The yields for CdTe and silicon technologies are similar, with CdTe having a slightly wider range of yields than any of the silicon technologies.

In another study, Peters et al. (2018) explored energy yield limits for various technologies, including temperature coefficients and band gap narrowing for the various solar cells. The results are shown in **Figure 24**. Despite having a band gap that results in a lower efficiency limit than silicon, the difference in modeled energy yield between silicon and CdTe is very small (820 and 813 kWh/m^2

annual yield in 2015). Based on these yield numbers, the same study suggests that when comparing efficiencies of silicon and CdTe cells measured under standard testing conditions, about 1.2% should be added to the value of CdTe for a fair comparison of the median worldwide yield of silicon and CdTe solar cells.

Figure 23. Annual Energy Yield

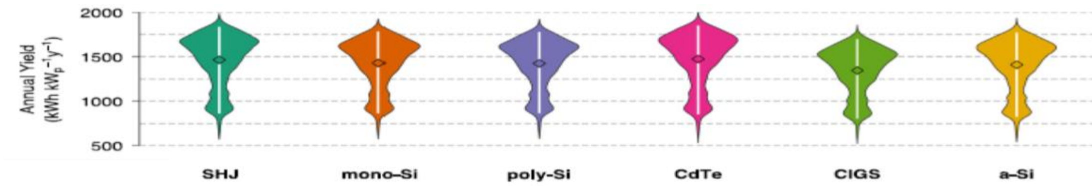


Figure 23. Annual calculated energy yield for various PV technologies (Huld & Gracia Amillo, 2015).

As an example: the current world record cell for silicon is 26.7%, the one for CdTe 22.1%. These values were both measured under standard testing conditions, and do not reflect typical operating conditions. If median worldwide conditions were considered, the value for silicon should be reduced by 1.4%, reaching 25.3% harvesting efficiency, and the value for CdTe by 0.2%, reaching 21.9%, where harvesting efficiency is the average efficiency of the solar cell under outdoor operation. These two numbers, 25.3% and 21.9%, are a better comparison of the relative theoretical effectiveness of the two technologies when it comes to generating electricity under real-world operating conditions.

Figure 24. Global Energy Yield Maps

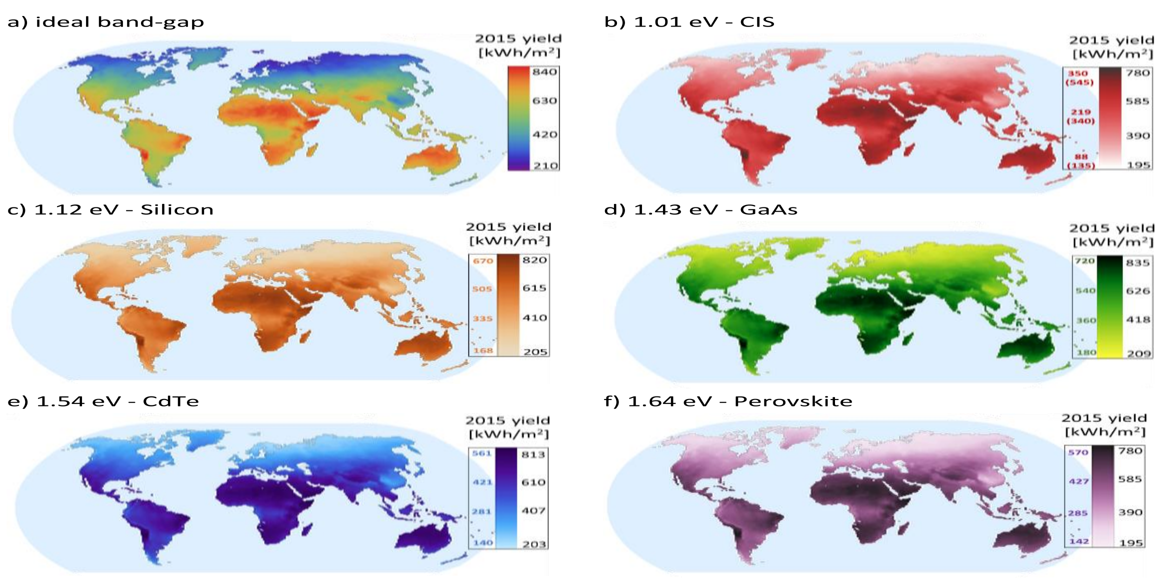


Figure 24. (A) gives the energy yield in kWh/m² for 2015 with a material having the ideal band gap in each location. (B)-(F) show the energy yields for the five considered materials. These five graphs are shown with two axes corresponding to the radiative limit (right) and a projection to record solar cell efficiencies (left, color) (Peters & Buonassisi, 2018).

C - Performance of CdTe PV in the Field

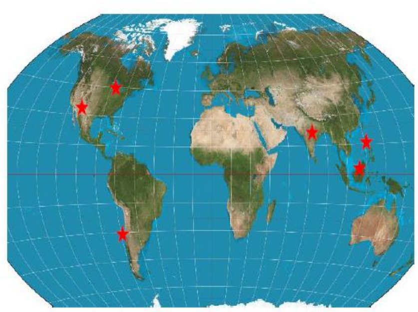
With more than 25 GW of modules sold, there are now numerous installations of CdTe modules around the world. For many of these installations, measurement data is available to compile a comprehensive picture of CdTe solar cell performance over time in the field. In this section, we summarize the available data.

II.C.1 - Outdoor Testing Sites and Results

First Solar maintains a number of testing sites around the world that are used to monitor the performance of CdTe PV technology under a variety of operating conditions. **Figure 25** shows photographs of one of these testing sites (upper left) and the additional equipment used to monitor weather data (lower left) (Buehler, 2015).

Dedicated sites are distributed around the planet and cover a variety of climate zones, including temperate climates in Ohio and Chile, the hot arid climate of Arizona, and hot humid climates of Malaysia, India and the Philippines. Monitoring across different climate zones is important because there are significant differences between different PV technologies regarding performance metrics, as well as soiling and degradation behavior. A more detailed discussion of the former is provided in PV Performance section **II.B.**

Figure 25. First Solar Test Locations



Location	Size	Climate
Arizona	320 kW	Hot Arid
Ohio	350 kW	Temperate
Malaysia	350 kW	Hot Humid/Wet
Chile	36 kW	Temperate
India	36 kW	Hot Humid/Dry
Philippines	36 kW	Hot Humid/Wet

Figure 25. Photographic images of a First Solar testing site (upper left) and the additional monitoring setup (lower left). A total of six sites spread all around the world (middle) is used for detailed monitoring (middle). The sites are distributed over various climate zones (right), to allow monitoring over a wide range of operating conditions (Buehler, 2015).

In addition to the detailed measurements, First Solar also monitors the performance of several of its commercial systems. **Figure 26** shows a map of the global distribution of First Solar PV systems in the year 2015 on the left. Those monitored for performance are marked in red. Also, here, monitored systems are distributed over several climate zones to cover a large variety of the operating conditions prevalent on earth. On the right-hand side, the measured system performance is compared with the results of performance modelling. The histogram shows that systems, overall, perform as expected.

The average modelling error is close to zero, with the distribution centering around that value. Errors are spread between -5% and +3%, with a width of about 2.5%. The result shows that the major contributors to CdTe performance are largely understood and captured in the modelling process. Systems, after construction, perform reliably independent of location.

Figure 26. First Solar Monitored Plants

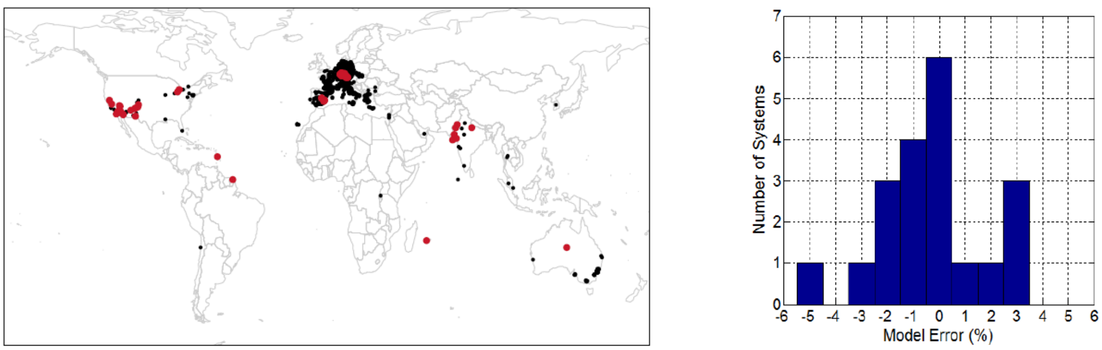


Figure 26. Left - Map of First Solar power plants in 2015. Monitored plants are shown in red. Right - Histogram of the modelling error for the various systems (Buehler, 2015).

While **Figure 26** shows the spatial distribution of First Solar systems, **Figure 27** (below) shows a comparison between the measured and the predicted lifetime performance of First Solar PV systems as a function of the commissioning date. Included are systems installed between 2004 and 2016, with the black bars marking different series of First Solar modules. The **Figure 27** shows that modules have performed reliably and predictably from the start. Improvements in modelling are also apparent – over time, and especially between series, efficiency and wattage of the monitored modules has improved. With more efficient modules, performance models need to be adapted to capture relevant effects. Especially from 2009 onwards, the spread of values has declined with fewer and fewer systems performing lower than predicted.

Figure 27. First Solar Performance

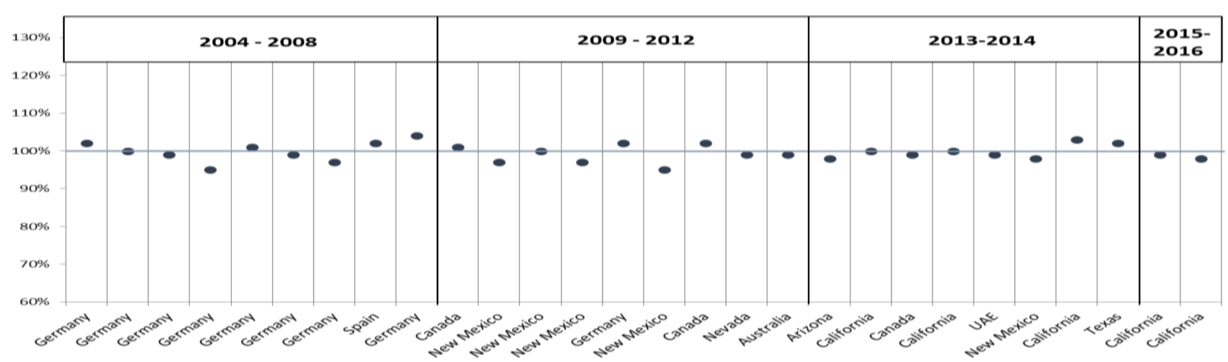


Figure 27. Comparison between the measured and predicted lifetime performance of First Solar PV systems by commissioning date (Buehler, 2015).

II.C.2 - Degradation

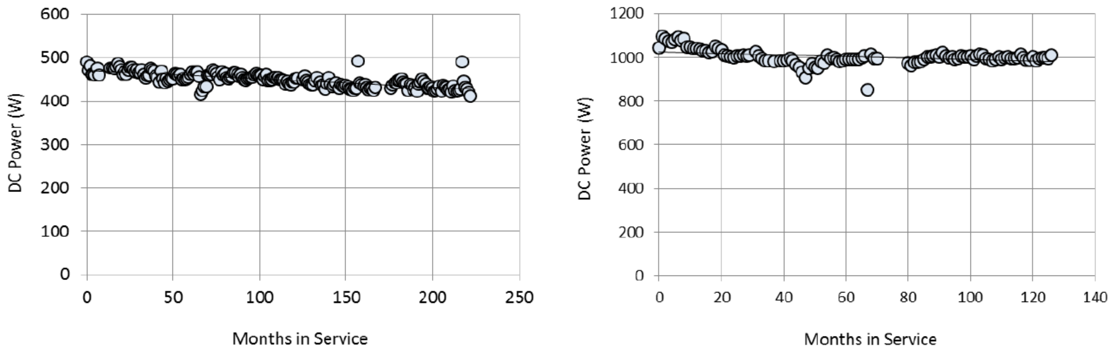
A variety of degradation mechanisms exist that result in a reduction of power output of all PV modules over time. Two categories of mechanisms can be distinguished: first, mechanisms that affect the semiconductor devices themselves, and second, mechanisms that affect the module construction, including material degradation in back sheet or module encapsulation. Degradation mechanisms are present in all semiconductors, and are specific to each technology, despite having a similar result: stress over the lifetime of operation reduces the power conversion efficiency of the solar cell over time, resulting in a regular and often predictable performance reduction. Degradation mechanisms in the module depend on the used module architecture and are caused by harsh environmental exposure. Examples are water ingress that can result in delamination or corrosion of different parts of the module. To explore module degradation, a number of testing procedures are applied. These procedures include indoor and outdoor measurements and are designed to represent a variety of conditions. Experience with these degradation procedures is used to develop models to predict he power output of a module. Comparison between simulated and measured performance results are often used to gauge the reliability and predictability of a PV module.

The annual degradation rate defines the relative reduction in power output over time. Reducing degradation has been shown to be a critical factor in reaching very low LCOE, as a longer lifetime for the module stretches its viable generating period out considerably in time, with higher annual production in each year. As a result, degradation has been a focus for technology improvement by the U.S. Department of Energy in recent years (Peters et al., 2019).

CdTe solar cells degrade differently from silicon PV modules, which makes a direct comparison between these two technologies less than straightforward. Especially, CdTe modules show fast initial degradation followed by a saturation at a much lower rate. Furthermore, continuous improvement in module technology has resulted in a distinct improvement of CdTe degradation over the last couple of years (Peters et al., 2019; Strevel et al., 2013; Gloeckler, 2017).

One of the longest running tests is a 600 W CdTe research installation established at NREL in 1995, which has been running ever since, and for which more than 19 years of continuous data is available. DC power output for this module, along with a 1200 W installation from 2003 is shown in **Figure 28** (Ngan et al., 2014). Degradation rates for these two installations are -0.47 ± 0.07 %/year and -0.33 ± 0.19 %/year. **Figure 28** show the potential for CdTe PV to operate for very long periods of time with relatively little degradation.

Figure 28. Historical CdTe PV Power Output



A) 600 W installation (1995) *B) 1200 W installation (2003)*

Figure 28. A) DC Power output over 19 years for a 600 W CdTe research module installation from 1995. B) DC Power output over 10 years for a 1200 W CdTe research module installation from 2003. The latter module is technologically close to First Solar's modules (Ngan et al., 2014).

Jordan et al. (2016) aggregated degradation rates from PV installations from the prior 20 years. The results are depicted in **Figure 29**. The study found degradation rates for Si technologies in the range of 0.5% to 1% per year. Higher degradation rates are suggested for CdTe, yet several things should be noted when considering these results. The paper aggregates published and self-reported data: the measurements were not carried out by NREL. An aggregation is also problematic as measurement results of thin-film PV modules are skewed depending on the exact measurement and calculation procedure, which is more intricate than that for silicon. In addition, the number of datapoints for CdTe is significantly smaller than for Si, hence statements about CdTe have a much lower level of statistical significance. Many studies even report only a single or few data points and have large uncertainties

Significant deviations between nameplate rating and beginning-of-life measurements have been documented, and performance ratio measurements taken with respect to nameplate values are often unreliable, a result that was also found in other studies (Peters et al., 2018).

Figure 29. Degradation Rates

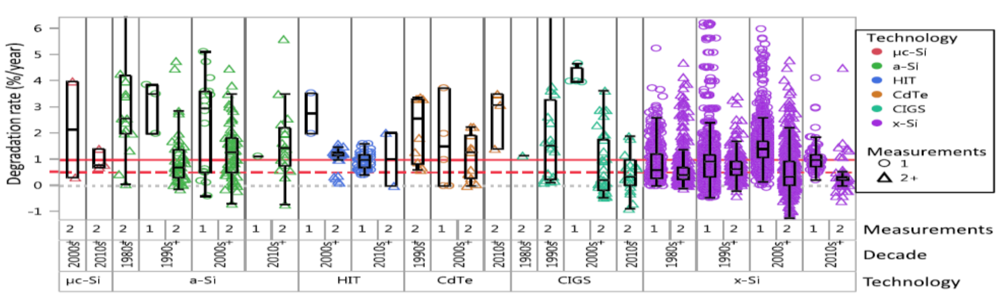


Figure 29. Aggregation of degradation results from outdoor measurements of various PV technologies (Jordan et al., 2016).

Jordan and Kurtz (2012) looked at PV system degradation for systems installed before and after the year 2000. Results from this study are shown in **Figure 30**. The study finds system degradation rate for post-2000 installations in the range of 0.6%/year. The study mentions that systems degrade less rapidly than modules. This discrepancy is attributed to the fact that “module investigations often focus on prototypes, whereas system investigations are more likely comprised of commercial products.” Confounding effects like mismatch, DC health and failure of other components could also contribute.

Figure 30. Degradation Location and Rates

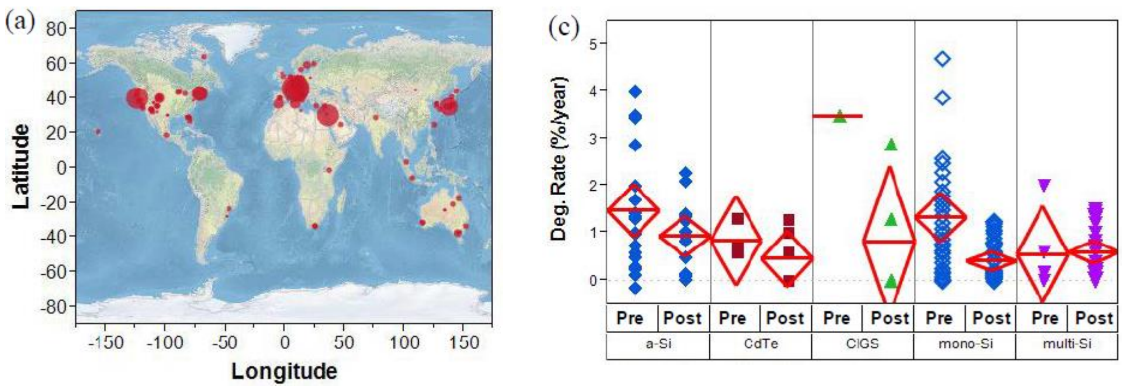


Figure 30. A) Locations around the world. C) Reported system degradation rates. The study distinguishes between installations before (pre) and after (post) the year 2000 (Jordan & Kurtz, 2012).

Jordan and Kurtz (2012) also review a number of additional studies of CdTe systems: “Marion et al. (2001) analyzed a CdTe system at NREL in Colorado, USA. Individual module efficiencies varied widely, with some improving by more than 10% while others degraded by more than 10% over a 5.5-year test period. However, the overall system degraded by approximately 0·6%/year. Ross et al. (2006) found a similar degradation rate for a system located in the hot and dry climate of Tucson, AZ, USA, over 3 years. In addition, a system in the moderate climate of Germany was found to be virtually stable. Foster et al. (2006) found degradation rates ranging from close to zero to 1%/year for several systems installed in a hot and humid climate of Mexico.”

A number of studies report higher degradation rates. Phinikarides et al. (2015), for example, report five-year degradation rates of 2.4% for a module installed in Cyprus. Schweiger et al. (2017) report differences in degradation over a 24-month period depending on location. An installation in India showed an initial increase in power of 4% followed by smaller than 2% annual degradation. Similar degradation rates are reported for the U.S. In Europe, strong seasonal effects are observed. Especially in Germany, a longer stabilization phase precedes the regular degradation, and over the experimental period no degradation was detected.

Overall, the data on CdTe module degradation in the field shows some variation across locations and time of analysis. Tests published in literature often rely on small sample sets, sometimes even a single module, and are often carried out over insufficient time to properly include the stabilization phase. An additional issue is the used reference value. Often nameplate capacities are used, without considering variations or doing prior characterization. Providing clear guidelines for how researchers should measure degradation in the future could potentially help ameliorate these issues.

Figure 31. Initial Stabilization

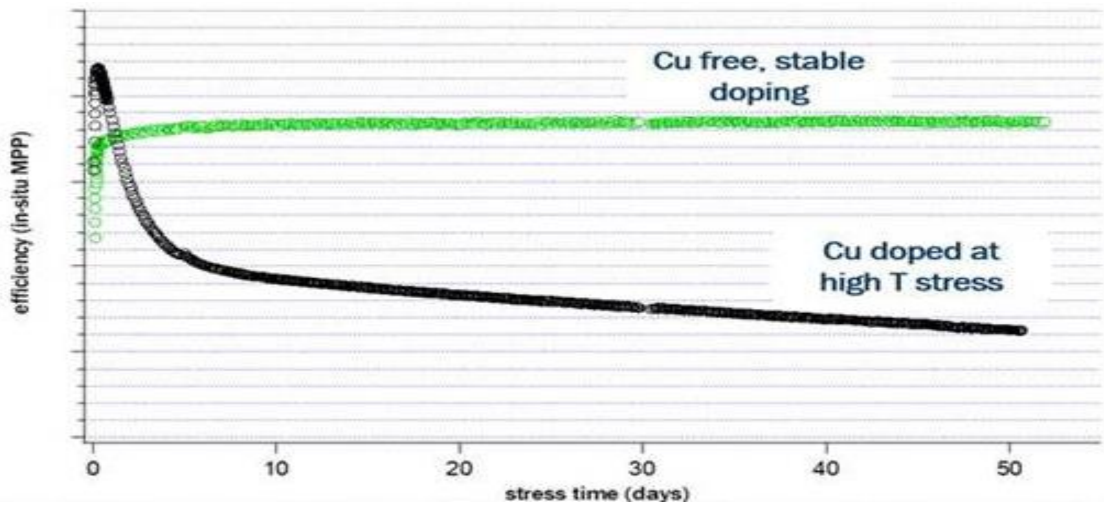


Figure 31. Recent results about a strategy to eliminate the consolidation phase in new First Solar CdTe modules (Metzger et al., 2019).

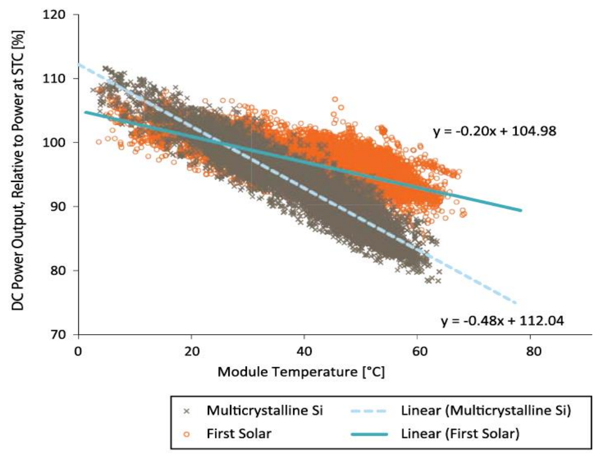
A recent study by First Solar, shown in **Figure 31**, indicated the possibility that next generation First Solar CdTe modules might not suffer the same initial period of degradation during stabilization (Metzger et al., 2019). By producing Cu-free modules, the initial degradation during light soaking tests at elevated temperatures was completely removed. This potential improvement may allow more straightforward comparison of degradation of modules made from different materials under outdoor conditions.

II.C.3 - Temperature Performance

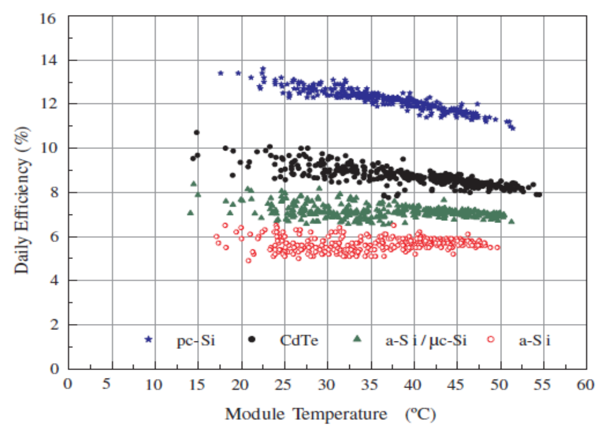
Field tests confirm the importance of temperature for PV performance, as described above in theoretical and laboratory studies, and also confirm that high-bandwidth materials like CdTe are less impacted by high temperature operation than silicon. The effect was documented by First Solar, for example in works by Strevel et al. (2012), but there are a number of examples for similar findings. **Figure 32** show the measurements presented by Strevel et al. (2012) taken at First Solar's test site in Perrysburg, Ohio (U.S.), measurements by Canete et al. (2014) from Jaen, Southern Spain, and measurements by Louwen et al. (2017) from Utrecht, Netherlands.

Figure 32. Temperature Effects on PV Modules

A) Strevel et al. – Perrysburg (US)



B) Canete et al. – Jaen (Spain)



C) Louwen et al. – Utrecht (Netherlands)

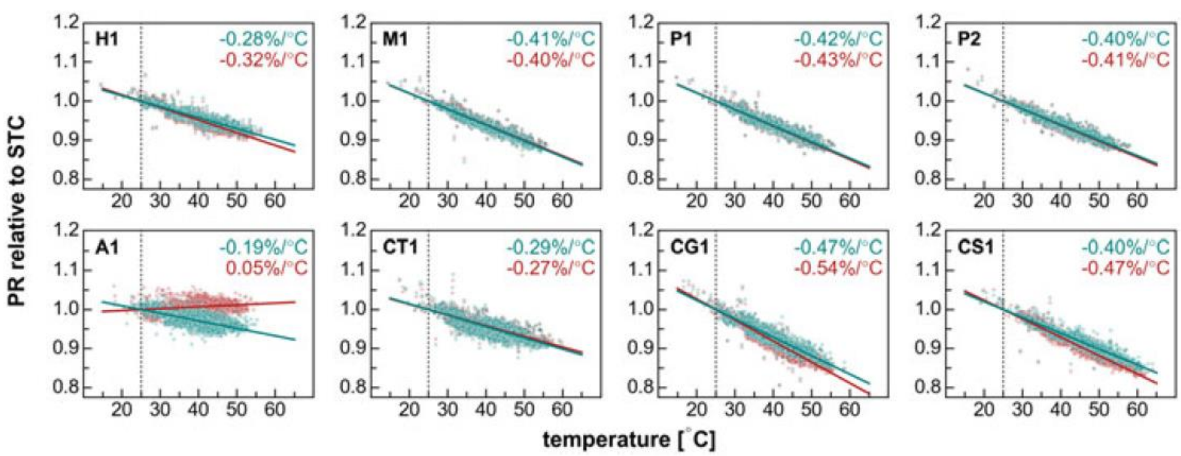


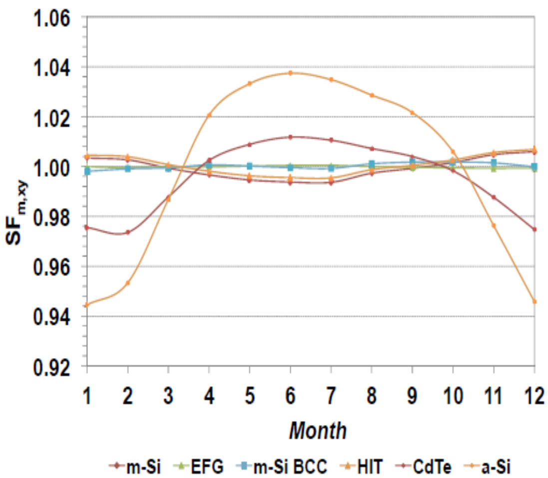
Figure 32. Examples for measured comparison of temperature effects for different module technologies for the US (A), Spain (B) and the Netherlands (C). Note that in the last figure Cadmium Telluride is abbreviated CT (Cañete et al., 2014; Strevel et al., 2012; Louwen et al., 2017).

Reported temperature coefficients in these studies vary between -0.2%/K (Strevel et al. 2012) and -0.29%/K (Louwen et al. 2017; Canete reports -0.25%/K). Reported values for silicon vary between -0.4%/K and -0.5%/K.

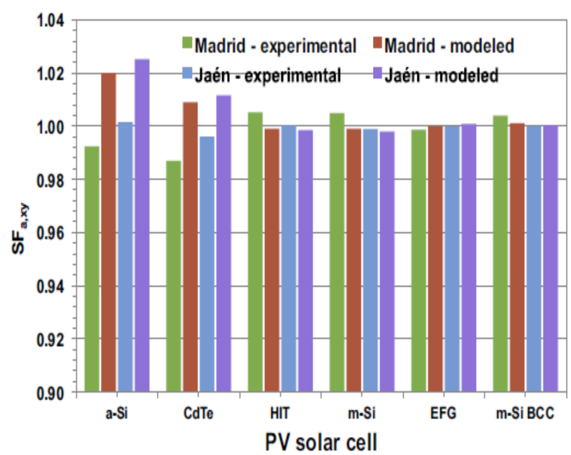
II.C.4 - Spectral Effect

The impacts of spectral absorption by water and aerosols has also been confirmed in the field. Alonso Abella et al. (2014) have captured the differences between module technologies by defining a spectral factor for each. The spectral factors define spectral gains (for values above 1) and losses (for values below 1) compared to the standard AM1.5 spectrum. Detailed experimental results for Jaen, as well as experimental and theoretical results for Jaen and Madrid are shown in **Figure 33**.

Figure 33. Spectral Factor in Spain



A) measured SF in Jaen, Spain



B) overall SF for different cities and technologies

Figure 33. A) Measured spectral factor (SF) over the course of a year in Jaen (Spain). B) Experimental and simulated results for the overall SF in Madrid and Jaen. (Alonso Abella et al., 2014)

The results for Jaen show a seasonal dependence of spectral factor for CdTe with losses in winter and gains in summer. Given the overall higher insolation level in summer, this results in a net spectral gain over the course of a year. Crystalline silicon technologies, in comparison, show very flat curves, as they utilize a much greater fraction of the sun spectrum. It should be noted that measured values of spectral factors depend on the spectral range of the available measurement equipment. As a result, there is a discrepancy between simulation and experimental results in this work. Overall gains for CdTe were smaller than expected, which can be attributed to additional effects that were not considered in the study.

A very insightful study is depicted in **Figure 34** in which the authors established a method to distinguish between temperature effects, low irradiance, spectral effects, angle of incidence, and soiling (Schweiger et al., 2017). The study was carried out at four sites with distinctly different operating conditions in Cologne, Ancona, Tempe and Chennai. The study showed spectral gains for the two included CdTe systems, with a notable spectral gain of more than 5% in Chennai. The study also clearly shows the better temperature performance of CdTe compared to c-Si in all locations.

Figure 34. PV Module Performance Ratio Comparison in Four Locations

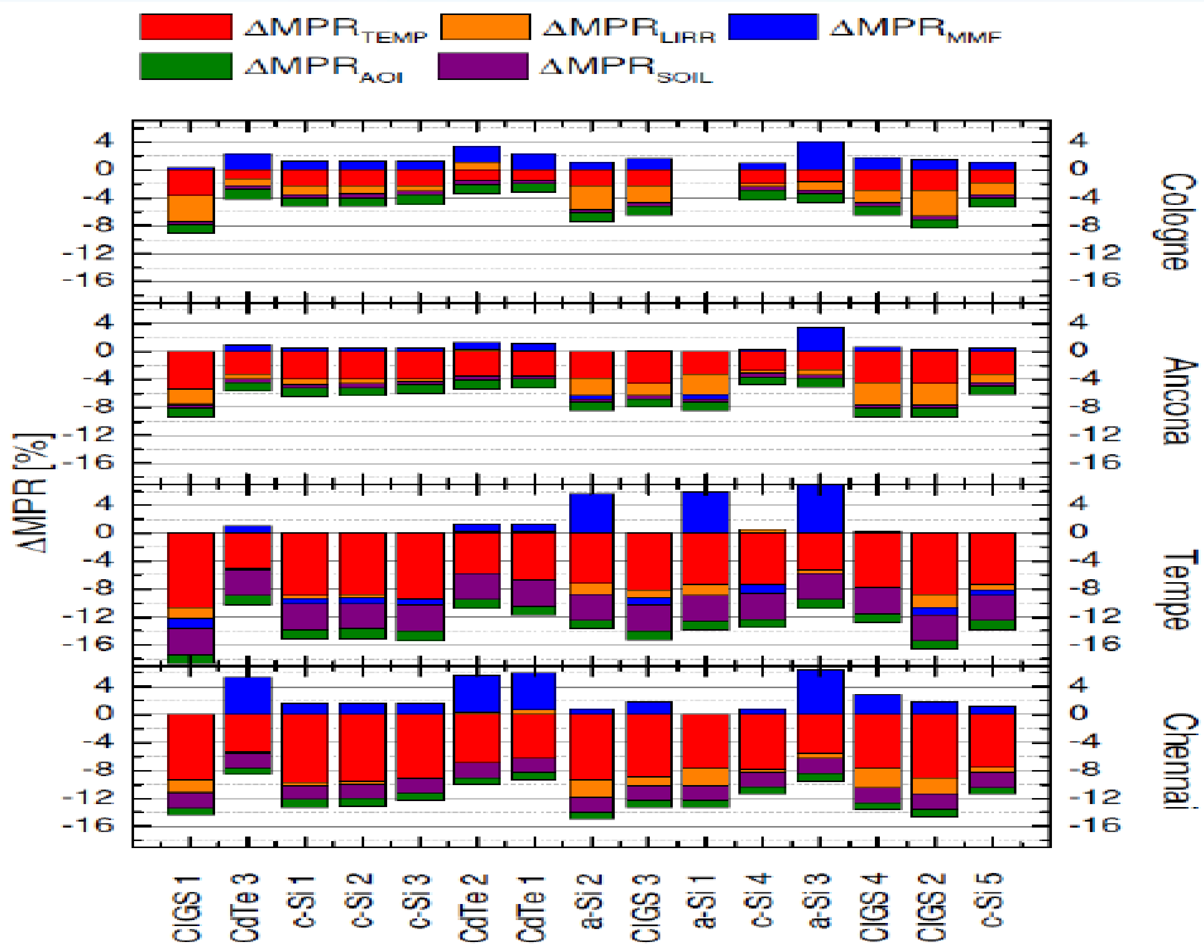
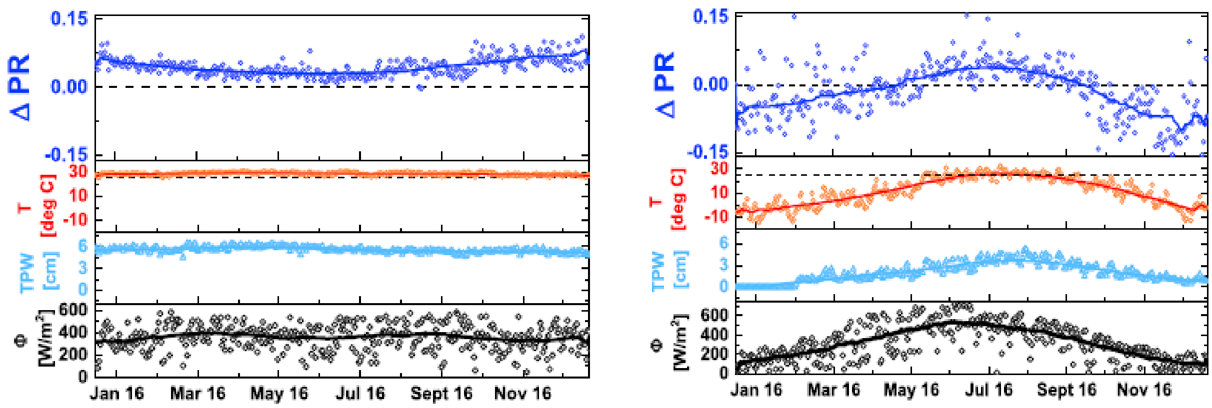


Figure 34. Breakdown of losses for installations in four locations (Cologne, Ancona, Tempe and Chennai) with distinctly different operating conditions, for a variety of installed technologies. Considered are temperature effects (red), low irradiance (orange), spectral effects (blue), angle of incidence (green) and soiling (purple). The authors note that low irradiance behavior is most pronounced in Cologne and benefits CdTe with a magnitude of +1.1% and that the spectral impact is mostly positive and high for CdTe technologies with a spectral gain of up to 5.3% in Chennai (Schweiger et al., 2017).

The difference in performance ratio between CdTe and silicon modules was also investigated by Peters et al. (2018) using measured data from Perrysburg (Ohio, U.S.) and Singapore. Measurement results are shown in **Figure 35**. The study shows a consistent performance advantage over the course of a year of CdTe compared to Si for Singapore, and a seasonal dependence of performance ratio differences for Perrysburg. The differences are attributed to the different sensitivities of CdTe and Si to temperature and humidity, with a sensitivity analysis indicating that temperature is the leading effect, but precipitable water only being slightly less important.

Figure 35. Performance Ratio Differences



A) Singapore *B) Perrysburg*

Figure 35. Performance ratio differences between CdTe and silicon PV installations in Singapore (A) and Perrysburg (B). Also shown are temperature, total precipitable water and irradiance levels in both locations over the course of the year 2016 (Peters et al., 2018).

Munshi et al. (2018) investigated how the performance of CdTe modules compares to polycrystalline silicon, if various installations are considered. In the paper, ground, rooftop and floating PV installations are explored, with all sites being located in the tropical conditions of Thailand. Results are shown in Figure 36.

The study shows a consistent performance advantage over the course of a year of CdTe compared to Si for Singapore, and a seasonal dependence of performance ratio differences for Perrysburg. The differences are attributed to the different sensitivities of CdTe and Si to temperature and humidity, with a sensitivity analysis indicating that temperature is the leading effect, but precipitable water only being slightly less important.

Figure 36. PV Power Generation Over a Month

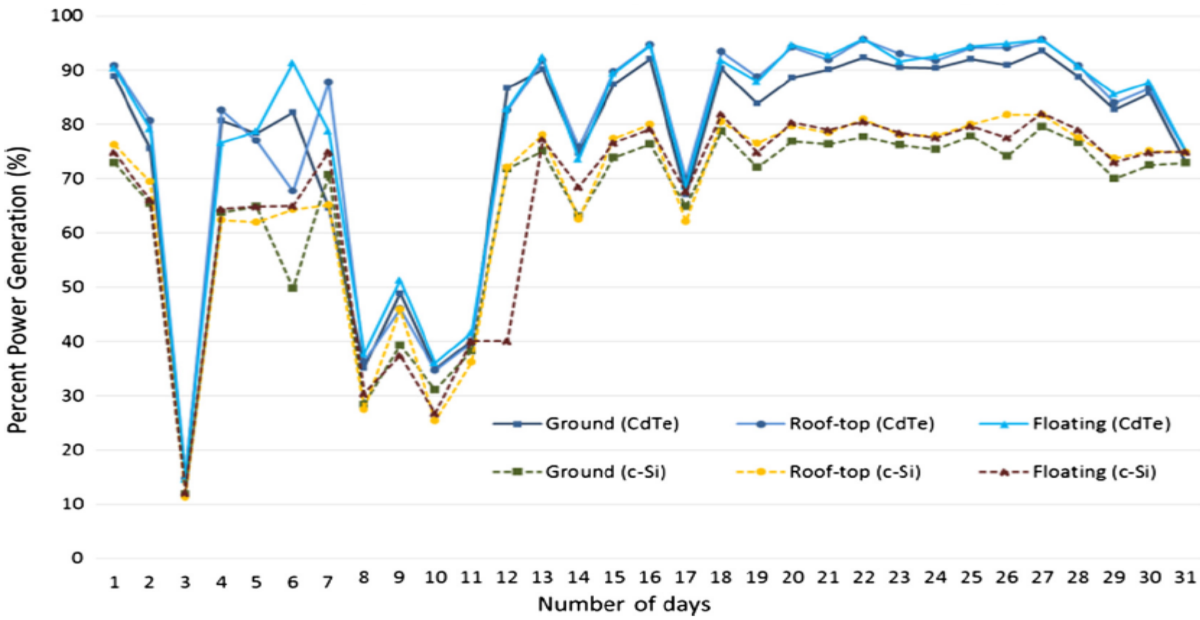


Figure 36. One-month comparison of Cadmium Telluride and polycrystalline silicon PV modules on different installation. Considered are ground-mounted, rooftop and floating PV systems (Munshi et al., 2018).

The study shows that the performance advantage for CdTe, driven by both temperature and spectral effects, is consistent over all installations. Notably, no differences are found for installations on water, for which lower module temperatures could be expected. These results, again, speak to the intrinsic material advantage of the higher band gap CdTe absorber, compared to silicon.

II.C.5 - ARC and Soiling

In the last decade, antireflection coatings (ARC) on the front glass, and more recently also anti-soiling coatings, have become a main feature of PV modules. ARC coatings reduce the 4% front surface reflection of the glass cover, and typically recover about half of this loss. Passow et al. (2018) experimentally investigated the impact of ARC coatings on the power generation of First Solar modules (2018). Results of a measurement series over 30 months are shown in **Figure 37**. The overall gain due to the ARC is 1.8%.

Figure 37. Anti-Reflective Coating Effects

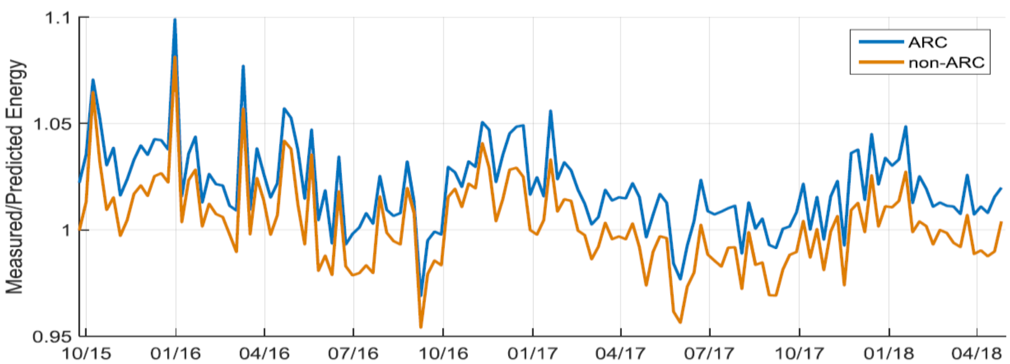


Figure 37. Ratio of average weekly measured to predicted power generation of a group of modules with (blue) and without (orange) anti-reflective coating (ARC) (Passow, 2018).

Figure 38. Soiling Effects

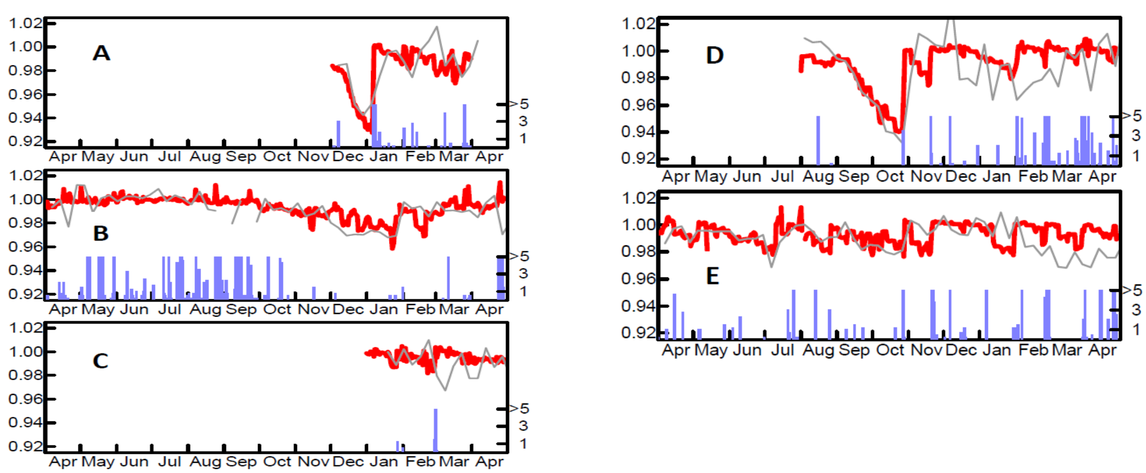


Figure 38. Daily ratios of effective irradiance (insolation) received by soiled to non-soiled modules (soiling ratios) over time (thick line), as well as normalized power output (thin line) over one year (2013 / 2014). Blue bars indicate rainfall (Gostein et al., 2014).

The soiling or buildup of dirt on PV modules can result in significant reductions in PV module power output. Gostein et al. (2014) investigated soiling levels and rates alongside PV plant performance in the desert southwest of the United States, the Arabian Peninsula, and Western Australia. The study found indication of a strong correlation between soiling level and power reduction, with, in some cases a 1:1 direct correlation. Soiling rates for the five investigated sites varied between 0.5% per week and 5% per week, underlining the importance of reducing soiling for PV modules in desert environments, particularly in humid, dust-prone climates (e.g., Arabian Peninsula), which can transform dry dust into clustered and sticky dust. Results of this study are shown in **Figure 38**.

Grammatico & Littmann (2016) investigated the anti-soiling benefits of antireflection coating. The results of this study are shown in **Figure 39**. The authors find that First Solar CdTe PV modules with ARC don't soil as much in semi-arid and desert climates. The average annual reduction in soiling rate in the desert southwest was 22% in one location and 25% in another. In climates with frequent rain, no or few benefits were observed.

Figure 39. Soiling Trends

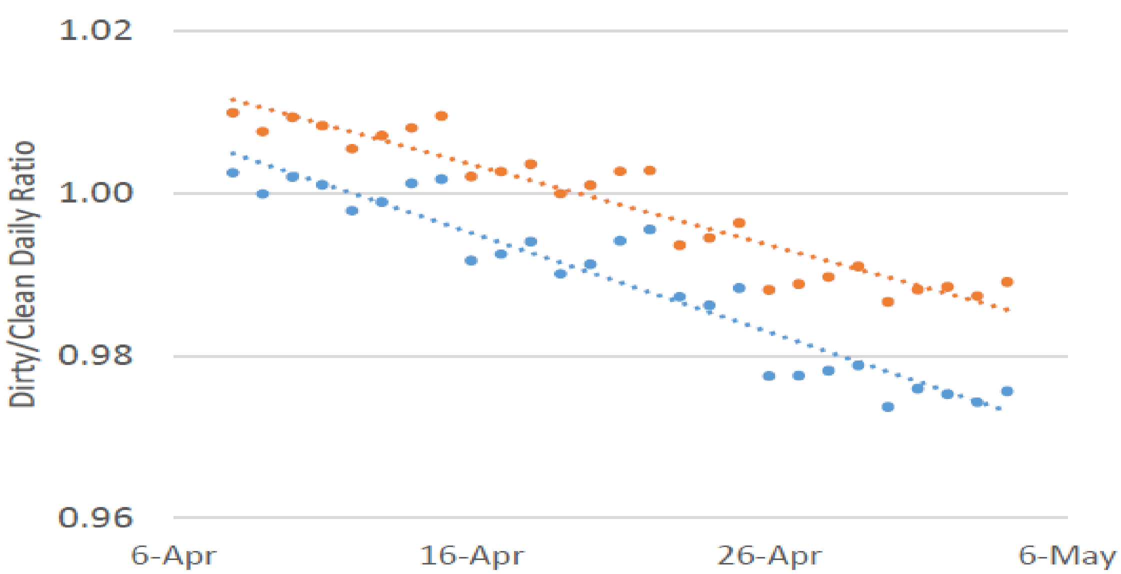


Figure 39. Soiling trends observed throughout Spring 2015. Blue circles are daily ratios of dirty to clean insolation for First Solar non-ARC CdTe modules, orange circles are daily ratios of dirty to clean insolation for First Solar ARC CdTe modules. The soiling rate of each data set is determined by the slope of each dotted line (Grammatico & Littmann, 2016).

D - Reliability Testing

II.D.1 - Indoor Testing Procedures and Results

Warranties for field performance of PV modules are typically granted for 25 years, with several producers giving even longer warranties. As innovation in PV progresses rapidly, field exposure testing to validate long-term performance for such long times is impractical, and the PV industry has developed accelerated testing procedures in the lab to mimic long term exposure and more rapidly assess probable future performance and degradation of modules in the field. A number of internationally accepted accelerated testing procedures exist to establish module reliability in the field. Procedures follow a general format with an initial measurement of a test sample, followed by an accelerated environmental exposure and a final test of power and safety of the sample. Three of the common stressors for PV modules are thermal cycling with temperatures being varied between –40 to +85°C, (the profile is shown in **Figure 40** on the left), humidity freeze cycling with temperatures being varied over the same range, though with a different time profile, and humidity kept at 85% during the hot period (profile shown in **Figure 40** on the right), as well as damp heat testing, with a constant exposure of 85°C and 85% relative humidity (not shown) (Strevel et al., 2013; IEC, 2008). Typically, modules are kept for 1000 hours (about 6 weeks) under these conditions. In addition, modules are tested for performance under electrical bias and UV exposure, as well as mechanical stresses such as static load, dynamic load, and hail.

Figure 40. Test Cycles

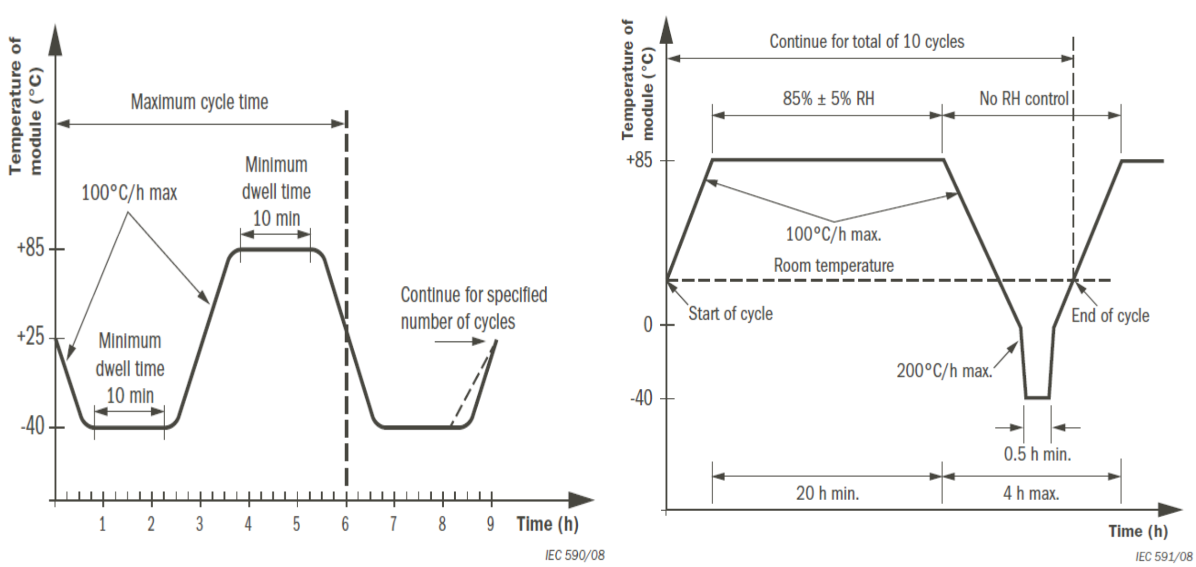


Figure 40. Left - IEC 61646 thermal cycling profile. Right - IEC 61646 humidity freeze profile (Strevel et al., 2013).

Historically, testing procedures for thin-film PV modules were defined by the IEC 61646 standard test protocols and were different from those used for silicon modules (IEC 61215), though now testing procedures for both technologies have been harmonized (IEC, 1993). A standard test for thermal cycling consists of 200 cycles; for humidity freeze testing, typically 10 cycles are used. This standard, together with the IEC 61730 safety standard, provides the general framework of certification to assure a common minimum level of testing procedures. They are common practice in industry (IEC, 2004). In recent years, the need to further refine PV module testing to evaluate more than initial quality has become apparent, and additional tests are being designed to provide better insight into the reliability and long-term performance of PV modules.

Figure 41 shows results for thermal cycling (left) damp heat testing (right) of First Solar Series 3 Black modules. In this particular experiment, thermal cycling was extended to five times the duration of the standard test, and damp heat testing was carried out with more than six times the conventional 1000-hour test. Results in **Figure 41** are for a sample population of 25 modules. No measurable power reduction was found after the extended thermal cycling. For the damp heat testing, it is important to note that the modules undergo an extended exposure in dark environmental chambers, after which a light soaking recovery process is carried out to eliminate the dark storage effects and restore power generation back to baseline. Three such exposures were conducted, one after about 2300 hours, one after about 4400 hours, and one upon test completion (6384 hours). Even after this extreme testing, the power output of the module was reduced by only 7 ± 3%. This result demonstrates the durability of First Solar's encapsulation and packaging procedure, which are also utilized in subsequent module versions (Series 4 and 6).

Figure 41. Test Cycle Effects on Power Output

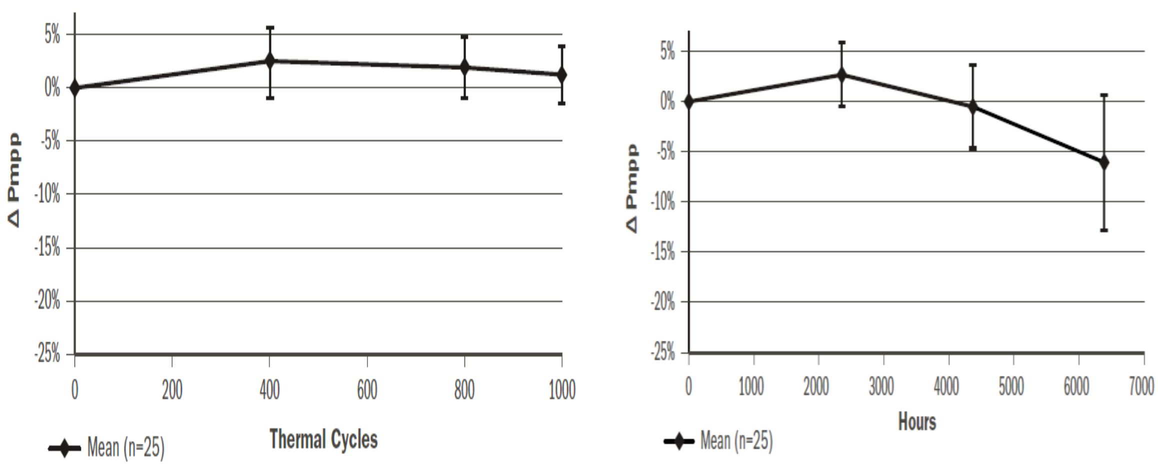


Figure 41. Left - result of extended thermal cycling. Right - Result of extended damp heat testing. Testing durations are five times for thermal cycling, and more than six times that of standard procedures for damp heat testing. No power reduction was observed for thermal cycling, during damp heat testing, power reduced by only about 7%, despite the harsh testing conditions (Strevel et al., 2013).

II.D.2 - Technological Innovation

As discussed in the previous section, PV reliability research and testing has evolved from a focus on initial quality to improving long-term reliability, which is essential given the long warranty life of commercial PV modules. The long-term reliability of PV modules can be improved via technological innovation (Strevel et al., 2013). While the improvements described below were first implemented in prior versions of First Solar modules (First Solar Series 3 Black Plus module, compared to the First Solar Series 3 Black module), they are also applicable to subsequent versions of First Solar modules (Series 4 and 6) and are therefore described in this section. The Series 3 Black and Series 4|6 module features innovations intended to provide improved long-term durability due to an upgrade in the encapsulating material. The Series 3 Black Plus and Series 4|6 module additionally features innovations in device technology to improve long-term power output degradation.

The packaging system of the Series 3 Black and Series 4|6 module employs an upgraded edge sealant which extends around the module perimeter and an improved encapsulant between the glass laminates. Both innovations provide a better protection from water ingress and improved electrical insulation. The edge sealant uses a carbon-based colorant – the reason for the product name (black). Carbon is known to not affect the active solar cell material negatively and to absorb UV light very efficiently. The material, hence, acts as a radical scavenger. The material has other advantages, including that the volume resistivity is between 10^{15} and 10^{16} Ωcm, more than ten orders of magnitude above the value provided in guidelines for electrical insulation. Moreover, it features high tolerance to extreme operating conditions (temperature and humidity), and it provides excellent solid insulation, with a relative thermal index (RTI) measured by First Solar at 105°C – a strong indicator that the material is suitable for operation in hot and arid climates.

The encapsulant acts as a secondary barrier against environmental influences after the edge sealant. The role of encapsulants for water ingress has been covered extensively in the literature (Kempe, 2005). A main feature of the improved encapsulant is a water vapor transmission rate (WVR) that is several times smaller than that of conventional EVA. A further feature of the new encapsulant is the observed very high strength of its bonding to glass even after harsh, accelerated testing. The encapsulant bond strength is on the order of 5 megapascals (~50 kg/cm^2), making it very difficult to separate the front and back of the modules and so it is very difficult to break the modules open.

The Series 3 Black Plus module and Series 4|6 modules also feature innovations in the device architecture. The main innovation is an improved back contact using ZnTe (see **Figure 42**). ZnTe improves the valence band offset from p-type CdTe. This results in a back contact that has a more ohmic characteristic and is more stable (Gessert et al., 1996; Rioux et al., 1993). The benefits of a ZnTe contact were first demonstrated in 2012 by a new device efficiency record of 17.3%. Following this achievement, the ZnTe contact was integrated into full-scale module fabrication. The nameplate improvement of this innovation is between 5 and 8 Wp. The ZnTe back contact improved both fill factor and V_{OC} of the modules.

Figure 42. ZnTe Back Contact Architecture

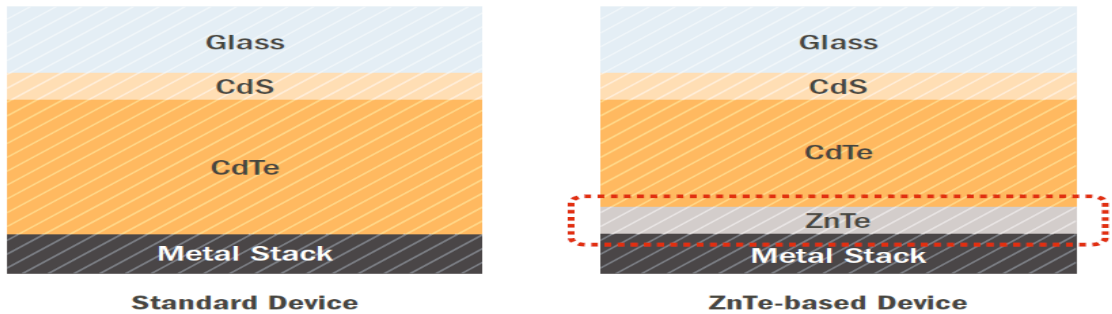


Figure 42. Solar cell architecture without (left) and with (right) ZnTe back contact. (Strevel et al., 2013).

Accelerated testing was used to examine the long-term power degradation behavior of the two module types. **Figure 43** (top) shows the power loss over time for the standard and ZnTe-based device. The 300-day exposure, which is believed to be equivalent to long-term operation, included extreme temperatures, full spectrum illumination beyond 1sun (1000W/m^2), and high-bias. The ZnTe based device showed a power loss below 10%, compared to a 17% reduction in the standard device. The observed degradation rate showed the potential to improve the long-term degradation values to –0.5% per annum for all climates, which has been documented in Series 4 and Series 6 modules.

Figure 43. ZnTe Back Contact Effects

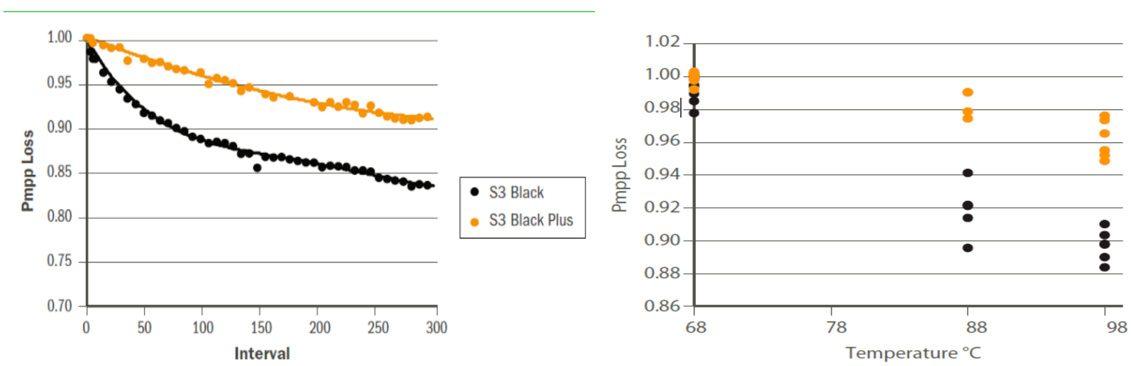
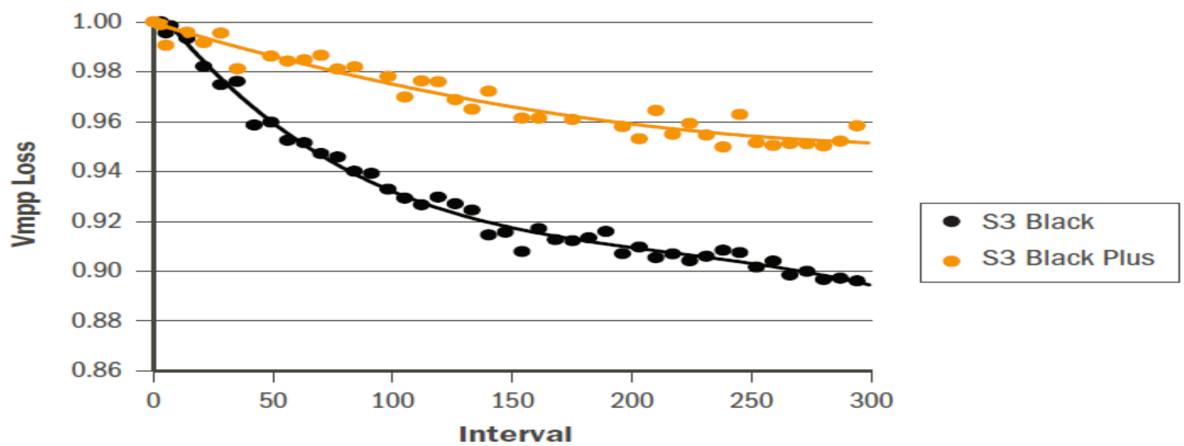


Figure 43. Left - Power loss after extended light soaking exposure. The ZnTe-based device (Series 3 Black Plus) showed less than 10% reduction after 300 days of testing. Right - Comparative power loss vs. accelerated temperature and light soaking stresses. The improved long-term stability of the ZnTe-based device (Series 3 Black Plus) is an indication of inhibited Cu migration due to the presence of ZnTe (Strevel et al., 2013). Note that ZnTe is also utilized in Series 4|6 modules.

ZnTe is also believed to retard Cu diffusion, thus helping to keep a Cu-rich back contact (Narayanswamy et al., 1999). Curtailing Cu diffusion results in improved long-term stability. Temperature variations under accelerated light soaking (**Figure 43**) show improved long-term stability of the ZnTe-based device.

While **Figure 43** (left) showed the total power degradation, **Figure 44** (top) shows the degradation in maximum power voltage. A slower degradation (6% compared to more than 10%) and faster stabilization (reaching an asymptote) aid system designers who have to take drifts in operating voltage into account for accurate energy prediction. Finally, **Figure 44** (bottom) shows that the very good predictability (ratio of actual energy produced to energy predicted; PER) of First Solar PV modules continues also for systems that include the latest innovation, which is also utilized in subsequent versions of First Solar PV modules (Series 4 and 6).

Figure 44. Stabilization and Predictability of CdTe PV



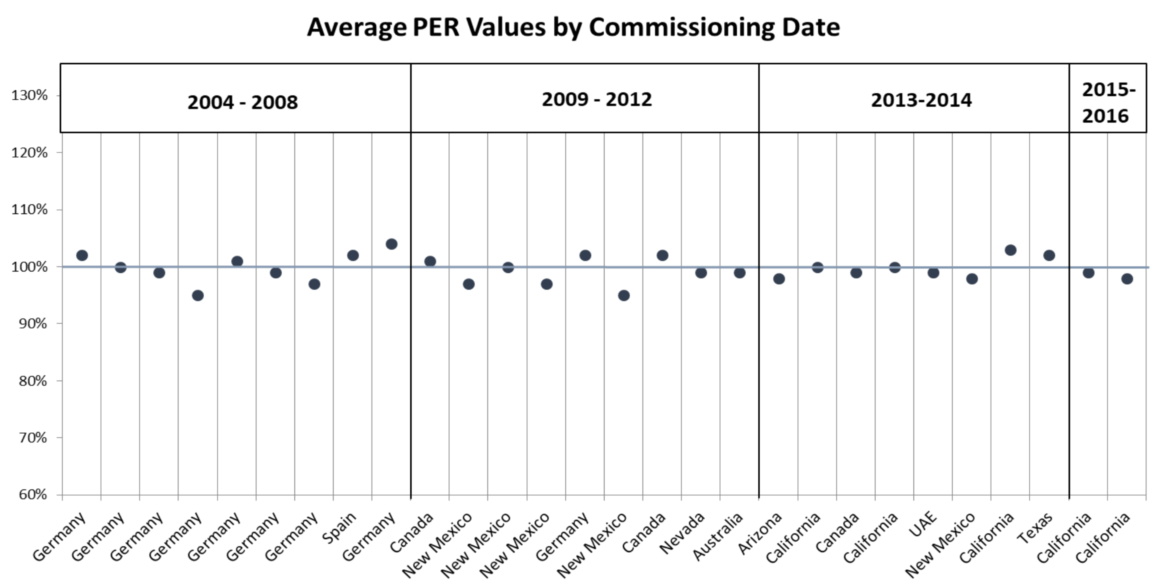


Figure 44. Top - Voltage loss after extended light soak exposure at the maximum power point. (Strevel et al., 2013). As with S3 Black Plus, ZnTe is also utilized in Series 4|6 modules. Bottom - Historical predictability of CdTe PV module architecture (First Solar, 2020a).

E - Future Efficiency Development

CdTe PV technology has not yet realized its full device performance or cost potential. This was illustrated earlier, in **Table 1**. There are a number of fundamental differences between the materials used by CdTe and Si PV technology. As a consequence, various and unique strategies exist for improving the future performance of CdTe PV cells and modules.

First, the binary material combination of cadmium and tellurium can be altered in ways that are impossible for silicon, as a wafer-based technology. One example is the addition of other elements to the mix, which could potentially be used to adjust the band gap of CdTe. Whereas silicon has a fixed band gap of 1.124 eV at room temperature, the value for CdTe can be adjusted upwards and downwards from 1.54 eV to achieve both lower and higher band gaps. This adjustment has several technological consequences.

II.E.1 – Band Gap Grading

Figure 45. Selenium Concentration in CdTe Film

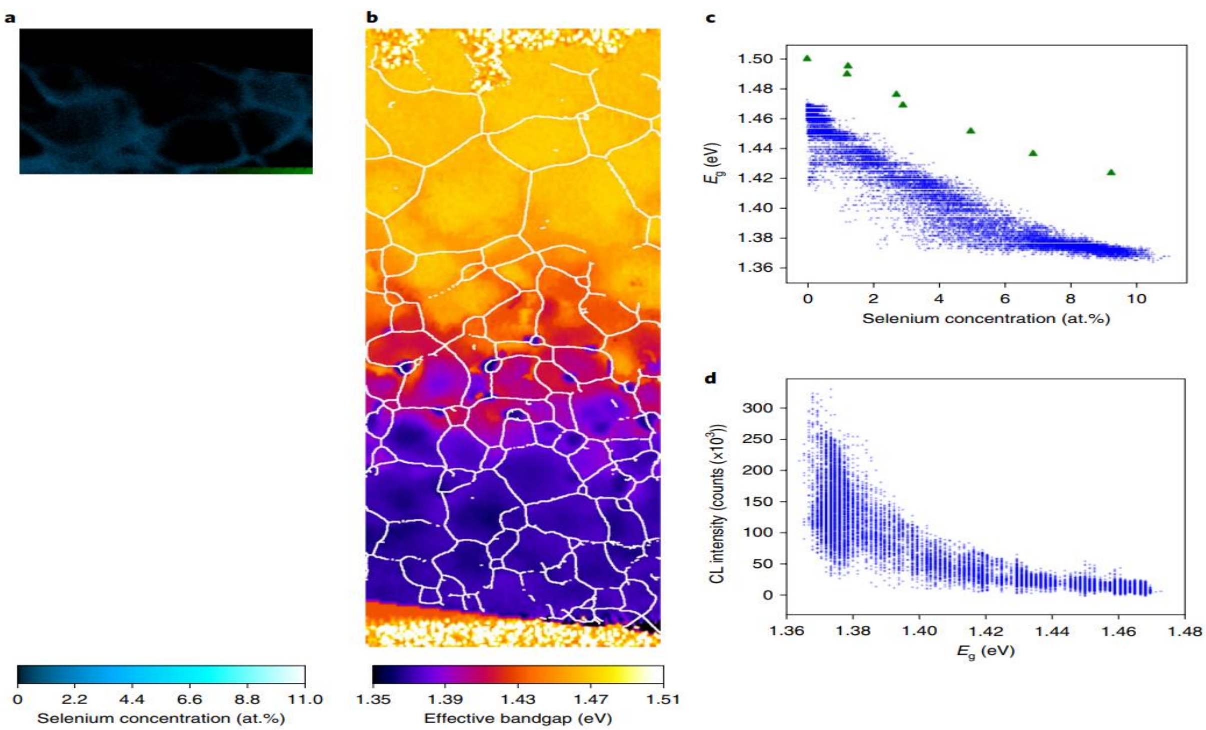


Figure 45. A) SIMS map of the selenium concentration in a CdTe film. The selenium concentration was varied here to values between 0 and 11%. B) Shows the peak emission energy of the same film measured by cathodoluminescence (CL). This energy corresponds to the band gap of the absorber material. C) Shows the correlation between selenium concentration and band gap for all points extracted from the previous two figures. D) Shows the band gap as a function of CL (Fiducia et al., 2019).

For example, it is possible to add selenium to cadmium telluride to generate a material with a lower band gap. By gradually adjusting the selenium concentration, regions with a graded band gap can be generated. This concept is shown in **Figure 45** (Fiducia et al., 2019). Adding between 0 and 10% of selenium results in a variation of the absorber band gap roughly between 1.46eV and 1.36eV. Higher concentrations of selenium have the opposite effect: at Selenium concentrations above approximately 40%, the band gap increases, and at 100%, it reaches 1.7eV (Weiss, 2018). Inclusion of selenium to lower the band gap allows extending the photo-active range of the solar cells, resulting in active absorption at higher wavelengths, and consequently, higher currents and higher efficiencies.

First Solar already uses a technique called band gap grading in its modules (Gloeckler, 2017). **Figure 46A** gives a historic overview of the developments that have allowed increasing the efficiencies of First Solar's PV modules. A first innovation was the introduction of a ZnTe buffer layer at the rear to improve contacts and passivation (section **II.D.2**), a second innovation was related to improving the quality of the bulk absorber material quality. Adjusting the material composition of the absorber was commenced in 2014 and has helped push cell efficiencies beyond the 20% mark.

Figure 46B shows the effect of not one, but two variations of composition of CdTe that are active in different wavelength ranges. The substitution of CdS at the cell front has improved the blue-response of the cell by eliminating parasitic processes, and band gap grading has allowed further increasing the cell's current to close to 31 mA/cm^2. Very high currents are one of the reasons for the outstanding efficiencies that First Solar was able to produce.

Figure 46. First Solar Efficiency Gains

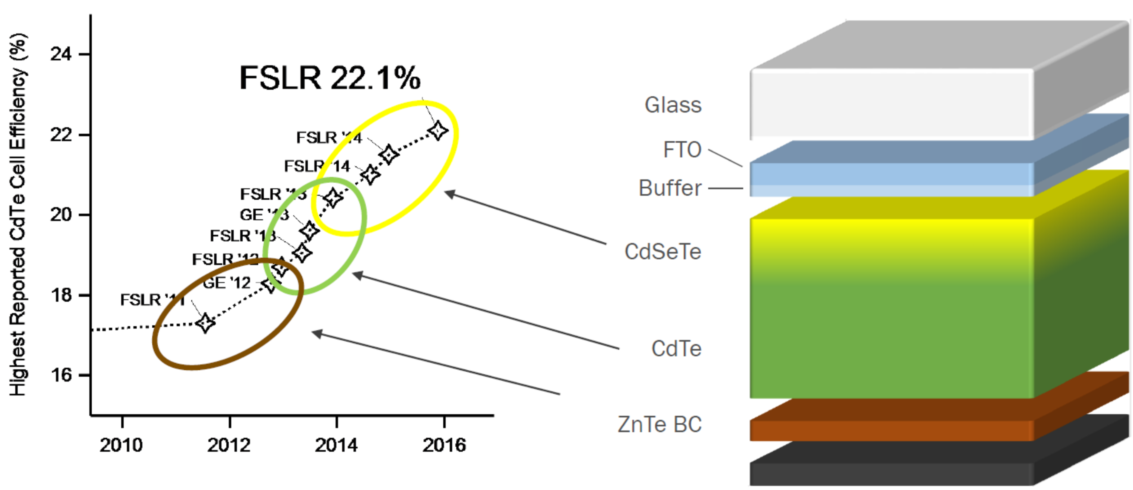


Figure 46A. Historic overview of First Solar's efficiencies, and which innovations were key in improving them (Weiss, 2018).

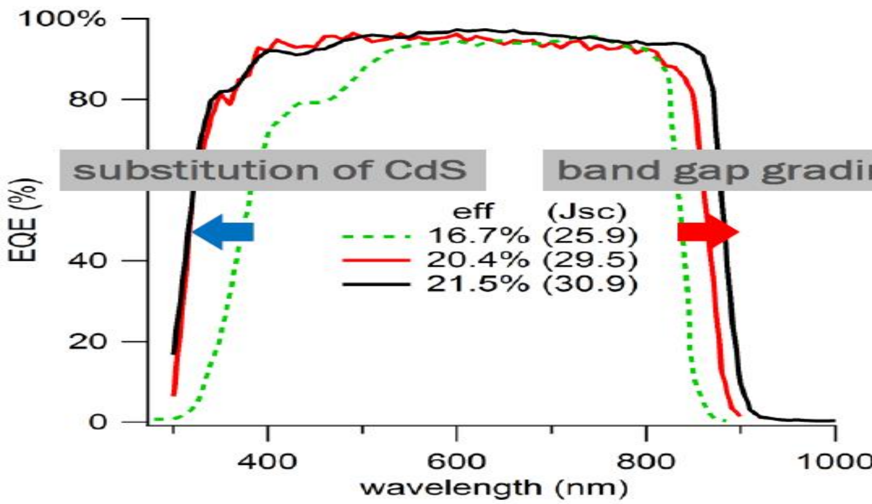


Figure 46B. External quantum efficiencies of different device generations. The substitution of CdS has improved the blue response of the cell, band gap grading has allowed extending the red response, together resulting in outstanding currents (close to 31 mA/cm^2) and efficiencies (21.5% in this case) (Weiss, 2018).

II.E.2 - Overcoming Low Voltages

CdTe devices with a voltage in excess of 1V were studied by Burst et al. (2016). **Figure 47** shows a histogram of past voltages measured at NREL for 2400 devices. The **Figure 47** clearly shows the type of improvement that these new architectures allow, as previously only very few devices achieved voltages in excess of 850 mV.

Figure 47. CdTe Overcoming 1 Volt Barrier

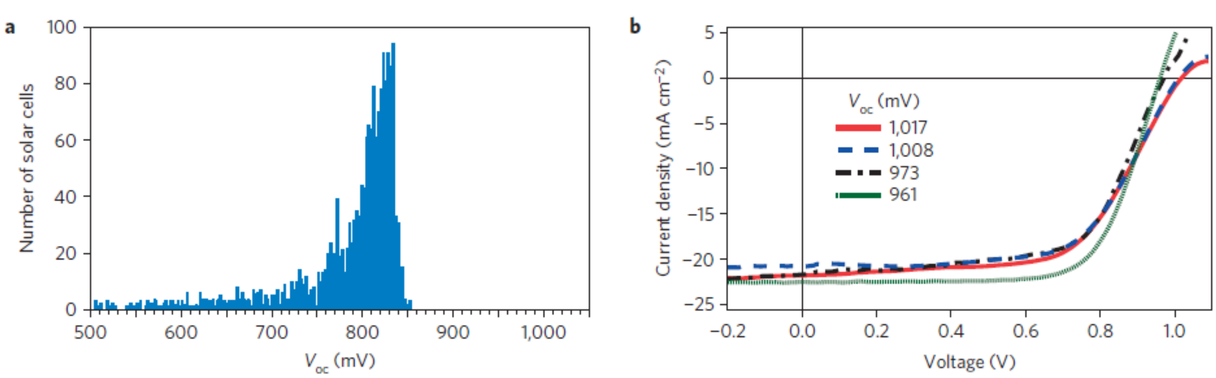


Figure 47. Burst et al. (2016) show how new concepts can overcome historical barriers of CdTe solar cells. A) Shows a histogram of VOC values measured at NREL for more than 2400 devices. No devices much above 850 mV appear in this chart. B) New developments have enabled CdTe to surpass the 1V barrier.

Another implementation of material composition variation is outlined in **Figure 48**. In this case, magnesium was used to generate CdTe with a higher band gap (Zhao, 2016). An intrinsic MgCdTe buffer layer was used as the front, hole-contact, and an n-doped layer of the material at the rear for the electron contact to create a hetero-type structure in CdTe solar cells. Similar structures have generated the highest possible voltages in silicon solar cells and are demonstrated here to also allow much higher voltages in CdTe.

Figure 48. Magnesium Effects on Band Gap

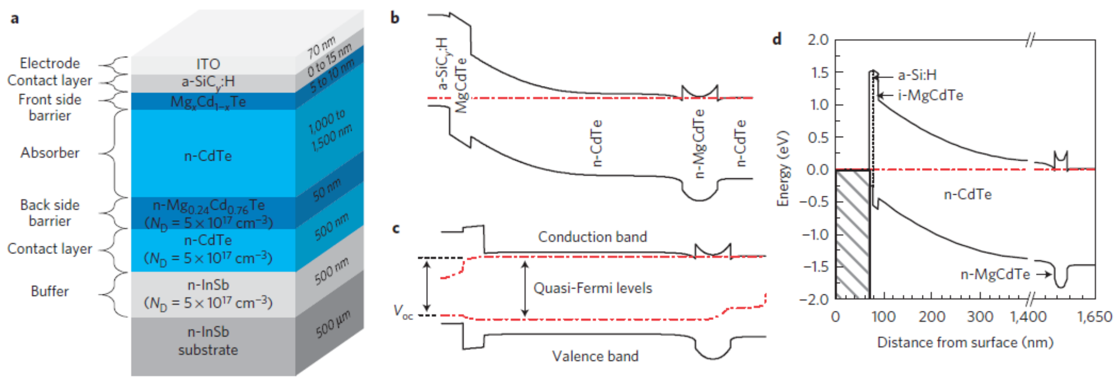


Figure 48. A) Device structure of a CdTe solar cell that incorporates Magnesium for band gap grading. B) and C) Show the band structure qualitatively of this device in the dark and under illumination. D) Shows the calculated absolute energy (Zhao, 2016).

All devices tested by Zhao (2016) improved the V_{OC} in a CdTe solar cell significantly, with the best devices achieving a value of 1.096V, which is close to the theoretical limit of 1.17V for the material. Measured characteristics as well as quantum efficiencies for the best fabricated device with an efficiency of 17% are shown in **Figure 49**. This device had a V_{OC} of 1.036V, a J_{SC} of 22.3mA/cm^2, and a fill factor (FF) of 73.6%.

Figure 49. Magnesium CdTe Cell Characteristics

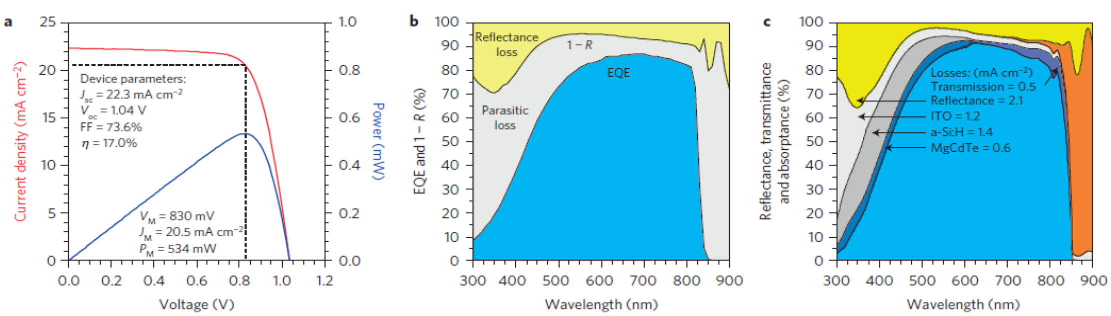


Figure 49. A) Measured J-V curve and associated device parameters for the solar cell with structure shown. B) Measured EQE and 1-reflectance with a calculated photo-current of 22.3 mA/cm^2. C) Simulated absorption spectrum for the best CdTe solar cell with a calculated photo-current of 23 mA/cm^2. The improved device has a 10nm $Mg_{0.3}Cd_{0.7}Te$ barrier layer (Zhao, 2016).

Being able to overcome classical voltage barriers is a huge step forward to generating CdTe solar cells with 25% efficiency and bringing the technology closer to what crystalline silicon can achieve. Yet, there are still technological barriers to be overcome to integrate these new device structures with the high current architectures currently used at First Solar.

II.E.3 - Next Generation Devices

Variations in the absorber band gap also open up the possibility to realize a concept with very high efficiencies: tandem solar cells. A tandem solar cell combines two electrically distinct absorbers with different band gaps to reduce thermalization (a thermodynamic loss present in every solar cell). A tandem solar cell made up of two absorbers has a theoretical efficiency limit of close to 45%, compared to a single-junction limit of approximately 33%. The limiting efficiency is determined by the combination of the two different band gaps and the electrical connection. For the latter, typically two types of connections are considered. The first is a two-terminal connection, in which the cells are separated by a tunnel junction and share one set of terminals. This architecture requires current matching and is very sensitive to band gap variations. The second connection is represented by the four terminal (4T) architecture, in which the cells are contacted independently and are only optically connected. This architecture does not rely on current matching and allows a broader combination of different band gaps. There are a number of variations of these two architectures, but also these can generally be separated into some that require current matching and others that don't. The limiting efficiencies for either case are shown in **Figure 50** (Mailoa, 2016).

Figure 50. Limiting Efficiencies for Tandem Solar Cells

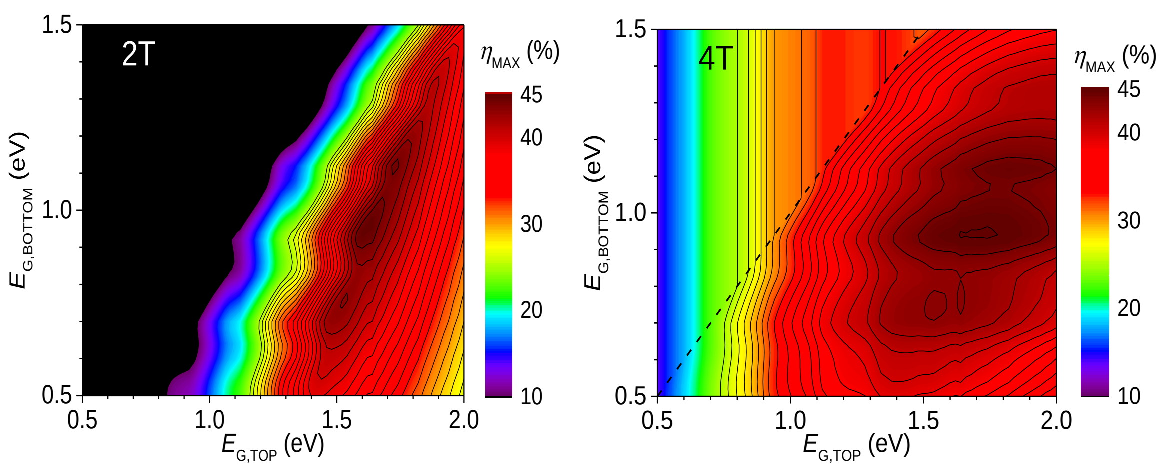


Figure 50. The figure on the left shows calculations for the two terminal (2T) architecture, in which the two cells are monolithically integrated, and electrically separated by a tunnel junction – making current matching necessary. The figure on the right shows the four terminal (4T) architecture, in which the two cells are contacted independently and only optically connected (Mailoa, 2016).

A study by Sofia et al. (2018) explored the techno-economic validity of tandem solar cells that include a CdTe sub cell. Particularly, the combination with another thin-film technology, CIGS, was explored due to similarities in the fabrication process, which constitute an advantage for tandem solar cell economics (Peters et al., 2015). The study concentrated on the levelized cost of electricity in the United States and compared single-junction solar cells to both a two terminal (2T) and a four terminal (4T) tandem made out of these materials. The cell structures are depicted in **Figure 51**.

Figure 51. Tandem Cell Structures

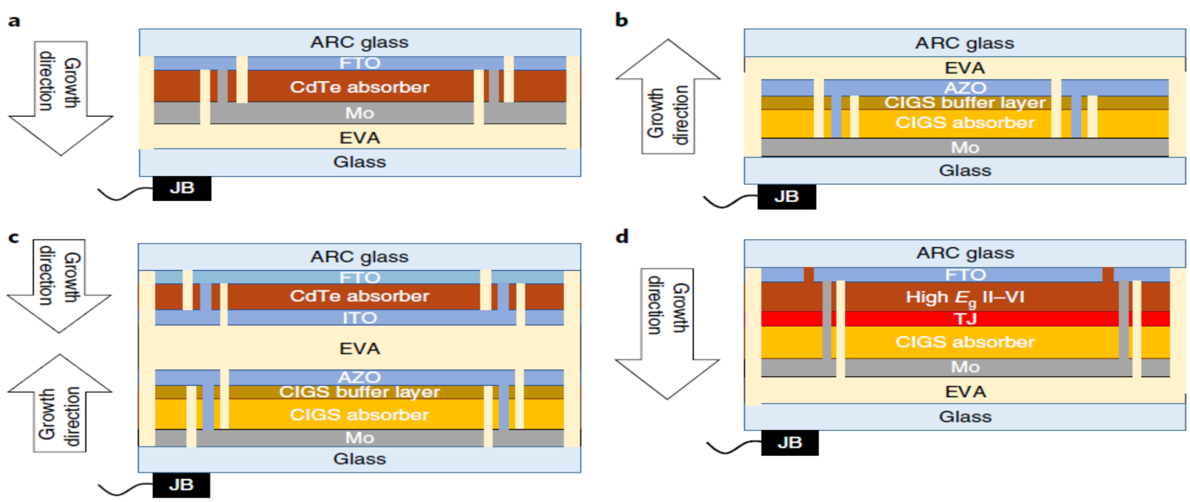


Figure 51. Cell structures explored in a comparison of single junction and tandem solar cells in the U.S. market (Sofia et al., 2018).

Calculated efficiencies for the single-junction solar cells and the tandems are shown in **Table 4**. It should be noted that efficiencies shown there correspond to record-level devices, but that certain properties had to be adopted for tandem integration. One example is the band gap of the top cell for the 2T tandem. Here, a band gap of 1.68 eV was assumed with an efficiency of close to 20%. Such a cell is currently not in existence and is one of the challenges that would have to be resolved for the realization of a monolithically integrated tandem. 4T integration is much less reliant on the band gap pairing, and efficient tandems can be generated with available cells. A requirement for the 4T tandem is that efficient CdTe solar cells can be produced with a transparent rear contact. Theoretical calculations show that a boost of 6.5% compared to single-junction efficiencies can be expected for a 4T tandem. Such a tandem would provide efficiencies on par with what the highest efficient silicon solar cells or even GaAs solar cell can achieve and could open up CdTe PV technology for additional market segments.

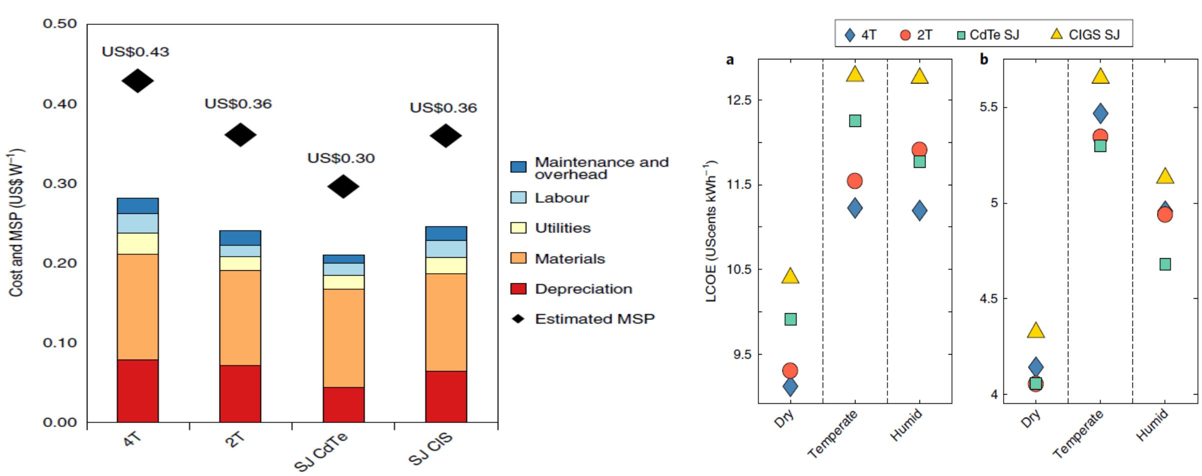
Table 4. CdTe and CIGS Efficiencies

Architecture	Efficiency (%)
CdTe Single Junction	19.9
CIGS Single Junction	19.8
2T Tandem	25.0
4T Tandem	26.5

Table 4. Single junction and tandem efficiencies (Sofia et al., 2018).

The results presented in **Table 4** suggest that tandem solar cells should be competitive in U.S. residential markets but should not be able to compete with conventional single junction solar cells in utility-scale markets (Sofia et al., 2018). This result is likely transferable to other tandem solar cell structures, for example, using a silicon bottom cell. The detailed LCOE calculation is shown in **Figure 52**. The main difference between residential and utility installations affecting the competitiveness of different solar cell concepts are the balance of system (BOS) and other soft costs. Overall system costs are larger for a smaller system, resulting in a larger premium for efficiency. The efficiency benefit of a tandem is, hence, worth the additional fabrication cost for a small, residential type installation, but may become uneconomic for large utility scale installations.

Figure 52. Module Cost Breakdown



A) Module cost *B) LCOE residential (left) and utility (right)*

Figure 52. Modeled module cost (A) and LCOE (B) for the considered single-junction and tandem solar cells. Despite the fact that the module cost of tandems is higher in terms of $/W (A), the higher efficiency generates additional value in a system. This value is high enough to make tandems, and particularly the most efficient, 4T, option the most economic choice in residential installations. On a utility scale, however, the lowest cost single junction solar cell may be the preferable option (Sofia et al., 2018).

F - Improving First Solar Competitiveness

Increasing the efficiency of modules is not the only way First Solar can improve the competitiveness of their products. In a theoretical study, Horowitz et al. (2017) showed that increasing the module area is beneficial to reducing the total installed system cost, and hence the levelized cost of electricity. The simulated effect of module area in installation cost is shown in Figure 53.

Figure 53. System Installation Cost

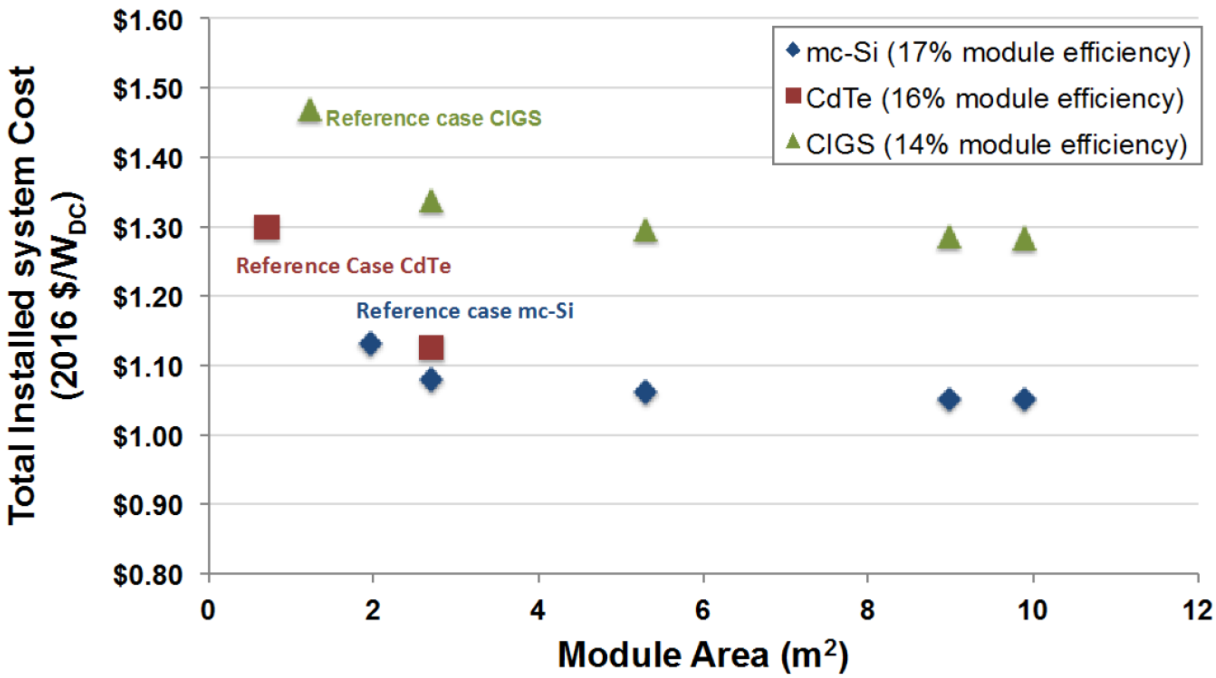


Figure 53. Effect of module area on total installed system cost for various PV technologies. Numbers represent U.S. weighted average cost (Horowitz et al., 2017).

In addition to being beneficial for installations, larger modules can also be fabricated at a lower cost. Realizing these benefits has likely triggered the decision of First Solar to produce their Generation 6 modules with an area of 2.47 m^2, rather than with the traditional size of 0.72 m^2. A cost estimate by NREL suggests that the minimum sustainable price, i.e. the lowest price at which the module should be sold to remain profitable would be reduced by almost 1/3; in the particular simulation shown from \$0.50/W to \$0.33/W. It should be noted that these numbers represent state of the art from 2016, and do not necessarily represent conditions in 2019 (**Figure 54**).

Figure 54. CdTe Module Manufacturing Cost

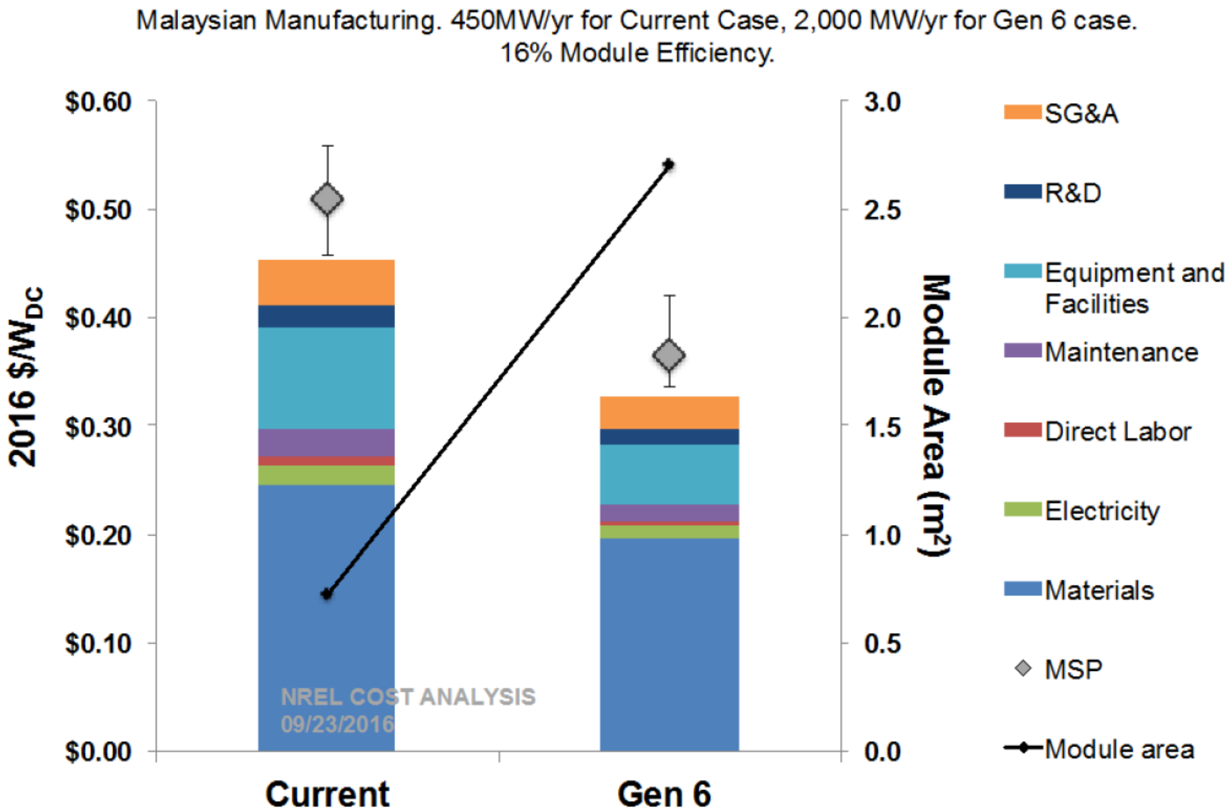


Figure 54. Effect of module size on CdTe module manufacturing cost and MSP, based on Capex Data (Horowitz et al., 2017; Jong, 2016).

III - ENVIRONMENTAL, HEALTH, AND SAFETY CONSIDERATIONS FOR CdTe PHOTOVOLTAICS

All technologies need to be carefully reviewed for possible environment, health, and safety (EHS) risks and held to high standards of EHS protection across the product lifecycle. This includes consideration of potential EHS risks associated with four aspects or phases of the technology's creation, use, and disposal: the materials used and their supply chains, the manufacturing process, the use of the technology, and its recycling, disposal, or other end-of-life management. Increasingly, many people suggest that this should be approached from the perspective of a circular economy, in which all materials are used and re-used in a continuous cycle, with no waste streams.

For CdTe PV, all of these considerations are important, and, as a manufacturer, First Solar has taken a number of steps to minimize EHS risks across the lifecycle of CdTe solar modules, using a precautionary approach. Early in the development of CdTe, for example, prior to significant manufacturing or deployment, research identified a number of recommendations related to industrial hygiene, biomonitoring, worker training, and recycling to ensure robust EHS performance (Fthenakis and Moskowitz, 2000), and these have been implemented throughout the product lifecycle. In addition, First Solar has proactively established standards for quality control in both its supply chain and manufacturing processes and has developed technologies, facilities, and programs to recycle modules and recover materials for future use.

CdTe PV is a mature PV technology with over 25 GW of solar modules deployed globally over the past 20 years, including 200+ million PV modules in over 18,000 projects in the Americas, Europe, Middle East, Africa, Asia, and Australia. This two-decade history of manufacturing and deployment allows for a track-record based approach to evaluating EHS risks (Hagendorf et al., 2017; VCCER, 2019; Fthenakis et al., 2020) to complement the precautionary approach taken during the original development and deployment of CdTe PV.

A - Materials and Supply Chain

A complete First Solar Series 6 module requires both raw materials and manufactured components (**Table 5**). These are sourced from qualified suppliers. First Solar spends over $1.9 billion globally, each year, on raw materials and manufactured components. First Solar has various quality control measures in place to curtail variation in suppliers and their products (2018). These measures reduce performance variations in the final First Solar PV module. Any new suppliers are required to undergo a rigorous Supplier Qualification process, which is linked to First Solar's Change Management System. The Supplier Quality group identifies and monitors cases of non-conformance with First Solar requirements and requires suppliers to take permanent corrective actions to address issues. A cross-functional team reviews suppliers for quality, cost, flexibility, service, technology, and sustainability, in order to provide feedback to continue meeting First Solar's needs. All suppliers must provide First Solar with confirmation that they follow fair labor standard laws aligned with Responsible Business Alliance (RBA) code of conduct and referencing international labor and human rights. First Solar also audits new and high-risk suppliers on environmental and social criteria with audit questions developed based on the RBA code of conduct (First Solar, 2018).

Table 5. First Solar Series 6 Module Composition

Item	Description	% Weight of Module
Semiconductor material	Thin-film Cadmium Telluride (CdTe)	0.12%
Laminate material	Polyolefin	2.02%
Bussing material	Copper Leaf Foil and Bus Bars	0.025%
Glass	Front (Substrate) Glass and Back (Cover) Glass	84.5%
Junction Box and Cable Assembly	Polyphenylene Housing and Halogen-Free Electrical Cables	0.56%
Frame and bars	Aluminum	12.5%
Frame adhesive	Silicon-based adhesive	0.83%

Table 5. Module composition of First Solar Series 6 modules (First Solar, 2019).

Of the raw materials, the semiconductor material used to convert sunlight to electricity is cadmium telluride, which comprises about 0.12% of the total module weight. The glass modules sealing the semiconductor comprise 84.5% of the module weight (30 kg). The aluminum frame and bars that frame the module comprise most of the rest of the weight (4.5 kg).

Table 6. Chemical and physical properties of CdTe and Cd

	CdTe	Cd
Melting Point (˚C)	1041	321
Boiling Point (˚C)	1050	765
Vapor Pressure (Mm Hg)	2.5 at 800°C	0.0075 at 257°C
Solubility Product	9.5×10^{-35}	2.3

Table 6. Properties of Cadmium Telluride and Cadmium (Bonnet & Meyers, 1998).

Considerable EHS research and analysis has focused on the CdTe semiconductor material. That work has demonstrated that CdTe properties differ considerably from the individual Cd and Te elements from which it is made (**Table 6**). The bonding properties of Cadmium Telluride (**Figure 55**) allow for higher chemical and thermal stability, which are important for long-term device reliability (Bonnet & Meyers, 1998) and for limiting toxicity, mobility and bioavailability (**Figure 56**). For instance, the melting point for Cadmium is 321 °C and Tellurium is 449 °C (Friberg, 1977), compared with 1041 °C for CdTe (**Table 6**).

Figure 55. CdTe Molecular Structure

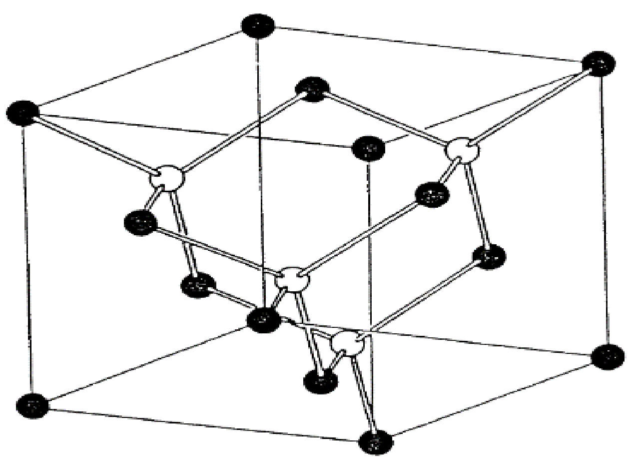


Figure 55. Molecular structure of Cadmium Telluride with strong chemical bonding (>5 eV) (Bonnet & Meyers, 1998).

Figure 56. CdTe Toxicology

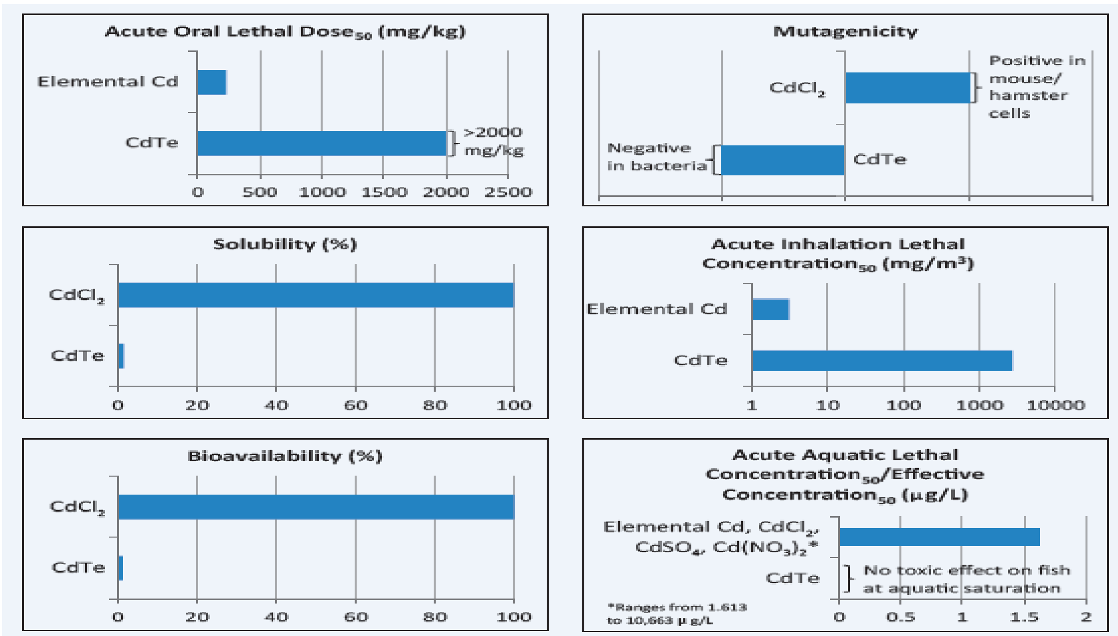


Figure 56. Toxicological properties of CdTe and other Cd compounds (Kaczmar, 2011; Zayed & Philippe, 2009).

As shown in **Figure 56**, CdTe exhibits toxicological properties that are approximately two to three orders of magnitude lower than that of Cd and soluble Cd compounds. Similarly, **Figure 57** shows ecotoxicological properties of CdTe are approximately three orders of magnitude lower than Cd, based on ecotoxicity characterization factors which relate chemical emissions to their life cycle environmental impact.

Figure 57. Ecotoxicity of Metals

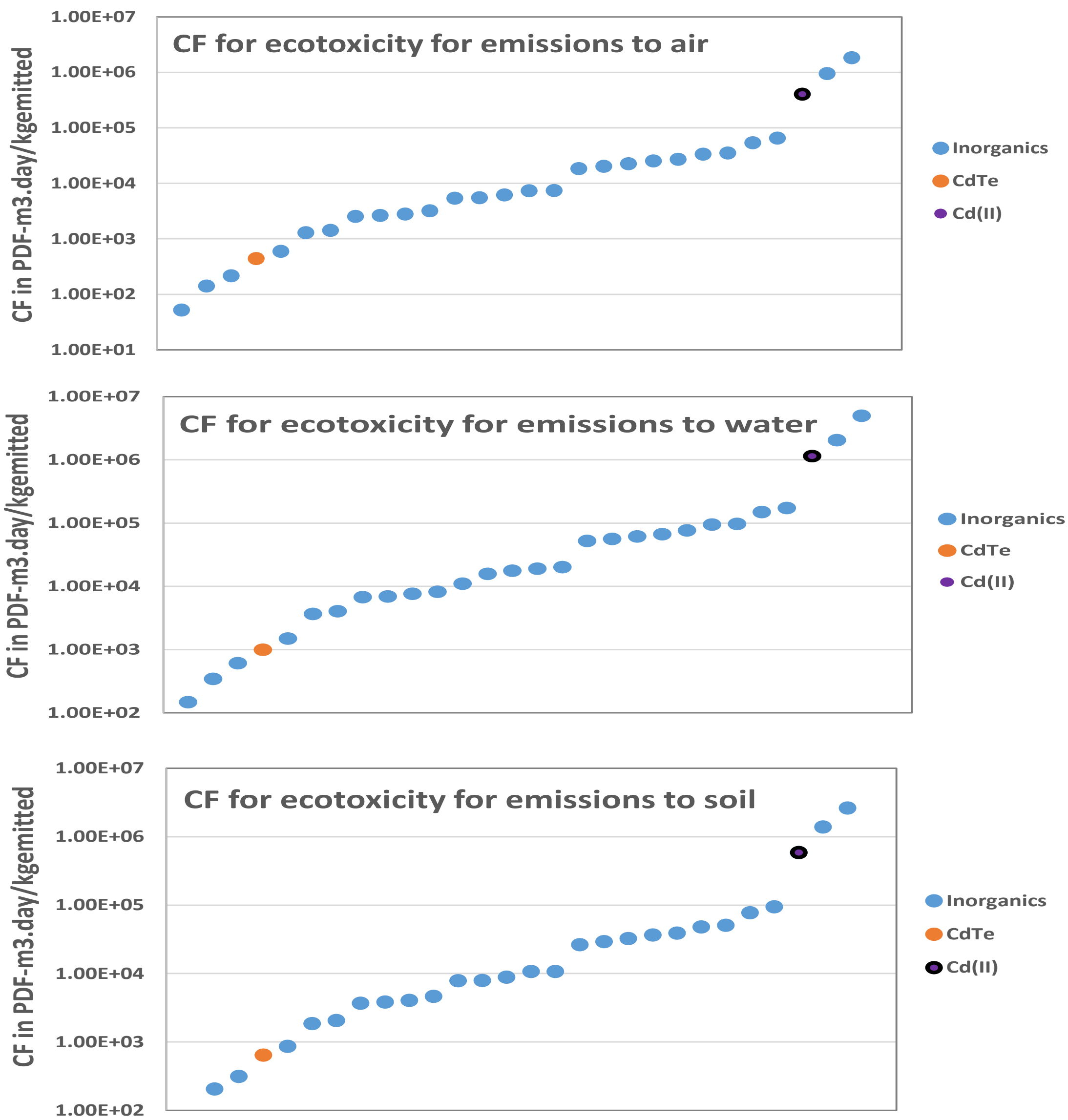


Figure 57. Ecotoxicity characterization factors (CF) for emissions to air, water, and soil for CdTe, Cd, and metal ions (Sinha et al., 2018b).

First Solar sources its CdTe from supply chains that originate in zinc and copper mining. Zinc mining has created an abundance of Cd as a byproduct, with a surplus projected due to reduced uses in other applications (Matsuno et al., 2012). Tellurium is sourced as a byproduct of copper mining and refining (**Figure 58**). First Solar's suppliers make CdTe from these mining byproducts, and the CdTe is then supplied as a stable compound to First Solar's manufacturing facilities. CdTe is then encapsulated in PV modules. At their end-of-life, modules are recycled, recapturing the CdTe for re-use (Raugei & Fthenakis, 2010). CdTe PV modules provide a sustainable energy source as a zero-emission technology during its regular use (**Figure 58**).

Figure 58. Circular Economy of CdTe

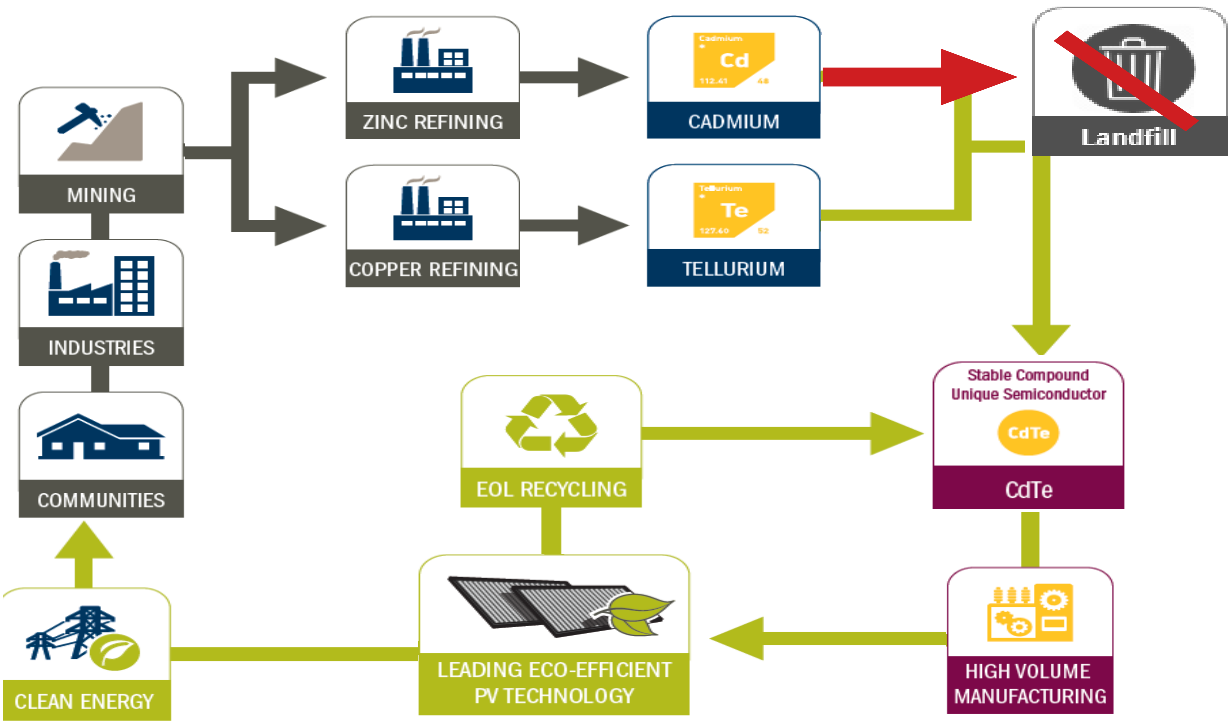


Figure 58. Material flows for CdTe based on Fthenakis (2004).

B - Manufacturing

PV consumers are essentially purchasing their electricity in advance, by purchasing modules intended to generate electricity from sunlight at no or very low additional operational cost for a very long time. As a result, PV manufacturers are responsible for creating PV modules that can withstand a range of outdoor environmental conditions over decades (25-30 years) and continue to perform reliably, as originally designed. Safety and reliability are inter-related in that when a PV module is performing according to its specifications, it is demonstrating both safety and reliability.

Figure 59. Series 6 Manufacturing Process

Figure 59. Hyperlink to First Solar manufacturing process video.

Manufacturing operations and their relevance to product safety and reliability are considered in this section with in-depth details on First Solar's Series 6 CdTe PV manufacturing process. An overview of manufacturing process is found in a First Solar video Figure 59.

III.B.1 - Manufacturing Facility

First Solar has now completed the upgrade of its Perrysburg, Ohio U.S. manufacturing plant to produce Series 6 PV modules, at a cost of $175 Million USD (First Solar, 2018). This facility now has the capacity to annually produce 0.6 GW of Series 6 solar modules. First Solar has also added a second high-volume manufacturing facility (1.2 GW annual capacity; $400 million USD investment) in Ohio, making First Solar the largest U.S. PV manufacturer. This facility upgrade added 500 employees to the Perrysburg area, increasing the total First Solar workforce to 6,433 in 2018 (First Solar, 2019). The upgraded facility utilizes an automated manufacturing process for the Series 6 PV modules (Figure 60). First Solar personnel on the manufacturing floor generally provide quality control functions and troubleshoot the production line. In addition to manufacturing, the First Solar Ohio campuses have a reliability lab, on-site wastewater treatment, and a PV module recycling facility that is reducing the total amount of waste from the manufacturing plants.

Figure 60. CdTe Module Automation

Figure 60. Automated manufacturing process for First Solar Series 6 manufacturing.

III.B.2 - Manufacturing Process

Once materials arrive at the Perrysburg facility, the Series 6 modules are manufactured in a single factory, along a continuous, automated assembly line, “under one roof” (Colville, 2017). There are three major steps in the PV module production process: semiconductor deposition, cell definition, and finishing (including testing the finished PV modules). Each step in the production line has a quality control checkpoint. The employees perform rigorous quality tests to ensure each step of the production process has a uniform result. The PV modules go through additional random batch quality sampling procedures. The production cycle takes approximately 3.5 hours to complete each PV module (First Solar, 2018). **Figure 61** shows the module structure including the thin film semiconductor thickness (~33 times thinner than a human hair) encapsulated in a glass-laminate-glass monolithic solid-state device, with additional details below.

Figure 61. First Solar CdTe Module Structure

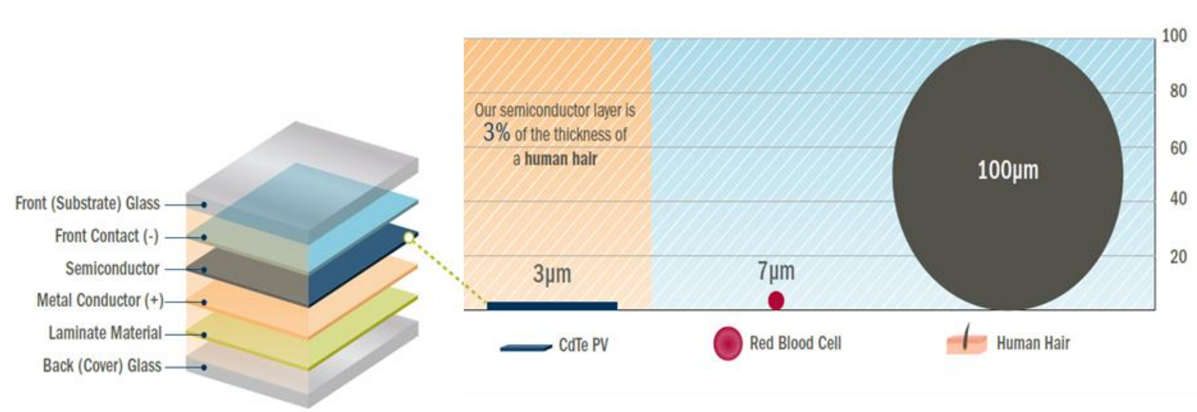


Figure 61. In the PV module structure, the CdTe semiconductor is a 3-micrometer thin film sealed between two glass layers (First Solar, 2018).

Each glass module (front substrate glass and back cover glass) in the PV module is supplied based on First Solar Series 6 module specifications, with tin oxide used as a transparent and conductive contact on the front glass. These glass modules are cleaned, inspected, and mechanically transported to a storage area.

A machine places the front glass module onto the semiconductor application (coater) line. A thin film of CdTe is deposited onto the tin oxide layer. Because of the high chemical and thermal stability of CdTe, multiple deposition methods can be used in the semiconductor application line, such as electrodeposition and vapor transport. First Solar uses a vapor transport deposition technique, which can yield higher deposition rates than other techniques such as closed-space sublimation (Bonnet & Meyers, 1998). The back contact ZnTe layer is deposited onto the PV module using a sputtering technique.

Workers perform a quality control analysis ensuring the semiconductor layer meets the specifications to ensure proper PV module performance. Once the quality control step confirms the semiconductor was correctly deposited, the modules are ready to be etched to define the cells.

A laser etching process scribes the individual PV cells, creating a path for the charge carriers to travel through the PV module. The quality control step checks the laser etching details before the module is encapsulated with polyolefin laminate and back glass. The interconnection bussing is added to electrically connect PV cells and deliver current to the junction box before the module is encapsulated.

The laminate and back cover glass are placed on top of the front glass, sealing the modules, and an edge seal is also applied. An additional anti-reflective coating is applied to the front glass. The CdTe semiconductor is encased within the PV module with an encapsulant bond strength on the order of 5 megapascals (~50 kg/cm^2 or ~725 $pounds/inch^2$).

The junction box and electrical cables are then affixed onto the module. Each PV module is flash tested with a sun simulator (1000 W/m^2) to ensure it performs at a certain power rating. This is the final step in the manufacturing process, after which the PV modules undergo final quality control. A random selection of newly produced modules are subject to rigorous quality testing, including testing for extended reliability (durability), in order to help ensure that the batch will withstand harsh outdoor environments.

III.B.3 - Personnel and Worker Safety

First Solar's manufacturing operation runs continuously (24 hours a day and 7 days a week). To ensure worker safety and optimal production rates, four crews work 12-hour shifts throughout the week. Production roles, production lines, and safety practices are standardized throughout all First Solar facilities worldwide. The majority of First Solar employees (71%) work in manufacturing facilities. In the U.S., there are over 1400 employees in the manufacturing department.

First Solar prioritizes worker safety and has taken proactive approaches to improve employee wellbeing and strives to become an injury-free workplace. The most common injury types in First Solar manufacturing facilities are bruise/contusion, strain/sprain, and cuts/lacerations. The primary mechanisms of injury are hit/struck into, hit/struck by and overexertion/awkward posture (ergonomics). Since 2008, when the injury rate was 2.6 injuries per 200,000 hours of exposure, First Solar has made significant improvements towards worker safety. In 2018, there were 0.43 injuries per 200,000 hours of exposure at First Solar. Even though this number increased from 0.29 in 2017, it is well below the glass manufacturing industry average of 4.9 (First Solar, 2019d). In 2017, First Solar began transitioning manufacturing lines from Series 4 to Series 6, with fewer associates and production hours worked due to retooling. The 2018 injury rate is similar to the 2016 injury rate (0.44 per 200,000 hours of exposure).

Employees are made aware of the mechanical, electrical, and chemical risks of being on the manufacturing floor. Since these risks can cause bodily harm, floor personnel are required to go through a full day of orientation and then hands-on training at their workstations. When they join the company, workers are given orientation training and hands-on learning from other floor workers until they are able to competently perform their role. During this training period, a veteran employee or line manager takes responsibility for the employee and watches over them on the floor.

Manufacturing floor personnel and their surroundings are carefully monitored throughout the facility. Employees and visitors are required to have personal protective equipment (PPE) when entering the floor. Even though much of the production line is automated, PPE is required to protect sight, hearing, hands, and feet. Incidents are recorded and reported to First Solar's multiple safety committees who meet bi-weekly and report to the Environmental, Health, and Safety committee every quarter. Each recorded incident is reviewed, and safety committees take corrective actions to prevent further injuries and ensure worker safety.

Floor personnel are tested for exposure to different chemicals and compounds including Cd compounds. The safety team routinely monitors facility air quality. Manufacturing equipment is self-enclosed with HEPA filtration used to capture particulate emissions (Lim, 2012). As shown in **Figure 62**, particulate Cd concentrations in indoor air are comparable across First Solar manufacturing facilities and are over an order of magnitude below permissible exposure limits.

Figure 62. First Solar Facility 2019 Air Samples

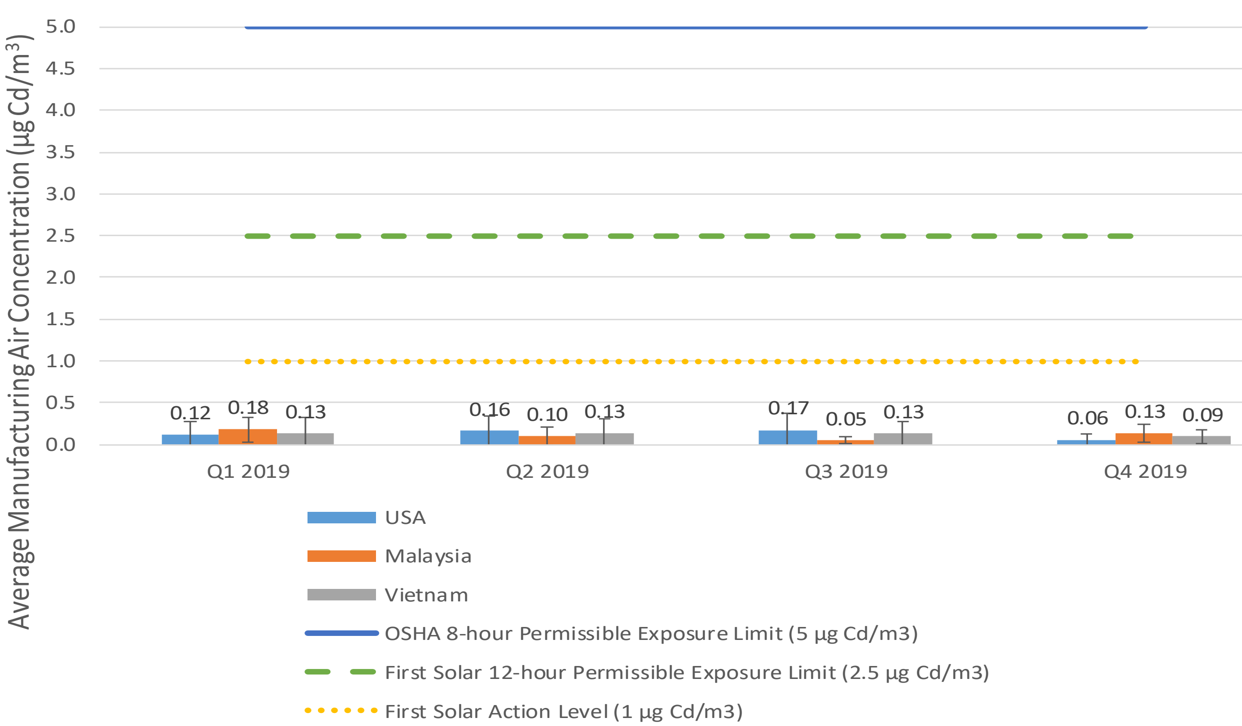


Figure 62. First Solar manufacturing indoor air sampling in 2019 shows all three facilities are well below the OSHA Exposure Limits and First Solar limits are stricter than OSHA limits. These figures are confirmed by independent auditors (First Solar, 2019b).

Research has confirmed the effectiveness of First Solar industrial hygiene programs. In a longitudinal biomonitoring study, First Solar studied thousands of workers in their Kulim, Malaysia facility over a period of five years. Worker blood and urine Cd samples were well below occupational safety limits and did not increase as a function of years worked (Sinha et al., 2016). External health and safety auditors annually reconfirm safety and health outcomes for workers as part of ISO 45001 certification. As shown in **Figure 63,** biomonitoring concentrations are comparable across First Solar manufacturing facilities and are about an order of magnitude below permissible exposure limits.

Figure 63. Biomonitoring of First Solar Workers

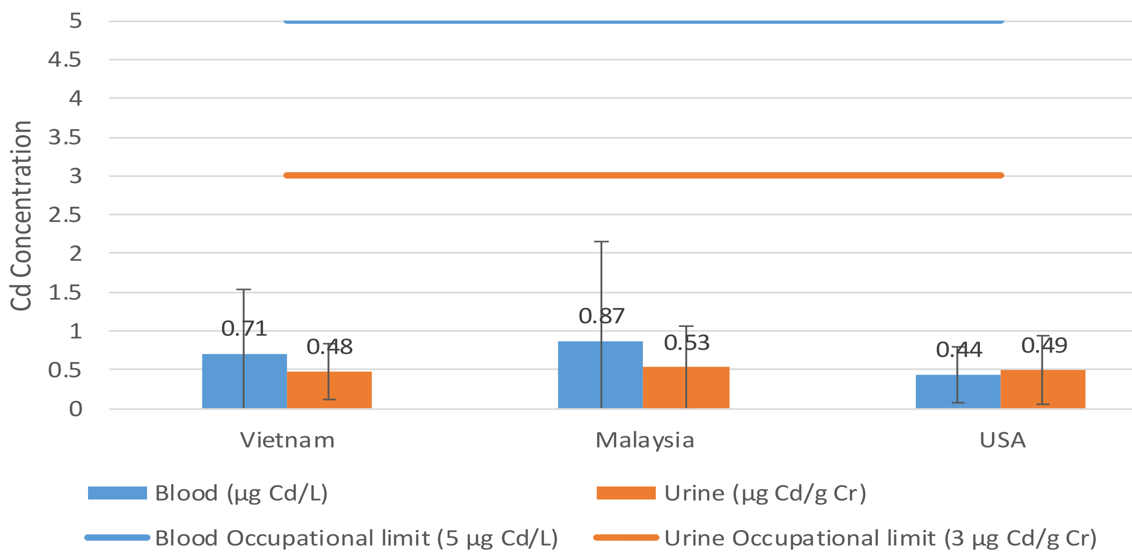


Figure 63. First Solar manufacturing floor worker's biomonitoring results in 2019 show no significant amount of cadmium when measured to OSHA limits for exposure (First Solar, 2019b).

III.B.4 - Production Quality and Safety

Throughout the production process each PV module is subjected to strict quality control measures. These measures help create a uniform product that performs reliably and safely throughout its 25-30 year life cycle. Quality control measures include in-line process monitoring and inspection, production reliability monitoring, quality and reliability lab testing, and outdoor proving grounds (Buehler, 2015).

From each batch of PV modules manufactured, modules are randomly selected and subjected to extended reliability tests in addition to those implemented on the manufacturing line. These modules undergo accelerated aging in environmental chambers that use multiple cycles of temperature, humidity, and light exposure extremes (**Figure 64**). After testing, these modules are recycled in First Solar's recycling facilities. These tests help ensure that the modules are able to withstand various environmental conditions in the field over long periods of time.

III.B.5 - Independent Quality Tests Certification

Outside auditors validate First Solar manufacturing practices. First Solar is required to maintain the procedures that are annually reconfirmed. CFV Solar Test Laboratory tested the Series 6 modules for quality assurance using the standards set in CSA/ANSI C450 (First Solar, 2018). The modules were subjected to extended environmental tests including temperature cycling, damp heat exposure, mechanical load testing, UV exposure, and potential induced degradation tests.

Furthermore, First Solar received the first International Electrotechnical Commission (IEC) TS 62941 certificate in the PV industry. The IEC awarded First Solar the TS certificate for setting the standard for best practices in product design, manufacturing, process control, testing, and raw material control and procurement (2018). Confirmation of First Solar best practices from independent auditors sets a standard for other competitors to gauge their standing in the PV industry.

Each First Solar facility is independently certified. The Perrysburg facility was awarded ISO 9001 for its Quality Management System, ISO 14001 for their Environmental Management System, and ISO 45001 for their Occupational Health and Safety Management System. DQS Inc. was the independent auditor verifying First Solar operations, with the certifications lasting until 2021. Each year First Solar facilities are audited to ensure good standing with the certification requirements. Annual ISO audits can range from 3 (surveillance) to 5 days (recertification every 3 years) with a team of 3 auditors. The audits are focused on the management requirements of the ISO standards and include a combination of document/records review, floor time walk-arounds for observation, and interviews with associates and contractors.

Figure 64. First Solar Reliability Testing

Figure 64. Hyperlink to First Solar reliability video.

III.B.6 - Value of Production Under One Roof

Having the ability to produce CdTe PV modules in a single manufacturing facility, "under one roof" (**Figure 65**) increases the reliability of the production system and helps control variation in product output. First Solar cell efficiency gains achieved in the laboratory have been tested and implemented through the module production process. The core technology gains are discussed further in the performance section **II.A.** The certifications from ISO and IEC are a result of First Solar quality and reliability systems, which includes setting the requirements for supply chain partners, implementing an automated production system, maintaining rigorous quality control measures, and keeping employees safe.

Figure 65. First Solar Manufacturing Facility

Figure 65. First Solar PV module production with all manufacturing stages in one facility (Colville, 2017).

End-to-end production within one facility is unique to thin film PV manufacturing and facilitates quality control through vertical integration of manufacturing processes and use of a single bill of materials. In contrast, crystalline silicon PV manufacturing involves multiple facilities, manufacturing processes, and bills of materials for silicon, ingot, wafer, cell, and module production (Colville, 2017).

C - Operational Life Cycle and Non-Routine Events

Environment, health, and safety considerations are also important once technologies are deployed in the field. Evaluations of field performance are made via testing and modeling, as well as via observations of field experience. Over 80,000 First Solar modules undergo extensive quality and reliability testing annually (First Solar, 2018). In addition, data have been collected for extreme weather events such as hurricanes and tornados, and modules have been tested for non-routine events such as fire and field breakage as discussed below.

Table 7. First Solar PV Plants in the United States

PROJECT	OWNER	LOCATION	STATE	STATUS	O&M	PPA SIZE (MW AC)	OFFTAKER
Sun Streams	First Solar	Maricopa County	AZ	Development		150	SCE
Agua Caliente	NRG Energy & BHE Renewables	Yuma County	AZ	Operation	✓	290	PG&E
American Kings	First Solar	Kings County	CA	Development		123	SCE
Little Bear Solar	First Solar	Fresno County	CA	Development		40	Marin Clean Energy
Windhub	First Solar	Kern County	CA	Development		20	SCE
California Flats	Capital Dynamics	Monterey County	CA	Construction	✓	280	PG&E & Apple
Rosamond	First Solar	Kern County	CA	Construction		150	SCE
Willow Springs	First Solar	Kern County	CA	Construction		100	SCE
AVSR1	Exelon	Los Angeles County	CA	Operation	✓	230	PG&E
Blythe	NRG Energy	Riverside County	CA	Operation	✓	21	SCE
Campo Verde	Southern Power	Imperial County	CA	Operation	✓	139	SDG&E
Cuyama	D.E. Shaw Renewable Investments	Santa Barbara County	CA	Operation	✓	40	PG&E
Desert Sunlight	NextEra Energy Resources, NRG Energy & Sumitomo Corp of America	Riverside County	CA	Operation	✓	550	PG&E and SCE
Kingbird	8point3 Energy Partners	Kern County	CA	Operation	✓	40	Cities of Pasadena, Riverside, Colton and Azusa
Lost Hills Blackwell	Southern Power & 8point3	Kern County	CA	Operation	✓	32	PG&E, City of Roseville
North Star	Southern Power & 8point3	Fresno County	CA	Operation	✓	60	PG&E
Portal Ridge	D.E. Shaw Renewable Investments	Los Angeles County	CA	Operation		32	PG&E and SCE
Rancho Seco	D.E. Shaw Renewable Investments	Sacramento County	CA	Operation	✓	11	SMUD
Solar Gen 2	Southern Power & 8point3	Imperial County	CA	Operation	✓	150	SDG&E
Stateline	Southern Power & 8point3	San Bernardino County	CA	Operation	✓	300	SCE
Topaz Solar Farms	BHE Renewables	San Luis Obispo County	CA	Operation	✓	550	PG&E
Cimarron	Southern Power and Turner Renewable Energy	Colfax County	NM	Operation	✓	30	Tri-State Generation and Transmission Association
Macho Springs	Southern Power	Luna County	NM	Operation	✓	50	El Paso Electric
Sunshine Valley	First Solar	Nye County	NV	Development		100	SCE
Switch Station 1 & 2	EDF Renewable Energy & J.P. Morgan	Clark County	NV	Operation	✓	180	NV Energy
Moapa Southern Paiute	Capital Dynamics	Clark County	NV	Operation	✓	250	LADWP
Silver State South	NextEra Energy Resources	Clark County	NV	Operation		250	SCE
Silver State North	Enbridge	Clark County	NV	Operation	✓	50	NV Energy
Barilla	First Solar	Pecos County	TX	Operation	✓	30	-
East Pecos	Southern Power	Pecos County	TX	Operation	✓	119	Austin Energy

Table 7A. Example southwest U.S. utility-scale solar projects utilizing CdTe PV technology.

Over 10 GW of CdTe PV has been deployed in the U.S., including both projects self-developed by First Solar and by third-party developers. Example projects are shown in **Table 7** and range from 10 to 550 MW AC. First Solar PV systems are designed for ground-mount utility scale projects. This market approach has shaped how the PV modules are installed and maintained. Engineering, Procurement, and Construction (EPC) contractors are used to install the PV systems. First Solar offers to operate and maintain the power system and provide end of life recycling options which are discussed in section **III.D.**

PROJECT	COUNTY	STATE	OWNER	OFFTAKER	FIRST SOLAR SERVICES	SIZE (MW ac)
Perry	Perry	AL	First Solar	-	Modules, Development	80
Russell	Russell	AL	First Solar	-	Modules, Development	80
Big Bend	Hillsborough	FL	TECO	TECO	Modules, O&M	20
Columbia	Columbia	FL	First Solar	-	Modules, Development	75
Payne Creek	Polk	FL	TECO	TECO	Modules, Construction	70
Balm	Hillsborough	FL	TECO	TECO	Modules, Construction	74
Grange Hall	Hillsborough	FL	TECO	TECO	Modules, Construction	61
Peace Creek	Polk	FL	TECO	TECO	Modules, Construction	56
Mountain View	Pasco	FL	TECO	TECO	Modules, Construction	62
Decatur	Decatur	GA	Southern Power	Georgia Power	Modules, Construction, O&M	83
Butler	Taylor	GA	Southern Power	Georgia Power	Modules, Construction, O&M	103
Taylor	Taylor	GA	Southern Power	Georgia Power	Modules, Construction, O&M	147
Twiggs	Twiggs	GA	First Solar	Georgia Power	Modules, Development	200
Elm City	Wilson	NC	Duke Energy	Duke Energy	Modules, Construction	40
Oceana	-	VA	Dominion Energy	Commonwealth of Virginia	Modules, O&M	18
Remington	Fauquier	VA	Dominion Energy	Commonwealth of Virginia	Modules, O&M	18
Waverly	Sussex	VA	First Solar	-	Modules, Development	118

Table 7B. Example southeast U.S. utility-scale solar projects utilizing CdTe PV technology.

III.C.1 - Field Breakage

Broken modules refer to PV modules with cracked glass which may result from extreme weather (e.g. impact fracture from hail) or human factors (e.g., stress fracture from installation damage). Based on warranty return statistics, module breakage is rare, occurring in approximately 1% of modules over the 25-year warranty operating life (0.04%/yr). Over one-third of breakages occur during shipping and installation, resulting in removal for take-back and recycling. For the remainder, routine module inspections and power output monitoring are used to identify modules that are non-functioning potentially due to breakage (Sinha & Wade, 2015). Utility-scale PV systems are sizeable investments that are continuously monitored (see section **III.C.4**).

Figure 66. CdTe PV Field Breakage Fate and Transport Evaluation

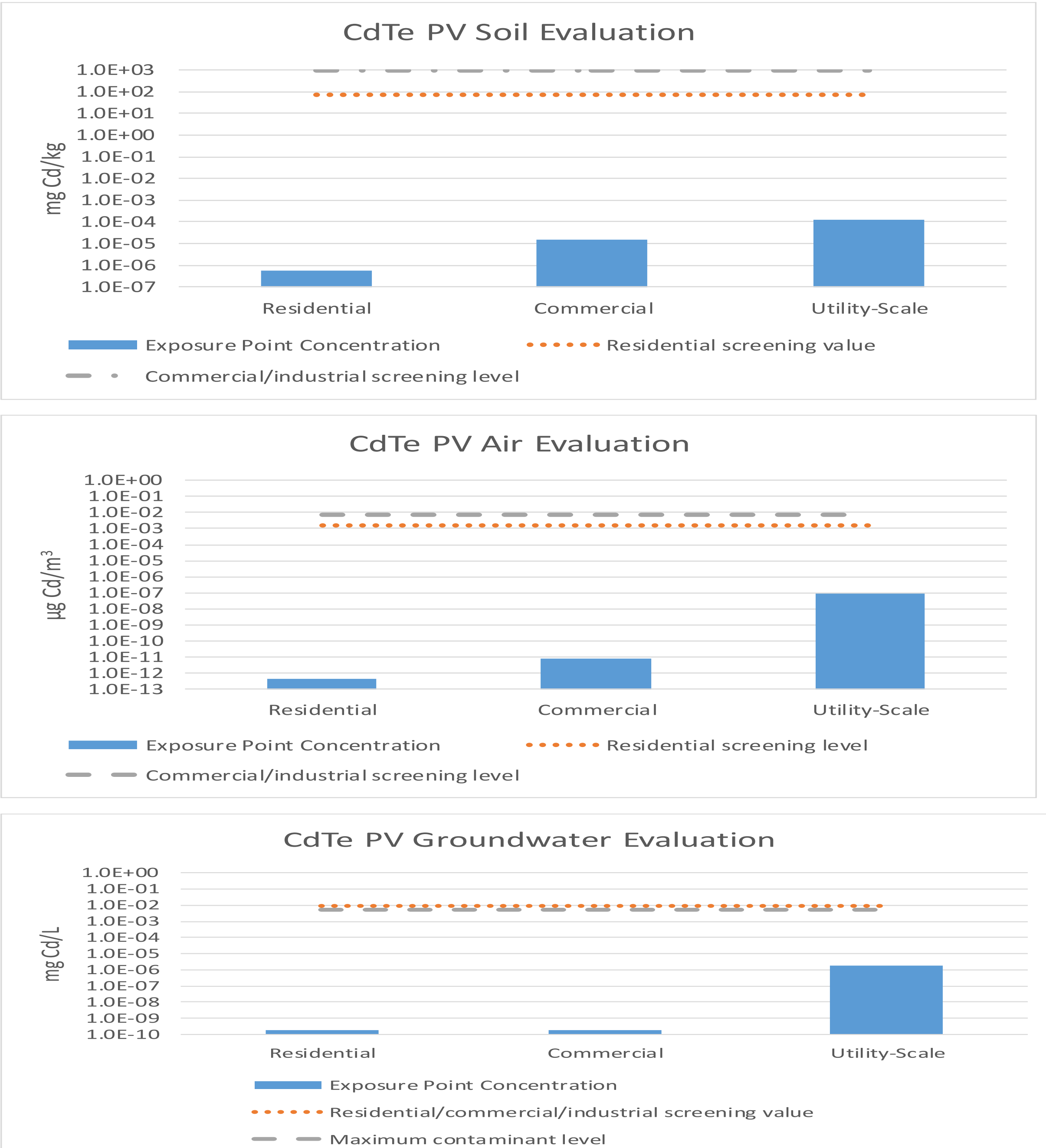


Figure 66. Comparison of Cd exposure point concentrations in soil (top), groundwater (middle) and air (bottom) to USEPA health screening levels for CdTe PV field breakage in residential rooftops, commercial rooftops and ground-mounted utility-scale scenario Exposure point concentrations are shown in blue and health screening levels are shown with dashed lines (IEA, 2019a).

Experimental and modeling analysis indicates that CdTe PV module field breakage does not pose significant environmental or health risks. This conclusion is based on multiple methodologies that have tested and modeled module breakage for the potential release of semiconductor materials:

- Worst-case (total release) modeling (Sinha et al., 2012a)
    - Assuming total semiconductor release in rainwater, potential Cd concentrations are below soil, air, and groundwater health screening levels and background levels using USEPA fate and transport methodology.
- Fate and transport modeling with USEPA Method 1312 Synthetic Precipitation Leaching Procedure (SPLP) test data (IEA, 2019a)
    - Assuming experimental semiconductor release in simulated rainwater (pH 4.2 and 1 cm module pieces), potential soil, air, and groundwater Cd concentrations are below health screening levels using USEPA fate and transport methodology.
- Long-term leaching test with simulated rainwater (CRIEPI, 1999)
    - Assuming experimental semiconductor release in simulated rainwater (40 days of pH 5 rainfall on cracked modules), potential Cd leachate concentrations are below drainage criteria.
- Long-term leaching test with actual rainwater (Steinberger, 1998)
    - Assuming experimental semiconductor release in actual rainwater (1 year of rainfall and 1 cm module pieces), potential Cd leachate concentrations are below health criteria for soil and water.

Some previous non-standard leaching tests have utilized finely ground samples, extended extraction cycles, and/or non-encapsulated modules which can provide data on the total quantity of metals in a sample, but not their availability under realistic field breakage conditions (Sinha & Wade, 2015; Fthenakis et al., 2020). Potential impacts to soil, air, and groundwater quality from CdTe PV module field breakage from IEA (2019) are summarized graphically in **Figure 66** and are well below health screening levels.

III.C.2 - Extreme Weather Events

A study by The University of Tokyo evaluated the potential environmental, health and safety risks of CdTe PV systems in the event of a natural disaster such as an earthquake, tsunami, or large fire (Matsuno, 2013). The study concluded that even in worst case scenarios, the environmental risks from CdTe PV systems impacted by an earthquake, tsunami, or fire would be minimal due to CdTe insolubility in water, limited emissions in case of fire, the robust design of a First Solar module, as well as its low CdTe content.

CdTe PV systems have also demonstrated high resilience to extreme weather in the field. More than 20 facilities using CdTe PV technology in North Carolina withstood Category 4 Hurricane Florence in 2018 without any damage. Another facility using CdTe PV technology in Florida sustained a direct hit from Category 4 Hurricane Michael in 2018 without any damage. A facility using First Solar technology in Puerto Rico withstood Category 5 Hurricane Maria in 2017 with minor damage affecting 0.5% of the PV modules (VCCER, 2019).

The 550-megawatt Desert Sunlight solar facility was struck by a tornado in 2015 (VCCER, 2019). This facility replaced 1.8% or 154,843 of the 8.8 million PV modules, with 135,000 recycled and the remainder disposed of. There were no indications of soil contamination reported to U.S. Bureau of Land Management from this event.

III.C.3 - Fire Tests

Experimental analyses indicate that CdTe PV modules do not pose significant environmental or health risks during fires based on:

- Experimental fire testing (Fthenakis et al., 2005)
- Worst-case (total release) modeling (Beckmann, J; Mennenga, A;, 2011)
- Fate and transport modeling with experimental fire test data (IEA, 2018)

Under the high temperatures of a building fire (800 to 1100˚C), module glass fuses together with Cd diffusing into glass, limiting release with 99.96% retention of Cd (Fthenakis et al, 2005). For ground mount systems, potential Cd emissions are limited by maximum grass fire temperatures (800-1000°C) which are below the melting point of CdTe (1041°C), and short flame residence times (15 seconds) for grass fires (University of Toronto, 2018). Potential impacts to air quality from rooftop and ground mount CdTe PV fires have been found to be below human health screening levels (Figure 67).

Figure 67. CdTe PV Fire Fate and Transport Evaluation

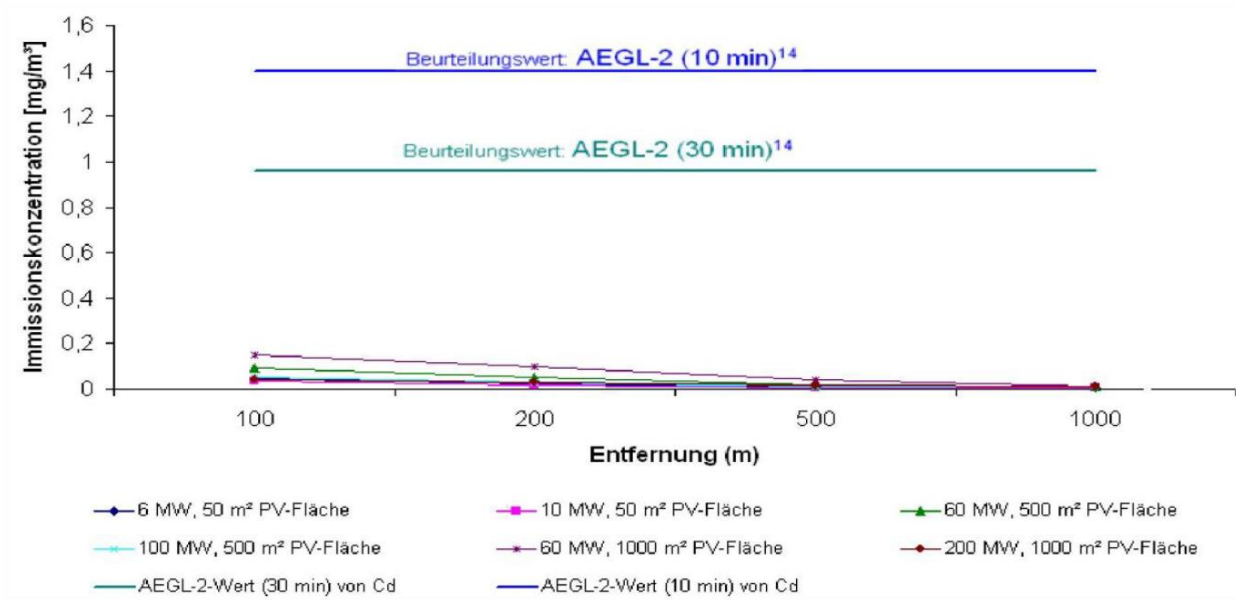


Figure 67A. Maximum ground-level ambient air Cd concentration and acute exposure screening guideline levels (AEGL) for building fires with rooftop CdTe PV. Y-axis shows ground-level Cd emissions concentration (mg/m^3) and x-axis shows downwind distance from fire (m). Acute exposure guideline (AEGL) assessment values for Cd are shown above the emissions concentrations (Beckmann and Mennenga, 2011).

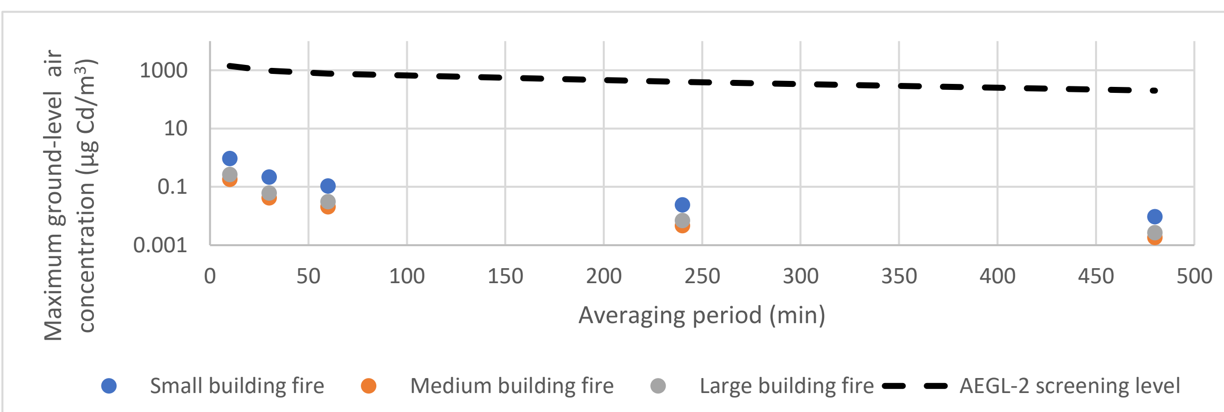


Figure 67B. Maximum ground-level ambient air Cd concentration and acute exposure screening guideline levels (AEGL) for building fires with rooftop CdTe PV (IEA, 2018).

III.C.4 - Operations and Maintenance (O&M)

The field performance and safety of PV systems is improved through proper operation and maintenance (O&M) processes. Utility-scale PV systems are sizeable investments where the reliability and durability of the PV modules and systems over the 25-30 year lifespan are critical factors that are continuously monitored (**Figure 70**). PV plant operation and maintenance (O&M) processes directly impact the return on investment. O&M practices can lead to optimal energy yield, as well as field safety through continuous monitoring of the condition of the field, whereas lack of O&M can lead to cascading power failures with fiscal losses. In the solar industry, O&M sector growth is tied to recent scaling of large-scale PV deployment. O&M companies use the energy availability metric to quantify the value of their services.

O&M best practices can help PV installations produce higher yields. The energy yield of a PV solar plant is affected by a large set of factors. Weather patterns, the time of day, and seasonal variability, are a few factors affecting the energy availability metric (Hunt et al., 2015). PV solar plants have different options in maximizing the value of solar energy, with storage of solar energy discussed later in section **V.B.**

The plant operator managing the O&M of a PV plant controls the power generation output. This output is predicted in advance and measured in real-time to ensure the PV plant is performing at optimal capacity. Software is integral in monitoring the status of the PV system and components in real-time. Plant operators use different software such as PVGuard, PVSyst, and PlantPredict to estimate plant performance and effective availability. The accuracy of the software depends on the input factors; some do not control for system interruptions such as inverter failure, forced outages, and outages outside of management control. Plant operators must account for the nuances unique to solar plants, such as partial plant downtimes where one inverter may be offline while the rest operate normally (Hunt et al., 2015).

As an O&M provider, First Solar has a central PV plant management for operations and on-site technicians for maintenance. In 2015, 5 Gigawatts of PV plants were managed by First Solar making them the largest O&M management company in the world (**Figure 69)** (GTM Research , 2015). In 2019, First Solar O&M increased to 10 Gigawatts under management, with high average availability (>99%) (2019). 10 Gigawatts of modules requires First Solar to manage over 70 square miles of area (**Figure 68**).

Figure 68. 1 MW Block of CdTe PV

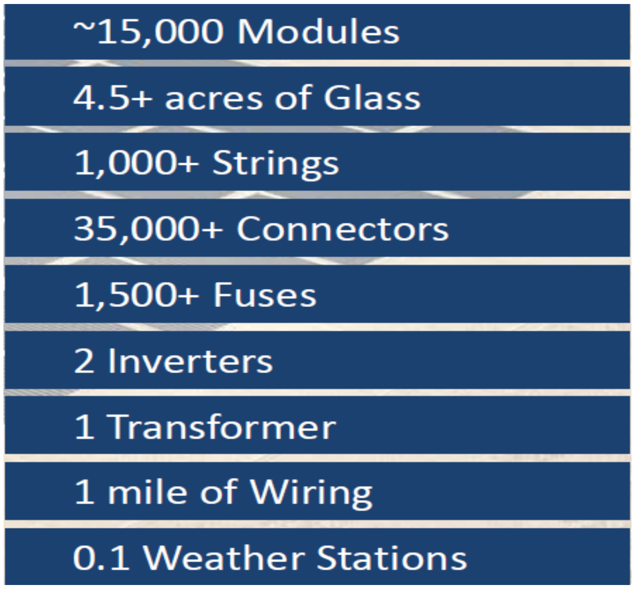


Figure 68. Components needed for 1 Megawatt block of First Solar PV.

A part of First Solar's Quality and Reliability Mission includes PV plant monitoring through measuring PV plant performance against predictions. First Solar captures PV system performance data through the plants it manages and through PV plant surveys. This ongoing validation of First Solar PV module performance is in addition to data from the 40+ First Solar field test sites. First Solar energy predictions were within ±5% of actual plant energy yield (Ghiotto et al., 2016).

On-site technicians address issues at the plant, including all types of outages, and perform proactive services to reduce potential downtime and component failure. Technicians inspect modules and manage the grounds around the modules. In response to plant equipment failures, critical system components are procured to provide the most cost-effective options to reduce PV plant downtime.

Figure 69. First Solar O&M Locations 2014

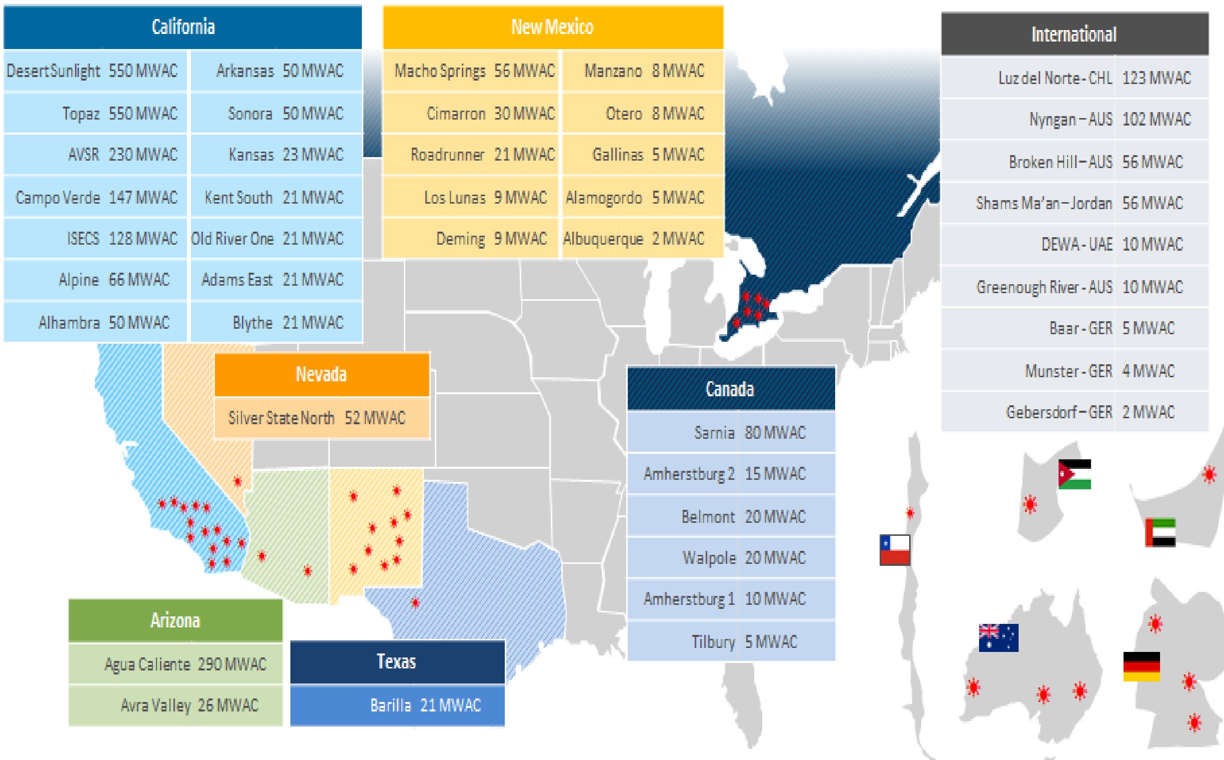


Figure 69. First Solar is the Operation and Maintenance service provider for many solar plants. This figure depicts First Solar's 2014 portfolio which has substantially grown to 10 GW in 2019.

Figure 70. First Solar O&M Facility

Figure 70. First Solar operations center for monitoring utility-scale PV plants.

D - PV End of Life

PV systems can become a noticeable contributor to global waste volumes if there are no recycling plans in place when the PV system reaches its end of life (IRENA & IEA, 2016). Recycling is expected to be a dominant strategy for sustainable end-of-life management. In the case of disposal, the use of sanitary landfills which include engineering controls for regulated solid waste disposal, such as daily cover, stormwater management, landfill liner, leachate collection, and groundwater monitoring, limit potential for emissions.

Figure 71. Landfill Evaluation

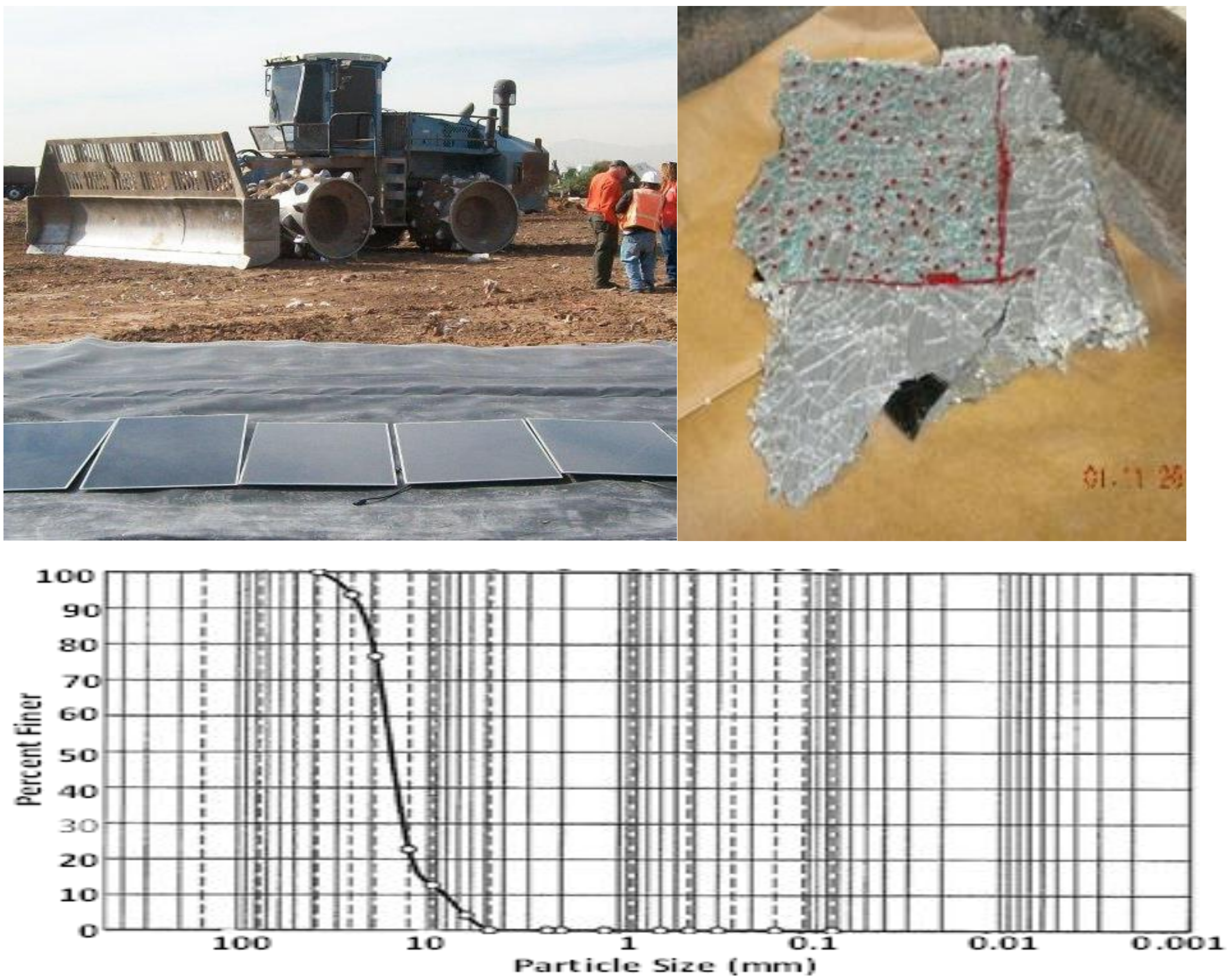


Figure 71. Landfill compactor used to crush PV modules in a municipal landfill in Arizona (top left) and compactor foot punch out (top right) and PV module fragment size distribution (bottom) (Sinha et al., 2014).

In the case of potential disposal in non-sanitary landfills, the U.S. EPA Delisting Risk Assessment Software (DRAS) model has been used to evaluate potential risks associated with the disposal of utility-scale volumes of CdTe PV modules in an unlined landfill using Toxicity Characteristic Leachate Procedure (TCLP) data for waste characterization (Cyrs et al., 2014; Sinha et al., 2014; IEA, 2020a). The results indicated that modeled Cd exposure from CdTe PV module disposal in an unlined landfill is below health screening levels and therefore unlikely to cause adverse impacts to human health or the environment.

Real-world crushing of CdTe PV modules was also conducted using a landfill compactor to evaluate the representativeness of the TCLP leachate data used in the DRAS modeling and the condition of PV modules after crushing (Figure 71). On average, approximately three-quarters of the crushed module fragments were larger than 1 cm (which is the sample size in TCLP testing), and the glass-glass encapsulation of the PV module fragments was maintained (Sinha et al., 2014). The low likelihood of potential impacts can be further limited by use of sanitary landfills or high-value recycling, with the latter providing economic and environmental benefits of resource recovery.

III.D.1 - Recycling and Decommissioning

First Solar has built recycling facilities to recover material from PV modules at end-of-life and from manufacturing scrap in the production facility. First Solar recycling facilities in the U.S., Malaysia, and Vietnam have the same certifications for environmental management (ISO 14001) and occupational health and safety (ISO 45001) as the manufacturing facilities with which they are co-located. In Germany, First Solar's recycling facility is as an authorized treatment facility under the EU WEEE directive, with associated requirements for environmental management and occupational health and safety.

Global PV waste volumes are expected to increase by orders of magnitude over the next decades (IRENA & IEA, 2016). As with other commercial PV modules, CdTe PV modules are composed primarily of glass, aluminum, and copper by weight. Whereas most recyclers only recover these bulk materials, the modules processed at First Solar's high-value recycling centers recover the bulk materials and the semiconductor material with over 90% yield (Fthenakis et al., 2017). Since First Solar focuses on utility-scale systems, each project has decommissioning plans developed for the systems which include specifications on dismantling, disposal and recycling, and site restoration. Because of the large quantities of metals (steel, aluminum, copper) associated with utility-scale PV systems, decommissioning these systems has the potential to be cost-neutral when scrap value is included in net decommissioning costs (Fthenakis et al., 2017; Sinha et al., 2017).

First Solar historically provided prefunded recycling services where recycling costs were forecasted and part of the module sale price. In 2013, First Solar transitioned to pay-as-you-go recycling services where recycling services are contracted when waste is generated through a recycling service agreement to reflect actual instead of forecasted recycling costs. Actual recycling costs have decreased approximately five-fold since 2007 through the development of three successive versions of recycling technology (Raju, 2013).

III.D.2 - Recycling Process

The recycling process has three main parts: pretreatment, delamination, and recovery. During the pretreatment phase, the aluminum frame and junction box with cables are removed (Fthenakis, 2004). The delamination phase uses mechanical crushing steps with a shredder and a hammermill. The final step is where the glass and semiconductor material are both recovered using hydrogen peroxide and sulfuric acid leaching solution (**Figure 72**). During this process, the semiconductor is leached and precipitated, with unrefined semiconductor material containing Cd and Te sent to a third-party supplier for refining and compounding back to semiconductor-grade CdTe. An estimated 90% of the semiconductor and glass is recovered in First Solar's recycling facility (Raju, 2013). The remaining 10% consists largely of glass fines which are too small to recycle and some encapsulant material which has not been completely separated from glass.

Figure 72. Recycling Process

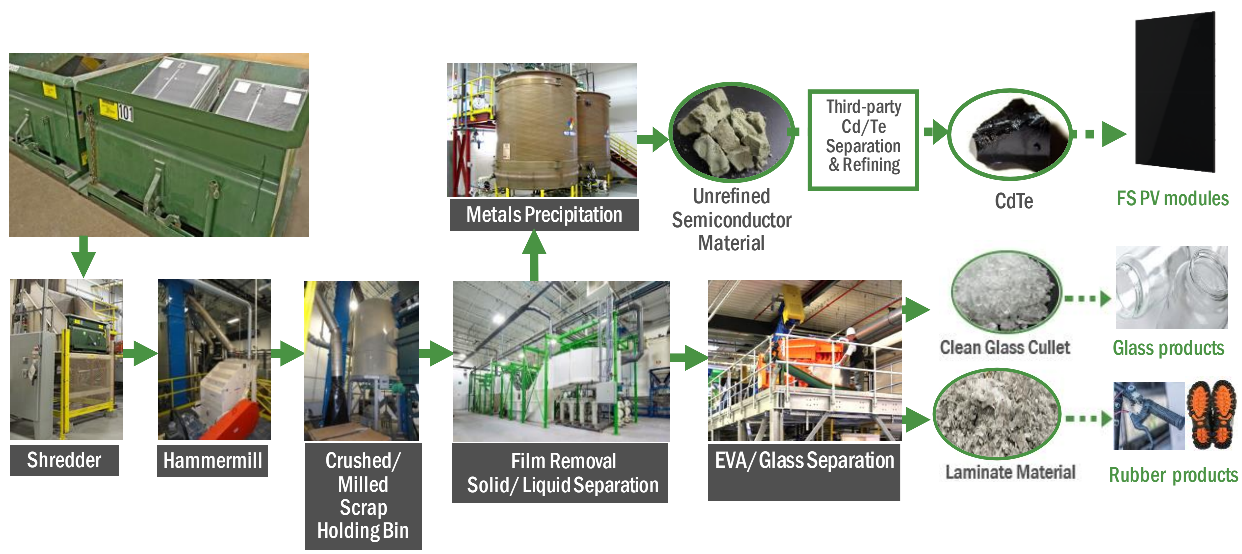


Figure 72. First Solar's recycling process flow (Version 3) (2019).

III.D.3 - First Solar Recycling Capacity

Currently, First Solar's recycling facilities range in capacity from 30 to 150 metric tons per day (Sinha et al., 2017). These facilities are found in Germany, Vietnam, Malaysia, and the U.S. The Perrysburg, Ohio U.S. facility has the capacity to process 150 metric tons with zero wastewater discharge (First Solar, 2019d). The U.S. recycling facility is continuously operating (24 hours a day and 7 days a week). In 2018, First Solar recycled about 21,000 metric tons of PV modules, including about 5,000 metric tons in the U.S. facility, the majority of which was manufacturing scrap. The recycled material figures will continue to increase as more modules reach their end-of-life. For perspective, IRENA and IEA have forecasted cumulative global PV module waste of about 1.7 million metric tons through 2030 under their regular-loss scenario (IRENA & IEA, 2016). With current recycling throughput of about 20,000-30,000 metric tons per year, First Solar recycling facilities could process the equivalent of 10-20% of global PV module waste from 2020-2030. If all four First Solar recycling facilities were operating Version 3 recycling (150 metric tons per day each), annual recycling throughput could be increased substantially to over 200,000 metric tons per year.

When considering manufacturing waste other than PV modules, First Solar recycled 15,740 metric tons and disposed of 7,250 metric tons in 2018 (First Solar, 2019). The 2018 recycled amounts include both hazardous and non-hazardous materials as set forth in U.S. Resource Conservation and Recovery Act, the Malaysian Environmental Quality Schedule Wastes regulations, the Vietnamese Law No. 55/2014/QH13 on Environmental Protection, and European Union Waste Electrical & Electronic Equipment directive (First Solar, 2019d; Sinha et al., 2017). As shown in **Figure 73**, 68-85% of total manufacturing waste was recycled from 2015-2018.

Figure 73. Manufacturing Waste Recycling and Disposal Breakdown 2015-2018

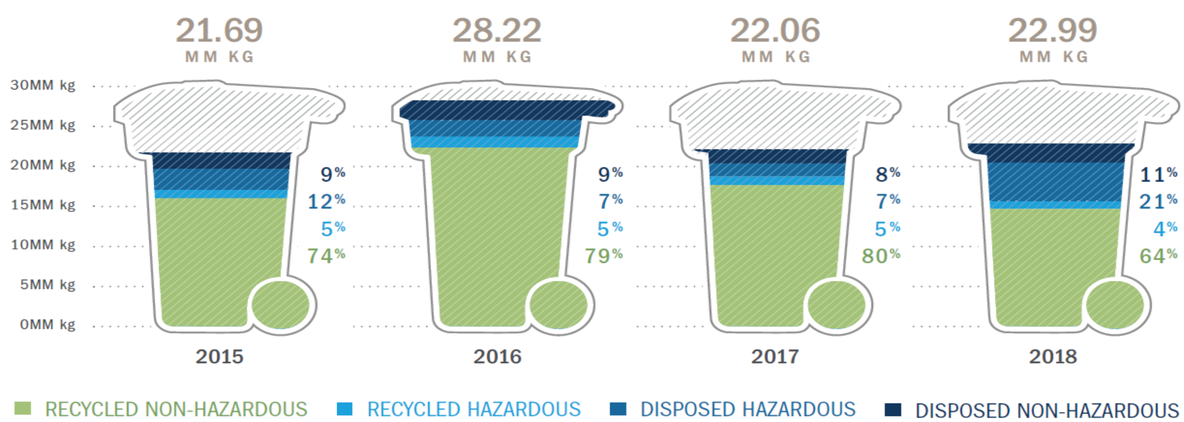


Figure 73. Waste percentages of recycled and disposed material for manufacturing waste other than PV modules at First Solar production facilities (First Solar, 2019d).

III.D.4 - Future of PV Recycling

The initial challenge of creating a commercial-scale recycling technology was addressed over a decade ago when First Solar established the PV industry's first global recycling program. Future challenges include addressing the collection cost of transporting the modules to a recycling facility. This requires setting up either mobile recycling operations or devising cost-effective transportation schemes for the modules. Along with the recyclers, PV system owners and policymakers will play an integral role in addressing the following key challenges for end-of-life management of PV modules (Sinha et al., 2017).

- Predictable waste volumes
- Collection logistics
- Off-takers for the recycling products.

IV - COMPARISON OF PV ENVIRONMENTAL IMPACTS

A - Overall Life Cycle Environmental Comparisons

The primary benefit of PV electricity is its superior environmental performance compared to conventional power plants. Across a wide range of indicators, PV technologies generally have lower environmental impacts than other energy technologies, both overall and on a basis of per unit energy generated. Among PV technologies, CdTe thin-film PV has a particularly good environmental performance.

Conventional U.S. electricity grid generation systems are predominantly powered by combustion-based or thermal power plants using coal, natural gas, and oil fuel that are alternatively labeled as carbon-based fuels or fossil fuels. Based on life cycle advantages relative to conventional grid power generation sources, Fthenakis et al. found that replacing grid electricity with ground-mount CdTe PV systems in the U.S. can result in 89–98% reductions of GHG emissions, criteria pollutants, heavy metals, and radioactive species (2008). These include reductions in life cycle emissions of Cd, which is routinely emitted during coal electricity generation and oil combustion (Figure 74).

Figure 74. Cd Emissions of Different Power Generation Systems

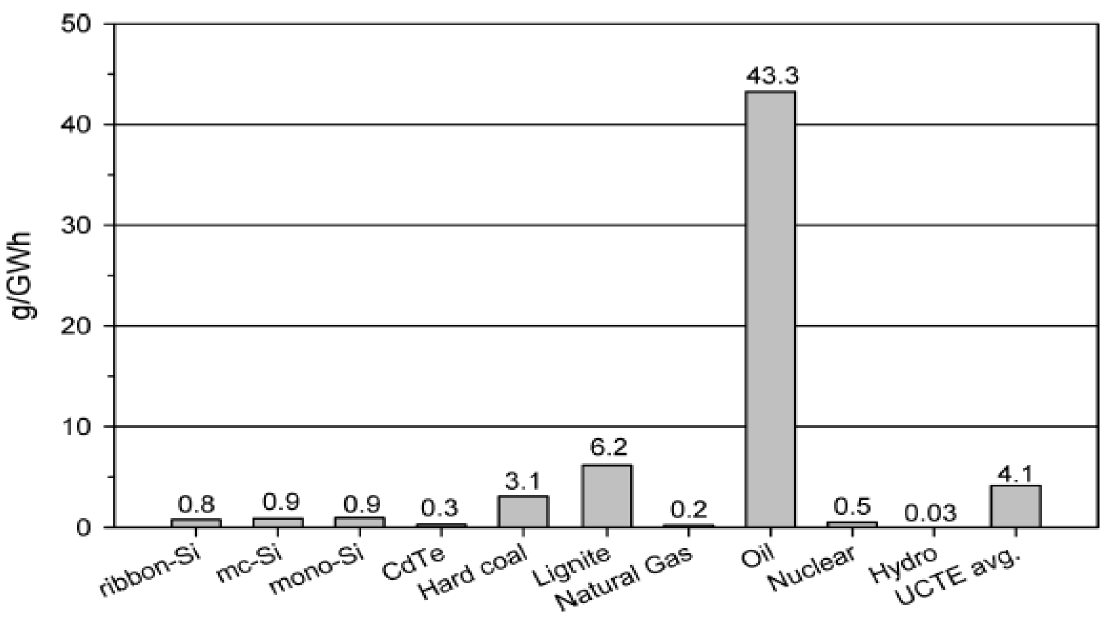


Figure 74. Life cycle Cd emissions per Gigawatt-hour Produced (Fthenakis et al., 2008).

A primary difference between PV systems and conventional generation is that PV systems have no emissions during operation. Combustion of fossil fuel for conventional generation have large use-phase emissions which are bound to increase as electricity demand increases. For example, use-phase emissions from energy consumption at conventional power plants and combined-heat-and-power plants in the U.S. amounted to approximately 2 billion metric tons of CO_2-equivalent (eq) per year over the period 2008-2018 (EIA, 2020b). PV and other zero emission systems on average displace about 950 lb $CO_{2,eq}$/MWh (430 kg $CO_{2,eq}$/MWh) for each MWh generated for the U.S. grid (EPA, 2020).

In addition to greenhouse gas emissions, U.S. grid electricity generation also emits on average about 0.3 kg/MWh each of the air pollutants sulfur dioxide (SO_2) and nitrogen oxides (NO_x) (EPA, 2020). PV systems do not create these air pollutants while producing the same electricity for the U.S. grid. Avoidance of grid electricity greenhouse gas and air pollutant emissions with use of PV electricity amounts to environmental and public health benefits of $20/MWh and $14/MWh, respectively (Wiser et al., 2016).

Solar energy and PV technologies also have additional environmental advantages, beyond reductions in air pollution and greenhouse gas emissions. J. Bergesen et al. (2014) carried out a hybrid life-cycle assessment for two thin-film PV technologies: CdTe and CIGS. A scenario using 2010 inputs is considered alongside a hypothetical future scenario for the year 2030 using technology roadmaps from NREL. The authors define 12 impact categories related to the manufacturing process that are related to environmental, human health, and natural resource impacts of energy generation. The factors include the usage of various metals, water depletion and land occupation. Impact factors are compared to a baseline of fossil fuels (marking 100%). The results are summarized in **Figure 75**, which shows the environmental and resource impacts of ground-mounted CdTe PV systems from 2010 and 2030 normalized to those of the 2010 U.S. electricity grid mix, based on U.S. EPA TRACI 1.0 and ReCiPe 2008 life cycle impact assessment methods (Bergesen et al., 2014).

Using 2010 data, the authors find that thin-film PV technologies perform at least 90% better than traditional fossil fuel generation in seven of the 12 categories, at least 50% better in three categories, and comparable or worse in the final two categories of land occupation and metal depletion (Bergesen et al., 2014). Land occupation is found to be similar for the PV technologies and fossil fuels, and metal depletion is significantly higher.

Fthenakis et al. (2008) found that replacing grid electricity with ground-mount CdTe PV systems in the U.S. can result in 89–98% reductions of GHG emissions, criteria pollutants, heavy metals, and radioactive species.

Figure 75. Life Cycle Environmental Impacts of CdTe and CIGS PV Modules

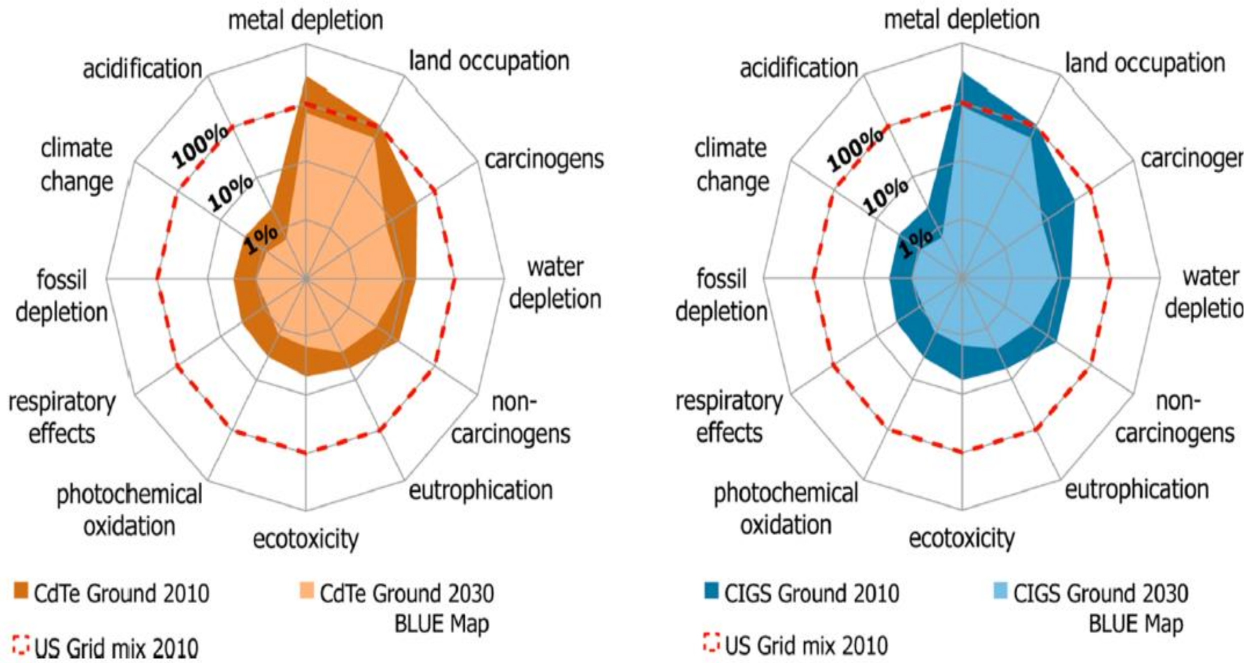


Figure 75. Impact of various resource- and environmental factors of ground-mounted thin-film PV technologies, considering 2010 state of the art and a hypothetical 2030 scenario according to the NREL roadmap. 2030 results include recycling of aluminum, copper, and steel in the balance of the system. Note that the image is applying a logarithmic scale (Bergesen et al., 2014).

The advantages of PV technologies further increase in the 2030 scenario, where increasing conversion efficiency provides significant improvements. Module dematerialization and background changes are also found to provide improvements, although these are smaller. The authors recommend development of strategies to recycle balance of system components and power electronics as metal depletion is closely linked to their production and use in the transformers, inverters, and wiring needed to deliver PV power to the grid. Copper is especially significant. These strategies are implemented in the 2030 scenario and decrease metal depletion below that of fossil fuels. As carcinogenic emissions are also linked to metal production, this strategy also further reduces this factor.

The life cycle health and ecological impacts of energy generation technologies have also been compared by the United Nations Environment Program (UNEP) (Figures 76-77). The results confirm the global environmental and health benefits of low-carbon technologies such as PV, wind, hydro, and geothermal. Within PV systems, thin-film PV systems (CdTe and CIGS) have lower life cycle health and ecological impacts than silicon PV systems due to the relatively low energy and material requirements of thin film PV manufacturing.

Figure 76. Life Cycle Human Health Impacts of Different Power Generation Systems

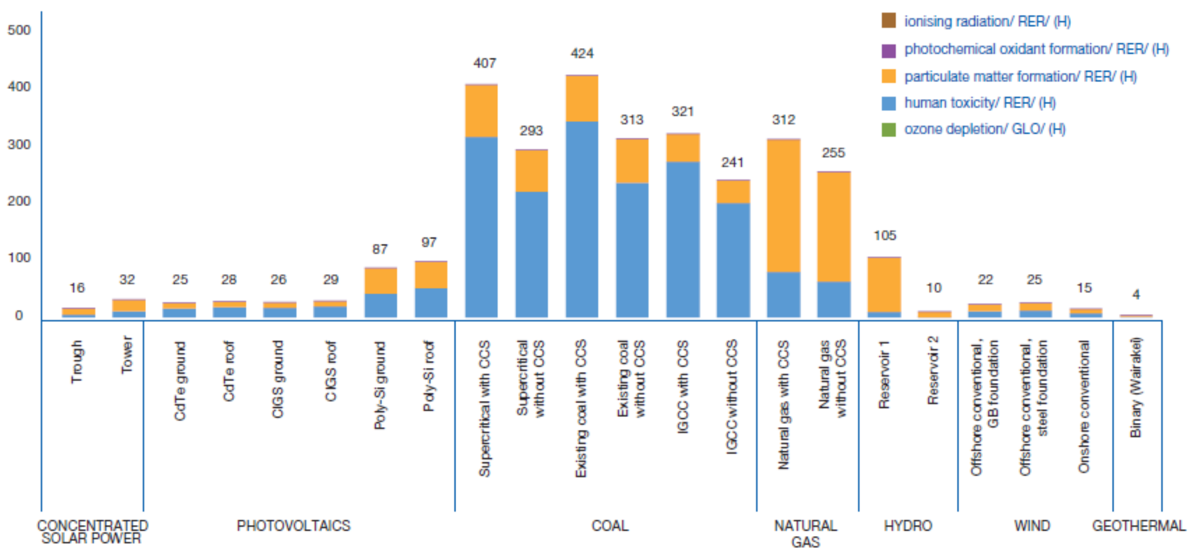


Figure. 76. Life cycle human health impacts of different power generation technologies (in disability adjusted life years per 1 TWh of electricity generated) (UNEP, 2016).

Specifically, life cycle impact categories such as human toxicity, particulate matter, ionizing radiation, and photochemical oxidant formation address potential human health impacts of technologies (**Figure 76**) while ecotoxicity, acidification, and eutrophication address potential ecological impacts (**Figure 77**). The major contributors to life cycle environmental impacts during CdTe PV module manufacturing are use of grid electricity, and the bulk raw materials that account for most of the PV module mass (glass and aluminum) (Stolz et al., 2016). The CdTe semiconductor is sourced as a mining byproduct, with most of the mining impacts allocated to the primary mining products (zinc and copper) (Fthenakis, 2004).

Construction of PV systems is also an important contributor to life cycle impacts, because of the use of large quantities of metals for structural support (steel and aluminum), wiring (copper), and power conversion (inverters and transformers) (Stolz et al., 2016). The use phase is the longest life cycle stage for PV systems, with typical operating lifetimes of 25-30 years. PV systems have zero emissions during routine operation, and operations and maintenance procedures are used to assure high system availability and energy yield. Potential impacts from non-routine events during operation have been discussed in section **III.C.** Recycling is expected to be a dominant strategy for sustainable end-of-life management of PV systems and is commercially available as discussed in section **III.D.** While recycling requires use of materials and energy, the products of recycling (e.g., glass, aluminum, copper, plastics, semiconductor material) can displace primary production of those materials, resulting in net environmental benefits from recycling (Stolz et al., 2018).

Figure 77. Life Cycle Ecosystem Impacts of Different Power Generation Systems

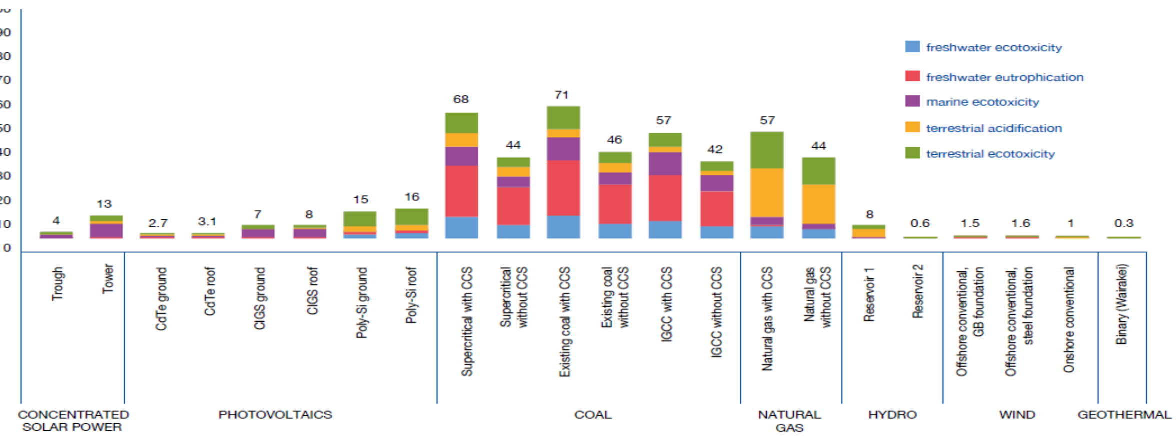


Figure 77. Life cycle ecosystem impacts of different power generation technologies (in species-year affected per 1000 TWh of electricity) (UNEP, 2016).

The standardization of life cycle inventories and methodology guidelines for life cycle assessment of PV has enabled the development of the International Energy Agency (IEA) (2020) global screening tool for assessing the life cycle impacts of PV systems (ENVI-PV): http://viewer.webservice-energy.org/project_iea/. This web service allows a user to input different current and future scenarios to see a comprehensive set of life cycle environmental impact indicators for thin film and silicon commercial PV technologies with both residential and large-scale system sizes. Consistent with the comparative life cycle assessment studies discussed above, CdTe PV systems have the lowest environmental impact among currently available commercial PV technologies (Figure. 78).

Figure 78. Life Cycle Environmental Comparison of PV Technologies

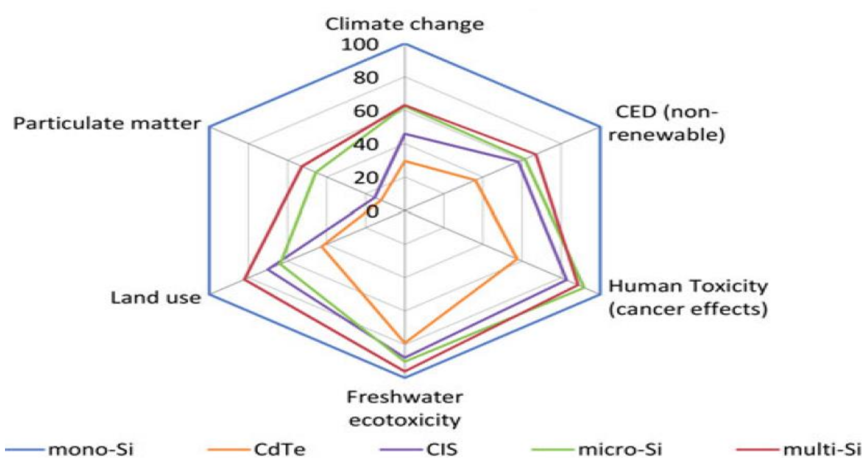


Figure 78. Comparative evaluation of the environmental performance of 3-kW residential PV systems based on ILCD Midpoint+ method with the ENVI-PV LCA screening (Pérez-López et al., 2017).

Collectively, these assessments demonstrate the high overall environmental performance of CdTe PV technologies, across their entire lifecycle, both with respect to other PV technologies and, especially, with respect to fossil fuel generated electricity. Overall, the environmental impacts of conventional, thermal power plants using carbon-based or fossil fuels dwarf those of renewable energy technologies. In most categories, the reduction in environmental impact from using PV technologies is between one and two orders of magnitude. The environmental impacts of renewable power sources primarily stem from its material uses, manufacturing processes, and land use. Renewable technologies are found to have zero or negligible emissions during the operational phase.

When comparing different PV technologies, thin-film solar modules tend to perform better than crystalline silicon technology. This is due to the less energy, and material intensive fabrication process of thin-film technology, but also depends on the energy mix used to fabricate the solar cells. In **Figure 79**, carbon footprint, water footprint, and air pollution are compared for conventional, thermal electricity generators and different PV technologies (First Solar, 2018). The graph shows the great potential of PV technology, and especially CdTe PV to transfer to a more sustainable electricity generation.

Figure 79. Life Cycle Environmental Footprint of Different Power Generation Systems

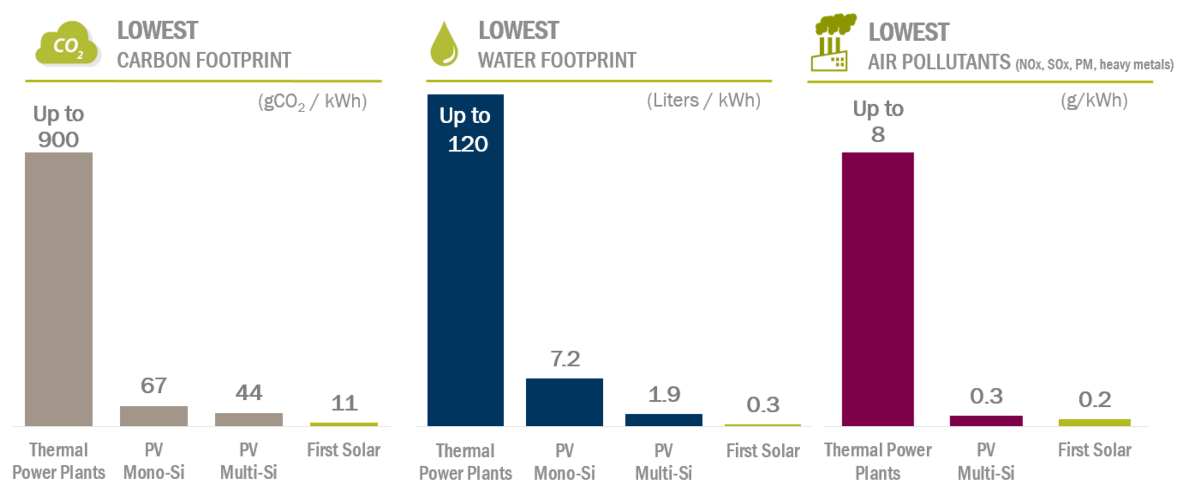


Figure 79. Comparison of carbon footprint, water footprint and air pollution of conventional thermal power plants and various PV technologies according to First Solar (First Solar, 2018).

First Solar achieves the small environmental footprint by using a fully integrated and resource-efficient PV module fabrication process in countries that provide electricity by sources with a moderate carbon intensity. The energy payback time that First Solar states is as low as six months under high irradiation conditions. In this way, PV power plants with First Solar modules generate 50 times as much electricity as is required for their construction over a 25-year time period.

As we describe below, ongoing and systematic environmental assessment can help the solar industry further reduce its already small long-term environmental impacts. For example, the management of disposal and end-of-life of PV systems will significantly impact overall environmental impact, and recycling practices can help reduce the already small environmental impacts. First Solar is able to recycle their CdTe modules with 90% efficiency. The recouped semiconductor material is reincorporated into new more efficient CdTe solar modules, reducing energy use, energy-related emissions, and materials consumption. The recouped glass is reincorporated into new glass products. Further PV technology innovation, especially, as described earlier in this report, with regard to future improvements in module efficiency, will also further reduce the environmental impacts of PV energy generation by reducing the use of materials and land per unit of energy generated.

B - Carbon footprint

The primary driver of solar energy's rapid growth in the past two decades stem principally from its ability to combat climate change. Studies about carbon footprint or global warming impact show a drastic advantage of PV technologies over conventional, thermal power plants using carbon-based fuels. Among PV technologies, CdTe consistently appears as the established technology with the lowest carbon footprint. In several studies, this advantage of CdTe is confirmed, and is also shown to hold over different locations.

Louwen et al. (2017) calculated the greenhouse gas emission of various PV technologies based on operating conditions in Africa, the Middle East and Europe (**Figure 80**) in units of $gCO_{2,eq}$/kWh. This quantity is affected by the amount of greenhouse gases emitted as a result of fabrication and the energy yield of the PV installations. The study states that all module technologies achieve emissions that are around or below 50 $gCO_{2,eq}$/kWh. This value is much lower than that of conventional electricity generation based on carbon-based fuels, for which the GHG emissions range from roughly 400 to over 1000$gCO_{2,eq}$/kWh, depending on fuel type. For CdTe PV modules, emission factors are as low as 15 $gCO_{2,eq}$/kWh, while the highest values of up to 120 $gCO_{2,eq}$/kWh are found for mono-Si PV modules in areas with low insolation. Overall, CdTe PV modules were found to be less than 30 $gCO_{2,eq}$/kWh for all areas assessed.

When comparing different PV technologies, thin-film solar modules (CdTe modules) tend to perform better than crystalline silicon technology. This is due to the less energy, and material intensive fabrication process of thin-film technology, but also depends on the energy mix used to fabricate the solar cells.

Figure 80. PV GHG Emissions in Different Regions

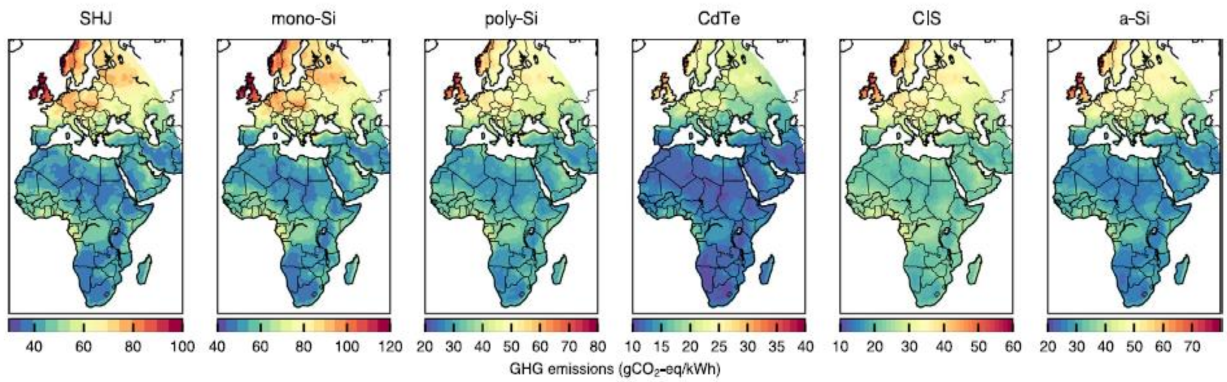


Figure 80. Greenhouse gas (GHG) emissions of various photovoltaic technologies according to Louwen et al. (2017).

Peng et al. (2013) performed a review of greenhouse gas emission and energy payback time of different PV technologies. The study from 2013 features CdTe PV modules with efficiencies between 6% and 11%, with data taken mainly from studies published between 1998 and 2011 (Fthenakis et al., 2005; Jungbluth et al. , 2007; Alsema et al., 2006; Raugei, M;, 2007; Kato et al., 2001; Wild-Scholten, 2009; Alsema, 1998; Ito et al., 2010; Fthenakis et al., 2009). Despite the comparably low efficiency of CdTe PV modules at this point in time, the greenhouse gas emissions for this technology were already found to be smaller on average than for other PV technologies, including two other thin-film technologies CIS and a-Si. Results are summarized in **Figure 81**.

Figure 81. PV GHG Emission Rate

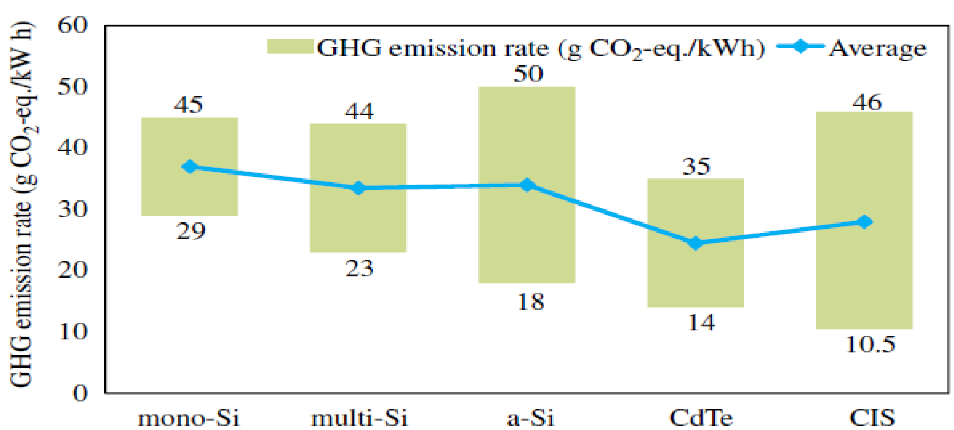


Figure 81. An overview of greenhouse gas emission rates from various PV technologies. Data was assembled from a number of literature studies (Peng et al., 2013).

The superior performance of CdTe was attributed to the lower life cycle energy demand when comparing crystalline silicon efficiencies to the recent progress in CdTe conversion efficiencies

A study by Leccisi et al. (2016) took a detailed approach to environmental impact factors of different PV technologies, considering detailed conditions at the location where the PV modules are manufactured, and including a breakdown of the different components of a PV system. The results for carbon footprint are summarized in **Figure 82**.

Figure 82. PV Production GHG Emissions

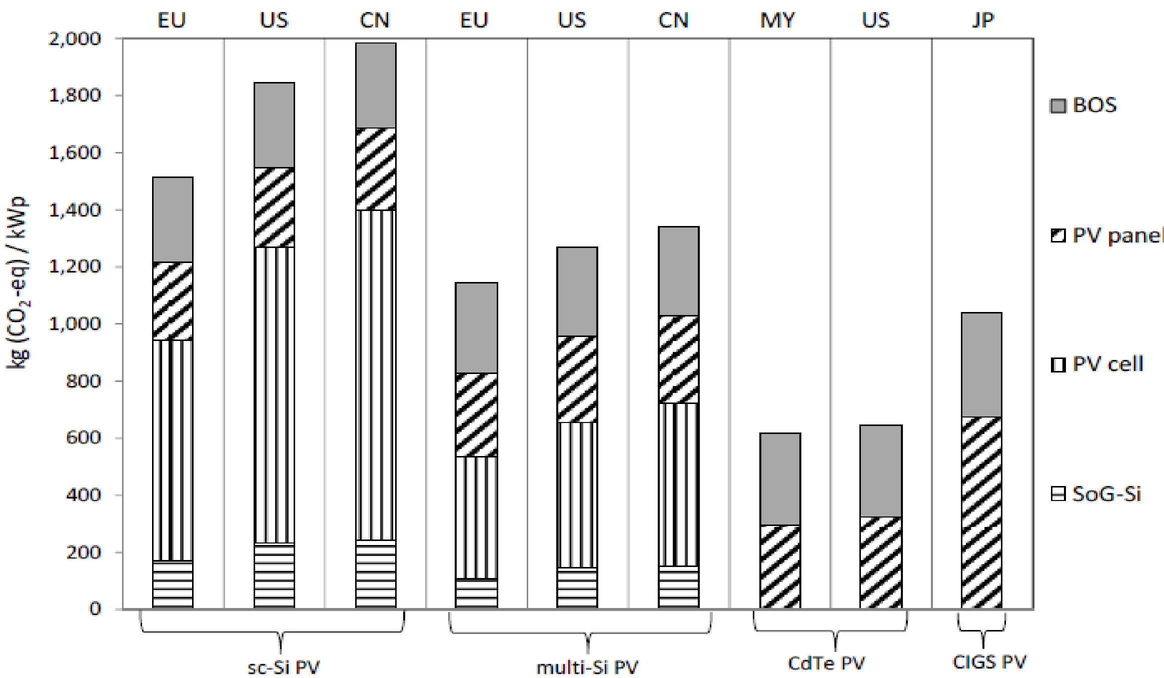


Figure 82. CO2 emissions associated with the production of various photovoltaic technologies for different regions and broken down into different system components (Leccisi et al., 2016).

The Leccisi et al. (2016) study confirms previous findings with the carbon footprint of CdTe PV being the lowest of all PV technologies and more than a factor of two below that of silicon. The study also confirms the advantage of producing in a location with a grid that features less carbon intensive electricity (EU, U.S., Malaysia) compared to a very carbon intensive one (China). The study particularly emphasizes the superior performance of CdTe PV technologies with the authors stating:

> *The most remarkable achievements have been obtained by CdTe PV, which can boast a two-thirds reduction in environmental impacts over the decade since its introduction to the market.*

Similar results are also shown in the 2018 Sustainability Report of First Solar. The company here states that the carbon footprint of its power plants is as low as 11g $CO_{2,eq}$/kWh based on updated

PV module efficiencies, compared to values as low as 14g $CO_{2,eq}$/kWh in Peng at al. (2013) with state-of-the-art about 10 years prior (**Figure 81 & 83**).

Figure 83. PV Carbon Footprint and Energy Payback

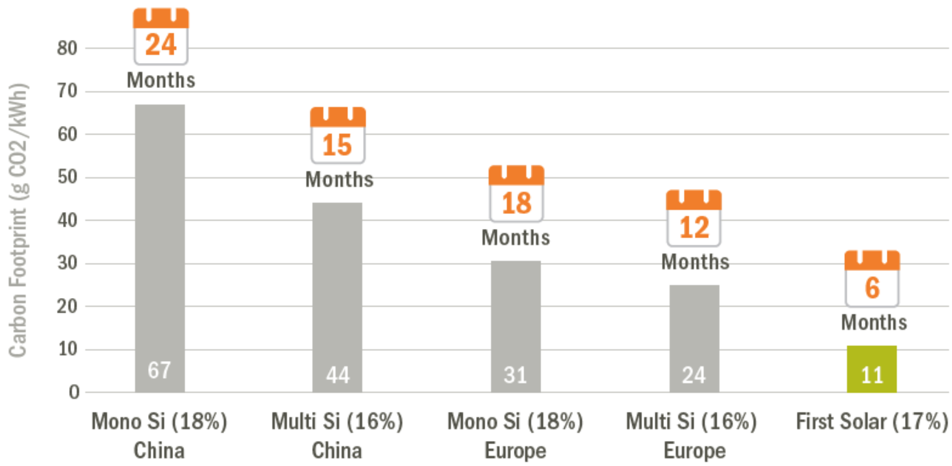


Figure 83. Carbon footprint and energy payback time of different PV technologies in different regions (First Solar, 2018).

The results from **Figure 83** illustrate an important feature of PV technologies, namely that there are still significant opportunities to further reduce their already low environmental impact. Three in particular are worth discussion with regard to GHG emissions. First, improving the efficiency of PV modules will, all else being equal, increase the amount of energy generated by each module (total kWh) and thus reduce the GHG emissions on a per kWh basis. Second, reducing the carbon intensity of the energy used in PV manufacturing and in the production of materials used in PV manufacturing (e.g., by increasing the percentage of renewables integrated into the electricity grid) will reduce GHG emissions, as this energy input is the greatest current source of GHG emissions.

Finally, recycling PV systems can also reduce life cycle GHG emissions of PV. Held investigated the impact of recycling on the global warming potential of CdTe PV modules (Held, 2009). A life cycle assessment is performed according to recycling procedures that were already commercially implemented. The study includes recycling and energy recovery of materials as well as further treatment and disposal of solid and liquid wastes. The study concludes that recycling would contribute to a significant net reduction of the environmental profile in both primary energy demand and greenhouse gas impact of end-of-life of CdTe PV modules.

The main contributors to the considered environmental impact categories are identified as chemicals, amongst which hydrogen peroxide is the most significant, and primary energy required in the fabrication of CdTe PV modules. Recycling of outgoing valuable material would significantly reduce the overall environmental impact of CdTe PV modules. In the analysis presented in the study, primary energy demand for the end-of-life phase of PV modules was reduced by approx. 13% relative from

93MJ/m² to 81MJ/m² and global warming potential for PV modules by approx. 30% from 8.5kg $CO_{2,eq}$ to 6.0kg $CO_{2,eq}$ per m². Results are shown in **Figure 84**.

Figure 84. Recycling GHG Net Benefits

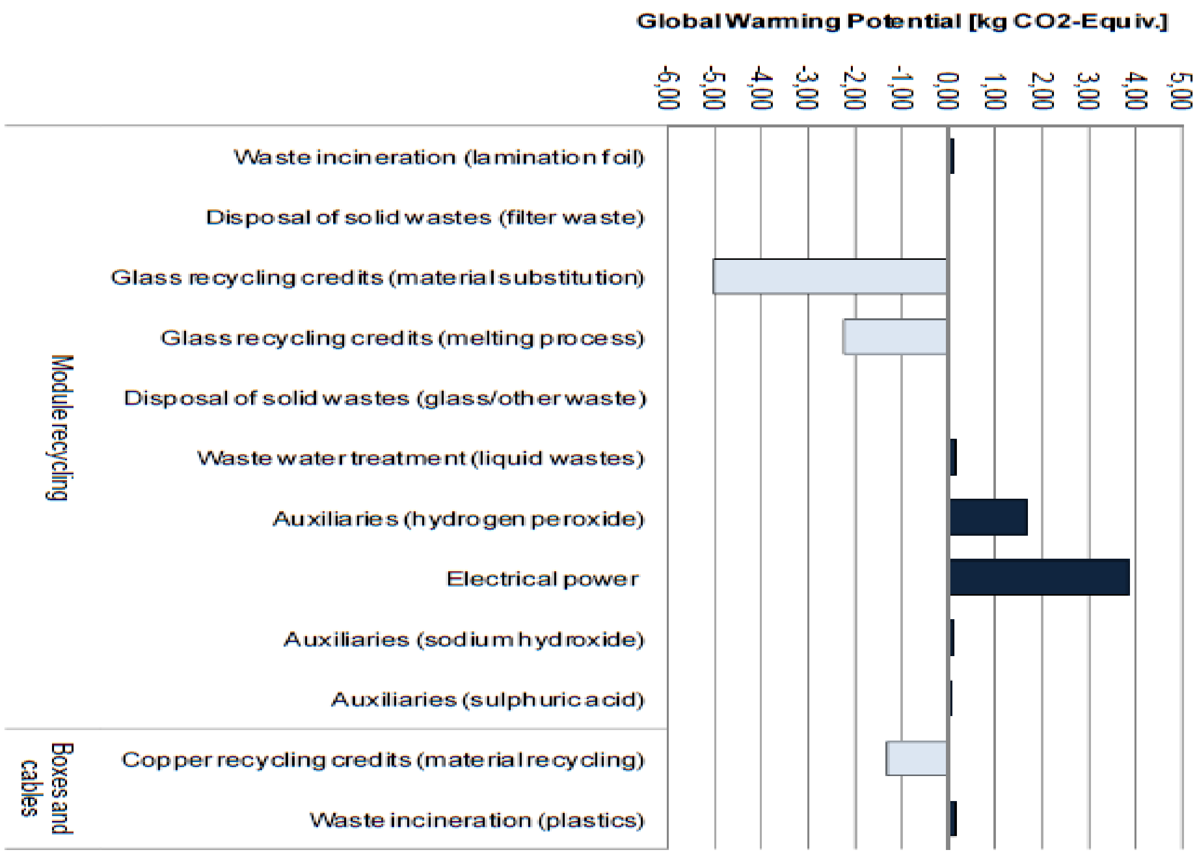


Figure 84. Changes in global warming potential per m² if modules are recycled (Held, 2009).

Ravikumar et al. (2015) found similar results in their investigation of the lifecycle benefits of recycling a PV module. This study considers recycling the entire CdTe PV system and is based on First Solar's high-value recycling process. By recycling an entire PV system, lifetime and energy footprint are reduced by about 24% of the energy used to manufacture the system in the first place. The factors with the greatest impact on the energy benefit of recycling were identified as reducing the energy required to recover unrefined semiconductor material from the module and ensuring high recovery of steel and glass from the end-of-life CdTe PV system. If only the module is recycled and the remaining system is not considered, 13.2 kg of glass, 0.007 kg of Cd, and 0.008 kg of Te can be recovered per m². The energy impact is, however, almost neutral. Results are summarized in **Figure 85**.

An additional important factor that was identified is energy required for transportation. Energy intensity here depends on the tradeoff between material recovery and recycling operations at the decentralized location, and transporting, recovering, and recycling the PV system components at a centralized location. A suitable strategy is required for either scenario.

An area for potential future improvement is reducing the energy for removal of EVA which currently requires about half of the unrefined semiconductor material separation energy.

Figure 85. Recycling Energy Net Benefits

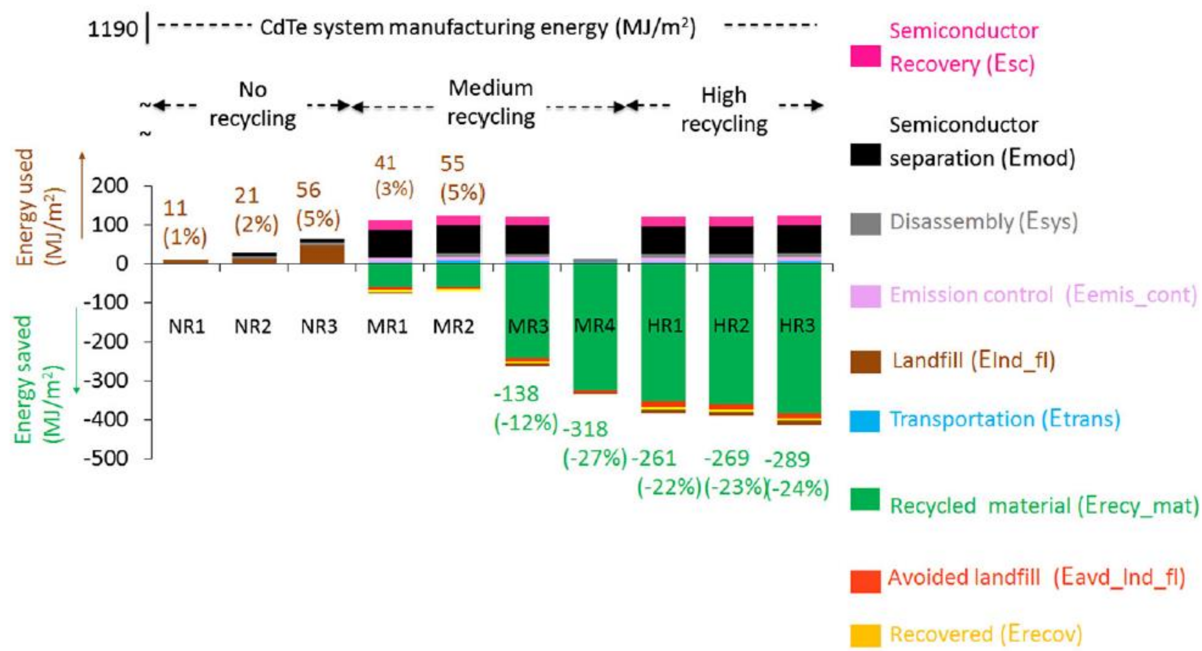


Figure 85. Net energy impact of CdTe photovoltaic (PV) system recycling for 10 scenarios. Negative values in green indicate a net energy benefit (energy saved > energy used) and positive values in brown indicate that energy used exceeds energy saved. The parentheses contain the net energy impact as a percentage of the current energy intensity of manufacturing CdTe PV systems, which is 1190 MJ/m2 (Ravikumar et al., 2015).

C - Water Use

Water use is an important factor in energy use and another environmental advantage for PV technologies. **Figures 75 and 79** illustrate the water benefits compared both to conventional, carbon-based energy power plants and other PV technologies. **Figure 75** finds water depletion to be at about 20% compared to that of carbon-based electricity generation and is projected to go down to 10% in the 2030 scenario.

Sinha et al. (2012) performed a detailed breakdown of the life-cycle water withdrawal for a CdTe PV system, considering 30-year and 60-year balance-of-system usage. The authors estimate that the life cycle water withdrawal for CdTe PV is between 382-425 L/MWh. Approximately half of the life cycle water withdrawal is associated with module manufacturing, one-third with balance of systems factors, and the remainder from takeback and recycling. Primary contributors during manufacturing are the use of grid electricity, glass, and on-site water. Balance of system factors include the use of steel, copper, inverters, and on-site water. Contributions to recycling include electricity, chemical use, and transport during takeback and recycling. The detailed breakdown in shown in **Figure 86**. Compared to conventional electricity generators, CdTe PV uses a much smaller amount of water. Considering state of the art in the southwestern USA, CdTe PV arrays can displace water withdrawal by between 1700–5600 L/MWh (Sinha et al., 2012b).

Figure 86. CdTe PV Life Cycle Water Withdrawal

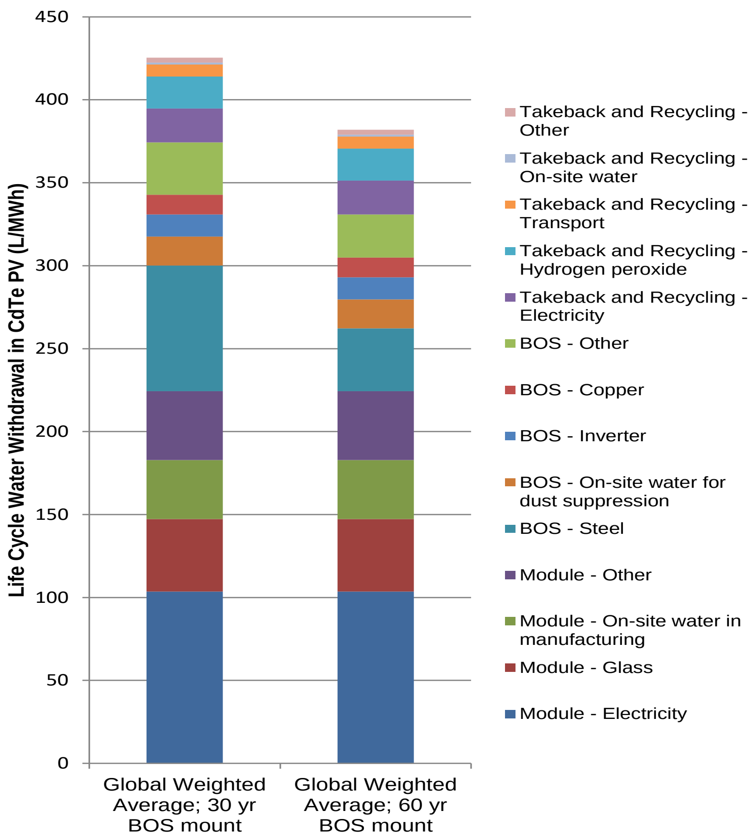


Figure 86. Life cycle water withdrawal of CdTe PV broken down into major contributions (Sinha et al., 2012).

First Solar also tracks water consumption per Watt produced from their manufacturing processes. In their Sustainability Report, First Solar states that water intensity was reduced by 35% between 2009 and 2017 (see **Figure 87**). The reduction was due to improvements in module efficiency, manufacturing throughput, and the implementation of water conservation and recycling projects. An increase in 2017 is caused by a ramp-down phase in production related to the transition to Series 6 manufacturing, as many facilities like cooling towers still ran during the ramp-down as before. Overall water consumption continued to be reduced in 2017 and 2018 by implementing recycling programs in Malaysia, where over 75 million liters of water were saved.

Figure 87. First Solar Water Use

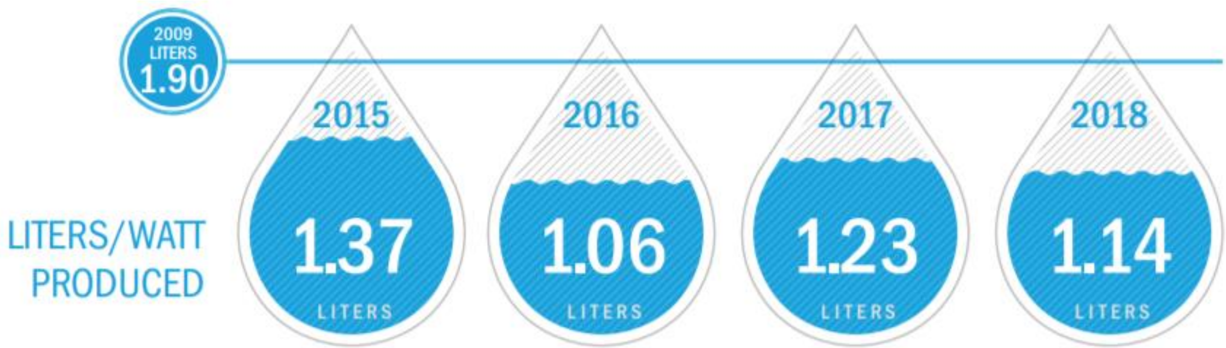


Figure 87. Reduction in water use per watt produced (First Solar, 2019).

D - Land Use

Land use is an important consideration for PV technologies. PV deployment requires space to capture sunlight, although the total amount required is comparatively low, as we discuss below, versus other energy technologies, as the amount of solar energy that falls on the Earth is very high. More importantly, design choices have significant implications for the overall environmental impact of PV technologies on land use. Design options by the installer include the choice of which space to use for PV deployment (e.g., building rooftops, brownfields, integration with agriculture, or natural ecosystems all have very different environmental profiles), how land is prepared for use (e.g., if land surfaces are graded), and how solar is integrated into the land environment (e.g., with regard to biodiversity or agricultural production). These design options can all significantly increase or decrease environmental impacts. For example, ground disturbance due to land surface grading can be reduced using the disk-and-roll site preparation method, or by eliminating site grading where feasible and simply replacing with vegetation mowing (Sinha et al., 2018b).

Fthenakis and Kim quantified the land transformation associated with different energy technologies (2009). The focus of their study is a comparison between conventional and renewable energy technologies, considering the full life cycle of each. The study considers PV, wind, hydroelectric and biomass as renewable options, and coal, nuclear and natural gas as conventional sources. The authors state that previous studies were often critical of the potential of renewables to address the climate crisis based on the charge that renewables would require comparably large amounts of land. The hypothesis that the authors work on is that previous studies did not consider the full life cycle of different technologies or the importance of direct and indirect land use and, for example, neglected the land transformation during surface coal mining.

To address this issue, the authors suggest a methodology in which they quantify

- direct land transformation for the power plant operation in the U.S.
- land transformation through mining and milling

- land use through storage, transportation and fuel disposal (where applicable).

A comparison of the total land transformation of all considered technologies with a variation of location and mode of operation for some is shown in **Figure 88**.

Figure 88. Life Cycle Land Transformation

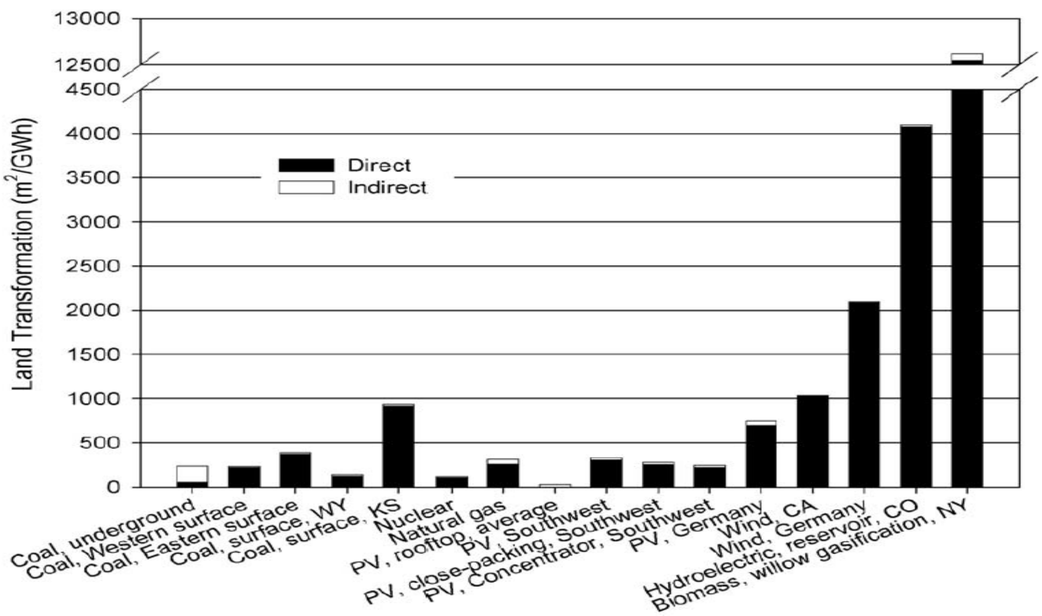


Figure 88. Life cycle land transformation for fuel cycles based on 30-years timeframe (U.S. cases unless otherwise specified). The estimates for PV are based on multi-crystalline PV modules with 13% efficiency. The reference case refers to a ground-mount installation with the U.S. Southwest insolation of 2400 kWh/m²/year, while the rooftop case is based on the U.S. average insolation of 1800 kWh/m²/year. For Germany, the insolation of Brandis, 1120 kWh/m²/year has been used. The packing ratio of the close-packing case is 2.1 compared with 2.5 for the reference case. The estimate for wind is based on a capacity factor of 0.24 for California and 0.2 for Germany (Fthenakis & Kim, 2009).

Contrary to previous findings, the study concludes that the life cycle land transformation of PV technology is comparable to that of coal, nuclear and natural gas. In some cases, surface coal mining can even have a much larger land transformation associated with it; in most cases, ground-mount PV systems in areas of high insolation transform less land than the coal-fuel cycle coupled with surface mining. PV also has the smallest land transformation impact of all renewable energy technologies, with wind and biomass coming in second and third, and biomass having by far the largest of any technology. In addition, biomass competes with agricultural products for land, as well as other aspects of the agricultural economy, e.g., water, fertilizer, labor, processing, etc. (Fthenakis & Kim, 2009).

The authors also state that conventional electricity-generation technologies pose secondary effects on land use that were not considered in their study. These include contamination and disruptions of the ecosystems of adjacent lands by fuel-cycle-related accidents. The authors also state that secondary effects like "water contamination, change of the forest ecosystem, and accidental land contamination will make the advantages of the PV cycle even greater than those described herein".

Evaluation of land use was extended in a study by Turney and Fthenakis (2011). In this paper, the authors investigate the impact of PV installations during construction and operation on 32 impact factors, addressing land use intensity, human health and well-being, plant and animal life, hydrological resources and climate change. The premise of the study is that solar installations replace traditional forms of power generation in the U.S. The authors find that in none of the investigated categories, PV has a clearly negative impact. In 22 categories, the impact of PV is clearly positive, in four it is neutral and for six the authors recommend further studies.

Land use intensity is considered one of the most important environmental factors. Considering the life cycle of both coal and solar plants, similar land occupation and land transformation is found for coal and solar installations for lifetimes between 20 and 30 years. For potential plant lifetimes >30 years, solar installations even have lower impact on land occupation and transformation than coal. The result from the study is shown in Figure 89.

Figure 89. Land Transformation and Occupation of Coal and Solar Power

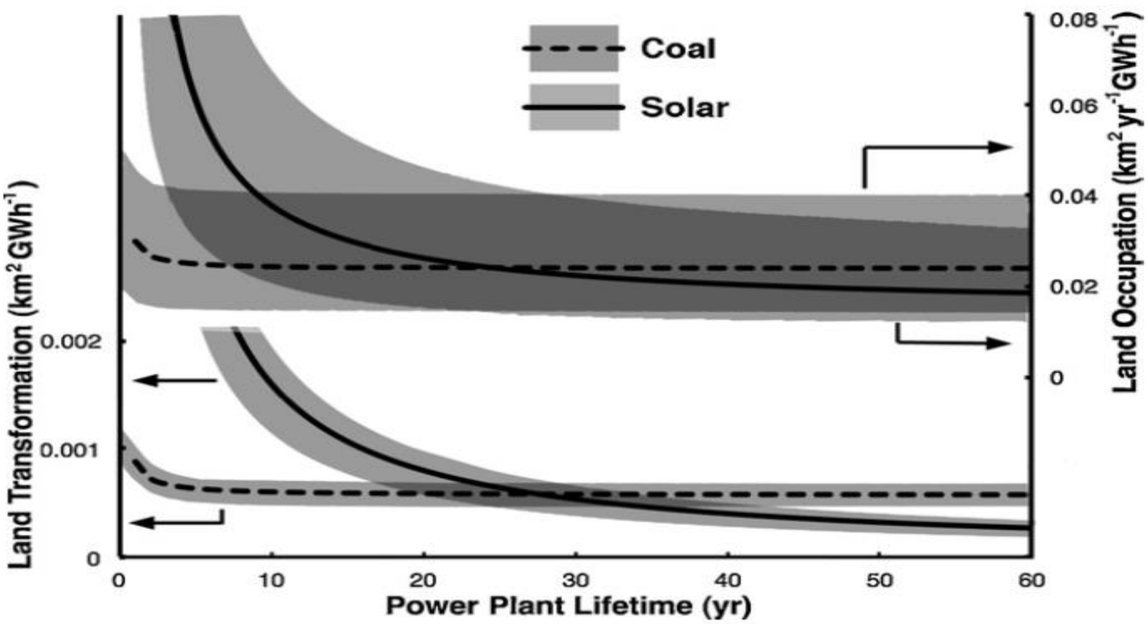


Figure 89. Comparisons of land use intensity metrics for large-scale solar and coal power. The left ordinate shows land transformation, and right ordinate shows land occupation. For both ordinates the dashed line is the average result for coal powered electricity while the solid line is the average result for solar powered electricity. The gray shaded areas give the range of sensitivity of the calculations as the input parameters are varied over their possible values. For typical plant lifetimes (20-30 years), solar and coal generation facilities have similar land transformation and occupation per electricity generated (GWh), when including the coal fuel life cycle coupled with surface mining. For potential plant lifetimes >30 years, solar energy can have lower land transformation and occupation per electricity generated (GWh) than coal generation (Turney & Fthenakis, 2011).

The authors also state that there are significant differences in environmental impact depending on the choice of site location (a result that is confirmed by other studies, see the biodiversity section **IV.F**). The most environmentally beneficial locations are previously disturbed sites with high insolation and absent wildlife. Solar power installations in forests, on the other hand, will release significantly more CO_2 (two to four times as much) than sites in deserts. Note that these estimates are for non-commercial forests, whereas commercial forests (timberlands) are periodically harvested, regardless of solar development. The difference in GHG emissions for forests is mainly due to clearance of vegetation but is further heightened by the lower insolation due to higher cloud cover in forest regions. Total emissions are calculated to be between 16 and 86 g $CO_{2,eq}$/kWh. This value is still low compared to emissions from coal-based electricity that were given with approx. 1100 g $CO_{2,eq}$/kWh.

The relationship between PV systems and agricultural productivity has also been evaluated. Adeh et al. (2018) explored the environmental effects of PV modules placed on an unirrigated pasture. The pasture was located on the Oregon State Campus and experiences frequent water stress. The authors observed and quantified changes to the microclimatology, soil moisture, water usage, and biomass productivity due to the presence of the solar modules. Sensors were installed on the site of the solar farm two years after its completion, including neutron probes for measuring soil moisture. Differences in soil moisture, relative humidity, air temperature, wind speed and wind direction were observed. Areas under PV solar modules maintained significantly higher soil moisture throughout the period of observation. Differences were also observed in late season biomass. The areas under PV modules produced up to 90% more biomass here than areas with full sun exposure. In addition, areas under PV modules were much more water efficient (more than 300%) than fully exposed areas. Results for soil moisture and biomass rate are shown in **Figure 90**.

Figure 90. PV Panel Shading and Soil Water Content and Biomass Produced

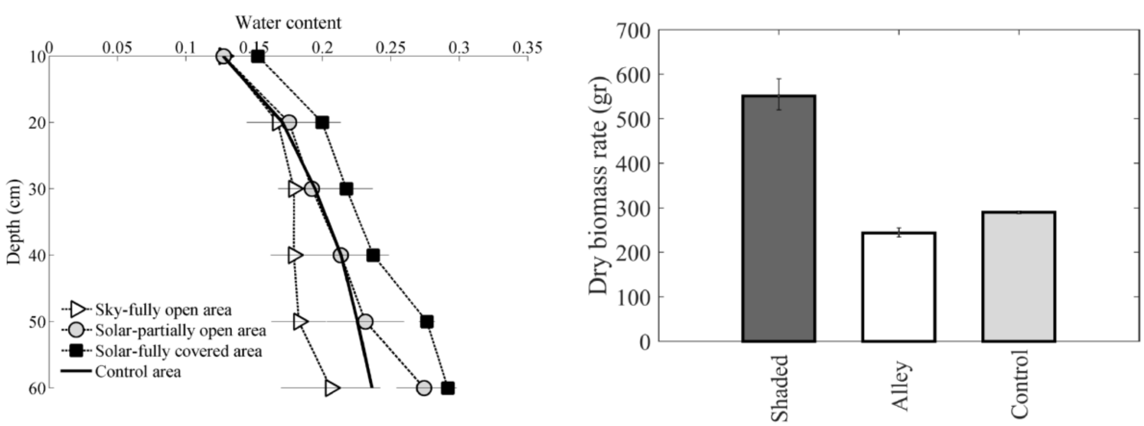


Figure 90. A) Water content as a function of depth in areas with full, partial and no PV coverage.
B) Comparison of dry biomass produced under three conditions: Solar Fully Covered (Shaded), Sky Fully Open (Alley) and control area (Adeh E. et al., 2018).

Based on the results of their study, the authors make recommendations for the design of solar plants to take advantage of potential gains in agricultural production. Semi-arid pastures with wet winters were identified as ideal candidates for “agrivoltaics” systems. Inhomogeneities in shading and exposure to water were identified as potential issues, and the author recommend working on designs that improve on these issues. Agrivoltaics is now considered a major opportunity for increasing U.S. and global PV production via strategies that also enhance land use and agricultural production and farm income (Weselek et al., 2019).

E - Dust and Particulates

A related facet of land use is the impact of land transformation on dust and particulate emissions. Ravikumar and Sinha investigated the impact of PV installations on downwind particulate matter concentrations in a 2017 study of the same title (Ravikumar & Sinha, 2017). Investigations were performed at the Desert Sunlight 550MW PV installation in Riverside County, California. Particulate matter with diameters below 2.5 μm (PM2.5) and 10 μm (PM10) was collected at four different stations on different parts of the plant over a period of three years. The three-year study period covered pre-construction, construction and post-construction. The authors hypothesize that the utility-scale PV installation reduces particle emissions from land occupied by PV modules due to a wind-shielding effect. The main findings to support this hypothesis are:

- Confidence intervals of the mean particle concentrations during construction overlap with or are lower than background concentrations for three of the four measurement stations.
- Post-construction particle concentrations downwind of the PV installation are significantly below background concentrations at three of the four measurement stations.

The supporting graphs are shown in **Figure 91**.

The significance of these findings lies in the role that PV installations could play in supporting downwind particle emission abatement in desert climates, similar to the one found at the site of this PV construction. Furthermore, particle emission reductions were observed within 10 months after completing the construction. The authors conclude that post-construction monitoring of downwind particle levels may be reduced to a one-year period for other projects with similar construction and operation conditions.

Utility-scale PV installation reduces particle emissions from land occupied by PV modules due to a wind-shielding effect.

Figure 91. Dust and Particulate Emissions from PV Plants

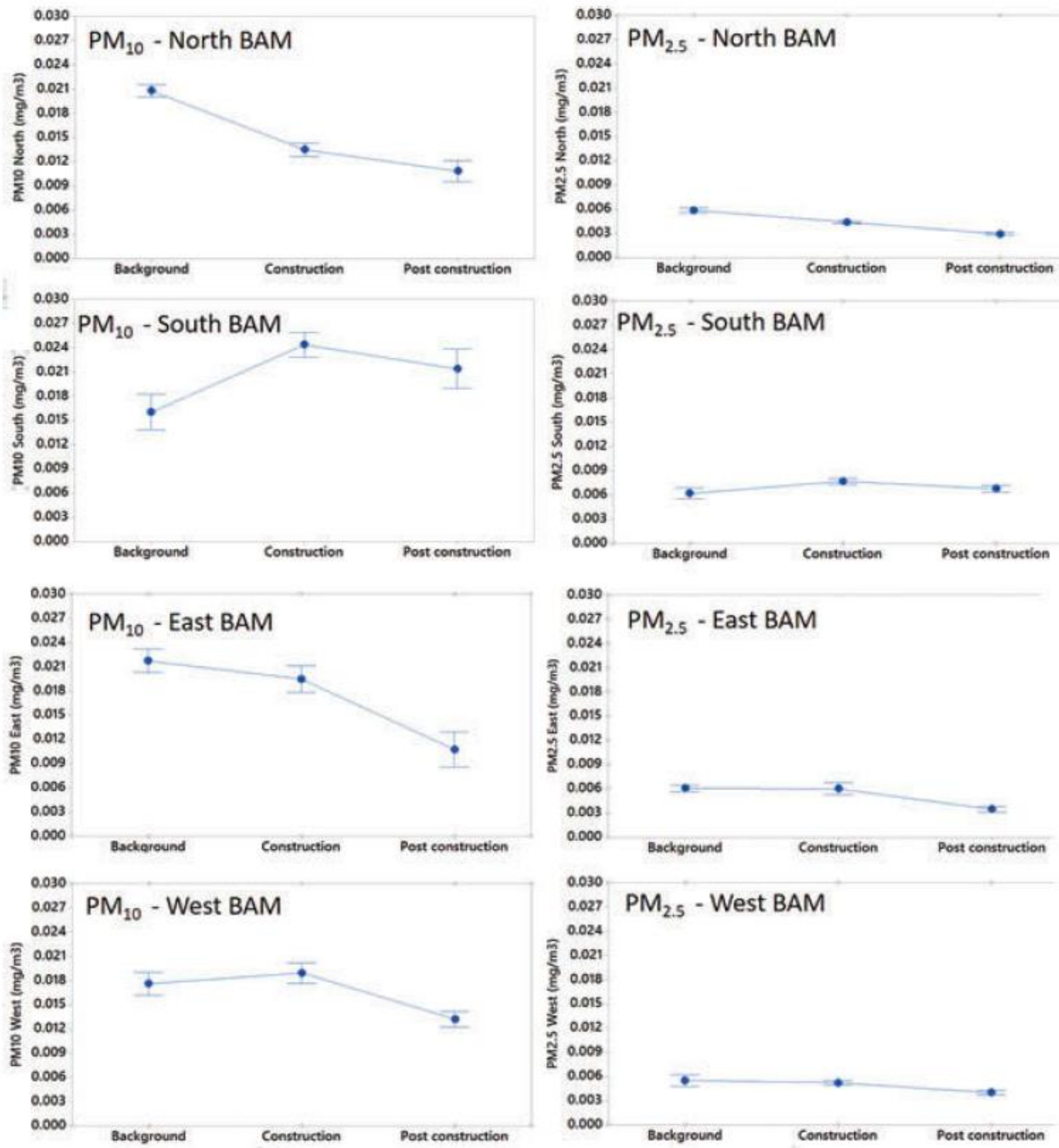


Figure 91. Particle concentration (PM10-PM2.5) before, during and after construction including confidence intervals of 95%. Taken from beta attenuation monitor stations around the PV plant (Ravikumar & Sinha, 2017).

F - Biodiversity

In a report by the German Renewable Energies Agency, opportunities for biodiversity due to PV installations are discussed (Peschel, 2010). In a first part, the report motivates how PV parks interact with ecosystems by discussing prior research findings, and then, in a second part, makes recommendations for best practices for conservation measures.

Regarding the impact of PV installations on biodiversity, the report draws a positive conclusion, but also cautions that further research is necessary. Prior studies reviewed by Peschel (2010) indicate that, although construction projects always constitute a certain disturbance of flora and fauna, if they are properly designed, solar parks can have a positive impact on biological diversity by improving the quality of habitats for animals and plants. PV installations also have a chance to create new habitats.

Even greater improvements can be achieved if sites with PV installations are integrated into greater ecosystem networks, especially if land with poor species diversity is concerned. Figure 92 presents a sketch for overall integration of PV installations in ecosystems. As an example, the report states that previously cleared agricultural land could be transferred into well maintained grassland, which additionally acts as a carbon sink and reduces the use of fertilizers, pesticide and environmental pollution. As degraded agricultural land is often proposed for large-scale solar facilities, this example is particularly relevant to the PV industry. Another example where PV installations can have a significant positive impact are contaminated areas and landfill sites. While the most significant improvements will be achieved for stressed sites, positive impacts are also possible for sites with higher nature value.

The report makes a number of recommendations regarding best practices, which can be considered alongside other siting considerations such as land costs, distance to transmission, hydrology, and topography:

- Site selection has a strong influence on the environmental impact. The report identifies sites along major transport routes, contaminated brownfield sites, former arable land, landfill sites and slagheaps as especially suitable, while recommends that protected sites only be considered within certain restrictions.
- Local conditions, environmental remediation and compensatory measures must be considered during the environmental impact assessment. To ensure environmentally friendly use, local authorities, environmental groups and the public should be involved in the planning process.
- Monitoring and quality control during construction is essential. The report recommends involving an environmental monitoring expert who is responsible for considering all relevant concerns before and during construction, and also for supervising the implementation of and adherence to defined conservation and abatement measures.
- Soil sealing should be avoided to provide habitats for animal and plant species.
- The canopy effect, i.e. non-uniform shading and water ingress into the ground should be considered but can have positive as well as negative effects.

- Helping conserve the regional genetic diversity of plants should be considered as a goal for site development.
- The report also recommends long-term monitoring of the sites to ensure learning and quality control of the implemented measures. Furthermore, the report emphasizes the importance of site maintenance.

Figure 92. Responsible Land Use

Figure 92. Sketch of the concept for integrating PV installations in a wider ecosystem, developed by the German Renewable Energies Agency (Peschel, 2010).

Recommendations were also made by Sinha et al. (2018). In this study, the authors explore species diversity and biological productivity of vegetation on the Topaz Solar Farms project in San Luis Obispo County, California (Sinha et al., 2018b). The PV farm has a capacity of 550 MW and was, at the time the paper was written, one of the largest installations in the world. The study finds that vegetation productivity on the solar farm is comparable to that on reference sites. Furthermore, monitoring revealed the presence of a wide variety of wildlife species, several of which fell under special conservation status. An example of the monitoring results is shown in Table 8. On-site vegetation is maintained by sheep grazing (Figure 93), demonstrating how PV power plants can accommodate agriculture. The study includes a "solar reef" framework, the concept that responsibly developed large-scale PV facilities can provide shelter, protection, and stable use of land to support biodiversity while also generating renewable energy.

Figure 93. Vegetation Management

Figure. 93 Vegetation management by grazing sheep (Sinha et al., 2018a).

In 2012 the WWF published a solar atlas, addressing issues on the land-energy nexus related to solar PV with the goal to enable 100% renewable energies by 2050 (Archambault, 2012). The atlas provides environmental impact categories and guidelines for utility-scale solar PV with a number of scores. Categories and sub-categories include community factors (dust, visual, noise, stakeholder engagement, labor), biology factors (species & plants, environmental impact studies, soil protection), water factors (storm water, usage), design and construction factors (site selection, grading, footprint), and end-of-life factors (site restoration, recycling). Guidelines provided in the atlas were considered during construction and operation of the Topaz solar farm, and high scores were achieved in all but one category (visual – the site is not completely out of sight from roads and neighbors) (Sinha et al., 2018b). The authors conclude that, as a result of applying these guidelines:

> *After the short-term solar project construction disturbance period, the vegetation within the project fencing can return to its native origins accompanied by the return of associated fauna. As a result, the acreage inside the project fence can become a refuge for species from the continuous ground disturbance and predation that occurs outside the project fence, as evidenced by biological monitoring data at the Topaz project*

Table 8. Vegetation Sampling

Scientific name	Common name	On-site (alley)	On-site (under array)	Stewardship land	Total
Achyrachaena mollis	Blow-wives	1			1
Amsinckia intermedia	Common fiddleneck	7	8		15
Avena fatua	Wild oat	10	12	4	26
Brassica nigra	Black mustard	2	3		5
Bromus diandrus	Ripgut grass	4	11		15
Bromus hordeaceus	Soft chess	3	7		10
Bromus madritensis subsp. *rubens*	Red brome	12	15		27
Calandrinia menziesii	Red maids		1		1
Capsella bursa-pastoris	Shepherd's purse	1			1
Deinandra fasciculata	Clustered tarweed		1		1
Descurainia sophia	Tansy mustard	4	2		6
Erodium cicutarium	Redstem filaree	35	12	20	67
Festuca microstachys	Small fescue	3	2		5
Hordeum murinum	Foxtail barley	17	18		35
Lamium amplexicaule	Henbit		1		1
Lasthenia gracilis	Common goldfields		1		1
Lepidium nitidum	Peppergrass		1	1	2
Lupinus bicolor	Miniature lupine			1	1
Phacelia ciliata	Great valley phacelia			2	2
Plagiobothrys canescens	Valley popcornflower		1		1
Plagiobothrys nothofulvus	Rusty popcornflower		1		1
Poa secunda subsp. *secunda*	One-sided blue grass	1	2		3

Table 8. Dominant species of vegetation by quadrat sampling location in 2015, tallied by species and number of quadrats in which it was dominant (1 m^2 quadrats) (Sinha et al., 2018).

G - Materials Hotspots

In addition to documenting the environmental footprint of PV systems, life cycle assessment can be used to improve the environmental footprint by addressing hotspots, or primary contributors to life cycle environmental impacts. Based on results from the EU product environmental footprint pilot study on PV, a primary environmental hotspot for PV systems is non-renewable resource depletion, due to reliance on metals such as steel, copper, aluminum, and semiconductor materials in PV modules and balance of systems (Stolz et al., 2016). The use of raw and manufactured materials in PV systems will continue to be a burden as the PV industry grows to larger scales and supplies a greater fraction of total U.S. electricity production beyond the 2% it supplied in 2018 (EIA, 2020c). For instance, copper will become a critical cost factor for PV systems, which use 11–40 times more per kWh generated than conventional fossil power generation systems (Hertwich et al., 2014)

The impact of PV systems can be calculated by the amount of installed capacity. For instance, creating 83 GW of PV capacity requires 0.6 million metric tons of copper which is more than 50% of the copper refined in the U.S. in 2013 (Bergesen et al., 2014). Meeting the IEA's BLUE Map scenario (39% of total global electricity generation from solar, wind, and hydropower) would require about two years of the current copper supply (Hertwich et al., 2014). The resource depletion environmental hotspot can be addressed by a number of strategies, including recovering these materials through recycling during project decommissioning (Sinha & Wade, 2018), increasing the efficiency of PV technologies, and finding alternative manufacturing and deployment strategies that use less copper.

V - THE VALUE OF SOLAR ENERGY IN CLEAN ENERGY TRANSITIONS

In the coming decades, the U.S. energy sector will undergo a major energy transition. The pace of that transition will be determined by how rapidly low-carbon energy technologies like solar energy can displace higher-carbon alternatives across the entire U.S. economy. This is not a simple undertaking; neither is it impossible. Already, this transformation is underway, with both renewable technologies and electric vehicles now available at competitive prices in markets for transportation and electricity generation.

Solar energy will likely play a significant role in the U.S. energy transition, both in replacing existing electricity generation technologies and as a source of new electricity generation to support the electrification of transportation fleets and industrial processes. As highlighted at the beginning of this report, some scenarios now suggest that solar energy may ultimately provide as much as 50% or more of the world's future energy supply by the second half of the 21st century. If that is indeed true, it will be because solar energy provides a wide array of benefits to societies and organizations that adopt it.

A - The Driver of Solar Energy Adoption: Eco-Efficiency

The primary driver of the growth of solar energy adoption is eco-efficiency. Eco-efficiency is the concept of creating more economic value with lower environmental impacts. When thin-film PV technology was commercialized two decades ago, other PV modules primarily utilized wafer silicon technology. Thin-film PV technology utilized glass as the manufacturing substrate instead of silicon wafers. The technology disrupted the industry by significantly lowering manufacturing costs. PV affordability (measured, as described above, by the LCOE of PV energy), as well as excellent environmental performance (as illustrated in the previous section IV.A by the low life cycle environmental impacts of the technology), in combination with strong demand, initially created by European feed-in-tariff structures, led to a new era of PV as a mainstream energy source.

The costs of renewable electricity systems have continuously decreased since the 1990s, and systems are still being optimized. A decade ago, the cost of producing a GW of electricity using gas, oil, and hard and brown coal sources was still lower than any PV source (Figure 12). Since then, PV costs have been reduced due to technological innovations, manufacturing optimization, and accessing larger markets, such as utility scale markets. Lazard's Levelized Cost of Energy (LCOE) comparison (Figure 13) summarizes current life cycle costs per MWh of new electricity generation. At $40/MWh, PV outcompetes gas-combined cycle ($56/MWh), coal ($109/MWh), and nuclear ($155/MWh) power generation systems (Lazard, 2019). Thin-film utility scale systems outcompete all other solar PV options (Figure 13), due to higher energy yield found in II.B.5 and competitive capital costs.

Today, the LCOE of renewable energy has reached a price lower than current price of grid electricity in most parts of the U.S. This grid parity has been achieved without monetization of environmental benefits such as greenhouse gas emissions reductions. PV has reached a competitive price with near neutral environmental impacts and only two decades of large-scale investments.

As a result of these cost reductions, solar energy is now one of the fastest growing new energy resources in the U.S, alongside new wind and natural gas power plants. PV and wind were 64% or 15.3GW of new installations in the U.S. in 2019 (EIA, 2020c), and gas combined cycle accounted for 6GW of new installations (**Figure 94**).

Figure 94. U.S. Energy Additions and Retirements 2019

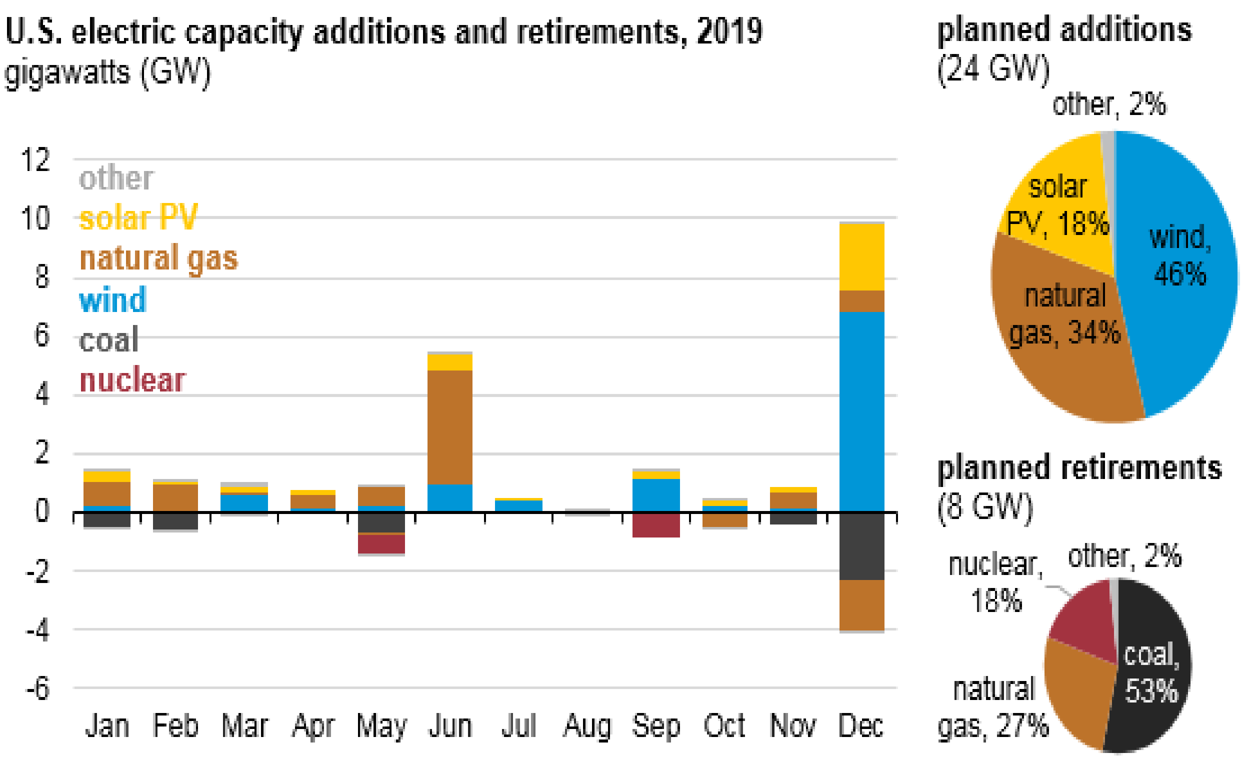


Figure 94. New electric generating capacity in the U.S. in 2019 (EIA, 2020c).

In turn, the low cost of solar energy can be combined with life cycle environmental performance to compare technologies on the basis of eco-efficiency, the ability to deliver more value with less environmental impact. In the U.S., for example, if the financial benefits of low-carbon energy from reducing climate risks (~$20/MWh) and improving air quality (~$14/MWh) are included among the benefits of solar energy, the results would further incentivize deployment of solar electricity, as shown in **Figure 95** (Wiser et al., 2016). With the inclusion of avoided water usage as well, the environmental benefits of solar energy amount to $20-50/MWh relative to conventional gas and coal electricity (Sinha et al., 2013).

Figure 95. Environmental and Health Benefits from Solar Penetration

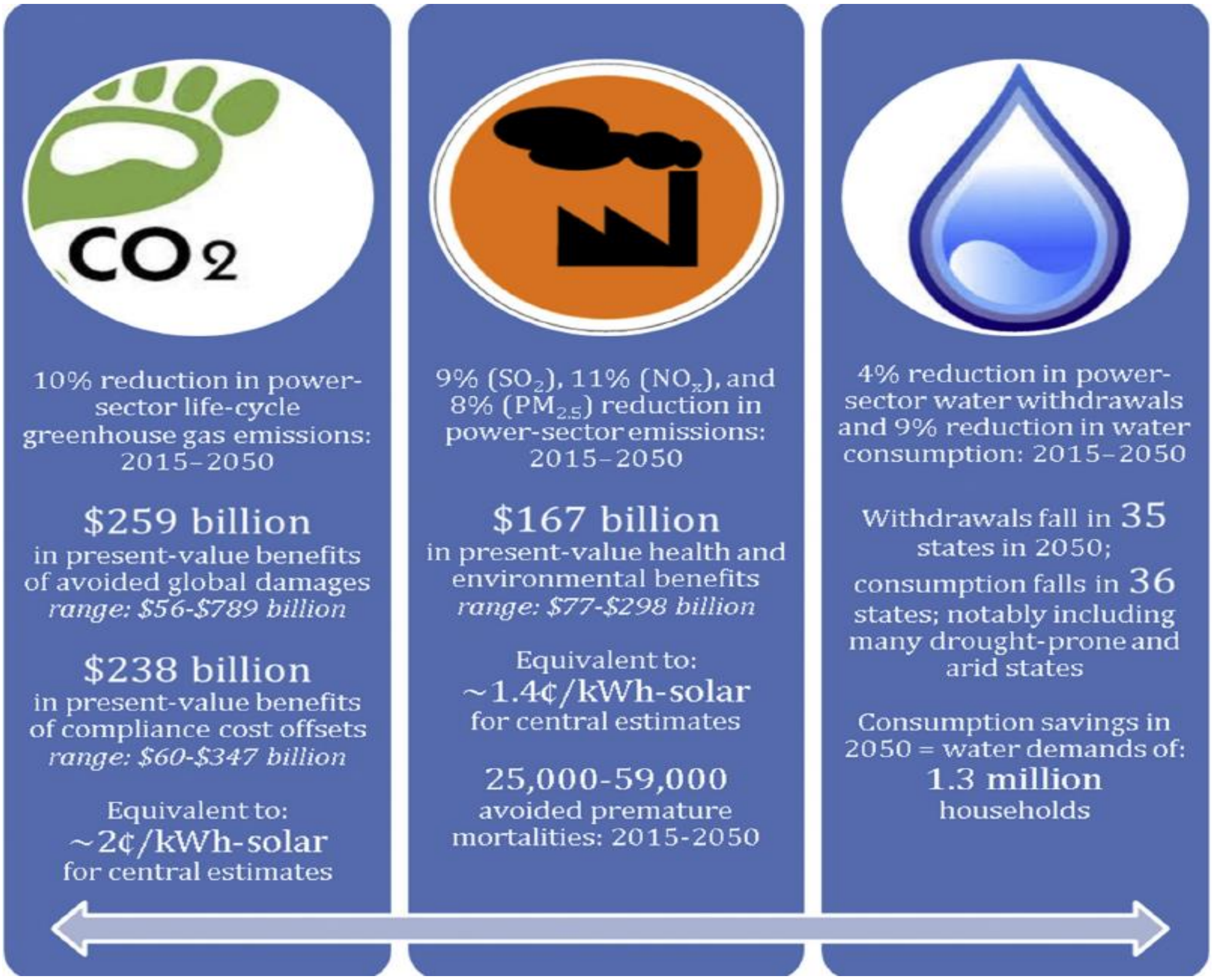


Figure 95. Environmental and health benefits of achieving large-scale solar penetration in the U.S. (14% of U.S. electricity demand by 2030 and 27% by 2050) (Wiser et al., 2016).

An eco-efficiency study of different kinds of PV systems and non-renewable power generation systems was conducted for the Bavarian State Ministry of the Environment and Consumer Protection (Seitz et al., 2013). As shown in Figure 96, ground-mounted and industrial rooftop CdTe PV systems have the highest overall eco-efficiency scores among PV systems. Larger PV systems have lower life cycle costs due to economies of scale, which are balanced in overall eco-efficiency scores by the low land use requirements of rooftop PV systems. CdTe PV systems have lower life cycle environmental burdens than CIS and mono-c-Si PV systems due to lower material and energy requirements in manufacturing.

Figure 96. PV Eco-Efficiency

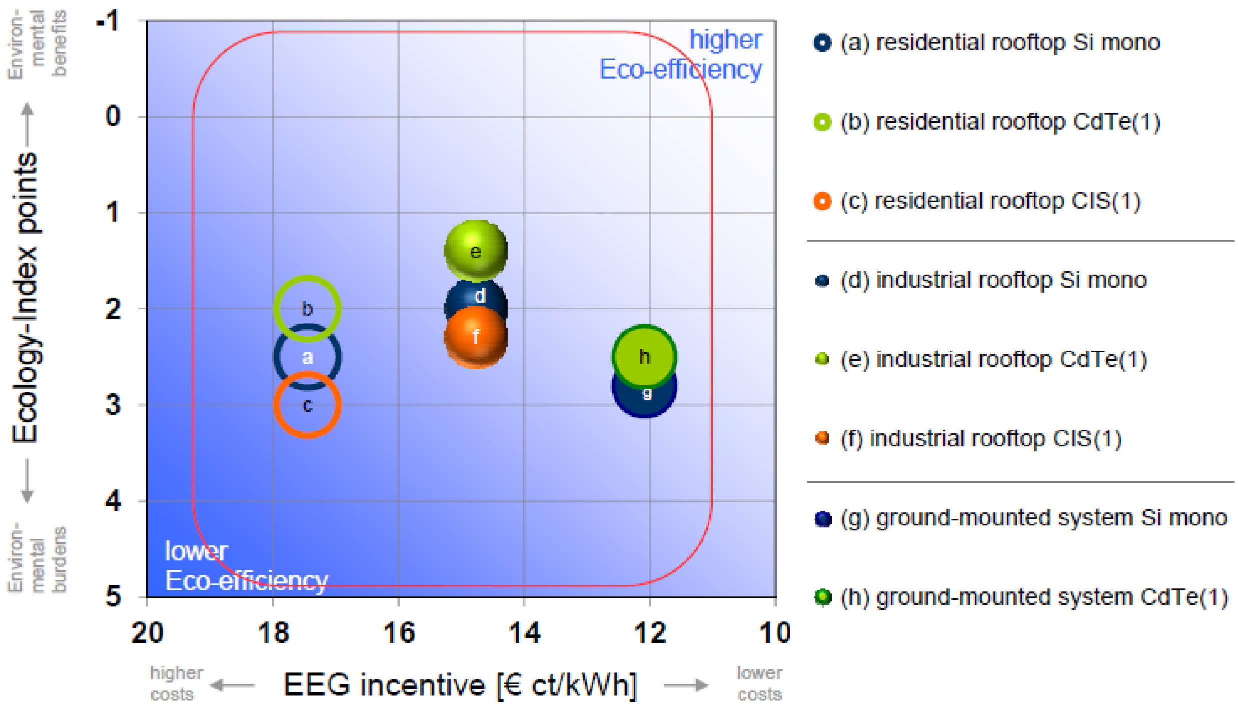


Figure 96. Eco-efficiency portfolio for three PV technologies Si-mono, CdTe (1) and CIS (1) for residential rooftops, large industrial rooftops and ground-mounted systems (Seitz et al., 2013).

B - Grid Integration of Solar Energy

Given solar energy's eco-efficiency advantages, we expect to see continued increases in solar energy adoption in future years. This is only likely to increase with accelerating commitments to cut carbon emissions drastically by many communities, companies, states, and countries. This growth of renewable energy will continue to displace traditional electricity generators, requiring the consideration of integrating renewable energy into the electricity grid.

One fundamental difference between fossil thermal and renewable electricity generators is their operating procedure. Steam turbines, gas turbines and combined cycle plants are rotating machines that are built to synchronize with the electricity grid. Wind and solar, on the other hand, use inverters for grid connection and are not by nature synchronous to the grid's frequency. Furthermore, solar and wind plants feature an intermittent power generation that, without further measures, does not precisely conform with the demand patterns experienced by our current electricity infrastructure. The further integration of wind and solar consequently is an infrastructure challenge that requires innovation both on the side of how PV power plants are operated, and how electricity is used.

Developing and deploying grid-friendly, large-scale PV power plants that support grid stability is one of the necessary steps to further the integration of PV generation into the power grid. As PV becomes more prevalent, it also needs to take an increasing responsibility to guarantee reliability and a high power quality. An exemplary layout for a large-scale (multi-MW) utility-scale PV power plant is shown in Figure 97. Components include solar modules, inverters, grid interconnections, controls and data acquisition.

Figure 97. PV Plant Components

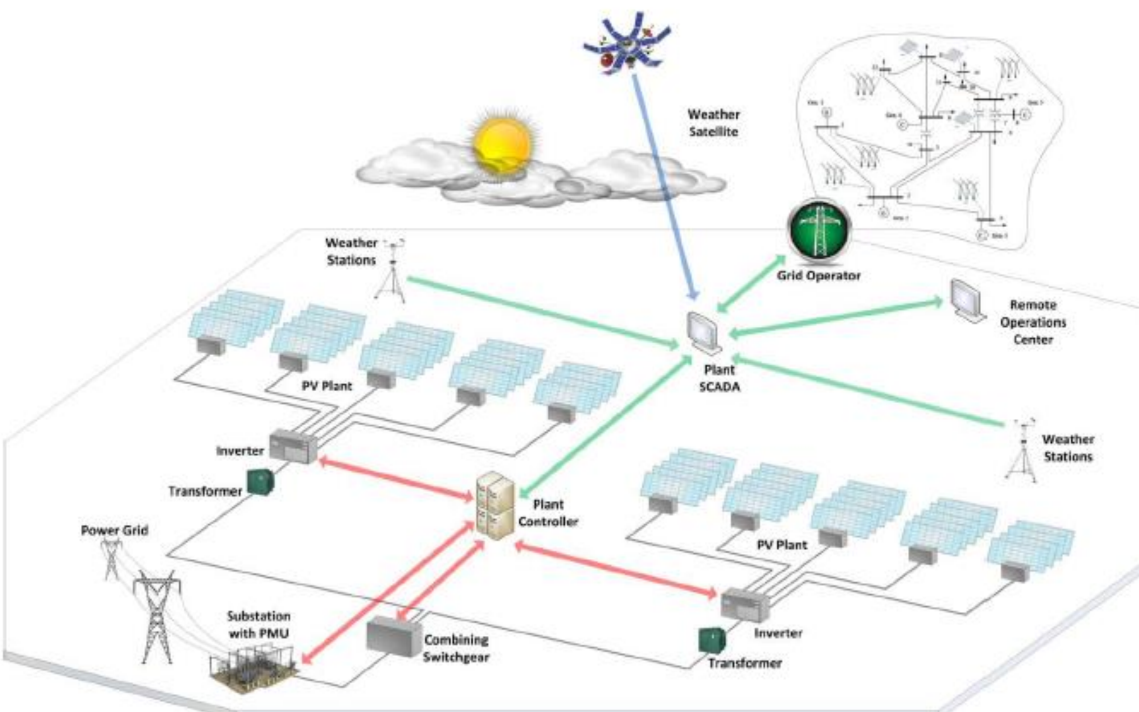


Figure 97 Components of a typical utility-scale PV power plant. Image from NREL (Gevorgian & O'Neill, 2016).

A typical power output profile of a PV installation is shown in Figure 98. This particular profile was recorded on two consecutive days for the Ilumina PV plant in Puerto Rico. The characteristic sinusoidal shape of the power generation with a peak around noon is visible. On the second day rapid fluctuations, most likely caused by clouds can also be seen. Either of those features requires a different management strategy. The Figure 98 also indicates one possible measure to better manage PV power plant operation: a 10% curtailment. The curtailment would give headroom to plant operators to respond to up and down regulation.

Figure 98. PV Plant Power Availability

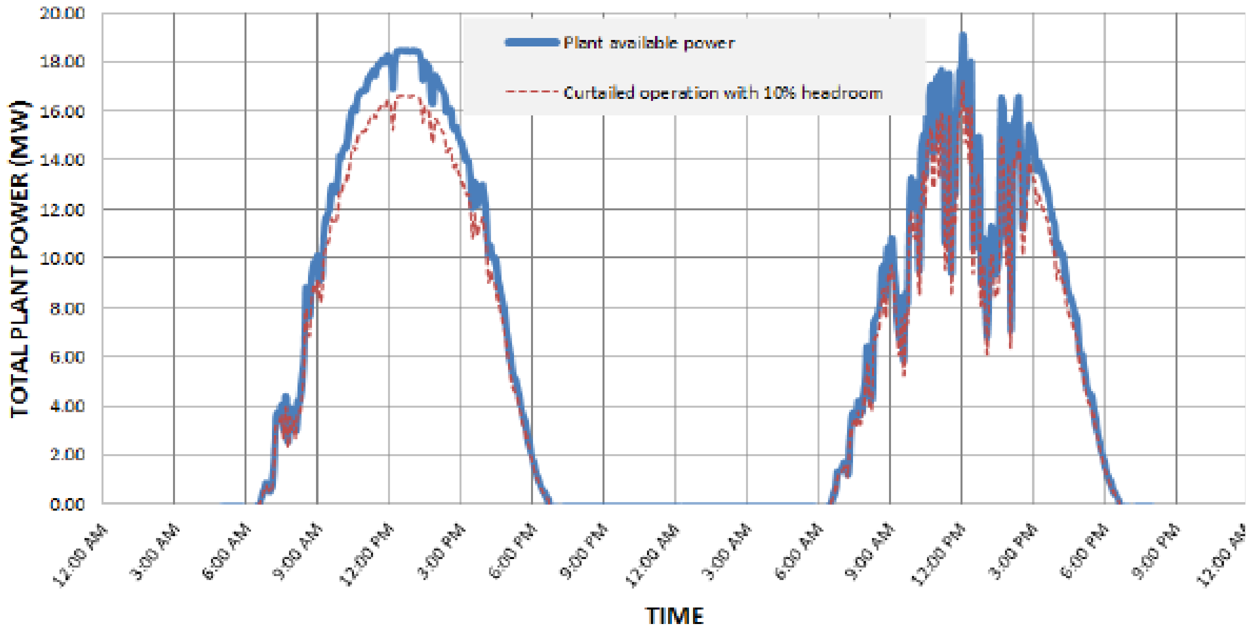


Figure 98. Total power of the Illumina PV power plan with reserve over two days with different weather (August 3rd, 4th 2014). The red curve indicates a potential 10% curtailment (Gevorgian & O'Neill, 2016).

One task of a grid operator is to match the power generation with demand. A demand curve in spring for California (CAISO) is shown in **Figure 99** (Loutan et al., 2017). This particular demand curve was recorded on April 24th, 2016. It also shows the contributions from different electricity sources. Both time and location are of significance, as they shape the demand. In this particular case, a spring day in California, means that PV installations already generate a fair amount of electricity after the winter months. Temperatures, on the other hand, are still low enough that people do not turn on air conditioning systems, resulting in relatively small demand around noon. This combination marks a worst-case scenario for solar PV, and results in an overproduction of electricity that has to be curtailed. On this particular day, more than 2GW of renewable generation were curtailed.

This phenomenon has also been named the "duck curve", due to the shape of the load profile resembling a duck, with the sharp rise of net load (i.e. total load – renewable generation; dashed red line in **Figure 99**) resembling the duck's neck. It's important to remember that this phenomenon is most emphasized only during certain days and not the entire year. As solar installation increases, curtailment will become more widespread, if no other measures are taken. Measures that reduce the need for curtailment and also the urgency of the duck curve include:

- Addition of electricity storage (for example pumped hydro or batteries) to the infrastructure to shift electricity generated during midday to evening or morning hours.
- Extension of the electricity grid. Adding distributed loads and generators to the system, especially in East – West direction will even out the load profile.

- Developing smart appliances that use electricity when it is most available, and – consequently – cheapest.
- Issues with grid stability can be addressed by the use of advanced inverter functions, as well as advanced project design and operation.

Figure 99. Power Load Profile for California

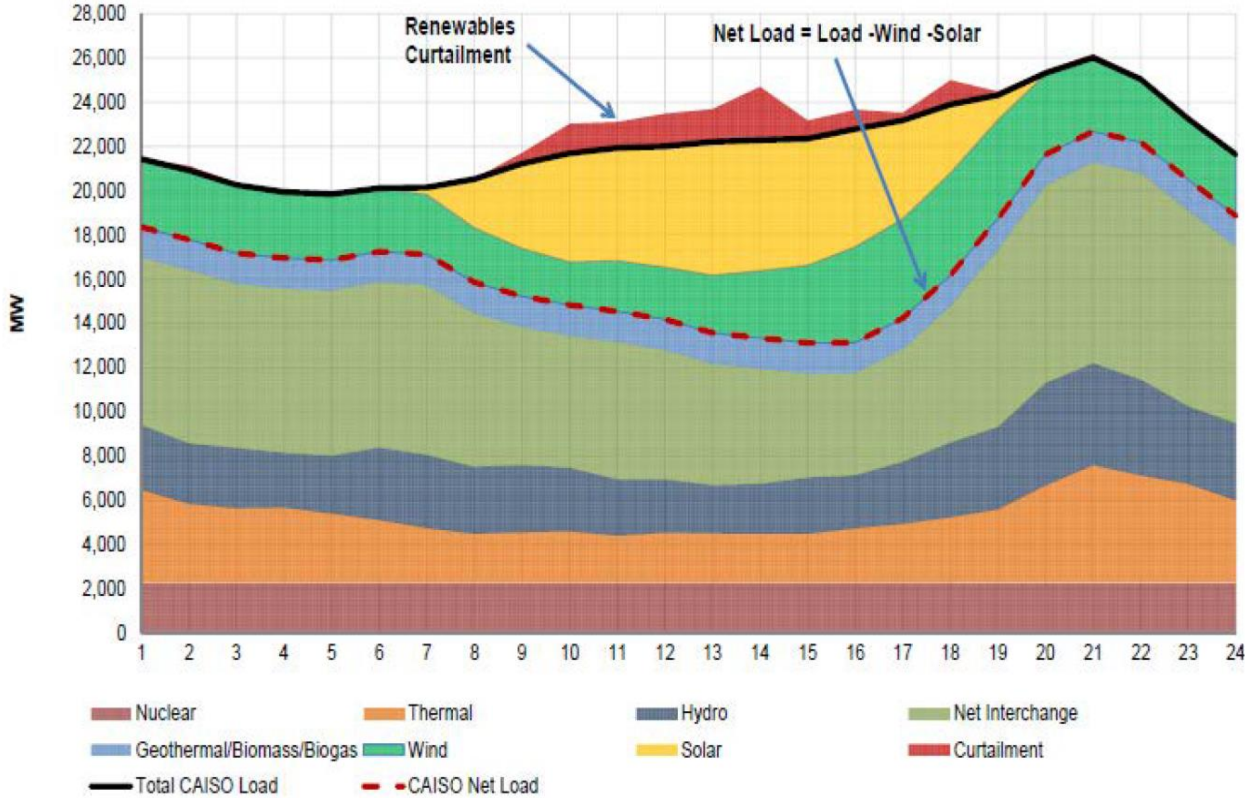


Figure 99. Load profile for California (CAISO) on April 24th 2016. Also shown are the different contributors (Loutan et al., 2017).

Special importance in integrating more solar falls under the ability of the electricity grid to react flexibly to demand. A grid that is capable to more flexibly regulate the generation of other contributors can reduce generation during times when more solar power is available. The benefits of such an operation are displayed illustratively in Figure 100. Without regulating thermal generation, PV electricity is curtailed, especially around noon. In a flexible system, increased generation from PV is anticipated and thermal generation reduced, resulting in much less curtailment.

Figure 100. Grid Flexible Solar

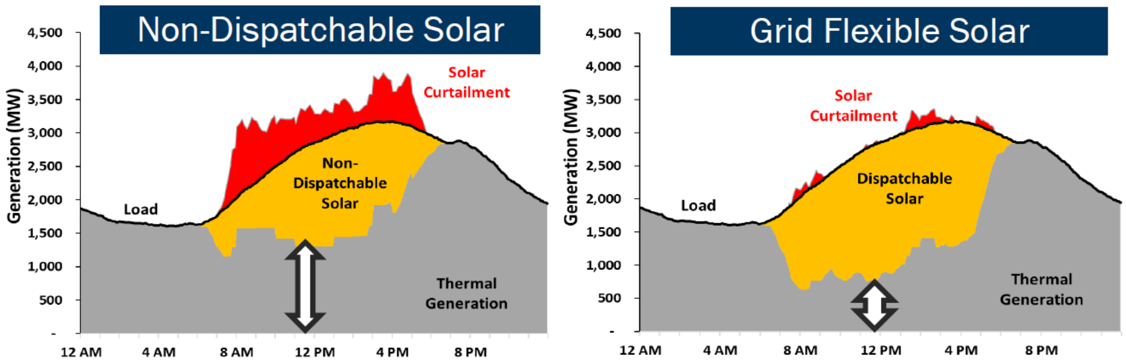


Figure 100. Illustration of how grid flexible solar reduced curtailment and thermal generation around noon (Loutan et al., 2017).

Grid flexible operation is dependent on accurate forecasts of the power generated by PV plants. Thermal generators have reaction times that make an instantaneous regulation impossible. To allow for grid flexibility, ramping of thermal generators has to be planned ahead, requiring forecasts of PV power generation of up to several days ahead (Energy and Environmental Economics, Inc., 2018). **Figure 101** illustrates schematically how forecasting and flexibility interact. The further ahead a forecast is made, the more flexibility exists to regulate the power generation assets in a grid. Yet forecasts of several days ahead also have much higher uncertainty than forecasts that look less far into the future. The tradeoff between flexibility and forecasting accuracy must be managed in a continuous scheme. Furthermore, uncertainties in demand must also be managed. This is typically done by adding a safety margin to the forecasted demand ("headroom"). Conversely, if demand is smaller than predicted it must be possible to turn off overgeneration ("footroom"). The result is a planning scheme in which head- and footroom decrease over time, as forecasting uncertainty decreases.

Figure 101. Power Management Tradeoff

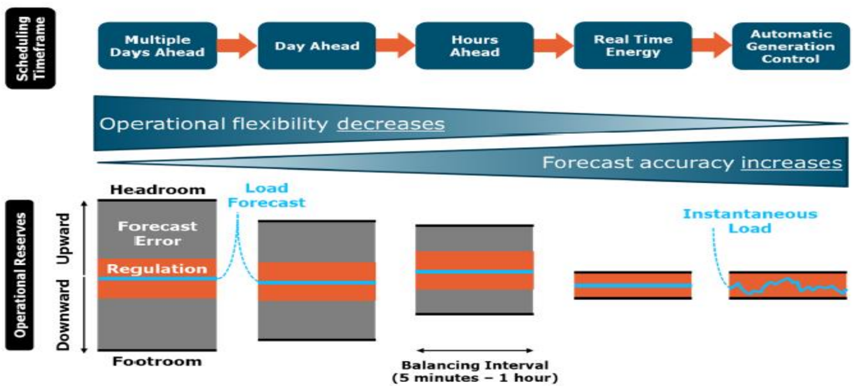


Figure 101. Commitment timeframes, forecast uncertainty, headroom and footroom (Energy and Environmental Economics, Inc., 2018).

The ability of a solar power plant to operate according to demands was tested on a 300MW First Solar PV power plant in California. For the plant to maintain the required regulation range (30MW), the peak power of all the plants' inverters needs to be estimated at any time. Available max power was estimated through maximum power point tracking of one of the eighty inverters. The measured AC power of the single inverter was taken as an indicator of the power available in the remaining 79. The plants ability to respond was tested on several times during the day. As an example, performance during the morning testing period is shown in Figure 102. The response whenever a new requirement for generation was set was close to immediate (compare red and yellow curves). However, this high precision could not be achieved on all occasions. In some cases, most likely, the internal ramp rate of individual inverters limited the response time of the system. Overall, results show PV power plants are well capable to support stability and reliability in a grid. The measured accuracy of the PV plant (87%) were better even than those of fast gas turbines (63%), and hydro or combined cycle plants (47%).

Figure 102. Automated Generation Control

Figure 102. Experimental validation of automated generation control (AGC). The figure shows the power output profile of a First Solar 300MW power plant with CAISOs footprint on August 24th 2016 between 9:47 and 10:10 (Loutan et al., 2017).

While grid flexibility will support the integration of solar PV into the grid, it is not sufficient to achieve the ambitious deployment targets for carbon neutrality. To achieve these targets, grid flexibility must be combined with additional measures like grid extensions and electricity storage. Adding storage is a very attractive option, as storage allows to shift generated electricity freely to other times of the day or year. Storage, hence, can make PV electricity fully dispatchable. While storage has the capability to achieve dispatchability by itself, a solution based on only storage is likely not practical due to the vast amounts of capacity required for shifts that exceed a couple of hours. How storage supports PV deployment is schematically sketched in Figure 103 (Morjaria, 2018).

Figure 103. Solar Energy Grid Services

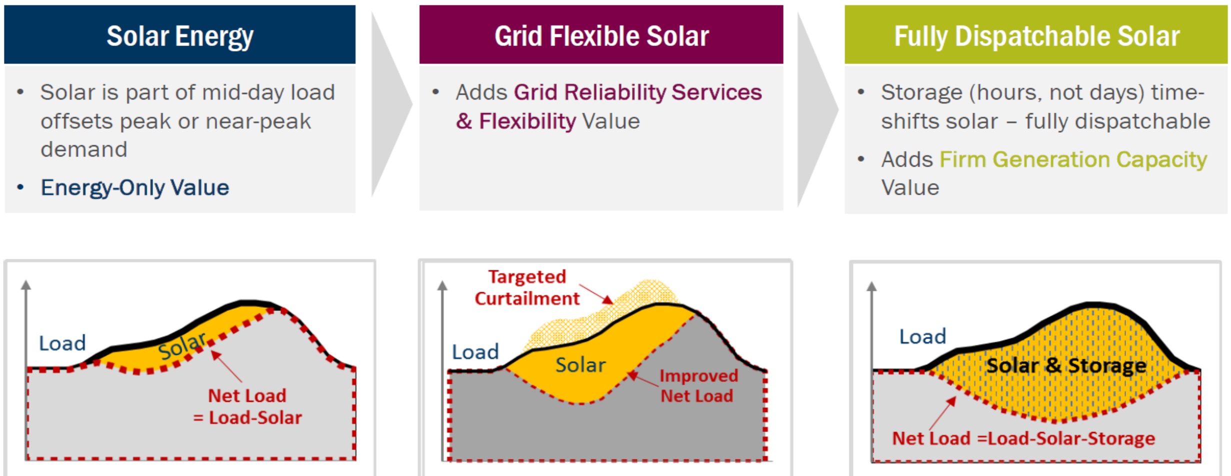


Figure 103. Progressing from simple PV deployment over grid flexible solar to fully dispatchable solar. (Morjaria, 2018).

Future growth in the solar industry will likely be influenced by parallel developments in related industries such as battery storage and electric mobility, where cars include batteries that store energy to meet transportation needs. Electricity can be stored in various ways; examples are pumped hydro, flywheels, compressed air or batteries. Battery storage has the advantage of being freely scalable and independent of geographic conditions (the main limitations for pumped hydro and compressed air). As indicated in **Figure 103**, a combination of grid flexibility and battery storage should be capable of greatly extending the ability of the grid to integrate solar PV. Significant extensions in solar adoption should be possible without extending the need for battery storage beyond a couple of hours' worth of capacity. California has begun using PVS systems to meet the demand during peak hours (Roy et al., 2020). The battery storage technologies are still being innovated with rapid learning curves and declining battery costs expected.

V.B.1 - Cost of PVS

Battery storage systems increase the dispatchability of PV systems to levels comparable to gas-peaker systems. Battery storage costs greatly impact the output cost for power, LCOE. To compare both the performance and cost of power generation systems, lifetime cost of operation (LCOO) can be used to measure PVS systems in comparison with gas-peaker plants. LCOO factors in the installation, maintenance, and operation cost over a target period window.

The target period capacity factor (TPCF) can be used to measure the dispatchability of PVS systems during peak demand hours. For example, a 50 MWac PV system with a 60 MW/240 MWh battery (3 hour storage) deployed in the U.S. Southwest can achieve a TPCF of 98%, thereby displacing a 70 MW combustion turbine plant (Roy et al., 2020). This PVS system also has an 8% LCOO advantage over natural gas turbine plants as seen in **Table 9**.

Table 9. Lifecycle Cost of Operation Comparison

S No.	Cost Parameter	50 MW$_{AC}$ PV-60 MW/240 MWh BESS AC-Coupled PVS	70 MW Conventional Combustion Turbine (CT) [1]
1	Plant Lifetime	20	20
2	Target Period Capacity Factor (HE18–HE20)	98.5%	95%
3	Total System Installed Costs (2018 $)	$132M	$79M
4	Lifetime Fixed O&M Costs [2]	$19.6M	$43.8M
5	BESS Extended Warranty Payment at $2/kWh/year [3]	$10.8M	-
6	Lifetime Variable O&M Costs	-	$3.1M
7	Lifetime Cost of Fuel with 1% price escalation [4]	-	$21M
8	Total Lifecycle Cost of Operation with 30% ITC + Fuel Costs [5] [3*] [6] + [4] + [5] + [6] + [7]	$122.8M	$146.9M

Table 9. LCOO of PVS and Gas Combustion Turbine in the U.S. Southwest (Roy et al., 2020).

When including environmental costs as a fiscal cost, a mid-range value for one metric ton of GHG emissions is $46 (Gillingham & Stock, 2018). If monetized through a carbon tax or other financial instrument, this social cost provides PVS an additional significant advantage over gas-peaker systems. A gas plant LCOO is substantially higher when considering environmental costs as seen in **Figure 104**.

Figure 104. PVS and CT Cost Comparison

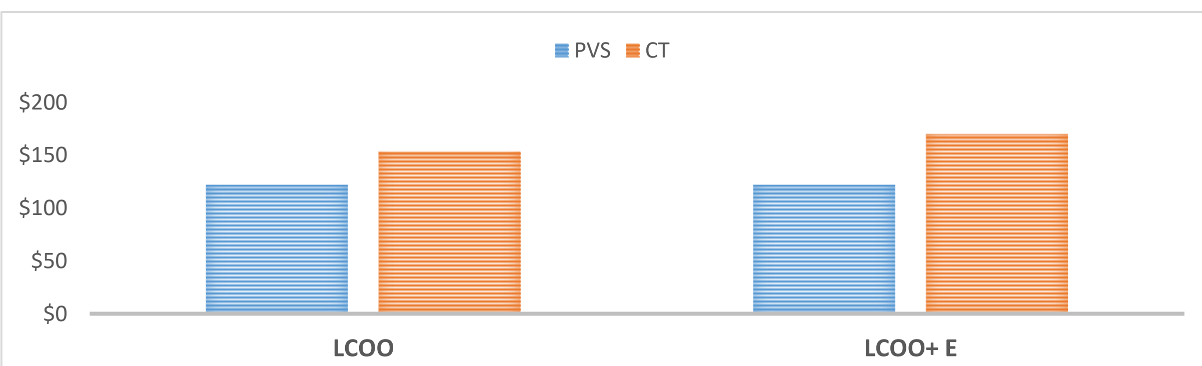


Figure 104. LCOO comparison between PVS and conventional gas combustion turbine (in M$) without and with environmental costs (Roy et al., 2020).

V.B.2 - Battery Development

Battery technology is one of the fastest developing research fields with relevance to renewable energies and photovoltaics. A complete overview of current developments is beyond the scope of this report, but a few results shall be highlighted. Battery development is driven predominantly by electromobility (EM), yet there are important innovations also being developed for stationary battery storage, especially in the field of Li-ion and flow batteries.

Kittner et al. (2017) explore how batteries have developed and could support renewable energies. The study looks at learning rates of lithium ion batteries to explore innovation and predict future trends. One-factor learning curves for different metrics are shown in **Figure 105**.

Figure 105. Battery Storage Technology Development

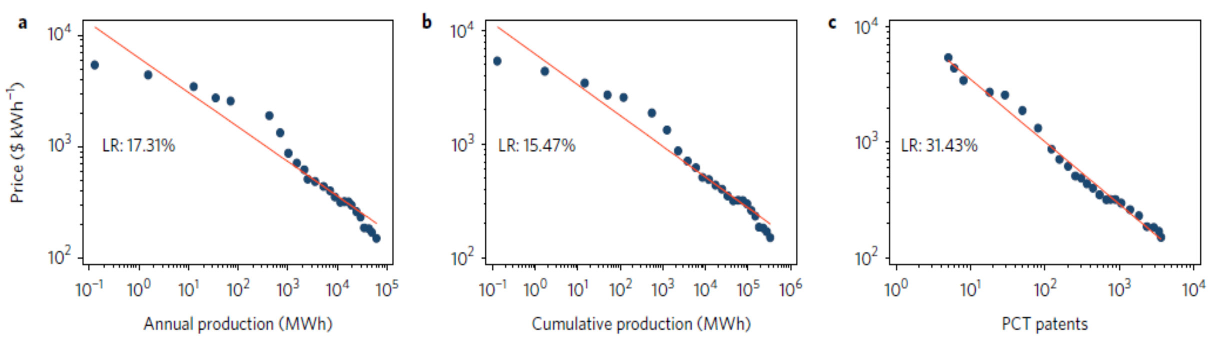


Figure 105. One-factor learning curves for lithium-ion battery storage. Left - Shows a learning rate of 17.3% for economies of scale. Center - The experience curve has a rate of 15.5%. Right - Patents rate is 31.4%. PCT stands for Patent Cooperation Treaty. Prices are given in 2015 USD (Kittner et al., 2017).

The study highlights the importance of reducing costs for broader adoption of batteries. Achievable cost reductions are evaluated differently, with this study providing comparably low values and other studies (Ziegler et al., 2019) being more conservative. The emphasis on cost reflects the fact that cost remains the single most important factor when it comes to a more widespread adoption of batteries in stationary applications. At 100$/kWh, battery storage becomes economically attractive to support distributed PV generation, yet the price pressure is higher for stationary applications than for electric vehicles. For this reason, as the study warns, battery development for stationary storage applications may continue to lag. To improve here, the authors recommend developing research strategies that consider a closer integration of electric vehicles into the power grid. As the fraction of electric vehicles in the total transportation fleet increases, they will likely become, first, a place to store renewable energy that would otherwise be curtailed and, later, if vehicle-to-grid technologies are developed, a source of renewable energy for the grid during peak periods.

While cost reductions are the most important factor to increase the adoption of batteries, other factors like legal and regulatory frameworks are also identified as playing a significant role. The authors recommend the development of a dedicated, multidisciplinary research strategy to address the societal and economic challenges of batteries.

C – U.S. Manufacturing Competitiveness and Employment

U.S. PV manufacturers face strong global competition. U.S. PV production is modest compared to global manufacturers seen in **Figure 106**. In 2017, North America produced 3.7% of the 100 GW worldwide total (Fraunhofer, 2019). Competing with Asian PV manufacturing counterparts requires U.S. manufacturers to match or exceed cost per watt and efficiency benchmarks.

Cost advantages historically achieved by Chinese manufacturers have been shown to be driven primarily by scale and supply chain development, rather than intrinsic regional factors (Goodrich et al., 2013). In China, access to low-cost capital has enabled rapid scaling of manufacturing capacity, with associated economies of scale and increase in supply chain leverage.

In the U.S., First Solar has constructed two GW-scale factories in Ohio (total of 1.9 GW) for Series 6 module manufacturing. Combined with multi-GW-scale factories in Malaysia and Vietnam, as well as additional planned growth, the combined scale of global CdTe PV manufacturing capacity is approaching 8 GW annually, in order to remain competitive with global competition.

Figure 106. PV Production by Type and Region

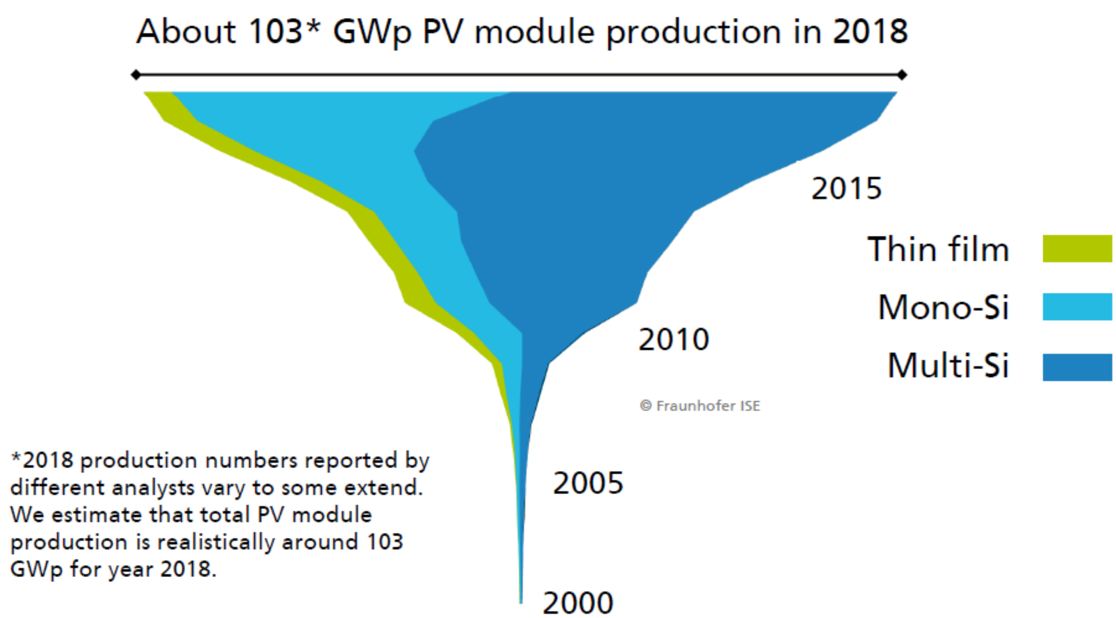


Figure 106A. Total annual PV module production type from 2000 – 2017 (Fraunhofer, 2019).

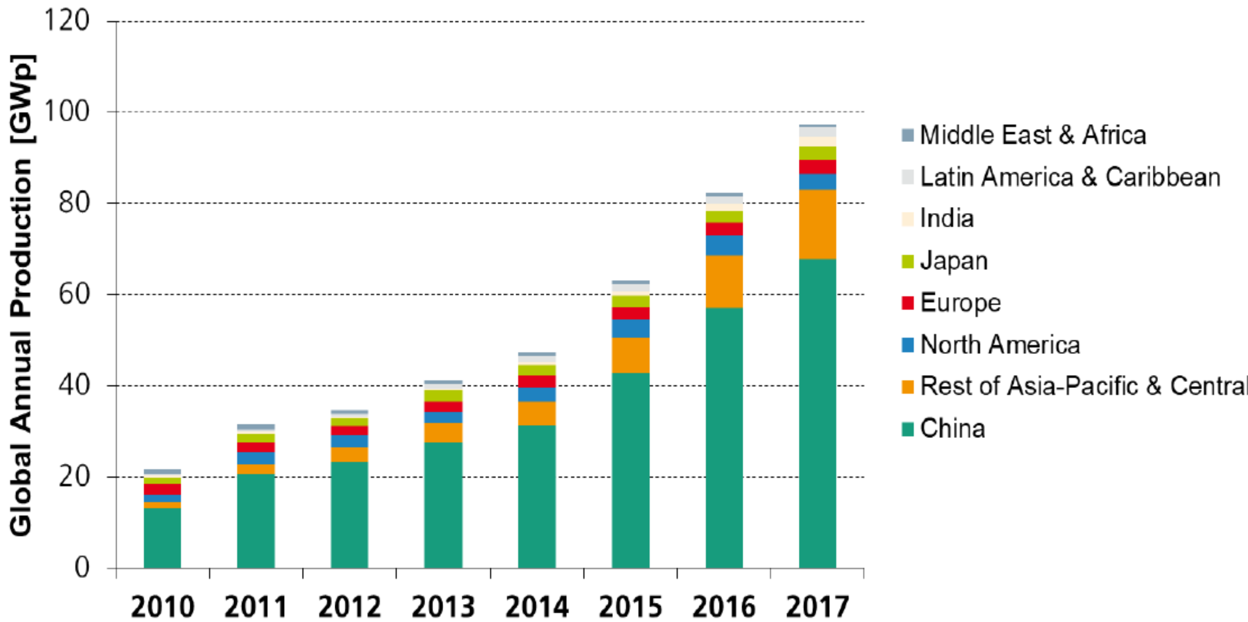


Figure 106B. PV module production from 2010-2017 (Fraunhofer, 2019).

The solar industry employs 242,000 people throughout manufacturing, construction, operation and maintenance, and recycling product life cycle in the U.S. (The Solar Foundation, 2018). The industry has seen a relatively continual growth in employment, although the short-term and long-term implications of the coronavirus pandemic remain unclear. Globally, the PV industry has had a compound annual growth rate of 36.8% in installation from 2010 to 2018 (Fraunhofer, 2019). Within the U.S., the utility-scale sector employs about 14% of the total solar workforce, yet it accounts for the majority of solar deployment (**Figure 107**). Long-term job growth in the solar industry over the past decade was primarily due to the falling costs of solar energy, which has been largely driven by the utility-scale segment. Scaling production in the utility-scale PV segment allows for more rapid grid penetration of solar energy due to economies of scale and grid integration capabilities (see the grid integration section **V.B**). Projected growth in utility-scale PV installations are the largest contributors to sector growth as shown in **Figure 107** (NREL, 2019).

In addition to direct employment, the solar industry contributes to indirect employment through its supply chain. For example, in 2017, First Solar spent approximately $1.95 billion on its global supply chain (manufacturing bill of materials, project spend, capital spend and indirect expenses). In total, direct and indirect employment corresponds to over 30,000 direct, indirect and induced jobs across First Solar and its supply chain worldwide. Approximately $917 million or 47 percent was spent on local suppliers in the U.S. to support module manufacturing operations and solar project development (First Solar, 2018).

Since 2010 First Solar has spent over $1 billion on research and development.

Figure 107. PV Installation Projections Through 2024

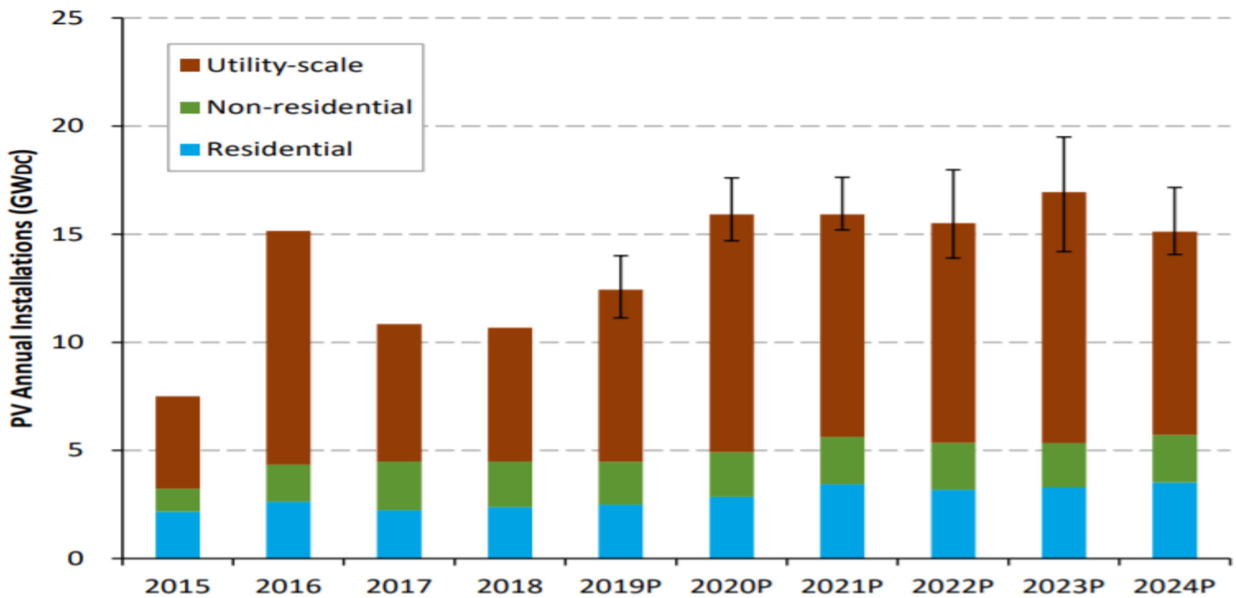


Figure 107. Annual PV Demand Projections (National Renewable Energy Laboratory, 2019).

D - Energy Access

Electricity access has become an essential component to modern daily life, work, and business throughout most of the world. Whether it is using power for daily needs or contributing to the economy, providing reliable energy access remains a challenge for a 2-3 billion people globally whose access to power from the grid is unreliable, and 1 billion people who had no access to the electric grid in 2018 (IEA, 2019c). These challenges will only grow as the push for carbon-neutral energy encourages electrification of transportation, industrial, commercial, and household uses of energy currently provided by carbon-based fuels.

Solar energy is a uniquely scalable technology, ranging from individual solar powered devices (W-scale) to residential (kW-scale), commercial (kW-to-MW-scale), and utility-scale (MW-scale) systems. While traditional grid-connected applications comprise the vast majority of applications, solar energy is also being used to provide energy access where there is no grid, or to redefine traditional central grids with distributed microgrids. Solar energy for rural and remote locations is generally significantly less costly than extending transmission and distributions lines into low income or rural population areas. In other areas, geographic barriers, such as mountainous terrain, can make extending the grid even more costly.

Energy access involves both technical and business-model innovation. On the business model side of the equation, low-income communities often do not provide attractive investment opportunities, and poorly designed business models can lead either to lack of payment for electricity or payments that exceed affordability and so exacerbate poverty. Critical to solving these problems is to design energy access projects so that they deliver high levels of social and economic value for energy users (Miller et al., 2015). This requires adopting user-centered and community co-production approaches in the design of energy technologies and projects that allow for systems to enhance the productive use of energy and to create positive feedback loops that enhance local economic development and grow local capacity (Miller et al., 2018). Adopting these approaches to project design can help increase the bankability of projects by delivering higher levels of value to remote and rural communities that enables higher repayment rates, reduces theft, and allows for growth of energy use and energy sales over time. If designed properly, electricity access can bring benefits to people through increased local business and employment opportunities, revenue generation, education attainment, and positive health outcomes.

A popular approach to the energy access issue has been the utilization of microgrids, which provide an alternative to centralized grids. Microgrids benefit people living in isolated areas, harsh terrains, or areas impacted by severe weather. Microgrids provide regional power from village-scale to regional-scale, with over 3,700 microgrids already in operation around the world (Bilich et al., 2017). Barriers to microgrids stem from financial burdens, policy challenges, and a lack of skilled technicians to operate a microgrid (Williams et al., 2015). Microgrid implementation in rural areas can provide electricity to underserved areas using multiple energy generation sources.

Current microgrids consist of energy generation systems (PV modules, wind turbines) and energy backup systems (diesel generators, battery banks). The adoption of these systems provides rural populations enough power to use small appliances such as mobile phones and cooking appliances. In a partnership between First Solar and Powerhive, variations of microgrid systems were tested. The microgrids used PV-Battery, PV-Diesel, and PV-Battery and Diesel systems to understand the life cycle impacts and tradeoffs (Bilich et al., 2017). This study took place in Kenya and each microgrid was evaluated with the parameters listed in Table 10.

Table 10. Microgrid Supporting a Village

Microgrid Parameters	
Village Demographics	100 people/5.7 people per household
Daily Demand Per Household	1.545 kWh/day
Total Daily Demand	27.108 kWh/day
Peak Load Factor	2.69
22 Year Avg Solar Insolation	5.935 kWh/m2day
Microgrid Lifetime	25 years
PV Module Type	CdTe
Battery Chemistry	Li-Ion (nickel-cobalt-manganese)
End Of Life Scenario	Landfill

Table 10. Characteristics of a community solar microgrid (Bilich et al., 2017).

V.D.1 - PV-Battery System

The microgrid composed of a PV energy generation source and battery backup system is dependent on daily solar insolation. Variation in generation resulted in a mismatch of demand and supply where there is a 7% unmet demand found in **Table 11**. This microgrid would supply 93% of all of the demand (Bilich et al., 2017).

V.D.2 - PV-Battery and Diesel System

The microgrid composed of a PV energy generation source and both a backup battery system and diesel generator meets the full electricity demand. Here, a 3.89 kW diesel generator covered electricity demand when the battery was depleted (Bilich et al., 2017).

V.D.3 - PV-Diesel System

The microgrid composed of a PV energy generation source and a 3.3 kW diesel generator had the most inefficient outcomes. The PV system only supplied 22.4% of the electricity demand found in **Table 11**. The diesel generator supplied 77.5% of the electricity demand (Bilich et al., 2017). This system had the highest emissions due to the large dependence on diesel combustion.

Table 11. Microgrid Comparison

Component	PV–battery	PV–hybrid	PV–diesel
solar PV module area (m^2)	42	42	8
BOS area (m^2)	42	42	8
charge controller (units)	7.18	7.18	N/A
batteries mass (kg)	675	675	N/A
unmet demand (%)	7	N/A	N/A
diesel contribution (%)	N/A	7	77.56
electricity from diesel (kWh)	N/A	17,316	191,859
diesel generators (units)	N/A	1	14.3
security fencing length (m)	29	29	12.7
distribution wiring length (m)	702	702	702
residential meters (units)	17.5	17.5	17.5
derate factor	0.743	0.743	0.92
lifetime electricity consumption by the community (kWh)	230,053	247,368	247,368

Table 11. Comparison of hybrid technologies for community PV energy systems (Bilich et al., 2017).

This study highlights the significance of appropriate configurations to meet local electricity demands. Communities can increase the PV generating capacity or battery system to meet current and future demands. The tradeoffs are found in costs and environmental impacts. Burning diesel to generate power will continue if it is there to meet increases in electricity demand. This option has both a cost factor and a larger negative environmental impact. Diesel generators are older technologies that do not require the same skill level PV modules and battery backup systems require. With a 4% increase in diesel-generated electricity, there is a corresponding increase in the per kWh impacts in climate change (29%), particulate matter (35%), photochemical oxidant (46%), terrestrial acidification (29%), and terrestrial ecotoxicity (14%) environmental categories (Bilich et al., 2017). PV-battery microgrids have proportionally lower increases in environmental impacts as more capacity is added to meet electricity demand.

E - Energy Resilience

Distributed solar energy systems and microgrids are becoming more prevalent in areas devastated by natural disasters. With the increase in damages from storms and weather systems, infrastructure and power grids are more vulnerable. With power grid failure, local populations suffer negative lasting effects. There is growing concern that increased climate change will also contribute to higher frequency or intensity storms that increase the vulnerability of the grid, and similar concerns are also on the rise about deliberate cyberattacks directed toward the electricity grid. There is growing interest in the possibility that distributed solar energy systems and solar-powered microgrids might be designed to enhance grid resilience by providing both backup power in the case of loss of grid electricity and the ability to island electricity services. However, one primary challenge to this model is that grid-tied rooftop distributed solar systems generally power down in the case of loss of grid power unless accompanied by a battery system.

One example of interest in the use of solar energy to enhance energy resilience is in Puerto Rico, where Hurricane Maria (Category 5, 2017) caused over 5000 deaths due to mass power outages, food shortages, hospital closures, and electric grid neglect (Bottger, 2018). Since the hurricane, large numbers of people have emigrated to the mainland U.S. (Hinojosa & Melendez, 2018). There is widespread interest among the public and legislators in solar energy, and especially community solar initiatives, to reduce dependency on imported energy. Puerto Rico imports 98% of its energy from U.S. fossil fuel sources, at a cost of $3 billion per year. In 2019, the legislature set a renewable portfolio standard of 100% for 2045, and the electric utility is seeking options to build increased renewable generation into its integrated resource plan. Individual households, businesses, and communities are also looking toward solar energy as a potential option for increasing resilience, too, and there are a number of local solar initiatives underway, even among the poorest communities.

There is growing concern that increased climate change will also contribute to higher frequency or intensity storms that increase the vulnerability of the grid, and similar concerns are also on the rise about deliberate cyberattacks directed toward the electricity grid. There is growing interest in the possibility that distributed solar energy systems and solar-powered microgrids might be designed to enhance grid resilience by providing both backup power in the case of loss of grid electricity and the ability to island electricity services.

VI - CONCLUSION

The U.S. and the globe are in the midst of a large-scale transformation of the energy sector. Solar energy will likely play a significant role in the U.S. energy transition, both in replacing existing electricity generation technologies and as a source of new electricity generation to support the electrification of transportation fleets and industrial processes. As the largest U.S. solar manufacturer, First Solar and its CdTe PV technology already have a significant role in the U.S. energy sector. In the past decade, over one-third of the total manufactured PV modules in the U.S. (2010-2018) were thin film CdTe PV modules (NREL, 2019). The track record of CdTe PV technology has been proven in lab and field performance. The historical performance of CdTe PV technology in terms of energy generation, reliability, environmental benefits and safety in diverse operating climates complements the theoretical findings presented in this report. CdTe PV outperforms other PV technologies and non-renewable energy production sources on a life cycle environmental basis. Solar energy will continue to have positive social and economic impacts in the U.S. as the growth of the CdTe PV industry continues.

Based on our review of CdTe PV competitiveness, product safety throughout its life-cycle, and environmental performance, this technology is expected to make a significant contribution to the U.S. energy transition. These conclusions are drawn on the basis of eco-efficiency as the driver of solar energy adoption, where eco-efficiency is the concept of creating more economic value with lower environmental impacts. The main findings in this report are summarized with respect to the eco-efficiency framework.

Creating economic value: CdTe PV technology is well positioned to contribute significant economic value as part of a low-carbon energy transition. Along with wind and combined cycle natural gas, utility-scale solar energy is the most cost-competitive source of new electricity generation based on levelized cost of energy. To the extent that module prices continue to fall and module efficiencies continue to increase, these economic benefits will continue to grow. To date, CdTe PV efficiency has increased steadily with record cell efficiency of 22.1%, record module efficiency of 19.0%, and average commercial modules of 420-450W (First Solar Series 6).

Innovation in module size and packaging, back contacts, and semiconductor band-gap grading have been used to improve CdTe PV device efficiency, long-term degradation rates, and cost per watt, and additional improvements in efficiency are expected in future CdTe PV technologies. In the future, synergies with battery storage and vehicle electrification are also expected to increase the demand for and integration of solar energy into the grid. Through use of advanced inverters, control systems, energy forecasting, and rapid ramping capabilities, large-scale PV power plants are also able to regulate real and reactive power output to provide grid-flexible operation and provide important grid services. CdTe PV technology is especially suited for hot and humid climates, where it has higher energy yield than crystalline silicon PV due to a lower temperature coefficient and lower spectral sensitivity to infrared light absorption by water vapor.

Creating environmental value: CdTe PV technology is also well positioned to contribute significant environmental value as part of a low-carbon energy transition. Overall, CdTe PV technology has among the lowest greenhouse gas emissions and smallest environmental footprints of any technology. Per unit energy generated, CdTe PV creates significantly lower overall life-cycle environmental impacts than the current U.S. electricity grid. Avoidance of grid electricity greenhouse gas and air pollutant emissions with use of PV electricity amounts to environmental and public health benefits of $20/MWh and $14/MWh, respectively.

Among commercial PV technologies, due to low energy and material use in manufacturing, CdTe PV has the lowest life cycle environmental impacts, including carbon footprint, energy payback time, water use, human health impacts, and ecosystem impacts. Properly designed and constructed solar facilities can have a positive impact on shared uses of land, including increasing agricultural productivity and enhancing biodiversity through revegetation, management of invasive and sensitive species, and preservation of land for alternative future uses. CdTe PV modules are also recyclable, reducing long-term waste from energy generation. First Solar's high-value recycling facilities have been operating commercially for over a decade and are able to recover more than 90% of a CdTe PV module for reuse in new solar modules and glass products. First Solar's global recycling facilities process 20,000-30,000 metric tons of manufacturing scrap and end-of-life PV modules annually.

Health, safety, and reliability improvements: First Solar CdTe PV modules are designed to provide 25+ years of reliable performance. CdTe is sourced as a byproduct of zinc and copper mining. All thin film PV manufacturing steps occur in a single facility, facilitating integrated quality control. Automated, enclosed equipment and air monitoring help ensure industrial hygiene, and worker biomonitoring is used to confirm occupational health. First Solar manufacturing facilities are certified to international standards for quality, environmental management, and occupational health (ISO 9001, ISO 14001, ISO 45001). Product reliability is continuously evaluated through in-line monitoring of production processes, indoor reliability testing with long-term test sequences, outdoor testing in temperate, tropical, and desert climates, and operations and maintenance programs that monitor performance in the field. The semiconductor layers are encapsulated within a 36 kg glass-glass module with encapsulant bond strength on the order of 5 megapascals (~725 pounds/inch2). Experimental data, fate and transport models, and field data from extreme weather events have confirmed the environmental product safety of CdTe PV in case of non-routine events such as field breakage and fire. Although the goal is to recycle all PV modules, standard waste characterization testing and fate and transport modeling have confirmed the environmental product safety of CdTe PV in case of landfill disposal. Strong chemical bonding in CdTe results in high chemical and thermal stability, which are important for long-term device reliability and product safety.

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