**Technical assessment for**

**Utility-scale Solar Photovoltaics**

Sector: Electricity generation

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**Prepared by:**

Anna Goldstein, Research Fellow

Aven Satre-Meloy, Research Fellow

Ashok Mangotra, Research Fellow

João Pedro Gouveia, Senior Research Fellow



[info@drawdown.org](mailto:info@drawdown.org) [www.drawdown.org](http://www.drawdown.org)

Table of Contents

[List of Figures 4](#_Toc10331891)

[List of Tables 4](#_Toc10331892)

[Acronyms and Symbols 5](#_Toc10331893)

[1 Literature Review 8](#_Toc10331894)

[1.1. State of PV technology 8](#_Toc10331895)

[1.2. Definition of Solar Farms 10](#_Toc10331896)

[1.3. Adoption Path 11](#_Toc10331897)

[1.3.1 Current Adoption 11](#_Toc10331898)

[1.3.2 Trends of Accelerating Adoption 12](#_Toc10331899)

[1.3.3 Barriers to Adoption 13](#_Toc10331900)

[1.3.4 Incentives for Adoption 14](#_Toc10331901)

[1.3.5 Adoption Potential 15](#_Toc10331902)

[1.4. Advantages and disadvantages of Solar PV Utility-scale 16](#_Toc10331903)

[1.4.1 Similar Solutions 16](#_Toc10331904)

[1.4.2 Arguments for Adoption 17](#_Toc10331905)

[1.4.3 Additional Benefits 17](#_Toc10331906)

[1.4.4 Drawbacks 18](#_Toc10331907)

[2 Methodology 23](#_Toc10331908)

[2.1 Introduction 23](#_Toc10331909)

[2.2 Data Sources 24](#_Toc10331910)

[2.3 Total Addressable Market 25](#_Toc10331911)

[2.4 Adoption Scenarios 25](#_Toc10331912)

[2.4.1 Reference Case / Current Adoption 27](#_Toc10331913)

[2.4.2 Project Drawdown Scenarios 27](#_Toc10331914)

[2.5 Inputs 28](#_Toc10331915)

[2.5.1 Climate Inputs 28](#_Toc10331916)

[2.5.2 Financial Inputs 29](#_Toc10331917)

[2.5.3 Technical Inputs 32](#_Toc10331918)

[2.6 Assumptions 32](#_Toc10331919)

[2.7 Integration 33](#_Toc10331920)

[2.8 Limitations / Further Developments 33](#_Toc10331921)

[3 Results 35](#_Toc10331922)

[3.1 Adoption 35](#_Toc10331923)

[3.2 Climate Impacts 36](#_Toc10331924)

[3.3 Financial Impacts 38](#_Toc10331925)

[4 Discussion 40](#_Toc10331926)

[4.1 Limitations 40](#_Toc10331927)

[4.2 Benchmarks 41](#_Toc10331928)

[5 References 42](#_Toc10331929)

[6 Glossary 55](#_Toc10331930)

# List of Figures

[Figure 1.1 - Global Cumulative Installed Solar PV capacity (Source: IRENA 2018) 12](#_Toc23606358)

[Figure 1.2 - EROI (%) of PV electricity compared to oil- and coal-fired thermal electricity (Adapted from Raugei et al., 2012) 20](#_Toc23606359)

[Figure 3.1 World Annual Adoption 2015-2060 36](#_Toc23606360)

[Figure 3.2 World AnnualGreenhouse Gas Emissions Reduction 2015-2060 38](#_Toc23606361)

# List of Tables

[Table 1.1 - Conventional versus SPV generation : some key impacts 21](#_Toc534461006)

[Table 2.1 Climate Inputs 29](#_Toc534461007)

[Table 2.2 Financial Inputs for Conventional Technologies 31](#_Toc534461008)

[Table 2.3 Financial Inputs for Solution 31](#_Toc534461009)

[Table 2.4 Technical Inputs Conventional Technologies 32](#_Toc534461010)

[Table 2.5 Technical Inputs Solution 32](#_Toc534461011)

[Table 3.1 World Adoption of the Solution 35](#_Toc534461012)

[Table 3.2 Climate Impacts 37](#_Toc534461013)

[Table 3.3 Impacts on Atmospheric Concentrations of CO2-eq 37](#_Toc534461014)

[Table 3.4 Financial Impacts 39](#_Toc534461015)

[Table 4.1 Benchmarks 41](#_Toc534461016)

# Acronyms and Symbols

* AC - Alternating Current
* A-Si - Amorphous Silicon
* BOS - Balance-Of-System
* C-Si - Crystalline Silicon
* CCS - Carbon Capture and Storage
* Cdte - Cadmium Telluride
* CIGS - Copper Indium Gallium Selenide
* CO2 eqv - Carbon Dioxide equivalent
* CPUC – California Public Utilities Commission
* CPV - Concentrating Photovoltaics
* CSP - Concentrated Solar Power
* DC- Direct Current
* DCF – Discounted Cash Flow
* DOE – Department of Energy (US)
* EIA – Energy Information Administration (US)
* EPBT - Energy Payback Time
* EPIA - European Photovoltaic Industry Association
* EROI – Energy Returned on Energy Invested
* ETOI - Energy Return On Investment
* ETP – Energy Technology Perspectives
* EV – Electric Vehicles
* GaAs – Gallium Arsenide
* GHG – Greenhouse Gases Emissions
* GTM - Greentech Media
* GW - Gigawatts
* IEA - International Energy Agency’s
* IEEJ – The Institute of Energy Economics, Japan
* IPCC – Intergovernmental Panel on Climate Change
* IRENA – International Renewable Energy Agency
* ISE – Fraunhofer Institute for Solar Energy Systems
* ITRPV – International technology Roadmap for Photovoltaic
* kW – Kilowatt
* kWp – Kilowatt (Peak)
* LBNL- Lawrence Berkeley National Laboratory
* LCA – Life Cycle Assessment
* LCOE - Levelized Cost of Electricity
* LED – Light Emitting Diode
* LUT -Lappeenranta University of Technology
* MIT – Massachusetts Institute of Technology
* MWp – Megawatt (Peak)
* NAFU -Net Annual Functional Units
* NAIU -Net Annual Implementation Units
* MW – Megawatt
* NOx - Nitrogen Oxides
* NPV – Net Present Value
* NREL - National Renewable Energy Laboratory (US)
* O&M - Operation and Maintenance
* OECD – Organization for Economic Co-operation and Development
* PD – Project Drawdown
* PDS - Project Drawdown Scenario
* PM2.5 - Particular Matter ( 2.5µm)
* PPA - Power Purchase Agreement
* PPB – Parts Per Billion
* PPM – Parts Per Million
* PSCs - Perovskite Solar Cells
* PV – Photovoltaic
* PVPS – Photovoltaic Power Systems Program (IEA)
* REF – Reference Case
* REmap – Renewable Energy Roadmap (IRENA)
* REN21 – Renewable Energy Policy Network for the 21st century
* RPO – Renewable Purchase Obligation
* RRS – Reduction and Replacement Solutions
* SEIA - Solar Energy Industries Association
* SO2 - Sulfur Dioxide
* SPV – Solar Photovoltaic
* TAM - Total Addressable Market
* TWh - Terawatt-Hours
* USD – United States Dollars
* WEO – World Energy Outlook (IEA)

Executive Summary

Project Drawdown defines “*Utility Scale Solar Phtovoltaics”* as a grid-connected utility-scale solar photovoltaic (SPV) powerplant having a capacity of over 1MW. Since 2010, the solar photovoltaic (SPV) market has grown rapidly - 398 gigawatts (GW) of total solar PV generation capacity has been installed worldwide till the end of 2017. In many markets, the newly installed capacity is coming primarily from utility-scale installations rather than from distributed systems. As a result, ambitious projections are now being made on higher adoption of renewable energy for power generation. Some recent scenarios have even predicted almost 60% of global electricity generation to come from solar energy by 2050.

The initial investment costs for SPV projects have been fallen dramatically over the last few years. As a result, new large solar PV based plants are constantly offering lower tariffs - sometimes even falling below conventional tariffs. As a result, more optimistic power scenarios are being painted with an ever-increasing share coming from the Solar Farms solution. To capture the appropriate level of the investment decision making agency, the solar PV market has been split between the two components of i) *Distributed Solar PV* (the agency here being the households and building owners) and ii) *Utility Scale Solar PV* (the agency for this solution being the utility which generates and supplies the electricity). The size of the total market available for being catered to by the solution is captured in the concept of the Total Addressable Market (TAM). In Project Drawdown, the size of TAM is arrived at by projecting the global electricity generation (in TWh) for the period from 2020 to 2050. How much of this market is actually fulfilled by this solution would depend on the level of ‘Adoption’ of this solution by the market. The current global adoption level of SPV generation (Rooftop plus Solar Farms) for 2018 has been estimated to be 457 TWh. With no definitive estimation of the break down between the two components, it has been assumed on the basis of historical data that rooftop generation would account for around 40 percent of the total market, while utility-scale solar PV would account for the remaining 60 percent.

Impacts of increased adoption of *utility scale solar PV* from 2020 to 2050 have been generated from the use of the RRS (Reduction and Replacement Solutions) Model based on three different growth scenarios compared to a *Reference*Scenario in which the market share of solar farms is fixed at the current levels. These three scenarios have been developed as: i) *Plausible* scenario which is based on the evaluation of adoption trajectories of five optimistic scenarios: IEA (2017) Energy Technology Perspectives 2DS and B2DS scenarios; IEA (2018) World Energy Outlook SDS; IRENA (2018d) REmap Case scenario; and Grantham Institute and Carbon Tracker (2017) Strong PV Scenario using a high growth trajectory. *Drawdown* and *Optimum* Scenarios are derived from three 100% RES scenarios of electricity generation by 2050, being Greenpeace (2015) Advanced Energy [R]evolution Scenario; Ram *et al.* (2019) scenario and Ecofys (2018) 1.5ºC scenario following a medium growth.

Results from the three modeled scenarios compared with the *Reference* scenario allow the estimation of climate and financial impacts of increased adoption of utility-scale PV systems. *Plausible* scenario presents a reduction of 43.5 Gt CO2e emissions, with negative US$269.7 of marginal first costs but with over US$5.1 trillion of net operating savings projected over the same period (2020-2050), principally because utility-scale PV does not require any fuel to operate. This allows for savings to start accruing from the first year of *Plausible* Scenario adoption itself. Both *Drawdown* and *Optimum* scenarios have similar savings among them with negative US$1.5 trillion in marginal first costs but with very significant savings with close to US$13.6 trillion in net operating cost savings over the period from 2020 to 2050. *Drawdown* considers 119.6Gt CO2e reduced emissions while in the *Optimum* this value is 118.1 Gt CO2e. The capital costs for *Plausible* adoption of the solution will require significant investments, as the cumulative capital costs are just over US$3 trillion and US$5 trillion for the other two PD scenarios. Given the recent history of capacity creation in the solar farms sector, it should come as no surprise if even the ambitious scenarios are overtaken in the future. However, it needs to be kept in mind that there are significant investment costs associated with the accelerated adoption of the solution. But, at the same time, it also becomes an opportunity to generate wealth and economic growth for nations, as the returns on these investments can also be fairly substantial.

# Literature Review

## State of PV technology

Sunlight is the origin of many of the primary energy sources on our planet. It is the sun which powers the process of photosynthesis and this becomes the driving force behind all fossil fuels and biofuels. Sunlight heats up the oceans and the air, thus creating the forces of wind and wave power.

The technology that allows us to convert energy from sunlight directly into electricity is called photovoltaics (PV). The photovoltaic effect was first discovered by Becquerel in 1839 (Perlin, 2004). When sunlight falls on a solar cell, it knocks off electrons from the semiconductor material in the cell. These electrons can travel across a positive-negative junction thus producing an electric current which can be used directly to power an external load or can be stored for later use.

It was only after the first silicon cell was created at Bell Labs in 1954 that this technology started to be developed (Perlin, 2004). PV cells convert solar irradiance into electricity by separating charges across a junction between two semiconducting layers. For making silicon solar cells, manufacturers undertake a process called “doping” and add slight amounts of positive and negative charges to the top and bottom layers of the junction as silicon on its own is a poor conductor of electricity. As sunlight falls on the solar cell, electrons flow across the junction and this generates electricity.

PV cells are wired together in series to form a module, and the modules are wired in parallel to form strings and larger arrays. Each PV cell generates only direct current (DC). This is then passed through an inverter to produce an alternating current (AC) - the usable form in which it is delivered to businesses and residences. PV systems are typically set up in two main ways: i) several panels can be installed on rooftops by homeowners and businesses, or ii) hundreds of panels can be installed in a large array by an electric utility. This present report is concerned largely with the second type of system i.e. utility-scale PV systems When discussing different types of module technologies, the term SPV necessarily includes all PV systems, as the underlying technology of both the rooftop and utility-scale PV systems is the same.

While there are many different types of PV cells under production, crystalline silicon PV cells are by far the most common, with over 90 percent of the market share (ITRPV, 2018). These devices are made using either monocrystalline or multi-crystalline wafers of silicon, which accounted for 27 percent and 62 percent of the PV market, respectively (Fraunhofer, ISE, 2018). The rest of the market is primarily with thin-film PV cells, which can be made of cadmium telluride (CdTe), copper indium gallium selenide (CIGS) or amorphous silicon (a-Si) (MIT, 2015). The chief advantage of thin-film cells is the lower material requirement, though this has been less advantageous in recent years due to a dramatic decline in the market price of silicon. Other types of PV cells, such as GaAs and multi-junction cells, are more expensive to produce and are primarily used in niche applications like satellites and spacecrafts. Other PV architectures that have been emerging from ongoing research efforts are the organic PV, quantum dot PV, and dye-sensitized PV, etc. Most recently, the perovskite solar cells (PSCs) have captured the attention of researchers as their efficiency has rapidly grown over the past six years from 4 percent to 20 percent, nearing that of commercial monocrystalline silicon cells, and researchers are optimistic that their performance gains can continue to rise further (Ibn-Mohammed, 2017). PSCs are an exciting development in PV research because they have low production costs and have efficiencies that are competitive with the best cells on the market (Green, 2014). While this research shows promise, it is still a nascent technology, and the long-term stability of PSCs yet remains to be proven (Gunther, 2015).

Depending on their design, different types of PV technologies vary greatly in how efficiently they can convert light into electricity. The U.S. National Renewable Energy Laboratory (NREL) in Golden, Colorado, tests PV cells to determine their efficiency under standardized conditions. They also publish a chart of the latest research-cell efficiencies, which can be seen in (NREL, 2017). The NREL data shows that the efficiency of state-of-the-art silicon cells is around 27 percent, though the typical efficiency of a commercial cell is between 15-18 percent.

The efficiency of a PV cell determines the system’s rated capacity, also known as its peak capacity, nameplate capacity, or nominal power. This value is reported in units of kW (sometimes kWp) for “peak kilowatt”), megawatts (MW), or gigawatts (GW), depending on the size of the system. A system’s capacity is calculated by using the following equation:

Eq (1)

where:

* is the efficiency of the panel.
* is the total panel area.
* is 1000 W/m2, approximate irradiance equivalent to sunshine at noon on a clear day.

PV systems are produced with a single capacity rating, but the amount of electricity actually produced by a PV system over the course of a year depends on several factors. First, electricity generated is proportional to the intensity of the sunlight it receives. This irradiance varies widely depending on geographic location, time of the day, weather conditions, etc. The ideal solar sites are located in equatorial regions of the world, as have been mapped by the online Global Solar Atlas (SolarGIS, 2018). Areas that are cloudier or are located at higher latitudes get less direct sunlight and have correspondingly lower generation potentials. Even so, PV technology has been readily adopted even in countries such as Germany with receive relatively lower irradiance.

Second, PV systems produce varying amounts of power depending on the angle of the panel relative to the sun. One of the primary differences between utility-scale arrays and rooftop installations is that panels in utility-scale arrays are often mounted with one or two axes of rotation for tracking the path of the sun through the sky. Single or dual-axis tracking greatly increases the electricity yield from a panel, in some studies showing an increase of 20-40 percent over fixed-tilt arrays (Vieira, 2016).

The amount of power a PV system produces is measured using its capacity factor, which is the ratio of the power that a panel actually generates to its maximum possible generation capacity. Capacity factor is also sometimes stated in units of “full load hours,” which can be divided by 8760 (the number of hours in a year) to arrive at a percentage factor. Utility-scale PV systems tend to have a capacity factor of 15-25 percent globally (REN21, 2016), with higher capacity factors in the summer and lower in the winter. The capacity factors of utility-scale PV installations are much lower than that of conventional, fuel-based power sources because PV systems can only operate during daylight hours. In this report, PV capacity is referred to both in terms of gigawatts (GW) or terawatts (TW) and solar PV electricity energy generation in terms of in terawatt-hours (TWh).

## Definition of Solar Farms

At present, there is no uniform benchmark to categorize an SPV system as a “Solar Farm”. NREL in their PV systems benchmark for 2017(Q1) has categorized all ground-mounted systems (fixed-tilt and one-axis tracker) above 2MW as “Utility-Scale” systems (NREL, 2017b)). The IEA categorizes systems above 1MW mounted on buildings or directly on the ground as Utility Scale. While the U.S.-based Solar Energy Industries Association (SEIA) and Greentech Media (GTM) define utility-scale as projects that are owned by or sell directly to a utility, the Lawrence Berkeley National Laboratory (LBNL) defines utility-scale as any ground-mounted solar project that is larger than 5 MW (Bolinger, 2015) has an exclusive scheme for development of Solar Farms where these are conceived as a concentrated zone of development of solar power generation projects in which developers are provided with the requisite infrastructure. Here, each solar farm has a capacity of 500MW and above (MNRE, 2016).

Added to this lack of a uniform benchmark for categorization of systems according to their size, there is another divergent issue in this field. While both rooftop and utility-scale PV systems can be made up of modules of either thin-film or crystalline silicon (c-Si) solar cells, the primary factor that distinguishes the two is the overall size of the system. Finding consistency in the literature on what system size constitutes “utility-scale” is difficult because different organizations use different definitions. In view of this lack of uniformity, for the purpose of project Drawdown, a “Solar Farms” (i.e. the solution) follows the International Energy Agency’s (IEA) classification of any PV system which has a rating greater than 1 MW and one which is grid-connected. The advantage of adopting such a classification is that it allows the projection of future growth of utility-scale solar PV on a scale which is consistent with the IEA’s own projections for the global solar sector as a whole (IEA, 2018).

## Adoption Path

### 1.3.1 Current Adoption

Current adoption[[1]](#footnote-1) for solar PV farms is estimated at only 0.5 percent (113 terawatt-hours) of total electricity generation (IEA, 2018), while fossil fuels still represent the lion’s share of electricity generation (natural gas 22%, coal 38.7%, and oil 4.74%). By the end of 2017, the SPV industry was booming with a total installed capacity of 386 GW. In all, the world had a cumulative installed PV capacity of 170 GW by the end of 2014 and this rose to 292 GW by the end of 2016, most of which was installed in only the previous three years as may be seen from the chart below (Figure 1.1). This growth trend has kept its pace, and 2017 was an amazing year for global solar power with capacity addition growing by 32 percent adding almost 95 GW during the year (IEA, 2018). The top five markets internationally in terms of annual capacity additions were China, US, India, Japan and Germany, and these five countries together with the UK and Italy represented over 80% percent of the global installed capacity (IRENA, 2018). China is the global leader with an installed capacity of 131 MW. The top 10 list of countries on the basis of annual installed capacity in 2017 included four Asian nations (China, Japan, India, and Korea) compared to three European nations (UK, Germany, and France) (BP, 2018). In the Americas, though there has been a slow-down in the US market, Brazil and Chile have made notable progress adding over 1 GW and 0.5 GW respectively in 2017. Global investments in solar energy have outstripped investments in all other forms of renewable energy.

Figure 1.1 - Global Cumulative Installed Solar PV capacity (Source: IRENA 2018)

Though the IEA and other international research agencies do not usually publish installed capacities separately for utility-scale and rooftop PV figures, some organizations are now starting to do so reflecting the growth in both these sub-sectors. There are trends which indicate that most of the major capacity developments in emerging markets are coming from utility-scale PV systems. For instance, the IEA Photovoltaic Power Systems Programme (PVPS) reports in “2018: Snapshot of Global Photovoltaic Markets” that centralized PV now represents more than 50 percent of the global market driven mainly by growth in China, the USA, and other emerging PV markets. Especially given that large-scale installations are typically less expensive (on a per unit basis) than small-scale or rooftop PV systems, many countries are choosing to add bulk solar capacity mainly through centralized PV installations (IEA-PVPS, 2018a).

### 1.3.2 Trends of Accelerating Adoption

One of the primary sources of data relating to renewable energy for this work have been the various reports and documents brought out by the International Renewable Energy Agency (IRENA) which has come to be considered a repository of renewable energy-related data. It has recently come out with its 2018 statistics report which gives country-wise and region-wise capacity/generation data, etc. (IRENA, 2018). IRENA has also painted its own scenario “A Roadmap to 2050” which projects an increase in global SPV generation capacity from 223 GW in 2017 to 7122 GW by 2050 (IRENA, 2018d).

The International Energy Agency has come out with its latest World Energy Outlook - 2018 which has a special focus on electricity and the transformation taking place within the global power sector. This annual publication is often felt to be the “gold standard” for global energy related data. Since the 2018 volume has electricity as its theme, it provides up-to-date information on matters related to our solution. Apart from being a data-mine, it also paints three future scenarios of the paths our energy sector will take over the period between now and 2040 (IEA, 2018). The first is the Current Policies Scenario which is business-as-usual scenario based on current laws and regulations without any major changes. It sees SPV generating 2956 TWh by 2040. The next is the New Policies Scenario which sees SPV increasing its generation to 3839 TWh by 2040. The most ambitious is the Sustainable Development Scenario which is intended to keep the global temperature rise to well below 2°C. It forecasts a 15-fold increase in electricity generation through SPV from 435 TWh in 2017 to 6409 GWh by 2040.

The energy major Shell has also put out its Sky Scenario which outlines a route which, if followed, will limit global temperature rise to within the Paris Agreement ordained 2°C. It forecasts a five-fold increase from SPV generation form 241 TWh by 2015 to 1351 TWh by 2040 (Shell, 2018). The Grantham Institute at Imperial College in partnership with Carbon Tracker makes an ambitious projection that SPV could supply 23% of global power generation by 2050 entirely phasing out coal and leaving natural gas with just 1% of the market share (Sussams, 2017). National Renewable Energy Laboratory (NREL)’s Electrification Futures Study and the US Energy Information Administration (EIA’s Energy Outlook 2017 (EIA, 2018) also provide valuable foresight into the future of SPV, especially in the US.

The startling pace of PV adoption globally has come as a surprise to most organizations including the IEA and the U.S. Energy Information Administration. Many organizations such as these have been inclined to raise their estimates for future PV growth with each successive report, as the ground reality of the market growth rates for both solar PV and concentrated solar power (CSP) have outpaced previous estimates. Even the U.S. Department of Energy’s “SunShot” scenario of 2012 (EERE, 2016) seems to have seriously underestimated growth of the solar market—it predicted only 302 GW of SPV capacity for 2030, which would actually represent a major slowdown on the current adoption path since the global capacity has already reached 435 GW by 2017 (IEA, 2018). Be that as it may, all experts are agreed that the growth rate for SPV, and especially for the solution, solar farms will continue to be quite high for the future as well.

### 1.3.3 Barriers to Adoption

The primary barrier to the adoption of this solution is the high first cost of installation. An NREL Report has estimated that the utility system costs were 2017US$ 5.44 per watt in 2010. Hence a 100MW plant would have cost US$544 million in 2010. However, these costs have been steadily and rapidly declining. In 2017, this there has been an almost five-fold decline in costs and a similar plant set up today would cost only US$ 111 million (NREL, 2017).

Adoption of utility-scale PV will depend in large part on the economics and financials of specific projects as well as the incentives, the policies and regulatory framework that encourages utilities and large players to set up and implement large-scale PV projects. The growth of the utility-scale solar also depends in large part on the development of policies and institutions necessary to govern and manage future “smart” electric grids that receive a large proportion of power from intermittent and variable sources of energy. Lack of appropriate and encouraging policies and incentives is also a barrier to adoption of this solution.

Another barrier to large scale development of solar farms is the availability of large tracts of cheap and suitable land. Land near the load centers of big towns tends to be rather costly and is usually not available in quantities required for large scale projects. Land of appropriate size and cost is usually located far away from load centers thus entailing high investments in evacuation infrastructure.

Availability of stable grids of adequate capacity is another barrier to investment in these projects. As these projects are usually located far away from the load centers, the project promoters are not keen to invest in evacuation costs. They look up to the public authorities to come up with the requisite infrastructure. And unless this comes up, such projects are not attractive enough to the investors.

### 1.3.4 Incentives for Adoption

The rapid growth of rooftop or distributed PV can be attributed in large measure to pro-solar policies and incentives such as net energy metering. This policy allows homeowners and businesses to get credits on their electricity bills for the amount of electricity they feed back into the grid thus offsetting their own electricity usage. Because utility-scale PV installations are often projects that sell the electricity generated to wholesale buyers or are owned directly by utility companies, these projects do not often benefit from policies such as net metering. Higher, feed-in tariffs are a way of compensating PV electricity generators. Long-term contracts and power purchase agreements (PPAs) that typically pay higher prices to the utilities to reflect the higher generation costs associated with PV systems are the preferred way of attracting investors. Such policies help offset the higher capital cost of PV systems as compared to conventional sources.

The main reason for the steadily falling cost of SPV projects, of course, has been the sharp fall in SPV module prices witnessed globally over the last few years. So much so that in some of the recent tariff-based bids for solar parks, the quoted tariffs have fallen even below the conventional energy tariffs. The growth curve thus seems set for a steep rise. However, of late there have been worries of over-capacity in the module manufacturing and also a slowdown in the international market due to the raising of import tariffs on modules by major markets like the US, China and India.

The economics of utility-scale PV projects are highly specific to country or city-level electricity market dynamics, but in many regions around the world, utility-scale PV is fast becoming cost-competitive with traditional sources of generation, and this is one of the primary reasons that the utility-scale sector has seen such rapid growth in the last few years. Utility-scale PV systems generally sell power to utilities or other buyers through a (PPA — a fixed-price contractual agreement to purchase a power plant’s electricity—and the price is typically calculated using Levelized Cost of Electricity (LCOE). LCOE represents the total system and operating costs divided by the total energy produced by the project over its lifetime. LCOE thus becomes a useful way to compare the costs of intermittent, renewable energy sources with energy generation costs from conventional projects. Given the significant cost reductions and increasing capacity factors for utility-scale systems, many PV projects are now competitive with or even becoming cheaper than conventional electricity in different regions of the world (IRENA, 2018b). Several LCOE assessments also show that solar and also wind are now cost-competitive with conventional generation, even without accounting for the CO2 externality costs of fossil based energy.

While utility-scale PV is set to continue its rapid growth due to favorable economics, an encouraging regulatory and policy framework is critical to its accelerated adoption. After the landmark climate agreement signed in Paris in 2015, many countries have set ambitious targets for greenhouse gases (GHG) emissions reductions as well as substantial renewable energy deployment. Many countries have adopted Renewable Purchase Obligations (RPO) mandate utilities to purchase a certain purchase of their power from renewable sources. For instance. India has set a target of installing 100 GW of SPV by 2022. In the USA, California’s regulations require utility companies and electric service providers to increase their procurement of renewable energy to 33 percent of the total by 2020, and many of the state’s utilities have already met this target or are even exceeding it (CPUC, 2015). With increasing pressure on energy utilities and state and national governments to source an increasing amount of electricity through renewable sources, and given the competitive economics of utility-scale PV, the market is primed to continue its rapid growth.

### 1.3.5 Adoption Potential

Most adoption scenarios in the literature predicted low, single-digit percentages of growth in total electricity generation through solar photovoltaics by the mid-point of the century; these included the IEA’s Energy Technology Perspective (2016) with its 6DS and 4DS scenarios with 4.2% (2187 TWh) and 5.8% (2703 TWh) respectively. But some, such as the Greenpeace Energy [R]evolution scenarios, envision renewables holding a much larger share of future electricity generation (nearly 20 percent of the electricity generation mix by 2050). This estimate is close to the figure of 10000 TWh electricity generation in the Energy [R]evolution scenario and around 13612 TWh in the Advanced Revolution Scenario (Teske, 2015).

In 2018, IRENA has also come out with another scenario called Remap which foresees the share of SPV rising from 1% of electricity generation at present to 22% by the year 2050 (IRENA, 2018d).

Two highly ambitious scenarios which foresee a 100% switch over to renewable energy are the Ram et. al. (2017) and the Ecofys scenarios. Ram et al (2107) study projects an 85-fold increase of SPV generation from 187 TWh in 2015 to almost 16,000 TWh by 2040 whereas the ECOFYS report (evocatively called ‘A Disruptive Approach’) foresees an almost 200-fold rise from 112 TWh in 2014 to 22,222 TWh in 2040 (Blok, 2018).

## Advantages and disadvantages of Solar PV Utility-scale

### 1.4.1 Similar Solutions

There are several solutions in the electricity generation sector that can replace conventional electricity-generating technologies such as coal, oil, and natural gas power plants which could be considered as similar/analogous solutions. Solutions similar to solar photovoltaics utility-scale that use the same resource: i.e. solar energy for electricity generation are considered here. These differ from our solution either in the level of agency (e.g. household or utility-scale level) or in the way the technologies work. These are:

* **Rooftop Solar Photovoltaic System:** In fact, the SPV programs started with small scale household and community-based systems and later on grew in scale to utility systems. The underlying technology is the same – the difference being in the scale and the implementing agency (i.e. household or utility). Many countries have mounted and run successful rooftop and decentralized SPV programs like the “Million Roofs Initiative” of the US (Strahs & Tombari, 2006). Rooftop and small community SPV programs still account for a roughly estimated 40% of all global investments in SPV and are the favored solution for providing decentralized and off-grid power to remote habitations and households.
* **Concentrating Photovoltaic Technology (CPV):** Another type of utility-scale PV technology which can be used to generate electricity is the CPV technology. This uses an optical system to focus large areas of sunlight on each solar cell for enhanced energy conversion. Usually, such systems are combined with a tracking system to increase efficiency and power generation. This technology is relatively new, and its share of the market small, but there is interest in exploring it further because of its significant efficiency gains especially in areas having direct sunlight and low moisture. This report does not consider CPV as a part of utility-scale installations because CPV systems at present constitute a very small share (370 MWp) by the end of 2016 or less than 1 percent) of total installed utility-scale PV capacity (Philipps, 2015).
* **Concentrated Solar Power (CSP):** systems are systems that use solar thermal energy to produce electricity. Instead of converting sunlight directly into electricity like photovoltaics (PV) does, these systems rely on the core technology of electricity generation: steam turbines. The difference is that rather than using coal or natural gas, CSP uses solar radiation to generate heat. A critical advantage of CSP over SPV is the ease of energy storage. Unlike PV panels and wind turbines, CSP generates heat before converting it into electricity - and heat is easier to store. When equipped with molten salt tanks for storing heat, CSP plants can continue to produce electricity even after the sun goes down.

### 1.4.2 Arguments for Adoption

As is the case with other renewable energy resources, the primary benefit of solar energy is that its fuel is free—the sun shines every day at no cost. In other words, once a PV system has been installed, its production of electricity does not incur any marginal costs. The only costs beyond installation are fixed operation and maintenance (O & M) costs, which, in the case of utility-scale PV, are minimal. Additionally, the total solar resource potential is practically inexhaustible. This is evident from a simple calculation. If average irradiance is 1000 W/m2 and the area of irradiance circumscribed by the Earth is 1.28 x 1014 m2 (the area of a circle with Earth’s radius), then the planet is constantly receiving 1.28 x 1017 W (1.28 x 105 TW) of power from the sun. If it is assumed that energy demand in 2050 will rise at the levels presented in the previous chapters, this usage is still only a minuscule fraction (~0.02 percent) of the available solar energy. Even with losses due to conversion efficiency and land area unavailable for solar harvesting, it is still an overwhelmingly abundant source of energy (Tsao, 2006).

Given that utility-scale PV installations will in most cases be deployed to replace fossil fuel power plants, the carbon mitigation potential of PV is also significant. There are, of course, indirect emissions associated with PV manufacturing and installation, and this issue will be discussed in greater detail below. According to the IEA, the large emission reductions resulting from the substitution of fossil fuel-based electricity generation with PV electricity are of orders of magnitude larger than emission increases due to PV lifecycle emissions and also the variability that may come with a higher penetration of PV electricity in future grids (IEA, 2014).

### 1.4.3 Additional Benefits

Further adoption of utility-scale PV will bring important benefits in addition to financial savings and carbon abatement. The public health benefits of replacing fossil fuel power plants with utility-scale PV can be enormous because PV avoids harmful pollutants including fine particular matter (PM2.5) sulfur dioxide (SO2) and nitrogen oxides (NOx) In its recent report on the public health and environmental benefits of achieving high penetrations of PV in the US, the US Department of Energy estimated that the monetary benefits of reducing pollutants in its *SunShot Scenario* totaled $167 billion in the form of lower future health and environmental damages, including a reduction of 25,000-59,000 premature deaths (EERE, 2016). Given these substantial benefits, it is perhaps not surprising that China is mounting a massive effort to grow its PV market and replace polluting sources of energy which are creating a serious public health crisis. Another benefit of solar PV systems and other renewable generation sources worth mentioning is the concept of energy independence. Because their production of electricity is not tied to fluctuating fuel prices, PV systems can enable nations to achieve a certain degree of independence from imported fuels. And in parts of the world that suffer from low levels of electrification—both in cities and rural areas—utility-scale PV can provide alternate means of ensuring greater energy access for the poor, bringing with it economic and social development.

While there exist many advantages of a growing market for utility-scale PV, there are also several disadvantages of over-reliance on PV for an increasing share of electricity generation. The *Future of Solar Energy Study* from MIT offers a thorough analysis of these and other issues; some of them are summarized below (MIT, 2015).

### 1.4.4 Drawbacks

One central challenge to an electrical grid or system receiving a large percentage of electricity from renewable sources like PV is that this energy is intermittent; the amount of electricity generated can fluctuate unexpectedly based on changing weather patterns as well as due to seasonal shifts in solar irradiance. As the share of renewable energy being injected into the grid increases, the grids have to cope with the unpredictability and intermittency of these sources. This impacts the grid stability and affects the quality of power. Grid management becomes a major problem as the grid operators have to cope with ever fluctuating and unpredictable amounts of energy being fed into the grid. At present, the grids schedule their operations in advance but with increasing renewables, this becomes a continuous balancing act. The grids need to be designed and their operators trained to cope with ever-increasing amounts of this energy.

A related barrier is a mismatch between the daily profile of solar irradiance, which peaks mid-day, and the daily profile for electricity demand. This mismatch is particularly problematic for residential and industrial electricity customers. A typical household’s electricity demands are highest in the evening, after the sun has set, while an industrial facility has relatively flat demand 24 hours a day (MIT, 2015). In terms of cost, this means that PV generation may be competing in real time with deflated market prices rather than average market prices for electricity (MIT, 2015). It should be noted that this effect is not universal —in places like the western U.S., electricity demand peaks during the day because of air conditioning usage (NREL, 2013).

Some countries and regional electricity markets with a high penetration of PV are already facing challenges related to these barriers. Germany presents an illustrative case, as the country receives a significant amount of electric generating capacity from renewable sources. During the mid-day hours when PV is producing peak power, supply can outmatch demand, driving electricity prices down and, as happened in October 2011 and as recently as May 2016, into the negative for a period lasting a full work day (Haas, 2013). One of the causes of this sudden drop in prices is the inflexibility in traditional electricity markets. When renewables are producing a large share of electricity supply, conventional power plants can be taken offline, but coal and nuclear plants cannot shut down quickly, and it is generally cheaper to generate electricity at a loss than it is to shut them down and then ramp them up again a few hours later, once PV stops producing electricity. This inflexibility leads to market inefficiencies and price volatility, which can harm the overall functioning of the market.

In terms of intermittency, renewable technology comparable to PV is wind power, but it often has a complementary generation profile to PV over the course of the day. As a result, there is a synergistic effect of deploying solar energy and wind energy together in a region (Nikolakakis, 2011). The intermittent nature of both PV and wind will require innovative market and governance structures that can keep prices from fluctuating while making sure that the power reaches those who need it. For this reason, future adoption scenarios for PV and wind power include assumptions that they will be adopted in parallel with energy storage or dispatchable generation sources such as natural gas. While these solutions can address the supply side of the equation, changes also need to occur on the demand side. Electricity consumers may have to shift their patterns of usage depending on when the intermittent sources are producing electricity, and one way they can be incentivized to do this is through dynamic electricity pricing schemes. While this report will not discuss in depth the challenges and opportunities for integrating renewables, it is clear that a future energy system relying on substantial amounts of electricity from renewable sources will function much differently than the majority of existing electricity markets and conventional grids.

Another potential disadvantage of adopting an increasing capacity of utility-scale PV is the material constraints on the expansion of production capacity for current PV technology. The demand for common materials like concrete, steel, plastic, glass, aluminum, and copper is likely to be accommodated at current and projected production rates, as will the case for critical materials silicon and silver) (MIT, 2015). However, several critical materials for thin-film PV (indium, gallium, selenium, and tellurium) are only mined as byproducts of other metals and their production may not be able to meet the levels required for global adoption. More research into such materials and their production would be necessary especially for thin-film PV materials and design.

There has been a substantial amount of research analyzing the lifecycle, as well as the energy return on investment (EROI) and energy payback times (EPBT), of solar PV. Historically, critics of PV argue that it has a low EROI value compared to conventional energy sources such as coal and natural gas, and they cite the energy intensiveness of purifying silicon as the primary reason for PV’s low EROI (WeiBbach, 2013). Lazard’s LCOE Analysis 12.0 (Lazard, 2018) argues, however, that while the EROI of electricity generation from fossil fuels has been viewed as being much higher than the EROI of renewable energy, and specifically PV, happening due to the use of outdated data and a lack of consistency in calculation methods. Their results show that the range of EROI values for PV are within the same range as oil-fired electricity systems and half that of coal-fired electricity systems, but they make the important note that coal-fired power plants have much higher lifecycle GHG emissions than PV, which could be reduced by using carbon capture and storage (CCS), but this would considerably reduce the coal-fired electricity’s final EROI. Estimates for EROI values of several different electricity sources are shown in Figure 1.2. It can be seen that conventional fuels have a high EROI, *i.e.* they provide a large energy return on the energy invested in them. Solar PV has a respectable EROI.

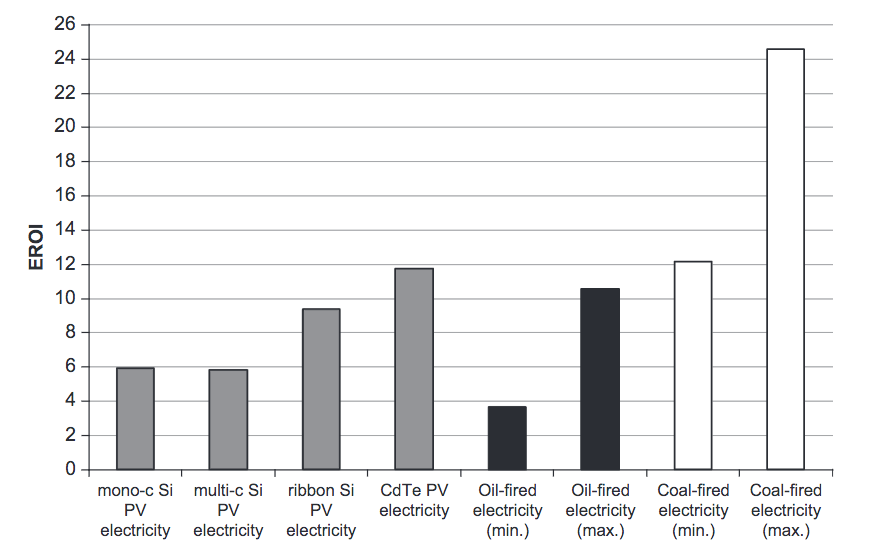


Figure 1.2 - EROI (%) of PV electricity compared to oil- and coal-fired thermal electricity (Adapted from Raugei et al., 2012)

An important metric for measuring the cost of energy from a particular project over its lifetime is the Levelized Cost of Electricity (LCOE) generated by the project on a per-unit basis. For this, the net present value (NPV) of various capital and operating costs is calculated to arrive at a consistent basis for comparing costs. The LCOE becomes a useful tool for comparing energy costs produced from different sources. In the case of solar PV, it becomes even more important because though the first costs for PV are high, there is hardly any operating cost as the “fuel” comes free of cost. As a result of this, the LCOE becomes quite favorable as compared to fossil-based projects that have to grapple with ever-increasing fuel prices (and pollution) throughout their lifetimes. Hence, though investment in PV projects may seem high initially, they become much cheaper over their lifetimes. The returns become even more favorable once the environment and carbon abatement costs are built into the equation. For this purpose, project advisors work out these also when considering investments in such projects (Lazard, 2018). The volume of data generated around LCOE of SPV projects is growing as these become a favored source for producing “green” energy.

Though there remains some debate in the literature about these aspects of solar PV, the trends suggest that EROI for PV will continue to increase while EPBT and lifecycle emissions will decrease as cell and production efficiencies improve. Most importantly, PV and other renewable technologies are already competitive in some locations of the world with conventional electricity-generating sources on many different levels, and though the intermittency challenges will certainly require innovative solutions, PV is quickly becoming one of the most economically sound and environmentally appropriate technologies for the coming energy transition. Table 1.1. presents a comparison of selected pros and cons of the solution with others in the same sector or with the same energy source.

Table . Solar energy solutions versus conventional electricity generation technologies

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Parameter** | **Conventional Electricity Generation Technologies** | **Concentrated Solar Power** | **Solar PV Utility- Scale Systems** | **Solar PV Rooftop Systems** | **Concentrating Solar PV Systems** |
| *Greenhouse Gas Emissions* | Extremely High | Very Low | Almost Zero | Almost Zero | Almost Zero |
| *Land Requirement* | Medium | Medium | High | Almost Zero | Medium |
| *Air Pollution* | Extremely High | Low | Almost Zero | Almost Zero | Almost Zero |
| *Electricity Generation Flexibility* | Very High | Medium | Low | Low | Low |
| *Resource Extractive Drawbacks* | Extremely High | Low | Very Low | Very Low | Very Low |
| *End of life Disposal Drawbacks* | Very High | High | Medium | Medium | Medium |
| *Water Consumption* | Very High | High | Very Low | Very Low | Very Low |
| *Gestation Period[[2]](#footnote-2)* | Very High | Medium | Low | Low | Low |
| *Modular Scalability[[3]](#footnote-3)* | Low | Medium | Very High | Very High | High |
| *Environment/Health Benefits* | Very Low | High | Very High | Very High | Very High |
| *Operation and Maintenance Costs* | High to Very High | Medium | Very Low | Very Low | Very Low |

# Methodology

## Introduction

Project Drawdown’s models are developed in Microsoft Excel using standard templates that allow easier integration since integration is critical to the bottom-up approach used. The template used for this solution was the Reduction and Replacement Solutions (RRS) which accounts for replacement of conventional electricity generation technologies (i.e. coal, oil, natural gas) and related emissions for an alternative solution (see the Drawdown RRS Model Framework and Guide for more details). These technologies are assumed to compete in markets to supply the final functional demand which is exogenous to the model but may be shared across several solution models. The adoption and markets are therefore defined in terms of functional units (TWh), and for investment costing, adoptions are also converted to implementation units (TW). The adoption of both conventional technologies and the present solution were projected for each of several scenarios from 2015 to 2050 and the comparison of these scenarios (for the 2020-2050 segment) is what constitutes the results.

For this solution, the approach was to analyze the impacts of increased adoption of utility-scale solar PV systems. To capture the appropriate level of agency, the solar PV market was split between *rooftop solar* (representing households and building owners) and utility-scale solar (i.e. *solar farms*), being the latest the focus of this technical report.

The model used for this analysis constructs both alternative ambitious adoption pathways (PD scenarios) and a Reference scenario (REF) for utility-scale solar PV. Following project Drawdown methodological assumptions (further description available on the Drawdown RRS Model Framework and Guide), and in order to grasp the total impact of an increased adoption of the solution during the assessed time frame; the REF scenario assumes future adoption of utility-scale solar PV remains fixed at the current base-year (*i.e.* 2014) percentage of Total Addressable Market (TAM), estimated at 0.5 percent (113 terawatt-hours) of electricity generation (IRENA, 2018). The TAM for this solutionis based on the common project Drawdown projected global electricity generation in terawatt-hours till 2050 (Section 2.3.).

The developed alternative PDS scenarios, draw on existing adoption scenarios for utility-scale solar PV to model several alternative adoptions. The RRS model contains both financial and climate analyses in order to model the global and regional impacts of adoption in the PDS scenarios compared to the REF scenario. What the model thus prognosticates is the total financial costs and benefits of adoption cases for utility-scale solar PV, as well as the contribution this adoption can make to annual and cumulative emissions reduction.

## Data Sources

This section presents key data sources utilized in the mode to evaluate the adoption of solar PV utility-scale. Data inputs for the model come from a variety of sources, primarily from peer-reviewed publications and from institutional reports. For all variable inputs, a variable meta-analysis of existing literature was conducted to create low, high, and mean estimates. For each solution variable, a sensitivity analysis of, on average, thirty data points reported in the literature was conducted. In some cases, as many as sixty-eight data points were considered. This allowed a robust and reliable analysis of financial, technological and climate parameters. These represent both optimistic as well as conservative estimates for the future costs and benefits of adopting this solution.

Recent capital cost estimates from several data sources, presenting data for all of the regions contained in this analysis were examined to determine the average capital cost of utility-scale PV installations (IEA, 2018; IRENA, 2018a; REN21, 2018; Lazard, 2018). It is acknowledged that capital costs for solar PV utility-scale systems can vary significantly by region, but exhaustive regional data were not available to calculate an average cost weighted by installation size. Available estimates are focused in OECD countries, reflecting the preponderance of present-day utility-scale PV installations in the developed world.

Cost estimates for fixed operation and maintenance (O&M) of utility-scale PV were collected from different sources i.e. (Bolinger, 2015; EIA, 2015; IEA, 2018 ; NREL, 2017; Lazard, 2018), and these estimates were used to calculate total operating costs of utility-scale PV adoption, which, combined with capital costs for installation, represent the total financial costs of adopting utility-scale PV in the PDS scenario. Fixed operation and maintenance costs for both renewable and conventional generation technologies can include expenses such as day-to-day preventative and corrective maintenance, labor costs, asset and site management, and maintaining health and safety, among others (Lo, 2014). Average fuel price was calculated considering average prices for both coal, oil and natural gas from 2005-2014 using IEA data (IEA, 2016a).

In order to compare capital and OM costs of utility-scale PV installation in the PDS scenarios with that of conventional generation technologies, cost data was obtained for fossil fuel-based electricity generating sources from the IPCC 5th Assessment Report (IPCC, 2014) which conducted its own sensitivity analysis of a number of sources from the literature, and other sources such as Lazard (Lazard, 2016). In all variables for conventional electricity generation sources, data for coal, oil and natural gas (primarily pulverized coal and combined cycle gas turbine technologies) were included and a weighted average. The weights are based on the percentage, for each fuel on the total global electricity generation for 2014 (World Bank, 2015).

In order to calculate the total impacts and benefits of increased solution adoption (for the PDS scenarios), technical data was also integrated, including average annual use, plants lifetime, and average efficiencies. All three of these are key to determining the variable OM costs and the total fuel costs for conventional generation sources, as these costs are determined by the average number of hours the power plant is generating electricity, as well as the average price of fuel inputs and the average efficiency rate. Average plants efficiency is calculated from several global sources (IPCC, 2014), as well as from the (EIA, 2015).

Though the average annual use of conventional generating technologies is much higher than that of utility-scale PV, due to the fact that PV can only generate electricity when the sun is shining, the range of capacity factors for different conventional generating sources can still vary based on the type of technology and location. For this reason, data was collected from a range of different sources like (EIA-US, 2016;IEA, 2016b; Lazard, 2016) that represent most of the regions contained in this analysis. Capacity factor data for utility-scale solar PV, on the other hand, is included for all regions, which enabled calculation of the average annual use of utility-scale PV installations across a wide range of regions with differing solar irradiance values.

The model’s analysis of the climate impacts of adoption are primarily derived from the direct emissions factor associated with the replacement of conventional generating technologies with utility-scale PV. This methodology is explained in greater detail in Drawdown RRS model framework and guidelines. In order to account for indirect emissions from conventional technologies and utility-scale PV—primarily those lifecycle emissions associated with manufacturing, transporting, installing and other non-generation activities—a range of peer-reviewed lifecycle analysis (LCA) studies were examined for the different types of PV technologies available in the market. The analysis draws from those conducted by (Hsu, 2012)) and (Kim, 2012) for c-Si and Hertwich for thin-film technologies (Hertwich, 2015) respectively. Hou provides LCA data and indirect emissions estimates for China (Hou, 2012).

## Total Addressable Market

Solutions assessed in the Electricity Generation Sector share a common market for future adoption defined by the total terawatt-hours (TWh) of generation demanded from 2015-2060. This shared total addressable market (TAM) is used to bound this sector technologies rollout over time. The TAM is determined based on the assessment of estimations of current and future electricity generation from a combination of models and scenarios from different sources, including Greenpeace (2015); International Energy Agency (IEA) - Energy Technology Perspectives (IEA, 2017); IEA World Energy Outlook (WEO) (IEA, 2018); Equinor (2018); Ecofys (2018); The Institute of Energy Economics Japan (IEEJ) Outlook 2019 (2018) and Ram et al. (2019). See Project Drawdown report - Assessing the Total Addressable Market and Major Assumptions for more details on the methodology used to develop the electricity TAM. The updated 2019 study follows the same methodological approach with the inclusion of newer sources.

Four prognostications of the TAM for this assessment were derived by using comparable scenarios from each of the above-mentioned sources which were categorized by expected climate mitigation scenarios (i.e. Ambitious, Conservative, and Baseline) and the scale of deployment of renewable energy sources (RES) (i.e. 100% RES scenarios). The sources used mostly provide results at a decadal level, which were interpolated to provide annual values for Project Drawdown calculations.

The Ambitious Project Drawdown TAM Scenario is constructed from the average of yearly values of four scenarios: the IEA (2017) 2D Scenario, the IEA (2017) B2D scenario, Renewal Scenario from Equinor (2018), and IEA (2018) WEO SD scenario. The Conservative Project Drawdown TAM Scenario follows the average yearly values of the IEA (2018) WEO New Policy scenario (NPS); Reform Scenario from Equinor. (2018), IEEJ Outlook (2018) Advanced Tech scenario, and IRENA (2019b) Roadmap 2050 REmap case. The Baseline Project Drawdown TAM Scenario is built by the average of the Equinor (2018) Rivalry Scenario, IEEJ Outlook (2018) Reference Scenario, IEA (2017) Reference Case and IEA (2018) WEO Current polices Scenario (CPS). These three Project Drawdown TAM scenarios show an estimated range of electricity generation from 45,286TWh to 49,706TWh by 2050. Baseline TAM is used for PD Plausible scenario assessment.

An ambitious TAM scenario for a 100% RES by 2050, which is aligned to project Drawdown Optimum and Drawdown scenarios, utilizes the Greenpeace (2015) Advanced [R]evolution Scenario, Ram et al (2019) analysis and Ecofys (2018) 1.5ºC degree scenario were considered. The estimated electricity generation for this TAM reaches 70,942 TWh by 2050.

## Adoption Scenarios

Electricity generation from utility-scale and rooftop PV (combined) has increased very rapidly in recent years, more than quadrupling from 96 TWh in 2012 (IRENA, 2018) to 531 TWh in 2017 (IEA-PVPS, 2018). It, therefore, becomes a challenge to project the rate of PV adoption with any degree of accuracy over the next 30 years. Many sources from the literature depict a yearly single-digit growth in the percentage of total electricity generation from solar PV in 2050 (IRENA, 2018d). However, given the rapidly growing market for utility-scale PV, these projections seem overly conservative, especially in light of the rapid cost and efficiency gains in the field of PV technology in recent years. It is also indicative of the future potential of solar PV adoption that some expert organizations like the REN21 and LUT have created scenarios for 100% adoption of renewable energy in the field of power (Ram, 2017). In all these projections, utility scale electricity generation from SPV is the centerpiece.

In this project, two different types of adoption scenarios have been developed; first is a Reference (REF) Case scenario which has been taken as the baseline: this scenario does not envisage any large scale or disruptive changes in this sector. The second is a set of more ambitious scenarios called the Project Drawdown Scenarios (PDS) each with varying levels of adoption of specific “solutions”. Called the Plausible, Drawdown and the Optimum Scenarios, they revolve around the extent and intensity of adoption of the specific solutions in the various fields. Results are published showing the levels and rates of adoption of the solution with reference to the baseline scenario. These are elaborated below.

### Reference Case / Current Adoption

For the purposes of Reference Case (REF), adoption is fixed at the current adoption[[4]](#footnote-4) levels (in percentage terms) of the market. For the purposes of Utility Scale SPV the current percentage of total electricity generation (TWh) provided by these plants has been kept constant throughout the study period up to 2050. As the market grows, the installed capacity of solar PV plants would need to grow equally in order to maintain the present percentage adoption levels of 2018. It is acknowledged that this, in reality, may not be a “business as usual” trajectory considering the speedy changes taking place in this sector worldwide; but it allows a sort of measure to evaluate the impact of recent and more aggressive policies to reverse global warming.

### Project Drawdown Scenarios

Three Project Drawdown scenarios (PDS) have been developed for each solution, to compare the impact of increased adoption of the solution to a reference case scenario. These are:

#### Plausible Scenario

This scenario represents an incremental and plausible growth of renewable energy solutions using medium to high growth trajectories to 2050 depending on the current maturity levels of the technology, and bounded by existing ambitious projections from other global energy systems models. For solar PV farms, this scenario is based on the evaluation of yearly averages of five optimistic scenarios: IEA (2017) Energy Technology Perspectives 2DS and B2DS scenarios; IEA (2018) World Energy Outlook SDS; IRENA (2018d) REmap Case scenario; and Grantham Institute and Carbon Tracker (2017) Strong PV Scenario using a high growth trajectory.

#### Drawdown Scenario

This scenario is optimized to reach drawdown by 2050 using more ambitious projections from existing sources. The scenario projects a 100% adoption of non-fossil fuel-based technologies in 2050; mainly RES but also includes several technologies that are considered transitional solutions (as nuclear energy) (See section 6). For solar PV farms, this scenario is based on the yearly average values of three 100% RES scenarios of electricity generation by 2050, being Greenpeace (2015) Advanced Energy [R]evolution Scenario; Ram et al. (2019) scenario and Ecofys (2018) 1.5ºC scenario. These scenarios represent very ambitious pathway towards a fully decarbonized energy system in 2050.

#### Optimum Scenario

This scenario represents the most optimistic case, in which clean, renewable energy solutions such as wind, solar, and other renewable energy sources capture 100% of electricity generation by 2050, with both fossil fuels and transitional solutions fully phasing out by 2050. Like the *Drawdown* Scenario, this scenario for solar PV farms is based on the yearly average values of three 100% RES scenarios of electricity generation by 2050, being Greenpeace (2015) Advanced Energy [R]evolution Scenario; Ram et al. (2019) scenario and Ecofys (2018) 1.5ºC scenario.

## Inputs

### Climate Inputs

In order to calculate the climate impacts of the project Drawdown scenarios, in terms of maximum annual emissions reduction, total emissions reduction, and PPM equivalent, the utility-scale solar PV generation was estimated globally and regionally from 2020-2050. Thereafter, the emissions reductions due to the replacement of conventional electricity generation sources with the SPV solution were calculated. The detailed methodology of these calculations is available at the Project Drawdown Integration Methodology report.

While being a renewable energy technology, solar PV farms do not have the direct emissions attributable to combustion of fossil fuels. However, the Project Drawdown modeling exercise considers the life cycle analysis of indirect emissions related to the different processes and factors that indirectly contribute GHG emissions from a utility-scale PV project. In modeling for the lifecycle emissions of utility-scale PV adoption in the scenarios, a fixed value of tons CO2-eq per TWh was used factoring in information from several PV technologies rather than using a weighted average from different types of PV technologies. This was more due to the lack of technology-wise data on indirect emissions. In fact, since this is a fast-developing field, future research should be conducted to assess the amounts of indirect emissions from different types of technologies and also to look at emissions of GHG other than CO2 from the processes involving new materials being deployed for production of SPV modules. At present, SPV is being projected as the “Cinderella Option” to reverse global warming but more research would be necessary to validate this.

Table . Climate Inputs

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| Indirect CO2 Emissions (Solution) | *t CO2-eq/TWh* | 18,961–74,865 | 46,913 | 43 | 27 |

Note: Project Drawdown data set range is defined by the low and high boundaries which are respectively 1 standard deviation below and above the mean of the collected data points[[5]](#footnote-5).

### Financial Inputs

RRS model constructs PDS adoption scenarios for utility-scale PV generation globally and regionally for each year until 2050. It has modelled both the capital costs and the fixed and variable OM costs associated with the alternative scenarios compared to those of the REF scenario. A detailed description of the methodology used is available in the Drawdown RRS Model Framework and Guide.

The financial calculations examine the first cost in US$ per kW and the operating cost in US$ per kW (fixed costs) and US$ per kWh (variable costs). For this, many inputs estimating annual output and lifetime output per solar PV electricity generation, along with first costs (per functional unit), were generated. A lifetime capacity of 50,923 hours was calculated depending on the average powerplant annual use.

There are two types of capital costs for a utility-scale PV system: the module cost and the balance-of-system (BOS) cost. The BOS costs include hard costs like electrical equipment and mounting hardware or tracking systems, as well as soft costs like labor and permissions (Energy and Environmental Economics, Inc., 2014). Costs for both modules and BOS are expected to decrease over time as the PV industry matures, following the standard equation for learning rates:

where:

* is the capital cost per kW in the stated year.
* is the cumulative production of the technology to date in the stated year.
* R is the learning rate, which is 1 - efficiency rate.

The learning rates for modules and BOS vary based on the technology and are necessarily different for both, hence these have been modeled separately. Several sources were studied (e.g. ITRPV, 2018; Munsell, 2018; Bolinger and Seel, 2015) to calculate the percentage share of total PV system costs attributable to the PV module as well as the BOS. The cost per kW which a module having an average efficiency would have in 2050 was then obtained from a meta-analysis of several different sources (Energy and Environmental Economics, Inc., 2014, p. 38) about the projected capacity in the Plausible PDS . This process was repeated for the BOS using the learning rates for utility-scale PV BOS (Energy and Environmental Economics, Inc., 2014, p. 38). By adding the module and BOS costs, the results for the total PV system cost per kW was obtained, and this, in turn, was used to calculate the learning rate for the entire PV system.

For the solution (i.e. Solar PV utility-scale systems), the current mix of conventional and fossil fuel electricity generation technologies (coal, gas, and oil) to be replaced by SPV were identified. Fixed and operational costs and operation for both these generation technologies (solution and conventional) were thereafter considered to obtain the difference between the two.

To capture the rapid decrease of costs in the SPV systems seen in recent years, a low boundary of data collected on installation costs was assumed, and this resulted in an average total first cost of US2014$1,734 per kilowatt[[6]](#footnote-6). A customized learning rate of 21.04% percent was developed, considering independent impacts of PV modules and balance of system (BOS) costs on the initial costs; this has the effect of reducing the installation cost to US$490 per kilowatt in 2030 and to US$336 in 2050 as compared to US$1,786 per kilowatt for the conventional technologies (i.e. coal, natural gas, and oil power plants). Additionally, a discount rate of 9.68 percent has been used which is appropriate for utility-scale projects and is used across all Drawdown electricity generation solutions with this level of agency. Utility-scale solar PV does not incur any variable operation and maintenance costs, so fixed OM costs are the only costs associated with the solution other than First Cost (Tables 2.2. and 2.3).

Fuel prices for conventional technologies are derived from IEA (2019) data, averaging 2007-2018 historical registries for oil, coal and natural gas used for electricity generation and calculated through a weighted average by fuel from the current electricity generation mix.

Table . Financial Inputs for Conventional Technologies

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| First costs (Conventional) | *US$2014/kW* | 470.5 – 3,101 | 1,786 | 24 | 8 |
| Fixed Operation and Maintenance Costs (Conventional) | *US$2014/kW* | 3.44 – 65.86 | 32.95 | 18 | 4 |
| Variable Operation and Maintenance Costs (Conventional) | *US$2014/kWh* | 0.0014 – 0.0079 | 0.0048 | 22 | 7 |
| Fuel Price (Conventional) | *US$2014/kWh* |  | 0.0492 |  | 1 |
| Learning Rate Factor (Conventional) | % |  | 2.00% |  |  |

Table .3 Financial Inputs for Solution

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| First cost | *US$2014/kW* | 704.0 – 2,763 | 1,734 | 68 | 10 |
| Fixed Operation and Maintenance Cost | *US$2014/kW* | 6.99 - 27.58 | 15.94 | 35 | 19 |
| Module Learning Rate | % | 18.2 – 29.5 | 23.08 | 21 | 18 |
| BOS Learning Rate | % | 11.5 – 22.1 | 16.8 | 20 | 13 |

### Technical Inputs

Table .4 Technical Inputs Conventional Technologies

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| Lifetime Capacity (Conventional) | *hours* | 121,807 – 222,351 | 172,079 | 12 | 6 |
| Average Annual Use (Conventional) | *hours* | 3,337– 6,587 | 4,962 | 23 | 4 |

Table .5 Technical Inputs Solution

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| Lifetime Capacity | *hours* | 44,825 – 53,829 | 49,327 | 12 | 11 |
| Average Annual Use | *hours* | 1,192 – 2,431 | 1,812 | 69 | 15 |

## Assumptions

Six overarching assumptions have been made for Project Drawdown models to enable the development and integration of individual model solutions. These are that infrastructure required for solution is available and in-place, policies required are already in-place, no carbon price is modeled, all costs accrue at the level of agency modeled, improvements in technology are not modeled, and that first costs may change according to learning. Full details of core assumptions and methodology are available on the Project Drawdown Reduction and Replacement Solutions (RRS) Model Framework and Guide report. Beyond these core assumptions, there are other important assumptions made for the modeling of this specific solution. These are detailed below.

1. Utility-scale PV systems are defined as any ground-mounted, grid-connected solar installation having a capacity greater than 1 MW(IEA, 2010; REN21, 2016).
2. Most of the literature contained in this report does not provide a specific prognostication for future adoption of utility-scale PV but does suggest, however, that the majority of future installations will conform to the definition used hereof utility-scale SPV projects. For this reason, several different data points were averaged and it is assumed that rooftop installations represent a constant share of around 40 percent of the market, with utility-scale solar capturing the remaining 60 percent (USDOE, 2012) (IEA, 2014).
3. The PV module on its own contributed to an estimated 44.7 percent of the installed cost for utility-scale installations.

## Integration

The complete Project Drawdown integration documentation with details on how all solution models in each sector are integrated, and how sectors are integrated to form a complete system is available at [www.drawdown.org](http://www.drawdown.org). These general notes are extracted from this document but the main document may be referred to for a complete understanding of the model integration process. Only the key elements of the integration process that are needed to understand how this present solution fits into the entire system are described here.

For the purpose of this integration, the data derived from individual solution’s models was fed into the sector-level integration models to generate the final results for all the solutions within a global system. The linkage between this sector and all the others is important, but major interactions occur with energy demand-side sectors like Transport, Buildings and Cities.

Through the process of integrating solar PV farms with other solutions, the total addressable market for electricity generation technologies was adjusted to account for reduced demand resulting from the growth of more energy-efficient technologies (for example LED lighting and heat pumps) as well as increased electrification from other solutions like electric vehicles and high-speed rail. Grid emissions factors were calculated based on the annual mix of different electricity generating technologies over time. Emission factors for each technology were determined through a meta-analysis of multiple sources, accounting for direct and indirect emissions.

## Limitations / Further Developments

More research and modeling is necessary to help policy-makers and project developers understand in detail the benefits of the adoption of this solution on a more effective scale. More so as utility-scale PV will not always make economic sense nor fit perfectly into any country’s existing electricity generation portfolio. In particular, the RRS model holds a number of factors constant in order to keep the global-scale modeling exercise from becoming too complex, but it is acknowledged that many of these factors, including prices of fuel and operating costs for conventional electricity, could change considerably over the period of analysis.

The RRS model is also based on a critical assumption about the percentage of solar PV that will meet the size and definition of “utility-scale,” and while this is necessary for the model, given the adoption data was used, it provides a rather coarse estimate of growth on a regional basis and could certainly be improved by the inclusion of specific datasets correlating to the country or region levels.

Finally, global analysis is complicated in many ways by the fact that the technical performance and costs of utility-scale PV can vary widely across regions depending on the viability of the solar resource and related factors of production. To account for these differences results where weighted appropriate, but this cannot be done in every case, and due to this limitation, often a more conservative estimate was selected for the climate and financial inputs so as not to overstate the potential benefits of adoption.

# Results

The following section depicts selected results derived from the RRS model evaluating the impact of increased adoption of Solar PV Utility-scale systems for electricity generation as compared to conventional technologies.

## Adoption

A comparison of the results from the three modeled PD scenarios with the Reference Scenario allows an estimation of the climate and financial impacts of increased adoption of utility-scale PV systems. As a result of this exercise, the Plausible Scenario (PDS1) projects that 20.5 percent of total electricity generation worldwide would come from utility-scale solar systems by 2050. In the Drawdown (PDS2) and Optimum Scenarios (PDS3) this share reaches 25 percent. It needs to be noted that the vast majority of additional utility-scale PV installed over the next 30 years will take place outside the (present) developed world. China alone is expected to have more PV generation in 2050 than the entire OECD countries. Table 3.1 below shows the adoptions of the solution in 2050 in functional units and percentage terms. The graph in Figure 3.1 depicts the long-term pathway trajectories for the different scenarios of utility scale solar PV systems.

Table . World Adoption of the Solution

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Solution** | **Units** | **Base Year (2014)** | **World Adoption by 2050** | | |
| **Plausible** | **Drawdown** | **Optimum** |
| Utility-scale Solar Photovoltaic (Solar Farms) | *Electricity Generation (TWh)* | 112.63 | 9,352 | 17,742 | 17,742 |
| *(% of market)* | 0.50% | 20.5% | 25.0% | 25.0% |

Figure 3.1 World Annual Adoption 2015-2060

Note: Drawdown and Optimum Scenarios have the same global adoption for this solution and therefore it is overlaid in the figure.

## Climate Impacts

The results of the analysis of emissions for each scenario (which include total emissions reduction and atmospheric concentration changes) are given below. For a detailed explanation of each result, the glossary may be seen at Section 6.

According to PD estimates, the Plausible Scenario results in the avoidance of 47.35 gigatons of carbon dioxide-equivalent greenhouse gas emissions between 2020-2050. Both the Drawdown and Optimum Scenarios are more ambitious in the growth of utility-scale PV technologies, with consequential impacts on greenhouse gas emission reduction of 127.99 gigatons of carbon dioxide equivalent over 2020-2050. Tables 3.2 and 3.3. provide additional information on the climate impacts of the solution adoption.

Table . Climate Impacts

|  |  |  |  |
| --- | --- | --- | --- |
| **Scenario** | **Maximum Annual Emissions Reduction** | **Total Emissions Reduction** | **Emissions Reduction in 2050** |
| *(Gt CO2-eq/yr.)* | *Gt CO2-eq/yr. (2020-2050)* | *(Gt CO2-eq/year)* |
| ***Plausible*** | 4.03 | 47.35 | 4.03 |
| ***Drawdown*** | 7.89 | 127.99 | 7.89 |
| ***Optimum*** | 7.89 | 127.99 | 7.89 |

The solution was integrated with all other Project Drawdown solutions and may have different emissions results from the models. This is due to adjustments caused by interactions among solutions that limit full adoption (such as by feedstock or demand limits) or that limit the full benefit of some solutions (such as reduced individual solution impact when technologies are combined). After integration, the impact on the emission reduction potential for this solution is 43.5 gigatons of carbon dioxide-equivalent in the *Plausible* scenario, 119.6 gigatons of carbon dioxide-equivalent for the *Drawdown* Scenario and 118.1 gigatons of carbon dioxide-equivalent for the *Optimum* Scenario. Figure 3.2. shows the world annual emissions reduction trajectories for the different scenarios for the long term.

Table . Impacts on Atmospheric Concentrations of CO2-eq

|  |  |  |
| --- | --- | --- |
| **Scenario** | **GHG Concentration Change in 2050** | **GHG Concentration Rate of Change in 2050** |
| *PPM CO2-eq (2050)* | *PPM CO2-eq change from 2049-2050* |
| **Plausible** | 4.13 | 0.34 |
| **Drawdown** | 10.81 | 0.61 |
| **Optimum** | 10.81 | 0.61 |

Figure . World AnnualGreenhouse Gas Emissions Reduction 2015-2060

Note: Drawdown and Optimum Scenarios have the same global adoption for this solution and therefore the world annual greenhouse gas emission reduction impact it is overlaid in the figure.

## Financial Impacts

The financial savings incurred by replacing conventional grid electricity sources with utility-scale PV are substantial. Despite having achieved grid parity in several regions of the world, solar PV farms at the global scale, while using conservative financial inputs and technology development, might still have higher investment cost than conventional technologies. The *Plausible* scenario presents negative US$269.7 billion associated with net first costs but over US$5.1 trillion of net operating savings projected over the same period (2020-2050), mainly because utility-scale PV does not require any fuel inputs. This allows for savings to start accruing from the first year of PDS adoption itself. Both PDS2 and PDS3 have similar savings among them with also negative US$1.34 trillion in marginal first costs but with very significant savings with over US$13.6 trillion in net operating savings over the period from 2020 to 2050.

The capital costs for PDS adoption of utility-scale PV will certainly require significant investments, as the cumulative capital costs are just over US$3.3 trillion under the *Plausible* Scenario and just over US$5 trillion for the other two PD scenarios. The learning rates used in this analysis lead to a continued decrease in the capital costs of utility-scale PV systems. These projected decreases in the capital costs of utility-scale PV are in line with most projections for future costs. Table 3.4 presents the financial results of the analysis for each scenario. For a detailed explanation of each result, please see the glossary (Section 6).

Table . Financial Impacts

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Scenario** | **Cumulative First Cost** | **Marginal First Cost** | **Net Operating Savings** | **Lifetime Cashflow Savings NPV (of All Implementation Units)** |
| *2015-2050 Billion US$* | *2015-2050 Billion US$* | *2020-2050 Billion US$* | *Billion US$* |
| **Plausible** | 3,345 | -269.7 | 5,102 | 563 |
| **Drawdown** | 5,098 | -1,454 | 13,642 | 1,889 |
| **Optimum** | 5,098 | -1,454 | 13,642 | 1,889 |

Figure 3.3 World Operating Cost Reduction 2015-2060

# Discussion

Solar photovoltaics have seen unprecedented levels of growth around the world since 2005, due primarily to advancements in technology and declines in costs. Of late, utility-scale systems have started becoming cost-competitive with fossil fuel generation around the world and grid parity is being achieved in some of the recent tariff-based bids. This positive trend is already in evidence as seen from the latest figures being received from different parts of the world. As a result, utility-scale PV is likely to continue its rapid growth in many regional markets and will play an increasingly important role in future global electricity supply, even regardless of climate mitigation goals. If utilities and project developers, spurred on by local and national governments, accelerate the adoption of utility-scale solar over the next 30 years, the world will reap major benefits in terms of greenhouse gas emissions reduction, as demonstrated by these results.

The rapid deployment of utility-scale PV will result in significant reductions in greenhouse gas emissions (and corresponding atmospheric concentrations) by displacing emissions associated with coal and natural gas. Solar thus has promising long-term potential, as the resource is plentiful, cheap and widespread, and future advances in both energy storage and photovoltaic technologies should continue to drive the adoption of this technology, even without specific policy interventions.

The financial benefits of rapid utility-scale PV adoption will also become significant and this can help jumpstart adoption. There are significant investment costs associated with accelerated adoption, but this also provides an opportunity to generate wealth and economic growth, as the return on investment is also substantial.

## Limitations

The accelerated installation of new utility-scale PV capacity will not be without challenges, however, as traditional electricity markets and grids are in many cases not designed to absorb a high penetration of intermittent and unpredictable renewable energy. There will be economic, policy, and social hurdles to overcome on the pathway set out in these Drawdown scenarios, and some of these will require significant changes to the way electricity is bought, sold and used. It is just a matter of time before the technologists come up with solutions to the challenges imposed by increasing levels of renewable energy injection into the conventional grids. Already much thought and effort are going into the design and development of “Smart Grids”. Given the immense climate and financial benefits of global utility-scale PV adoption, it is just a matter of time before these challenges are met and the hurdles overcome in order to realize the ensuing benefits.

## Benchmarks

Table 4.1 depicts a benchmark of Project Drawdown results for 2050 for the three scenarios as compared to six other publicly available ambitious scenarios from Greenpeace (2015), IEA ETP (2016), IEA WEO (2018), Shell (2018) and Ram et al. (2017). Most of the benchmarked results account for all solar PV electricity generation since no results are available from those sources differentiating utility and rooftop solar PV technologies. Shell (2018) and Ram et al. (2017) provide detailed results for utility-scale solar. PD scenarios are within the boundaries of the projections from other sources in all scenarios.

Table . Benchmarks

|  |  |  |
| --- | --- | --- |
| **Source and Scenario** | **Electricity Generation from SPV in 2050**  **(TWh)** | **Market Share in 2050 (%)** |
| **Project Drawdown – Plausible Scenario (PDS1)** | **9,353[[7]](#footnote-7)** | **20.5%** |
| **Project Drawdown – Drawdown Scenario (PDS2)** | **17,7427** | **25.0%** |
| **Project Drawdown – Optimum Scenario (PDS3)** | **17,7427** | **25.0%** |
| IEA Energy Technologies Perspectives (2016) – 2DS | 5,103**[[8]](#footnote-8)** | 12.3% |
| Greenpeace Energy [R]evolution (2015) – Energy Revolution Scenario | 9,914**8** | 19.9% |
| Greenpeace Energy [R]evolution (2015) – Advanced Energy Revolution Scenario | 13,613**8** | 20.2% |
| IEA World Energy Outlook (2018) - Sustainable Development Scenario | 5,631**8** | 11.0% |
| IRENA (2017) Roadmap-2050, REmap Case | 5,8458 | 14.1% |
| Ram et al. (2017) - 100% RE Scenario | 26,2177 | 47.3% |

# References

Aguado-Monsonet (1998). *The environmental impact of photovoltaic technology*. Institute for Prospective Technological Studies. European Commission, Joint Research Centre. Seville.

Alsema, E.A. & Wild-Scholten, M.J.de. (2011). *Environmental Impact of Crystalline Silicon Photovoltaic Module Production.* Symposium G – Life-Cycle Analysis Tools for “Green” Materials and Process Selection) (p - 895). Materials Research Society. Retrieved from: https://www.cambridge.org/core/journals/mrs-online-proceedings-library-archive/article/environmental-impact-of-crystalline-silicon-photovoltaic-module-production/7BF7B20468FD82E6DEEF6EE986FB5BF4

Alsema,E.A., Wild-Schloten, M.J.de., Fthenakis, V.M., Agostinelli, G.,Dekkers, H., Roth, K. & Kinzig. (2007). *Fluorinated Greenhouse Gases in Photovoltaic Module Manufacturing: Potential Emissions and Abatement Strategies*. 22nd European Photovoltaic Solar Energy Conference. Milan. Retrieved from: http://www.clca.columbia.edu/papers/deWild%20etal%20-%20paper%20EPVSEC22%20Milano%20-%2020070830%20MdW.pdf

AMPERE. (2014). *AMPERE Database, Regions Definitions, EU FP7*. AMPERE Project. Retrieved from: https://secure.iiasa.ac.at/web-apps/ene/AMPEREDB/dsd?Action=htmlpage&page=about#regiondefs

Black & Veatch. (2012*). Cost and Performance Data for Power Generation Technologies*. Prepared for the National Renewable Energy Laboratory. Black & Veatch Holding Company. Retrieved from https://www.bv.com/docs/reports-studies/nrel-cost-report.pdf

Blok, K., Exter, P.v. & Terlouw, W. (2018). *Energy Transition within 1.5ºC: A disruptive approach to 100% decarbonisation of the global energy system by 2050*. Utrecht: Ecofys

Bolinger, M., & Seel, J. (2015). *Utility-scale Solar 2014 (No. LBNL-1000917)* (pp. 1–43). Lawrence Berkeley National Laboratory. Retrieved from https://emp.lbl.gov/sites/all/files/lbnl-1000917.pdf

Bolinger, M., Seel,J. & LaCommare, H. (2017*). Utility-Scale Solar 2016 : An Empirical Analysis of Project Cost, Performance, and Pricing Trends in the United States*. Lawrence Berkeley National Laboratory

Bolton, D. (2016). *Germany has so much renewable energy that people are being paid to consume electricity*. Retrieved July 21, 2016, from http://www.independent.co.uk/environment/renewable-energy-germany-negative-prices-electricity-wind-solar-a7024716.html

BP. (2018). *BP Statistical Review of World Energy 2018*. British Petroleum. London

Castillo-Ramírez, A., Meija-Giraldo & Munzo-Galeano, N. (2017). Large-Scale Solar PV LCOE Comprehensive Breakdown Methodology. *CT & F - Ciencia, Tecnologia y Futuro, pp. 117-136.* Retrieved November 25, 2018, from http://www.scielo.org.co/pdf/ctyf/v7n1/0122-5383-ctyf-7-01-00117.pdf

CPUC (2015). *California Renewables Portfolio Standard (RPS)*. California Public Utilities Commission. San Francisco. Retrieved July 21, 2016, from http://www.cpuc.ca.gov/RPS\_Homepage/.

de Moor, H., Schaeffer, G.K., Seebregts, A. et al. (2003). *Experience curve approach for more effective policy instruments.* Photovoltaic Energy Conversion, 2003. Proceedings of 3rd World Conference on. Vol. 3. IEEE.

DEA (2012). *Technology Data for Energy Plants Generation of Electricity and District Heating, Energy Storage and Energy Carrier Generation and Conversion*. Danish Energy Agency and Energinet, Denmark. Retrieved from: https://www.energinet.dk/SiteCollectionDocuments/Danske%20dokumenter/Forskning/Technology\_data\_for\_energy\_plants.pdf

Denholm, P., Clark, K., & O’Connell, M. (2016). *On the path to sunshot: emerging issues and challenges in integrating high levels of solar into the electrical generation and transmission system*. NREL (National Renewable Energy Laboratory (NREL), Golden, CO (United States)). Retrieved from http://www.osti.gov/scitech/biblio/1253978

Dominguez-Ramos, A., M. Held, R. Aldaco, M. Fischer, and A. Irabien. (2010). Prospective CO2 emissions from energy supplying systems: Photovoltaic systems and conventional grid within Spanish frame conditions. *International Journal of Life Cycle Assessment 15(6): 557–566.*

Ecofys (2018). *Energy transition within 1.5ºC.* A disruptive approach to 100% decarbonization of the global energy system by 2050. Ecofys- A Navigant Company. Retrieved from: <https://www.navigant.com/-/media/www/site/downloads/energy/2018/navigant2018energytransitionwithin15c.pdf>

Edenhofer, O., Pichs Madruga, R. & Sokona, Y. United Nations Environment Programme, World Meteorological Organization, Intergovernmental Panel on Climate Change, & Potsdam-Institut für Klimafolgenforschung (Eds.). (2012). *Renewable energy sources and climate change mitigation: special report of the Intergovernmental Panel on Climate Change*. New York: Cambridge University Press.

EERE. (2016). *Sunshot 2030*; Washington: US Department of Energy. Retrieved from <https://www.energy.gov/eere/solar/sunshot-2030>

EIA, US. (2015). *Updated capital cost estimates for utility scale electricity generating plants*. Washington: U.S. Energy Information Administration Retrieved from http://www.eia.gov/forecasts/capitalcost/

EIA, US. (2016). *Capital Cost Estimates for Utility Scale Electricity Generating Plants*. US DOE Energy Information Administration. Washington. Retrieved from https://www.eia.gov/analysis/studies/powerplants/capitalcost/pdf/capcost\_assumption.pdf.

EIA, US. (2018). *Frequently Asked Questions*. US DOE Energy Information Administration. Washington. Retrieved on 15 November from: https://www.eia.gov/tools/faqs/

EIA. (2018). *International Energy Outlook 2017*. US Department of Energy. Energy Information Administration. Washington. Retrieved from: https://www.eia.gov/outlooks/ieo/pdf/0484(2017).pdf

Elshurafa, A.M., [Albardi](https://www.sciencedirect.com/science/article/pii/S0959652618316652#!), S.R., [Bigerna](https://www.sciencedirect.com/science/article/pii/S0959652618316652#!),S. & [Bollino](https://www.sciencedirect.com/science/article/pii/S0959652618316652#!), C.A. (2018). Estimating the learning curve of solar PV balance–of–system for over 20 countries: Implications and policy recommendations. *Journal of Cleaner Production, pp-122-134.*

Energy and Environmenal Economics Inc (2014). *Capital cost review of power generation technologies.* San Francisco. Retrieved from https://www.wecc.biz/Reliability/2014\_TEPPC\_Generation\_ CapCost\_Report\_E3.pdf. Energy and Environmental Economics, Inc.

Equinor (2018). *Energy Perspectives 2018, Long-term macro and market outlook.* Equinor. Retrieved from: <https://www.equinor.com/en/news/07jun2018-energy-perspectives.html>

Finnegan, S., Jones, C. & Sharples, S. (2018). *The embodied CO2e of sustainable energy technologies used in buildings: A review article*. Energy and Buildings, Vol 181, 15 Dec, 2018. pp.50-61.

Fraunhofer ISE. (2015). *Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale*. Fraunhofer ISE. Berlin.

Fraunhofer ISE. (2016). *Photovoltaics Report*. Fraunhofer, Institute for Solar Energy. Berlin. Retrieved from https://issuu.com/kanagagnana/docs/2016-11-17\_photovoltaics\_report

Fraunhofer ISE. (2018, August 27). *Photovoltaics Report*. Fraunhofer, ISE. Berlin. Retrieved from https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf

Green, M. A., Emery, K., Hishikawa, Y., Warta, W. & Dunlop, E.D. (2014). *Solar Cell Efficiency Tables (Version 45).* Wiley Online Library. Retrieved from: https://doi.org/10.1002/pip.2573

Green, M. A., Ho-Baillie, A., & Snaith, H. J. (2014a). The emergence of perovskite solar cells. *Nature Photonics, 8(7), 506–514.* Retrieved fromhttp://doi.org/10.1038/nphoton.2014.134

Greenpeace. (2015). *World Energy [R]evolution, a sustainable world energy outlook*. Retrieved from http://www.greenpeace.org/international/Global/international/publications/climate/2015/Energy-Revolution-2015-Full.pdf

GTM Research, & SEIA. (2015). *US Solar Market Insight Report: 2014 Year in Review*. Retrieved from: www.seia.org/research-resources/solar-market-insight-report-2014-q4

Gunther, M. (2015). *Meteroic rise of perovskite solar cells under scrutiny over efficiencies*. Retrieved from The Royal Society of Chemistry (GB). Retrieved from https://www.chemistryworld.com/news/meteoric-rise-of-perovskite-solar-cells-under-scrutiny-over-efficiencies/8324.article

Grantham Institute and Carbon Tracker (2017). Expect the Unexpected. The Disruptive Power of Low-carbon Technology. Grantham Institute- Climate Change and the Environment and Carbon Tracker Initiative. Retrieved from <https://www.imperial.ac.uk/media/imperial-college/grantham-institute/public/publications/collaborative-publications/Expect-the-Unexpected_CTI_Imperial.pdf>

Haas, R., Lettner, G., Auer, H., & Duic, N. (2013). The looming revolution: How photovoltaics will change electricity markets in Europe fundamentally. *Energy, 57, 38–43.* http://doi.org/10.1016/

Hayward, J., Graham, P.W. (2017). *Electricity generation technology cost projections: 2017-2050*. Newcastle, Australia. CSIRO. Retrieved from https://publications.csiro.au/rpr/pub?pid=csiro:EP178771

Hayward, J., Graham, P.W. (2013). *A global and local endogenous experience curve model for projecting future uptake and cost of electricity generation technologies*. Energy Economics, 40, 537-548. https://doi.org/10.1016/j.eneco.2013.08.010

Hertwich, E.G., Gibon, T., Bouman, E.A., Arvesen, A., Suh, S., Heath, G.A., Bergesen, J.D., Ramirez, A., Vega, M.I. & Shi, L. (2015). *Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies*. In W. Clark (Ed.), Proceedings of the National Academy of Sciences of the United States of America. 112(20), pp. 6277-6282. Cambridge: PNAS. Retrieved from https://doi.org/10.1073/pnas.1312753111

Hondo, H. (2005). Life cycle GHG emission analysis of power generation systems: Japanese case. *Energy 30 - 2042–2056.* Retrieved from http://www.univie.ac.at/photovoltaik/umwelt/LCA\_japanstudy.pdf

Hou, G., Sun, H., Jiang, Z., Pan, Z., Wang, Y., Zhang, X., Zhao, Y. & Yao, Q. (2016). Life cycle assessment of grid-connected photovoltaic power generation from crystalline silicon solar modules in China. *Applied Energy, 164, 882–890.* http://doi.org/10.1016/j.apenergy.2015.11.023

Hsu, D., O’Donoughue, P., Fthenakis, V., Heath, G. A., Kim, H. C., Sawyer, P., Choi, J.K. & Turney, D. E. (2012). Life cycle greenhouse gas emissions of crystalline silicon photovoltaic electricity generation: systematic review and harmonization. *Journal of Industrial Ecology, 16, S122–S135.* http://doi.org/10.1111/j.1530-9290.2011.00439.x

Ibn-Mohammed. T., Koh, S.C.L., Reaney, I.M., Acquaye, A., Schileo, G., Mustapha, K.B. & Greenough, R. (2017). Perovskite solar cells: An integrated hybrid lifecycle assessment and review in comparison with other photovoltaic technologies. *Renewable and Sustainable Energy Reviews, 1321–1344.* doi:doi.org/10.1016/j.rser.2017.05.095

IEA and NEA (2010). *Projected Costs of Generating Electricity – edition 2010*. Organisation for Economic Co-operation and Development - International Energy Agency and Nuclear Energy Agency. France. Retrieved from http://www.worldenergyoutlook.org/media/weowebsite/energymodel/ProjectedCostsofGeneratingElectricity2010.pdf

IEA and NEA (2015). *Projected Costs of Generating Electricity – edition 2015.* Organisation for Economic Co-operation and Development - International Energy Agency and Nuclear Energy Agency. France. Retrieved from https://www.oecd-nea.org/ndd/pubs/2015/7057-proj-costs-electricity-2015.pdf

IEA ETSAP. (2010). *Technology Brief E02 - Gas-fired Power*. Paris: International Energy Agency Energy Technology Systems Analysis Programme. Retrieved from http://www.iea-etsap.org/web/e-techds/pdf/e02-gas\_fired\_power-gs-ad-gct.pdf

IEA PVPS. (2015a). *A Snapshot of Global PV (1992-2014).* Paris: International Energy Agency Photovoltaic Power Systems Programme. Retrieved from http://www.iea-pvps.org/fileadmin/dam/public

IEA PVPS. (2015b). *Trends 2015 in Photovoltaic Applications (No. IEA-PVPS T1-27:2015).* Paris: International Energy Agency Photovoltaic Power Systems Programme. Retrieved from http://www.iea-pvps.org/fileadmin/dam/public/report/national/IEA-PVPS\_-\_Trends\_2015\_-\_MedRes.pdf

IEA PVPS. (2015c). *Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems*. Paris: International Energy Agency Photovoltaic Power Systems Programme. Retrieved from https://www.iea.org/renewables2018/.

IEA PVPS. (2016). *Snapshot of global photovoltaic markets 2015*. International Energy Agency Photovoltaic Power Systems Programme. Retrieved from http://www.iea-pvps.org/fileadmin/dam/public/

IEA PVPS. (2017). *Trends 2016 in Photovoltaic Applications : Survey report of selected countries between 1992 and 2015*. Paris: International Energy Agency Photovoltaic Power Systems Programme. Retrieved from https://www.cansia.ca/uploads/7/2/5/1/72513707/iea\_pvps\_trends\_2016.pdf

IEA PVPS. (2018). *Trends 2018 in Photovoltaic Applications : Survey report of selected IEA countries between 1992 and 2017*. Paris: International Energy Agency Photovoltaic Power Systems Programme.

IEA PVPS. (2018a). *2018: Snapshot of Global Photovoltaic Markets*. Paris: International Energy Agency Photovoltaic Power Systems Programme.

IEA. (2010). *Technology Roadmap: Solar Photovoltaic Energy 2010*. International Energy Agency. Paris, France. Retrieved from http.://www.iea.org/media/freepublications/technologyroadmaps/solar/

IEA. (2012a). *Technology Roadmap: High-Efficiency, Low-Emissions Coal-Fired Power Generation*. International Energy Agency. Paris, France. Retrieved from http://environmentportal.in/files/file/

IEA. (2012b). *Energy Technology Perspectives 2012 – Pathways to a Clean Energy System*. International Energy Agency. Paris, France. Retrieved from http://www.iea.org/publications/freepublications/publication/ETP2012\_free.pdf

IEA. (2014). *Projected Costs of Generating Electricity – edition 2010*. Organisation for Economic Co-operation and Development - International Energy Agency and Nuclear Energy Agency. France. Retrieved from http://www.worldenergyoutlook.org/media/weowebsite/energymodel.

IEA. (2014a). *Technology Roadmap: Solar Photovoltaic Energy*. International Energy Agency. Paris, France. Retrieved from http://www.iea.org/publications/freepublications/publication/TechnologyRoadmapSolarPhotovoltaicEnergy\_2014edition.pdf.

IEA. (2014b). *Energy Technology Perspectives 2014 - Harnessing Electricity’s Potential*. International Energy Agency. Paris, France. Retrieved from http://www.iea.org/etp/etp2014/

IEA. (2016a). *Energy Prices and Taxes – Third quarter 2016*. Quarterly Statistics. International Energy Agency. Paris, France.

IEA. (2016b). *Energy Technology Perspectives 2016 - Towards Sustainable Urban Energy Systems*. International Energy Agency. Paris, France. Retrieved from http://www.iea.org/etp/etp2016/

IEA. (2017). *Energy Technology Perspectives 2017 : Catalysing energy technology transformations*. International Energy Agency. Paris, France. Retrieved from : https://www.iea.org/etp2017/.

IEA. (2018a). *World Energy Outlook 2018*. International Energy Agency. Paris, France. Retrieved from : https://www.iea.org/weo/

IEA. (2018b). *TRENDS 2018: Snapshot of Global Photovoltaic markets*. International Energy Agency. Paris, France.

IEA. (2018c). *Renewables 2018*. International Energy Agency. Paris, France. Retrieved from: https://www.iea.org/renewables2018/

IEA (2019). Energy Prices and Taxes – Quarterly Statistics – First Quarter 2019. International Energy Agency. OECD/IEA, Paris.

IEEJ. (2018). *IEEJ Outlook 2019 – Energy transition and a thorny oath for 3E challenges.* The Institute of Energy Economics Japan. Available at: <https://eneken.ieej.or.jp/data/8122.pdf>

IPCC. (2012*). Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN)*. New York, NY: Cambridge University Press. Retrieved from http://www.ipcc.ch/report/srren/

IPCC. (2014*). Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA Retrieved from: https://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc\_wg3\_ar5\_full.pdf

IRENA. (2015). *Renewable Power Generation Costs in 2014.* International Renewable Energy Agency, Abu Dhabi. Retreived on 10 November 2018 from https://www.irena.org/publications/2015/Jan/Renewable-Power-Generation-Costs-in-2014.

IRENA. (2016). *The Power to Change: Solar and Wind Cost Reduction Potential to 2025*. International Renewable Energy Agency, Abu Dhabi. Retrieved on 20 November 2018 from https://www.irena.org/publications/2016/Jun/The-Power-to-Change-Solar-and-Wind-Cost-Reduction-Potential-to-2025.

IRENA. (2016a). *Renewable Energy Statistics 2016*. International Renewable Energy Agency, Abu Dhabi. Retrieved from http://www.irena.org/DocumentDownloads/Publications/IRENA\_RE\_Capacity\_Statistics\_2016.pdf

IRENA. (2017). *IRENA: Cost and Competitiveness Indicators: Rooftop Solar PV*. International Renewable Energy Agency, Abu Dhabi.

IRENA. (2018). *Renewable Energy Statistics 2018;* International Renewable Energy Agency, Abu Dhabi.Retrieved on 15 November 2018 from https://www.irena.org/publications/2018/Jul/Renewable-Energy-Statistics-2018.

IRENA. (2018a). *Global Trends in Renewable Energy Costs*. International Renewable Energy Agency, Abu Dhabi

IRENA. (2018b). *Renewable Power Generation Costs in 2017*; International Renewable Energy Agency, Abu Dhabi. Retrieved on 25 November 2018 from https://www.irena.org/publications/2018/Jan/Renewable-power-generation-costs-in-2017.

IRENA. (2018c). *Renewable Energy Topic; featured Dashboard.* International Renewable Energy Agency, Abu Dhabi. Retrieved from http://resourceirena.irena.org/gateway/dashboard/

IRENA. (2018d). *Global Energy Transformation: A Roadmap to 2050.* International Renewable Energy Agency, Abu Dhabi. Retrieved on 15 November 2018 from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Apr/IRENA\_Report\_GET\_2018.pdf.

IRENA. (2019). *Global energy transformation:* The REmap transition pathway (Background report to 2019 edition), International Renewable Energy Agency, Abu Dhabi.

ITRPV. (2015). *International Technology Roadmap for Photovoltaic: 2014 Results.* International Technology Roadmap for Photovoltaics (PV). Retrieved from http://www.itrpv.net/Reports/Downloads/

ITRPV. (2016). *International Technology Roadmap for Photovoltaics: 2015 Results* (pp. 40–41). International Technology Roadmap for Photovoltaics (PV). Retrieved from http://www.itrpv.net/Reports/

ITRPV. (2017). *International technology Roadmap for Photovoltaic : Results 2017 including maturity report 2017.* VDMAe.V. Frankfurt. Retrieved from http://www.itrpv.net/Reports/Downloads/

ITRPV. (2018). *International technology roadmap for Photovoltaic : Results 2018*. VDMAe.V. Frankfurt. Retrieved from http://www.itrpv.net/Reports/Downloads/

j.energy.2013.04.034

Kim, H. C., Fthenakis, V., Choi, J.-K., & Turney, D. E. (2012). Life Cycle Greenhouse Gas Emissions of Thin-film Photovoltaic Electricity Generation: Systematic Review and Harmonization. *Journal of Industrial Ecology, 16, S110–S121.* http://doi.org/10.1111/j.1530-9290.2011.00423.x.

Kriegler, E., Riahi, K., Bauer, N., Schwanitz, V. J., Petermann, N., Bosetti, V., … Edenhofer, O. (2015). Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. *Technological Forecasting and Social Change,* 90, 24–44. http://doi.org/10.1016/j.techfore.2013.09.021

Lazard. (2015). *Lazard’s Levelized Cost of Energy Analysis – Version 9.0*. New York: Lazard. Retrieved from https://www.lazard.com/media/2390/lazards-levelized-cost-of-energy-analysis-90.pdf

Lazard. (2016). *Lazard's Levelized Cost of Energy Analysis - Version 10.0*; New York: Lazard. Retrieved on 10 November 2018 from https://www.lazard.com/media/438038/levelized-cost-of-energy-v100.pdf..

Lazard. (2017). *Lazard's Levelized Cost of Energy Analysis - Version 11.0*; New York: Lazard. Retrieved on 11 November 2018 from https://www.lazard.com/media/450337/lazard-levelized-cost-of-energy-version-110.pdf.

Lazard. (2018). *Lazard's Levelized Cost of Energy Analysis - Version 12.0*; New York: Lazard. Retrieved from : https://www.lazard.com/media/450773/lazards-levelized-cost-of-energy-version-120-vfinal.pdf

Leun, K. v. d. (2018*). Solar PV shows a record learning rate.* Rapidshift. Retrieved from http://www.rapidshift.net/category/solar/

Lo, C. (2014). *Power plant O&M: how does the industry stack up on cost*? Retrieved July 30, 2016, from: http://www.power-technology.com/features/featurepower-plant-om-how-does-the-industry-stack-up-on-cost-4417756/

Masanet, E, Chag, Y., Gopal, A., Larsen, P., Morrow III, W., Sathre, R., Shehabi, A. & Zhai, P. (2013). Life cycle assessment of electric power systems. *Annual Review of Environmental Resources, 38:107–36.* Doi: 10.1146/annurev-environ-010710-100408

MIT. (2015). *The future of solar energy: an interdisciplinary MIT study*. Retrieved from http://energy.mit.edu/publication/future-solar-energy/

MNRE. (2016). *Solar-Park-Guidelines*. Retrieved from www.mnre.gov.in: https://mnre.gov.in/file-manager/UserFiles/Solar-Park-Guidelines.pdf

Newbery D. (2017). *How to judge whether supporting solar PV is justified*. Cambridge Working Paper Economics. University of Cambridge. Retrieved from: http://www.econ.cam.ac.uk/research-files/repec/cam/pdf/cwpe1715.pdf

Nikolakakis, T. & Fthenakis, V. (2011). The optimum mix of electricity from wind- and solar-sources in conventional power systems: Evaluating the case for New York State. *Energy Policy, 39(11), 6972–6980*

Nils, M. & Tedin, H.O.(2016). *Greenhouse Gas Emissions and Energy Payback Time for multi- and mono-Si Photovoltaic Systems -* A Study on Solar Energy from Photovoltaic Systems Located in Sweden. LUP Student papers. Retrieved from: <http://lup.lub.lu.se/luur/download?func=downloadFile&recordOId=8879209&fileOId=8879218>

NREL (2016a). *On the Path to Sunshot : The role of Advancements in Solar Photovoltaic Efficiency, Reliability and Costs*. National Renewable Energy Laboratory, US DOE. Golden.

NREL. (2013). *Solar energy and capacity value.* National Renewable Energy Laboratory. Retrieved from <http://www.nrel.gov/docs/fy13osti/57582.pdf>

NREL. (2016*). Research Cell Efficiency Records*. Retrieved July 20, 2016, from http://www.nrel.gov/ncpv/

NREL. (2017). *SPV O & M Cost Model and Cost Reduction*. National Renewable Energy Laboratory, US DOE. Golden.

NREL. (2017a)( September 12). *NREL Report Shows Utility-Scale Solar PV System Cost Fell Nearly 30% Last Year*. NREL News. National Renewable Energy Laboratory, US DOE. Golden. Retrieved November 20, 2018, from https://www.nrel.gov/news/press/2017/nrel-report-utility-scale-solar-pv-system-cost-fell-last-year.html

NREL. (2017b*). US Solar Photovoltaic System Cost Benchmark : Q1 2017*. National Renewable Energy Laboratory, US DOE. Golden

NREL. (2018). *Annual Technology Baseline*. National Renewable Energy Laboratory, US DOE. Golden . Retrieved from: https://atb.nrel.gov/

Nugent, D. & Sovacool, B.K.(2014). Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey. *Energy Policy. pp. 229-244.*

Pacca, S., Sivaraman, D & Keoleian, G.A. (2007). Parameters affecting the life cycle performance of PV technologies and systems. *Energy Policy, 3316-3326.*

Perlin, J. (2004). *The Silicon solar cell turns 50*. National Renewable Energy Laboratory, Golden, CO (US). Retrieved from <https://www.nrel.gov/docs/fy04osti/33947.pdf>

Philipps, D. et al. (2015). *Photovoltaics Report 47*. Fraunhofer Institute for Solar Energy Systems ISE, Freiburg.

Quandl. (2016). *Coal prices and charts*. Retrieved July 31, 2016, from: https://www.quandl.com/collections/markets/coal

Ram M., Bogdanov D., Aghahosseini A., Gulagi A., Oyewo A.S., Child M., Caldera U., Sadovskaia K., Farfan J., Barbosa LSNS., Fasihi M., Khalili S., Dalheimer B.,Gruber G., Traber T., De Caluwe F., Fell H.-J., Breyer C. (2019). *Global Energy System based on 100% Renewable Energy –Power, Heat, Transport and Desalination Sectors.* Study by Lappeenranta University of Technology and Energy Watch Group, Lappeenranta, Berlin, March 2019. Retrieved from: <http://energywatchgroup.org/wp-content/uploads/EWG_LUT_100RE_All_Sectors_Global_Report_2019.pdf>

Ram M., Bogdanov, D., Aghahosseiniu, A., Oyewo, A.S., Gulagi, A., Child, M., Fell, H.K., Breyer, C. (2017). Global Energy System based on 100% Renewable Energy – Power Sector., Study by Lappeenranta University of Technology and Energy Watch Group. Lappeenranta, Berlin, November 2017.

Raugei, M., Fullana-i-Palmer, P., & Fthenakis, V. (2012). The energy return on energy investment (EROI) of photovoltaics: Methodology and comparisons with fossil fuel life cycles. *Energy Policy, 45, 576–582.* http://doi.org/10.1016/j.enpol.2012.03.008

REN21. (2015). *Renewables 2015: Global Status Report*. Paris: REN21 Secretariat. Retrieved from http://www.ren21.net/wp-content/uploads/2015/07/REN12-GSR2015\_Onlinebook\_low1.pdf

REN21. (2016). *Renewables 2016: Global Status Report*. Paris: REN21 Secretariat. Retrieved from http://www.ren21.net/wp-content/uploads/2016/06/GSR\_2016\_Full\_Report\_REN21.pdf

REN21. (2018). *Renewables 2018: Global Status Report*. Renewable Energy Policy Network for the 21st Century Paris.

report/PICS/IEA-PVPS\_-\_\_A\_Snapshot\_of\_Global\_PV\_-\_1992-2015\_-\_Final\_2\_02.pdf

Rhyne, I., Klein, J. (2014). Estimated Cost of New Renewable and Fossil generation in California. California Energy Commission. Draft Staff Report. Retrieved from http://www.energy.ca.gov/2014publications/CEC-200-2014-003/CEC-200-2014-003-SD.pdf

Schmidt T. S., R. Born, and M. Schneider (2012). Assessing the costs of photovoltaic and wind power in six developing countries. *Nature Climate Change 2, 548 – 553.*

Seel, J., Barbose, G., & Wiser, R. (2013). *Why are residential PV prices in Germany so much lower than in the United States. A Scoping Analysis Note for the February*. Retrieved from http://energy.gov/sites/prod/files/2014/01/f6/sunshot\_webinar\_20130226.pdf

Shell. (2018). *Shell Scenarios - Sky: Meeting the goals of the Paris Agreement*. Shell. Houston. Retrieved from : www.shell.com/skyscenario

SolarGIS. (2018). *Maps of Global horizontal irradiation (GHI)*. Retrieved from: http://solargis.info/doc/free-solar-radiation-maps-GHI

SolarPower Europe. (2015). *Global Market Outlook for Solar Power 2015-2019*. SolarPower Europe. Retrieved from: http://resources.solarbusinesshub.com/images/reports/104.pdf

Sussams, L. et al (2017). *Expect the Unexpected : the Disruptive Power of Low-carbon Technology*. London: Carbon Tracker Initiative.

Teske, S., Sawyer, S. & Schafer, O. (2015). energy [R]evolution : *A sustainable world energy outlook 2015; 100% Renewable Energy for All*. Brussels: Greenpeace.

Thomas Nikolakakis, & Vasilis Fthenakis. (2011). *The optimum mix of electricity from wind- and solar-sources in conventional power systems: Evaluating the case for New York State*. Energy Policy, 39(11), 6972–6980.

Tour, A. de la, Meniere, Y. & Glachant, M. (2013). *What cost for photovoltaic modules in 2020 ? Lessons from experience curve models.* Working paper 13-ME-03. MINES ParisTech, HAL,Paris. Retrieved from : https://www.researchgate.net/publication/273698183\_What\_cost\_for\_photovoltaic\_What\_cost\_for\_photovoltaic\_modules\_in\_2020\_Lessons\_from\_experience\_curve\_models

Tsao, J., Lewis, N., & Crabtree, G. (2006). *Solar FAQs.* US Department of Energy, Office of Basic Energy Science. Retrieved from Solar FAQs : https://www.sandia.gov/~jytsao/Solar%20FAQs.pdf

US Energy Information Administration. (2015). *Updated capital cost estimates for utility scale electricity generating plants.* Washington: U.S. Energy Information Administration. Retrieved from: http://www.eia.gov/forecasts/capitalcost/

US Energy Information Administration. (2018, November 25). US Energy Information Administration : Independent Statistics and Analysis. Retrieved from: *Frequently Asked Questions : General Energy:* https://www.eia.gov/tools/faqs/

US Energy Information Administration. EIA. (2018). *Annual Energy Outlook 2018*. Washington: US Energy Information Administration. Retrieved from: https://www.eia.gov/outlooks/aeo/

USDOE. (2012). *Analysis of PV and CSP Growth in the SunShot Scenario in SunShot Vision Study 2012.* Washington: US Department of Energy. Retrieved from : <https://www.energy.gov/sites/prod/files/SunShot%20Vision%20Study.pdf>

Vieira, R. G., Guerra, F. K. O. M. V., Vale, M. R. B. G., & Araújo, M. M. (2016). Comparative performance analysis between static solar panels and single-axis tracking system on a hot climate region near to the equator. *Renewable and Sustainable Energy Reviews, 64, 672–681.* http://doi.org/10.1016/j.rser.2016.06.089

Weißbach, D., Ruprecht, G., Huke, A., Czerski, K., Gottlieb, S., & Hussein, A. (2013*).* Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants. *Energy, 52, 210–221.* http://doi.org/10.1016/j.energy.2013.01.029

World Bank. (2015). *Breakdown of Electricity Generation by Energy Source. World Development Indicators*. The World Bank data in The Shift project Data Portal. Retrieved from http://www.tsp-data-portal.org/Breakdown-of-Electricity-Generation-by-Energy-Source#tspQvChart.

World Bank. (2016). *Global Economic Monitor (GEM) Commodities* | World DataBank. Retrieved July 27, 2016, from: http://databank.worldbank.org/data/reports.aspx?source=global-economic-monitor-(gem)-commodities#

Zhao, Y., & Zhu, K. (2016). Organic–inorganic hybrid lead halide perovskites for optoelectronic and electronic applications. *Chem. Soc. Rev., 45(3), 655–689.* <http://doi.org/10.1039/C4CS00458B>

# Glossary

**Adoption Scenario** – the predicted annual adoption over the period 2015 to 2060, which is usually measured in **Functional Units**. A range of scenarios is programmed in the model, but the user may enter her own. Note that the assumption behind most scenarios is one of growth. If for instance, a solution is one of reduced heating energy usage due to better insulation, then the solution adoption is translated into an increase in the use of insulation. There are two types of adoption scenarios in use: **Reference (REF)** where global adoption remains mostly constant, and **Project Drawdown Scenarios (PDS)** which illustrate the high growth of the solution.

**Approximate PPM Equivalent** – the reduction in the atmospheric concentration of CO2 (in **PPM**) that is expected to result if the **PDS Scenario** occurs. This assumes a discrete avoided pulse model based on the Bern Carbon Cycle model.

**Average Abatement Cost** – the ratio of the present value of the solution (**Net** **Operating Savings** minus **Marginal First Costs**) and the **Total Emissions Reduction**. This is a single value for each solution for each **PDS Scenario** and is used to build the characteristic “*Marginal Abatement Cost*” curves when Average Abatement Cost values for each solution are ordered and graphed.

**Average Annual Use** – the average number of functional units that a single implementation unit typically provides in one year. This is usually a weighted average for all users according to the data available. For instance, the total number of passenger-km driven by a hybrid vehicle in a year depends on the country and the typical number of occupants. We take global weighted averages for this input. This is used to estimate the **Replacement Time**.

**Cumulative First Cost** – the total **First Cost** of solution **Implementation Units** purchased in the **PDS Scenario** in the analysis period. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

**Direct Emissions** – emissions caused by the operation of the solution, which are typically caused by the lifetime use of the solution. They should be entered into the model normalized per functional unit.

**Discount Rate**- the interest rate used in discounted cash flow (DCF) analysis to determine the present value of future cash flows. The discount rate in DCF analysis considers, not just the time value of money, but also the risk or uncertainty of future cash flows; the greater the uncertainty of future cash flows, the higher the discount rate. Most importantly, the greater the discount rate, the more the future savings are devalued (which impacts the financial but not the climate impacts of the solution).

**Emissions** **Factor**– the average normalized emissions resulting from consumption of a unit of electricity across the global grid. Typical units are kg CO2e/kWh.

**First Cost**- the investment cost per **Implementation Unit** which is essentially the full cost of establishing or implementing the solution. This value, measured in 2014$US, is only accurate to the extent that the cost-based analysis is accurate. The financial model assumes that the first cost is made entirely in the first year of establishment and none thereafter (that is, no amortization is included). Thus, both the first cost and operating cost are factored in the financial model for the first year of implementation, all years thereafter simply reflect the operating cost until replacement of the solution at its end of life.

**Functional Unit** – a measurement unit that represents the value, provided to the world, of the function that the solution performs. This depends on the solution. Therefore, LED Lighting provides petalumen-hours of light, Biomass provides tera-watt-hours of electricity and high-speed rail provides billions of passenger-km of mobility.

**Grid Emissions** – emissions caused by the use of the electricity grid in supplying power to any operation associated with a solution. They should be in the units described below each variable entry cell. Drawdown models assume that the global electric grid, even in a Reference Scenario, is slowly getting cleaner and that emissions factors fall over time resulting in lower grid emissions for the same electricity demand.

**Implementation Unit** – a measurement unit that represents how the solution practice or technology will be installed/setup and priced. The implementation unit depends on the solution. For instance, implementing electric vehicles (EV) is measured according to the number of actual EV’s in use, and adoption of Onshore Wind power is measured according to the total terawatts (TW) of capacity installed worldwide.

**Indirect Emissions** – emissions caused by the production or delivery or setup or establishment of the solution in a specified area. These are NOT caused by day to day operations or growth over time, but they should be entered into the model normalized on a per functional unit or per implementation unit basis.

**Learning Rate/Learning Curve** - Learning curves (sometimes called experience curves) are used to analyze a well-known and easily observed phenomenon: humans become increasingly efficient with experience. The first time a product is manufactured, or a service is provided, costs are high, work is inefficient, quality is marginal, and time is wasted. As experienced is acquired, costs decline, efficiency and quality improve, and waste is reduced. The model has a tool for calculating how costs change due to learning. A 2% learning rate means that the cost of producing a good drop by 2% every time total production doubles.

**Lifetime Capacity** – this is the total average functional units that one implementation unit of the solution or conventional technology or practice can provide before replacement is needed. All technologies have an average lifetime usage potential, even considering regular maintenance. This is used to estimate the **Replacement Time**. and has a direct impact on the cost to install/acquire technologies/practices over time. E.g. solar panels generate, on average, a limited amount of electricity (in TWh) per installed capacity (in TW) before a new solar panel must be purchased. Electric vehicles can travel a limited number of passenger kilometers over its lifetime before needing to be replaced.

**Lifetime Operating Savings**–the operating cost in the PDS versus the REF scenarios over the lifetime of the implementation units purchased during the model period regardless of when their useful life ends.

**Lifetime Cashflow NPV**-the present value (PV) of the net cash flows (PDS versus REF) in each year of the model period (2015-2060). The net cash flows include net operating costs and first costs. There are two results in the model: Lifetime Cashflow NPV for a Single **Implementation Unit**, which refers to the installation of one **Implementation Unit**, and Lifetime Cashflow NPV of All Units, which refers to all **Implementation Units** installed in a particular scenario. These calculations are also available using profit inputs instead of operating costs.

**Marginal First Cost** – the difference between the **First Cost** of all units (solution and conventional) installed in the **PDS Scenario** and the **First Cost** of all units installed in the **REF Scenario** during the analysis period. No discounting is performed. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

**Net Annual Functional Units (NAFU)** – the adoption in the PDS minus the adoption in the REF in each year of analysis. In the model, this represents the additional annual functional demand captured either by the solution in the **PDS Scenario** or the conventional in the **REF Scenario**.

**Net Annual Implementation Units (NAIU)** – the number of **Implementation Units** of the solution that are needed in the PDS to supply the **Net Annual Functional Units (NAFU).** This equals the adoption in the PDS minus the adoption in the REF in each year of analysis divided by the average annual use.

**Net Operating Savings** – The undiscounted difference between the operating cost of all units (solution and conventional) in the **PDS Scenario** minus that of all units in the **REF Scenario**.

**Operating Costs** – the average cost to ensure the operation of an activity (conventional or solution) which is measured in 2014$US/**Functional Unit**. This is needed to estimate how much it would cost to achieve the adoption projected when compared to the **REF Case**. Note that this excludes **First Costs** for implementing the solution.

**Payback Period** – the number of years required to pay all the **First Costs** of the solution using **Net Operating Savings**. There are four specific metrics each with one of **Marginal First Costs** or **First Costs** of the solution only combined with either discounted or non-discounted values. All four are in the model. Additionally, the four outputs are calculated using the increased profit estimation instead of **Net Operating Savings**.

**PDS/ Project Drawdown Scenario** – this is the high growth scenario for the adoption of the solution.

**PPB/ Parts per Billion** – a measure of concentration for atmospheric gases. 10 million PPB = 1%.

**PPM/ Parts per Million** – a measure of concentration for atmospheric gases. 10 thousand PPM = 1%.

**REF/ Reference Scenario** – this is the low growth scenario for the adoption of the solution against which all **PDS scenarios** are compared.

**Replacement Time**- the length of time in years, from installation/acquisition/setup of the solution through usage until a new installation/acquisition/setup is required to replace the earlier one. This is calculated as the ratio of **Lifetime Capacity** and the **Average Annual Use**.

**TAM/ Total Addressable Market** – represents the total potential market of functional demand provided by the technologies and practices under investigation, adjusting for estimated economic and population growth. For this solutions sector, it represents the world and regional total addressable markets for electricity generation technologies in which the solutions are considered.

**Total Emissions Reduction** – the sum of the grid, fuel, indirect, and other direct emissions reductions over the analysis period. The emissions reduction of each of these is the difference between the emissions that would have resulted in the **REF Scenario** (from both solution and conventional) and the emissions that would result in the **PDS Scenario**. These may also be considered as “emissions avoided” as they may have occurred in the REF Scenario, but not in the PDS Scenario.

**Transition solutions** - are considered till better technologies and less impactful are more cost-effective and mature.

**TWh/ Terawatt-hour** – A unit of energy equal to 1 billion kilowatt-hours.

1. Current adoption is defined as the amount of functional demand supplied by the solution in the base year of study. This study uses 2014 as the base year due to the availability of global adoption data for all Project Drawdown solutions evaluated. [↑](#footnote-ref-1)
2. Gestation period means the time it takes to actually set up the project once the investment decision is made.  [↑](#footnote-ref-2)
3. Scalability means how easily can we upgrade the size of the plant by adding more modules or turbines. [↑](#footnote-ref-3)
4. Current adoption is defined as the amount of functional demand supplied by the solution in 2018. This study uses 2014 as the base year due to the availability of global adoption data for all Project Drawdown solutions evaluated [↑](#footnote-ref-4)
5. In some cases, the low boundary is negative for a variable that can only be positive, and in these cases the lowest collected data point is used as the “low” boundary. [↑](#footnote-ref-5)
6. All monetary values are presented in US$2014 [↑](#footnote-ref-6)
7. Solar PV utility scale electricity generation. [↑](#footnote-ref-7)
8. Total Solar PV electricity generation. [↑](#footnote-ref-8)