Technical assessment for Distributed Solar Photovoltaics

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*Note: For some of the technical reports, the result section is not yet updated. Kindly refer to the model for the latest results.

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Acronyms and Symbols

- AC - Alternating Current
- A-Si - Amorphous Silicon
- BIPV - Building Integrated Solar PV
- BOS - Balance-Of-System
- CCS - Carbon Capture and Storage
- Cdte - Cadmium Telluride
- CIGS - Copper Indium Gallium Selenide
- CO_2 eq - Carbon Dioxide equivalent
- CPUC – California Public Utilities Commission
- CPV - Concentrating Photovoltaics
- C-Si - Crystalline Silicon
- 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 Return On Investment
- ETP – Energy Technology Perspectives
- EV – Electric Vehicles
- FiT - Feed-in-Tariff
- GaAs – Gallium Arsenide
- GHG – Greenhouse Gases Emissions
- GTM - Greentech Media
- GW - Gigawatts
- IEA - International Energy Agency
- 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
- kW_p – 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
- MW – Megawatt
- MW_p – Megawatt (Peak)
- NAFU - Net Annual Functional Units
- NAIU - Net Annual Implementation Units
- NOx - Nitrogen Oxides

- NPV – Net Present Value
- NREL - National Renewable Energy Laboratory
- O&M - Operation and Maintenance
- OECD – Organization for Economic Co-operation and Development
- PD – Project Drawdown
- PDS - Project Drawdown Scenario
- $PM_{2.5}$ - 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 Programme
- REF – Reference Case
- REmap – Renewable Energy Roadmap (IRENA)
- REN21 – Renewable Energy Policy Network for the 21st century
- RPO – Renewable Purchase Obligation
- RPS – Renewable Portfolio Standards
- RRS – Reduction and Replacement Solutions
- SEIA - Solar Energy Industries Association
- SO_2 - 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 "Distributed Solar" as a distributed solar photovoltaic (PV) system, typically sited on rooftops, that includes both residential solar PV and community-scale solar PV systems with an installed capacity below 1 megawatt. In a PV system, sunlight falling on a solar cell produces electricity as a result of the phenomenon of the photoelectric effect. The solar cells deployed in such systems are typically divided into three generations. The first-generation solar cells, which presently capture the majority of the market, are based on crystalline silicon (Si) - either single crystalline or multi-crystalline. The second-generation solar cells are thin-film solar PV cells, which are again of three types, i.e. a) amorphous and micromorph silicon; b) cadmium telluride; and c) copper-indium-selenide and copper-indium-gallium-diselenide. Third-generation solar cells, such as high concentration PV cells, dye sensitized solar cells, and organic solar cells, are still under development and are not yet fully commercialized.

How much of the total requirement of electricity generation is actually met by distributed solar depends on the level of Adoption of this technology by the market. For this, experts make projections for the future adoption of this solution and these projections are presented in the form of "scenarios". Most adoption scenarios of this technology earlier predicted only a low, single-digit percentage of total electricity to be generated by all solar PV (including both distributed as well as utility scale) by 2050; but in view of the rapid recent adoption of this technology in many countries, the scenarios have also raised their levels of ambition. In fact some recent scenarios have even predicted that almost 60% of global electricity generation would come from solar PV by 2050. Such increased projections are largely based on increasing solar cell efficiencies and rapidly declining costs for PV systems, thus making them competitive with conventional generating sources in many parts of the world.

The total addressable market for distributed solar is based on projected global electricity generation in terawatt-hours from 2020-2050, with current adoption level in 2018 estimated to be only 0.7 percent of global electricity generation. With no definitive estimates of the type of future solar PV adoption, it is assumed (on the basis of historical data) that distributed installations would cover approximately 40 percent of the market, while utility-scale solar PV (i.e. solar farms) would capture the remaining 60 percent.

Climate and financial impacts of such increased adoption of distributed solar from 2020 to 2050 were modeled on the basis of three growth scenarios, which were assessed in comparison to a *Reference* Scenario where the solution's market share was fixed at the current level of adoption. The *Plausible* Scenario projects 13.7 percent of total electricity generation worldwide coming from distributed solar by 2050 replacing conventional electricity generation technologies. In the *Drawdown* and *Optimum* Scenarios, the market share for this solution reaches over 14 percent. On the climate impact analysis, Plausible Scenario results in the avoidance of 28.8 gigatons of carbon dioxide-equivalent greenhouse gas emissions between 2020-2050. Both the *Drawdown* and *Optimum* scenarios are more ambitious in the growth of distributed PV technologies, with impacts on greenhouse gas emissions reductions over 2020-2050 of near 68.9 and 68.0 gigatons of carbon dioxide-equivalent, respectively. For the achievement of these climate impacts, *Plausible* scenario presents US$499 billion associated with net first costs and over US$3.1 trillion of net operating savings are projected over the same period from 2020 to 2050. Both *Drawdown* and *Optimum* scenarios have similar numbers among them with near US$320 billions of marginal first costs and over 7.2 trillions of net operating savings.

Solar technologies have a very promising long-term potential, since solar resources are cheap, plentiful and widespread and future advances in both battery and PV technologies would continue to drive down the investment costs and advance the adoption of this technology, even in a world without specific policy interventions for distributed solar PV. Based on the financial impacts alone, it is clear that global adoption of distributed solar is economically viable and will provide a significant return on investment.

1 LITERATURE REVIEW

1.1. STATE OF PV TECHNOLOGY

Solar energy is the primary source of energy for all life on Earth. Humans, like all other living things, rely on the sun for warmth and food. However, humans also harness the sun's energy in other ways. The energy stored in fossil fuels for one, also had its origin in sunlight. This energy was converted into chemical energy by plants millions of years ago and these plants became fossilized and they are now providing energy to the world. Solar Photovoltaic (PV) systems are another means of harnessing solar energy. They are unique in that they directly convert the incident solar radiation to electricity with no ill-effects of noise, pollution, or moving parts.

How does PV achieve this? Some materials exhibit a property known as the 'photoelectric effect' that causes them to absorb photons of light and release electrons (charge generation). When these free electrons are channelized, an electric current is generated. This can be then put to productive uses. The photoelectric effect was first discovered by Edmund Bequerel in 1839 (PRES, 2011). In 1905, Albert Einstein described the nature of light and the photoelectric effect on which photovoltaic technology is based. Based on this work Albert Einstein won a Nobel Prize in Physics in 1921. The first photovoltaic cell was developed by Bell Laboratories in 1954. However, it was too expensive. The space industry began to make the first serious use of the technology to provide power aboard space crafts in the 1960s,. The space program advanced the development of this technology and led to reductions in the cost of PV cells. During the 1970s oil crisis, PV gained traction as an alternate source of power for non-space applications (PRES, 2011).

PV cells are wired together in series to form a module, and then modules are wired in parallel to form panels and then - large arrays. Standard crystalline silicon (Si) solar module consists of 60-72 cells (IRENA, 2015). Each PV cell generates direct current (DC). This is usually fed into an inverter to produce alternating current (AC) in which form it is generally used. As prices have dropped, the adoption of solar PV (including distributed solar PV) has increased considerably. Around 30% of solar PV capacity installed globally in 2015 were systems of less than 100 kW (IRENA, 2015).

In many regional markets, however, newly installed solar PV systems are primarily utility-scale installations rather than distributed or roof-top solar PV. The primary factor that distinguishes the two is the size of the system. The definition of what utility scale solar PV is, varies across organizations. While the US based Solar Energy Industries Association (SEIA) and Greentech Media (GTM) define "utility scale" projects as those owned by or those which sell power directly to a utility. The Lawrence Berkeley National

Laboratory (LBNL) in the US defines utility-scale as any ground-mounted solar project that is larger than 5 MW in size (Bolinger, 2015). However, for the purpose of this report the International Energy Agency's (IEA) definition of utility solar PV has been followed. It refers to any PV system greater than 1 MW and which is grid connected. Thus, for this report, "Distributed Solar" refers to any distributed solar PV system of size less than 1 MW. It may or may not be connected to the grid. Though, it needs to be kept in mind that not all of these systems are residential solar PV systems- some are mid-size community scale solar systems. This report includes all such systems also under the head of "Distributed Solar".

Distributed solar PV installations can be categorized in two ways. The first and most common system is the one in which the SPV system is connected to the main electricity grid. Based on policies in place, excess distributed PV electricity can be fed back to the grid and home-owners can be credited for it in two ways. If the electricity generated by distributed PVs is credited to the homeowner or business to offset their grid electricity usage, this is known as "net metering". Alternately some authorities have regulations in place that allow home-owners to be paid a feed-in-tariff (FiT), *i.e.* a rate for the electricity generated by solar PV that is consumed by the household itself and a separate rate is paid for whatever electricity is supplied to the grid.

The second kind of residential solar PV system is a 'Stand-Alone' system. This is typically found in isolated locations where the possibility of connection to the main grid is remote. These stand-alone systems often deploy a battery bank in addition so that electricity can still be obtained even when the sun is not shining. Such systems also frequently use a generator to back up the batteries. The International Renewable Energy Agency (IRENA) has reported that globally off-grid solar PV combined with storage systems provides more than 6 million households with 100% of their electricity consumption (IRENA, 2015). It further reports that around 89 million people in developing countries use at least one solar lighting product.

Such stand-alone systems comprise only a small percentage of the current residential solar PV expansion. IRENA reports that off-grid systems comprise only 10% of the current total of solar PV installations. However, with the mushrooming of local solar companies such as MKopa in Kenya and SELCO in India, it is expected that these off-grid products will only increase in the future.

Distributed solar PV systems can also be categorized into two discrete market segments- residential and commercial, based on the type of building on which they are installed. IRENA defines residential PV systems to be systems that are less than 20 kW in size and are installed on sloped roofs, while commercial systems typically do not exceed 1 MW and are most often installed on flat or low sloped roofs. It is important to recognize this difference, because commercial feed-in-tariffs (FiTs), wherever provided, are usually more than those for residential solar PV systems and therefore the overall costs of such systems are less per implementation unit. There are also economies of scale for the larger systems which sharply reduce the per unit costs.

Solar cells have developed over and are categorized under three generations. First generation solar cells are based on crystalline silicon (c-Si) which is either single crystalline or multi-crystalline in structure. Crystalline Silicon solar cells account for more than 97% of the overall cell production (IEA-PVPS, 2018a) The rest of the market is primarily second generation, thin-film solar PV which mainly includes three families, a) amorphous Si (a-Si) and micromorph silicon (μ-Si) b) Cadmium Telluride (CdTe); and c) Copper-Indium-Selenide (CIS) and Copper-Indium-Gallium-Deselenide (CIGS) cells. 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 prices of silicon. Because of their flexibility thin film solar cells can double up as distributed shingles and tiles, building facades, or as the glazing for skylights and can also serve as the core of Building Integrated Solar PV (BIPV) systems.

Third generation solar cells are those that are still not yet widely commercialized but show promise and are still under development. There are four types of third generation solar cells/systems under development: a) Concentrating solar PV that utilizes optical devices such as mirrors or lenses to concentrate direct solar radiation onto very small, highly efficient multi-junction solar cells, b) Dye Sensitized Solar Cells (DSSC) that split the task of charge generation and charge separation where these two tasks are done by a semiconductor and a dye respectively, c) Organic solar cells that are composed of an organic or polymer material that is inexpensive though not very efficient, and d) Novel and emerging technologies. Most recently, a new class of thin film solar cells called the peroskvite cells have captured the attention of researchers as their efficiency approaches that of silicon cells (NREL, 2016), though the long-term stability of the technology remains to be proven (Gunther, 2015). Although the performance and stability of third generation solar cells are presently limited, they show substantial potential.

Residential solar PV systems are almost exclusively made up of first generation solar PV cells because of their low cost and highest commercially available efficiency. Building Integrated Solar (BIPV) and Building Added PV (BAPV) systems are slowly catching on. The IEA has estimated that incorporating BIPV on building facades could increase PV suitable surfaces by 35% (IEA, 2016b). However, as the suitability of such surfaces for generating electricity from the incident radiation is usually low, this lowers the economic viability of this technology.

The efficiency of a PV cell determines its rated capacity, also known as peak capacity, nameplate capacity, or nominal power. This value is reported in units of kW (sometimes kW_p for "peak kilowatt"), MW, or GW, depending on the size of the system. Capacity is calculated by the following equation:

$$Capacity = \eta \cdot A \cdot P_{sun}$$

where:

- η is the efficiency of the panels.
- A is the total panel area.
- P_{sun} is 1000 W/m^2, approximately equivalent to sunshine at noon on a clear day.

1.2. Adoption Path

1.2.1 Current Adoption

PV modules are produced with a single capacity rating (usually its peak rating), but the amount of energy actually produced by the system over the course of a year depends on several factors. First, the strength of the current generated is proportional to the intensity of the sunlight received. This insolation (amount of solar radiation incident on a given area) varies widely depending on geographic location of a place. Ideal solar resources are to be found in equatorial regions of the world, as may be seen in the figure below. Areas that are cloudier or have higher latitudes get less direct sunlight and thus have correspondingly lower generation potential. Even so, solar systems have been readily adopted even in countries like Germany with relatively low irradiance. Second, PV systems produce different amounts of power depending on the angle of the panel relative to the sun. Distributed panels are usually installed in a fixed orientation, whereas panels in large utility-scale arrays can be mounted with one or two axes of rotation for optimally tracking the path of the sun through the sky. Tracking greatly increases the electricity yield from a panel.

The ability of a PV system to actually produce energy as a ratio of its theoretical potential is captured in the concept of capacity factor of the system. This factor is also sometimes stated in units of "full load hours," which can be divided by 8760 hours per year to give a percentage. PV systems tend to have a capacity factor of 15-20% globally, with higher capacity factors in the summer and lower in the winter. The capacity factors of PV installations are much lower than that of fuel-based power sources by comparison because PV cells can only generate during daylight hours.

Current adoption[1] for distributed solar PV is estimated at only 0.7 percent (174 terawatt-hours) of total electricity generation (IEA, 2018), while fossil fuels still represent the lion's share of electricity generation (natural gas 23%, coal 38%, and oil 3.7%).

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[1] 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

By the end of 2017, the PV 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. This growth trend has kept its pace and 2017 was an amazing year for global solar power with capacity addition growing by 32 per cent 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, yet there has been a slow-down in the US market, Brazil and Chile have made notable progress adding over 1GW 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. depict the strong global growth of solar PV systems since 2008.

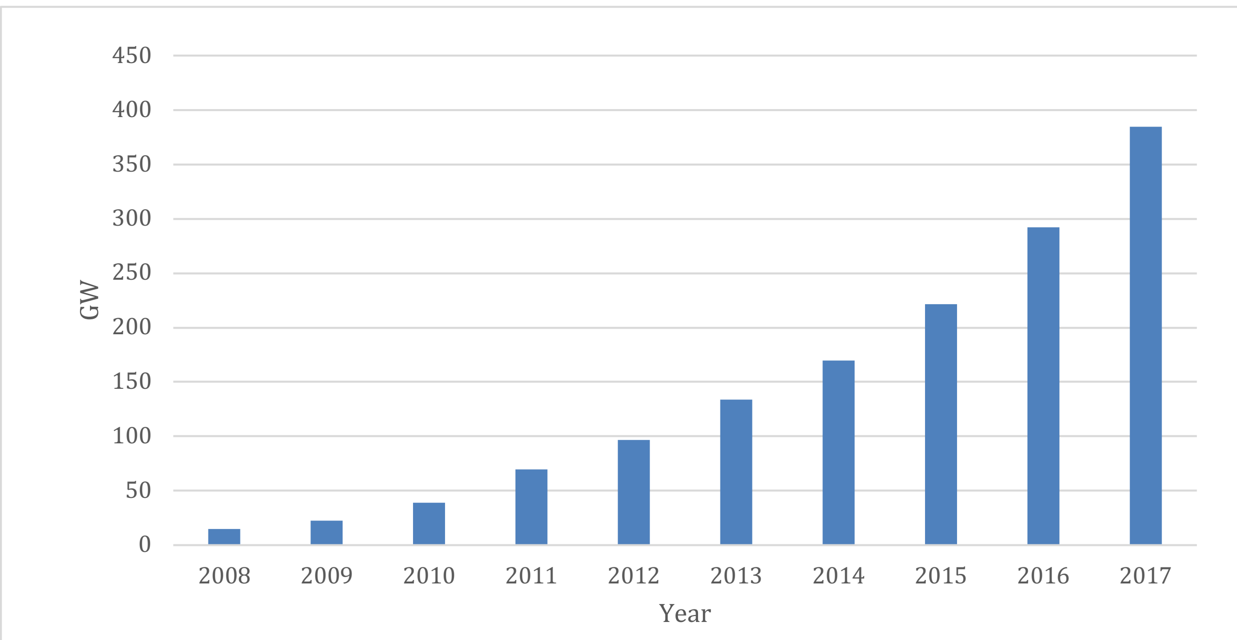

Figure 1.1 Global Cumulative Installed Solar PV capacity (Source : IRENA 2018)

Though the IEA and other international research agencies do not usually publish installed capacities separately for utility-scale and distributed solar 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 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 distributed PV systems, many countries are choosing to add bulk solar capacity mainly through centralized PV installations (IEA PVPS, 2018b).

1.2.2 Trends to Accelerate Adoption

One of the primary sources of data relating to renewable energy for this work has 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 solar PV (utility and distributed scale) generation capacity from 223 GW in 2017 to 7,122 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 the solution. It also presents 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 solar PV generating 2,956 TWh by 2040. The next is the New Policies Scenario which sees solar PV increasing its generation to 3,839 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 Solar PV from 435 TWh in 2017 to 6,409 GWh by 2040.

The energy company 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^{o}C. It forecasts a five-fold increase from PV generation form 241 TWh by 2015 to 351 TWh by 2040 (Shell, 2018). The Grantham Institute at Imperial College in partnership with Carbon Tracker makes an ambitious projection that PV 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 foresights into the future of PV, 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 (US Department of Energy, 2012) seems to have seriously underestimated growth of the solar market—it predicted only 302 GW of solar PV 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 agree that the growth rate for solar PV will continue to be quite high for the future as well.

1.2.3 Barriers to Adoption

The primary barrier to the adoption of this solution is the high first cost of installation. A 2018 Report by Lazard has found that distributed systems currently cost between US$1850 and 3250 per kW (Lazard, 2018). However, these costs have been steadily and rapidly declining and there has been an almost five-fold decline in costs since 2010 and hence this barrier has been lowered substantially.

Adoption of distributed 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 small communities and householders to set up distributed PV systems. The growth would also depend in large part on the development of policies and institutions necessary to govern and manage future "smart" electric grids that encourage and compensate the small "prosumers" who both produce as well as consume electricity. Lack of appropriate and encouraging policies and incentives is a major barrier to adoption of this solution.

1.2.4 Adoption Potential

Most adoption scenarios in the literature predict low, single-digit percentages of total electricity for solar photovoltaic generation by the mid-point of the century; e.g. IEA ETP (2016) 6DS and 4DS scenarios with 4.2% (2,187 TWh) and 5.8% (2,703 TWh) respectively (IEA, 2016b). But some, such as the Greenpeace Energy [R]evolution scenarios, envision it holding a much larger share of future electricity generation (near 20 percent of the electricity generation mix), with close to 10000TWh in the Energy [R]evolution scenario and around 13,612 TWh in the Advanced Revolution Scenario (Greenpeace, 2015).

Two highly ambitious scenarios which foresee a 100% switch over to renewable energy are the LUT and the ECOFYS scenarios. The LUT/EWG report (Ram *et al*., 2017) projects an 85-fold increase of solar PV 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).

1.3 ADVANTAGES AND DISADVANTAGES OF DISTRIBUTED SOLAR PV

1.3.1 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, and that could be considered similar solutions. Here solutions similar to distributed solar photovoltaics are considered which use the same resource: *i.e.* solar energy for electricity generation. Besides distributed solar PV, there are alternative renewable energy technologies with either difference in the level of agency (*e.g.* utility-scale level) or in the way the technologies work:

- **Solar Photovoltaic Utility Scale:** or solar farms use the photovoltaic (PV) technology to generate electricity. In this system, when sunlight falls on a silicon based cell, It excites an electron from the valence band across the band gap to the conduction band, from which it can travel to an outside circuit. This stream of electrons is the electric current which is channelized to provide electricity for day to day use. The cells are connected to form a module and the modules can then be connected to form panels of varying sizes. In utility scale solar PV systems, these are larger than 1 MW, are grid connected and generally supply bulk power to the grid. These are ground mounted and sometimes come with tracking systems which give them enhanced efficiencies. With the passage of time, the capability of solar parks to deliver bulk power at rates competitive with even conventional sources has gained strength. Technical and financial capacities have been built to set up and manage large scale solar parks. Of late such large scale projects have boomed and account for almost 60% of PV generation globally. And this share is expected to increase with time and reach over 65% by 2050 (Ram *et al.*, 2017).
- **Concentrated Solar Power (CSP)** or solar thermal electricity. Instead of converting sunlight directly into electricity like photovoltaics (PV) do, it relies on the core technology of fossil-fuel generation: steam turbines. The difference is that rather than using coal or natural gas, CSP uses solar radiation as its primary fuel. Sunlight is concentrated to heat molten salts which can store heat and later transfer this heat to water to run a steam turbine. A critical advantage of CSP is energy storage. Unlike PV panels and wind turbines, CSP makes heat before it makes electricity, and heat is easier to store. When equipped with molten salt tanks for heat storage, CSP plants can continue to produce electricity well after the sun goes down.
- **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).

1.3.2 Arguments for Adoption

Like other renewable sources, one major benefit of solar energy is that fuel is free—the sun shines every day at no cost. In other words, the operating costs of a solar PV system are minimal. Additionally, the total solar resource potential is practically inexhaustible. If it is assumed that energy demands in 2050 will rise as high as 30 TW, this usage is only a small fraction (~0.02%) of the available solar energy. Even with losses due to conversion efficiency and land area unavailable for solar harvesting, it is still an overwhelmingly generous source of energy (Tsao, 2006).

Given that for the most part, the electricity generated by roof-top solar PV will replace the electricity generated from fossil fuels, the carbon mitigation potential of roof-top solar PV is significant. The lifecycle emissions of roof-top solar PV systems are orders of magnitude less than the emissions from fossil fuel plants.

In addition, the public health benefit of roof-top PV is important, as the use of PV avoids the emission of harmful pollutants such as fine particulate matter, sulphur dioxide and nitrogen dioxide from fossil fuel power plants. In its 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 (US Department of Energy, 2012).

There are benefits of PV installation for global equity and security, as solar energy allows some degree of energy independence for nations who would otherwise have to import 100% of their energy resources. The strife over oil resources would also reduce. Additionally, PV systems can be installed as distributed generation systems in areas where there is a microgrid or no grid at all. Distributed solar PVs can be installed with little to no harmful environmental impacts, though these PV systems do compete directly with other environment-friendly solutions such as white roofs (roofs painted white to reflect solar radiation for cooling) and green roofs (roof-top gardens) for eco-friendly spaces on top of buildings.

1.3.3 Additional Benefits and Burdens

Accepting that PV will be a major part of the future global energy system requires several issues to be contended with. The " Future of Solar Energy" Study from MIT offers a thorough analysis of these and other issues (MIT, 2015); some of these are summarized here. One challenge is that PV provides intermittent energy; the amount of electricity generated can fluctuate unexpectedly depending on the weather conditions. As a result, PVs will need to be adopted in conjunction with energy storage and/or rapidly dispatchable generation sources like natural gas, to ensure that power is consistently available to meet the grid demands and/or flexible demand-side resources. Additionally, the intermittency of PV can also be mitigated by integrating the grid over large areas to smooth local fluctuations, by coupling solar with complementary renewables like wind power, and by increasing the flexibility of electric loads and using demand management (in addition to using batteries or dispatchable power).

Another barrier is the mismatch between the daily profile of solar insolation, 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. It should be noted that this effect is not universal—in places like the western US, electricity demand peaks during the day because of air conditioning usage (NREL, 2013). This issue can be addressed by adopting time-of-use tariffs to smoothen the demand curve.

There may also be a materials constraint on the expansion of production capacity for current PV technology. According to the MIT study, the need for commodity materials (concrete, steel, plastic, glass, aluminum, and copper) will likely be accommodated at current production rates, as will be the demand for key materials for producing crystalline silicon (silicon and silver) However, the same report shows that several critical materials for thin film PVs (indium, gallium, selenium and tellurium) are only mined as byproducts of other metals and will thus limit the ability to meet the levels of production needed for significant global adoption. More research into materials reduction in thin film PV design and exploitation of fresh resources will help address this issue.

A paradigm shift with more and more solar PV systems being owned by individuals and households is being witnessed. Large amounts of distributed solar energy being fed into the grid could potentially destabilize the grid if the grid topology does not change. This is because the high penetration of solar in the distribution grid can cause challenges with power quality and reverse power flows through substation equipment. Another way that the rise of individual solar PV affects the grid is that in some countries like Germany, energy from solar energy is required to be consumed first- before the energy from conventional power plants is consumed because the operating costs are low. Fossil fuel plants are base load power plants and are difficult to switch on and off every now and then. Thus, the energy that they produce when solar energy satisfies the total demand of the grid becomes redundant and this can cause electricity tariffs to become negative.

There has been a substantial amount of research in analyzing the lifecycle costs, as well as the energy return on investment (EROI): energy return on energy invested and energy payback times (EPBT) which is the ratio of energy required during the module life cycle and the energy produced by the module over its life time. 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 intensive process of purifying silicon as the primary reason for PV's low EROI But it is also counter-argued by some experts that while the EROI of conventional electricity from fossil fuels has been viewed as being much higher than the EROI of renewable energy this is largely a misconception due to the use of outdated data and a lack of consistency in calculation methods (WeiBbach, 2013; Raugei, 2012). Their results show that the range of EROI values for PV are within the same range as oil-fired electricity systems and almost half that of coal-fired electricity systems But, they make the important point that coal-fired power plants have much higher lifecycle GHG emissions as compared to PV. If these were to be reduced by using carbon capture and storage (CCS) systems, 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 while conventional fuels have a high EROI, *i.e.* they provide a large energy return on the energy invested in them even Solar PV has a respectable EROI.

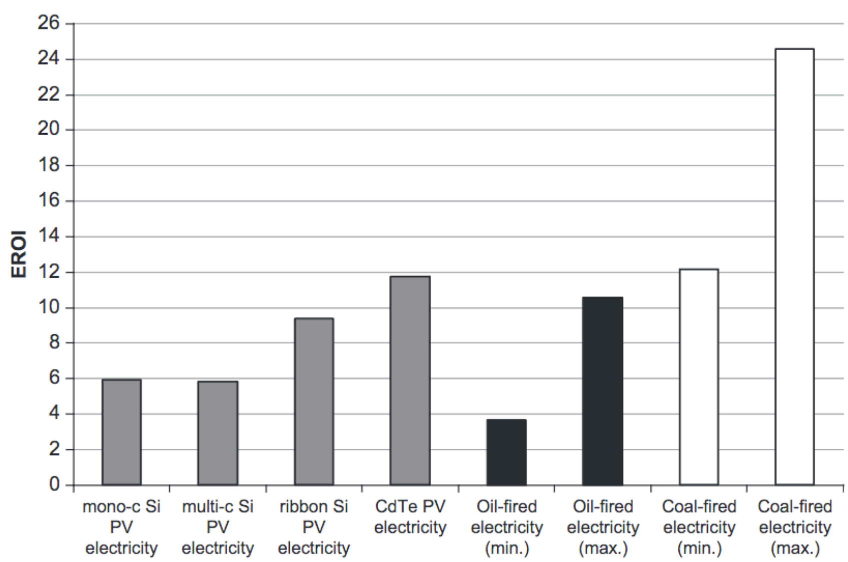

Figure 1.2 EROI (%) of PV electricity compared to oil- and coal-fired thermal electricity (Adapted from Raugei et al., 2012)

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.

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 PV projects is growing as these become a favored source for producing "green" energy.

However, intermittency and mismatched load profiles are both disadvantages of PVs compared to dispatchable electricity sources, which can be ramped up and down on demand. Wind also suffers from intermittency, but it often has a complementary generation profile to PVs over the course of a day. As a result, there is a synergistic effect of deploying solar energy and wind energy together in a region (Nikolakakis, 2011). 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 1.1 - Solar energy solutions versus conventional electricity generation technologies

Parameter	Conventional Electricity Generation Technologies	Concentrated Solar Power	Solar PV Utility-Scale Systems	Distributed Solar PV 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]	Very High	Medium	Low	Low	Low
Modular Scalability[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

[2] Gestation period means the time it takes to actually set up the project once the investment decision is made.
[3] Scalability means how easily can we upgrade the size of the plant by adding more modules or turbines.

2 METHODOLOGY

2.1 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 into implementation units (TW). The adoptions of both conventional and 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 distributed solar PV systems. To capture the appropriate level of agency, the solar PV market was split between *distributed solar* (representing households and building owners) and utility-scale solar (i.e. *solar farms*), being the first 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 distributed solar PV following the project Drawdown methodological assumptions whose further description available in the Drawdown RRS Model Framework and Guide. In order to grasp the total impact of an increased adoption of the solution during the assessed time frame, the REF scenario assumes that the future adoption rate of distributed solar PV remains fixed at the current year (i.e. 2018) level percentage of Total Addressable Market (TAM). This is estimated at 0.7 percent (183 terawatt-hours) of electricity generation. The TAM for this solution is 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 distributed 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 distributed solar PV, as well as the contribution this adoption can make to annual as well as cumulative emissions reduction.

2.2 DATA SOURCES

This section presents key data sources utilized in the model to evaluate the adoption of distributed solar. 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 done to create low, high, and mean estimates. For each solution variable, a sensitivity analysis of an average of thirty three data points reported in the literature was conducted. In some cases as many as 103 data points were taken into consideration. This allowed the calculation of robust and reliable inputs for the financial, technological and climate analyses that 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 distributed solar PV installations (IEA, 2018; IRENA, 2017; REN21, 2018; Lazard, 2018). Available estimates of distributed PV systems were concentrated in OECD countries, reflecting the preponderance of present-day PV installations in the developed world.

Cost estimates for fixed operation and maintenance (O&M) of distributed PV systems were collected from (Bolinger, 2017; EIA, 2018; IEA, 2018; NREL, 2017; Lazard, 2018), and these estimates were used to calculate the total operating costs of distributed PV technologies adoption, which, combined with capital costs for installation, represent the total financial costs of adopting this solution in the PDS scenario. Fixed operation and maintenance costs for both renewable and conventional generation technologies can include expenses such as day-to-day preventive 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 O&M costs of distributed PV installation in the PDS scenarios to that of conventional generation technologies, cost data for fossil fuel-based electricity generating sources were obtained from the IPCC 5th Assessment Report (IPCC, 2014). This report had presented its own sensitivity analysis of a number of sources from the literature[4], and other sources such as OECD (Lazard, 2018). 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 with a weighted average. The

[4] The IPCC's 5th Assessment Report analyzes the following sources: Coal: Black and Veatch (2012), DEA (2012), IEA/NEA (2010), IEA (2013a), IEA-RETD (2013), Schmidt et al. (2012), US EIA (2013). Gas Combined Cycle: Black and Veatch (2012), DEA (2012), IEA/NEA (2010), IEA (2011), IEA (2013a), IEA-RETD (2013), Schmidt *et al.* (2012), US EIA (2013).

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 (on PDS scenarios), technical data was also integrated, including average annual use, plant 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 plant efficiency is calculated from several global sources (IPCC, 2014; IEA, 2014), as well as from the U.S. (EIA, US. , 2016).

Though the average annual use of conventional generating technologies is much higher than that of distributed PV systems, 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 (EIA-US , 2016; IEA, 2016a; Lazard, 2016) that represent most of the regions contained in this analysis. Capacity factor data for distributed solar PV, on the other hand, is included for all regions, which enables calculation of the average annual use of these PV installations across a wide range of regions with differing solar irradiance values.

The model's analysis of the climate impacts of adoption is primarily derived from the direct emissions factor associated with the replacement of conventional generating technologies with distributed 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 distributed solar PV systems—primarily those lifecycle emissions associated with manufacturing, transporting, installing and other non-generation activities— a range of peer-reviewed lifecycle analysis (LCA) studies were analyzed 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 thin-film technologies, respectively. Hou provides LCA data and indirect emissions estimates for China (Hou, 2016).

2.3 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.

2.4 Adoption Scenarios

Because electricity generation from both utility-scale and distributed PV has increased so rapidly in recent years, more than a fivefold increase in total electricity generation from 96 TWh in 2012 to 531 TWh in 2017 (IRENA, 2018; IEA-PVPS, 2018a), it is a significant challenge to project PV adoption over the next 30 years with any degree of certainty. Many sources from the literature earlier depicted a single-digit percentage of total electricity generation from solar PV in 2050 (IPCC, 2014). Given the rapidly growing market for utility-scale PV, however, these projections now seem overly conservative, especially in light of the myriad cost and efficiency gains of PV technology in recent years. It is also indicative of the future potential of solar PV adoption that the IEA has created scenarios specifically for rapid renewable energy growth, including for adoption of solar PV.

Two different types of adoption scenarios were developed: a Reference (REF) Case which was considered the baseline, where not much changes in the world, and a set of Project Drawdown Scenarios (PDS) with varying levels of ambitious adoption of the solution. Published results show the comparison of one PDS to the REF, and therefore focus on the change to the world relative to a baseline.

2.4.1 Reference Case / Current Adoption

For the Reference (REF), adoption is fixed at the current adoption (in percent) of the market. That is, the current percentage of total electricity generation (TWh) provided by distributed solar PV plants constant throughout the study period to 2050. As the market grows, the total number of distributed solar PV systems adopted grows equally to maintain the percent adoption at its starting value in 2014. It is acknowledged that this, in reality, may not be a “business as usual” considering changes taking place worldwide, but it allows measurement of the impact of recent and even more aggressive policies on greenhouse gas emissions.

2.4.2 Project Drawdown Scenarios

Three Project Drawdown scenarios (PDS) were developed for each solution, to compare the impact of increased adoption of the solution to a reference case scenario, being:

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 distributed, 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 (2018c) 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 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.

2.5 INPUTS

2.5.1 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, distributed solar PV generation was estimated globally and regionally from 2020-2050 and then the emissions reductions were calculated due to the replacement of conventional electricity generation sources with the solution. The detailed methodology of these calculations is available at the Project Drawdown Integration Methodology report.

While being a renewable energy technology, solar PV distributed systems do not have direct emissions related to combustion of fuels. Project Drawdown modeling considers the analysis of indirect emissions related to the different factors that contribute to an LCA for solar PV systems. In modeling the lifecycle emissions of distributed PV adoption in the scenarios, it is used a fixed value (t CO_2-eq per TWh) considering information from several PV technologies rather than a decreasing one due to the difficulty of projecting future grid-tied emissions on a regional basis. The climate results will thus be more conservative than would be the case if it was assumed a decreasing average lifecycle emissions value for solar PV systems.

The values collected in the RRS model show lifecycle GHG emissions for a range of different photovoltaic technologies (both thin-film and crystalline-Si) across different regions and system sizes, though all data are for ground-mount, utility-scale PV systems. Some of the data used are an average of different lifecycle indirect emissions estimates from several sources. Data points from the literature that are used to calculate averages per PV system type are weighted based on the total share of global PV production for each type of technology. These weights come from Fraunhofer Institute for Solar Energy Systems and Projects in

Solar Energy AG (2016). Table 2.1 presents the boundaries of the data on the RRS model and the selected input.

Table 2.1 Climate Inputs

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Indirect CO_2 Emissions (Solution)	*t CO_2-eq/TWh*	21,327 – 79,429	50,378	44	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].

2.5.2 Financial Inputs

RRS model constructs PDS adoption scenarios for distributed solar PV generation globally and regionally for each year until 2050. It is 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 calculated. A lifetime capacity of 41,401 hours (around 24 years) was calculated depending on the average powerplant annual use.

There are two types of capital costs for PV systems: module and balance-of-system (BOS). BOS costs include hard costs like the electrical equipment and mounting hardware, as well as soft costs like labor and permitting (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:

$$Cost_{2050} = Cost_{2014}\left(\frac{Units_{2050}}{Units_{2014}}\right)^{\log R / \log 2}$$

[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.

where:

- $Cost$ is the capital cost per kW in the stated year.
- $Units$ 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 rate for modules and BOS varies based on technology and is necessarily different, so it was modeled separately. It was first analyzed several sources (e.g. IEA PVPS, 2015a; Bolinger and Seel, 2015, Fraunhofer ,2018) to calculate the percentage share of total PV system costs from the PV module and BOS. Then it was calculated the 2050 cost per kW for a module using an average efficiency rate obtained from a meta-analysis of several different sources (IRENA, 2015; IPCC, 2012) and the projected capacity in the PDS scenario (i.e. Plausible). This process was repeated using the efficiency rates for utility-scale PV BOS (IPCC, 2012; Energy and Environmenal Economics, 2014; IEA, 2014; Seel, 2013). By adding the module and BOS costs, the results depict a total PV system cost per kW, that was used to calculate a learning rate for the entire PV distributed systems.

For the solution (solar PV distributed), the conventional current mix of fossil fuel electricity generation technologies (coal, gas, and oil) replaced were identified. Costs and operation for both generation technologies (solution and conventional) were considered to obtain the differential result.

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.

To capture the rapid decrease of costs seen in recent years, the low boundary of data collected on installation. costs is assumed, which results in a total first cost of US$2,012 per kilowatt[6]. A customized learning rate of 19.48 percent was developed, accounting for independent impact on PV modules and balance of systems; this has the effect of reducing the installation cost to US$653 per kilowatt in 2030 and to US$462 in 2050, compared to US$1,786 per kilowatt for the conventional technologies (i.e. coal, natural gas, and oil power plants). Additionally, a discount rate is fixed at 4 percent for households and commercial projects and used across Drawdown solutions with a similar level of agency. As utility-scale solar PV, distributed 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).

Table 2.2 Financial Inputs for Conventional Technologies

[6] All monetary values are presented in US$2014

	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 2.3 Financial Inputs for Solution

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
First costs (Solution)	*US$2014/kW*	927.6 – 3,096	2,012	105	23
Fixed Operation and Maintenance Costs (Solution)	*US$2014/kW*	14.56– 29.03	21.79	23	9
Learning Rate Factor - PV Module (Solution)	%	16.60-28.00	22.30%	26	14
Learning Rate Factor - PV BOS (Solution)	%	11.50– 22.10	16.80%	19	14

2.5.3 Technical Inputs

Table 2.4 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 2.5 Technical Inputs Solution

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Lifetime Capacity (Solution)	*hours*	41,194 - 49,415	45,305	17	12
Average Annual Use (Solution)	*hours*	1,082.5– 2,273	1,678	73	17

2.6 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.

Assumption 1: The solution presented in this report is defined as distributed PV systems typically sited on rooftops, that include both residential solar PV and community-scale solar PV systems with under 1 megawatt of capacity.

Assumption 2: Most of the literature contained in this report does not provide a specific prognostication for future adoption of distributed PV but does suggest, however, that the majority of future installations will meet the definition of utility-scale systems. For this reason, several different data points were averaged and it is assumed that distributed installations represent a constant share of around 40 percent of the market, with utility-scale solar capturing the remaining 60 percent (US Department of Energy, 2012; IEA, 2014).

Assumption 3: The PV module itself contributed 41 percent of installed costs for solar PV installations (IEA PVPS, 2015a; Bolinger and Seel., 2015a; GT. Research 2015IRENA, 2017; Fraunhofer, 2018).

2.7 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 will be available at www.drawdown.org. Those general notes are excluded from this document but should be referenced for a complete understanding of the integration process. Only key elements of the integration process that are needed to understand how this solution fits into the entire system are described here.

Therefore, the data derived from individual solutions models was then inputted into sector-level integration models to generate final results for all solutions within a global system. The links between this sector and all the others is important, but major interactions occur with energy demand-side sectors like Transport and Buildings and Cities.

Through the process of integrating solar PV distributed systems 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. Emissions factors for each technology were determined through a meta-analysis of multiple sources, accounting for direct and indirect emissions.

2.8 Limitations / Further Developments

The RRS model holds a number of factors constant in order to keep global-scale modeling 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 "distributed," 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.

Another critical assumption that is made on the RRS model is that all distributed solar PV systems replace electricity from the grid. This needs further refinement but is seen as a conservative approach, as the grid do not reach all places where stand-alone PV systems can be deployed within the timeframe considered by the model. Indeed, in some places it replaces energy from diesel generators which means that the GHG savings of solar PV could be even greater than those calculated by the RRS model.

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

3 Results

In the following section are depicted selected results derived from the RRS model evaluating the impact of increased adoption of Solar PV Distributed for electricity generation when compared to conventional technologies.

3.1 Adoption

Comparing the results from the three modeled scenarios to the Reference Scenario allow estimating the climate and financial impacts of increased adoption of distributed PV systems. The Plausible Scenario (PDS1) projects 13.7 percent of total electricity generation worldwide coming from distributed solar PV by 2050. In the Drawdown (PDS2) and Optimum Scenarios (PDS3), the market share for this solution reaches over 14 percent. Below in Table 3.1 are shown the adoptions of the solution in 2050 in functional units and percent. Figure 3.1 depicts the long term pathway trajectories for the different scenarios of solar PV distributed systems.

Table 3.1 World Adoption of the Solution

Solution	Units	Base Year (2014)	World Adoption by 2050		
			Plausible	Drawdown	Optimum
Distributed Solar Photovoltaic (Solar Distributed)	*Electricity Generation (TWh)*	75	6,235	10,105	10,105
	(% market)	0.33%	13.7%	14.2%	14.2%

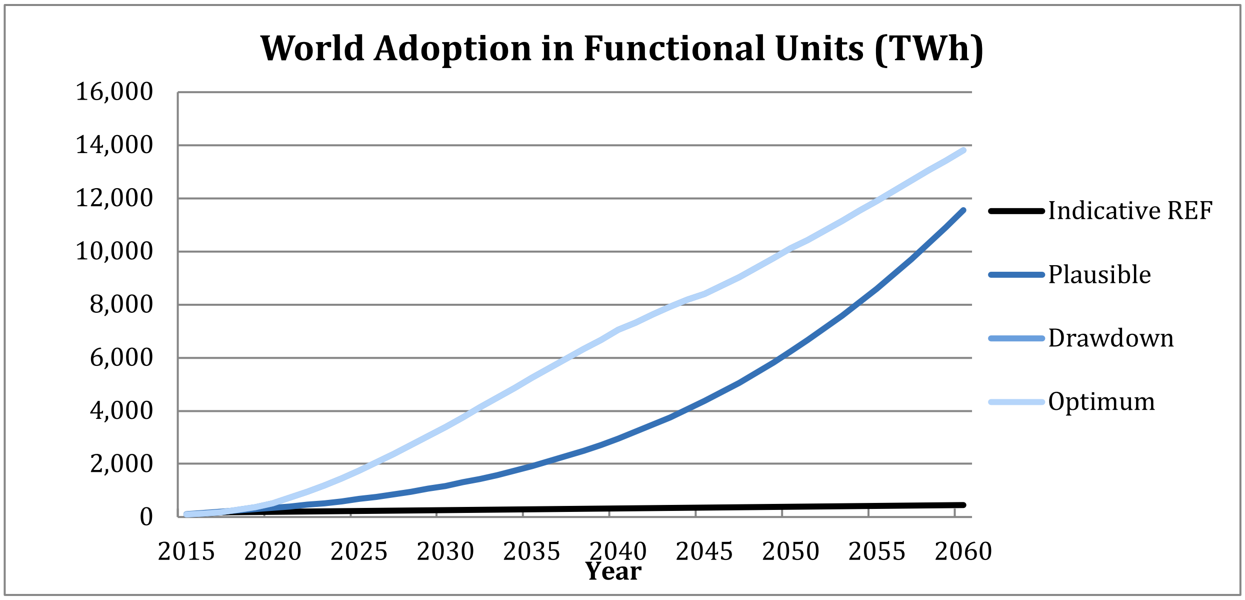

Figure 3.1 World Annual Adoption 2015-2060

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

3.2 Climate Impacts

Below are the emissions results of the analysis for each scenario which include total emissions reduction and atmospheric concentration changes. For a detailed explanation of each result, please see the glossary (Section 6).

The Plausible Scenario results in the avoidance of 31.31 gigatons of carbon dioxide-equivalent greenhouse gas emissions between 2020-2050. Both the Drawdown and Optimum Scenarios are more ambitious in the growth of distributed PV technologies, with impacts on greenhouse gas emissions reductions over 2020-2050 of near 73.3 gigatons of carbon dioxide-equivalent. Due to the replacement of carbon-emitting fossil fuel electricity sources, even considering a conservative, fixed estimate for lifecycle emissions from distributed PV, the climate impact of the different scenarios adoptions is notable. Tables 3.2 and 3.3. provide additional information on the climate impacts of the solution adoption.

Table 3.2 Climate Impacts

Scenario	Maximum Annual Emissions Reduction	Total Emissions Reduction	Emissions Reduction in 2050
	(Gt CO_2-eq/yr.)	*Gt CO_2-eq/yr. (2020-2050)*	*(Gt CO_2-eq/year)*
Plausible	2.67	31.33	2.67
Drawdown	4.43	73.32	4.43
Optimum	4.43	73.32	4.43

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 emission reduction for this solution is 28.8 gigatons of carbon dioxide-equivalent in the *Plausible* scenario, 68.9 gigatons of carbon dioxide-equivalent for the *Drawdown* Scenario and 68.0 gigatons of carbon dioxide-equivalent for the *Optimum* Scenario. Figure 3.2. show the world annual emissions reduction trajectories for the different scenarios for the long term.

Table 3.3 Impacts on Atmospheric Concentrations of CO_2-eq

Scenario	GHG Concentration Change in 2050	GHG Concentration Rate of Change in 2050
	PPM CO_2-eq (2050)	*PPM CO_2-eq change from 2049-2050*
Plausible	2.73	0.22
Drawdown	6.19	0.34
Optimum	6.19	0.34

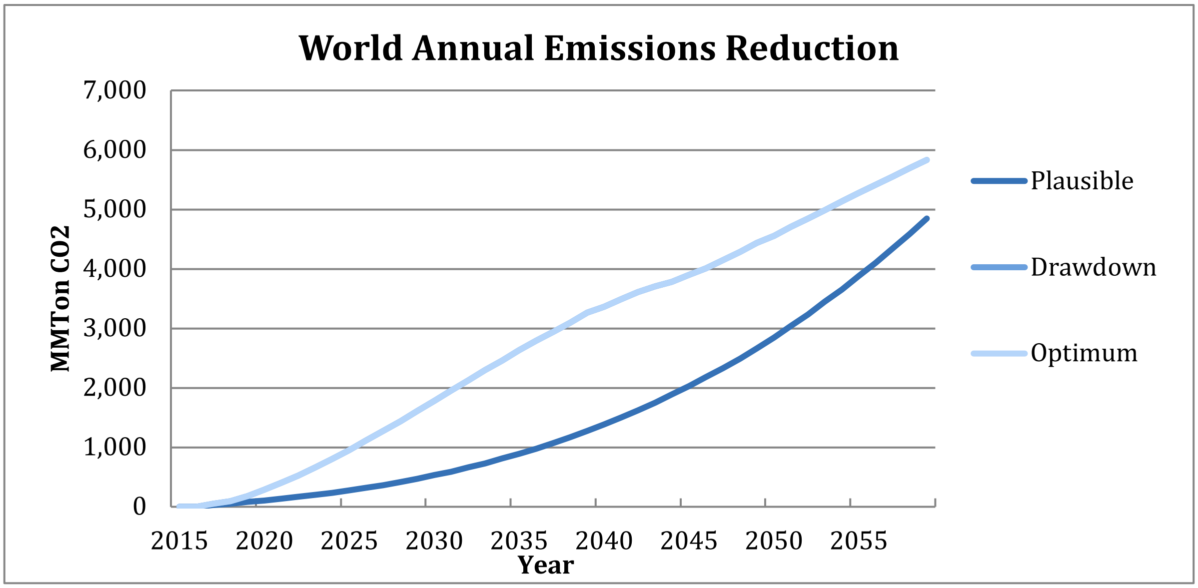

Figure 3.2 World Annual Greenhouse Gas Emissions Reduction 2015-2060

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.

3.3 Financial Impacts

The financial savings incurred by replacing conventional grid electricity sources with distributed PV systems are substantial. Plausible scenario presents US$480 billion associated net first costs and over US$3.1 trillion of net operating savings are projected over the same period from 2020 to 2050, principally because solar distributed PV does not require any fuel inputs. This allows for savings to start accruing from the first year of PDS adoptions. Both PDS2 and PDS3 have similar numbers with near US$255 billions of marginal first costs and over 7 trillions of net operating savings.

The capital costs for PDS adoption of distributed PV will certainly require significant investments, as the cumulative capital costs are close to $3 trillion under the Plausible Scenario and over $4.1 trillion for the other two PD scenarios. The learning rates used in this analysis lead to a continued decrease in the capital costs of these distributed PV systems. These projected decreases in the capital costs are in line with most projections for future costs. Below in Table 3.4 are the financial results of the analysis for each scenario. For a detailed explanation of each result, please see the glossary (Section 6).

Table 3.4 Financial Impacts

Scenario	Cumulative First Cost	Marginal First Cost	Net Operating Savings	Lifetime Cashflow Savings NPV (of All Implementation Units)
	2015-2050 Billion USD	*2015-2050 Billion USD*	*2020-2050 Billion USD*	*Billion USD*
Plausible	3,003	499	3,127	1,610
Drawdown	4,166	320	7,241	3,528
Optimum	4,166	320	7,241	3,528

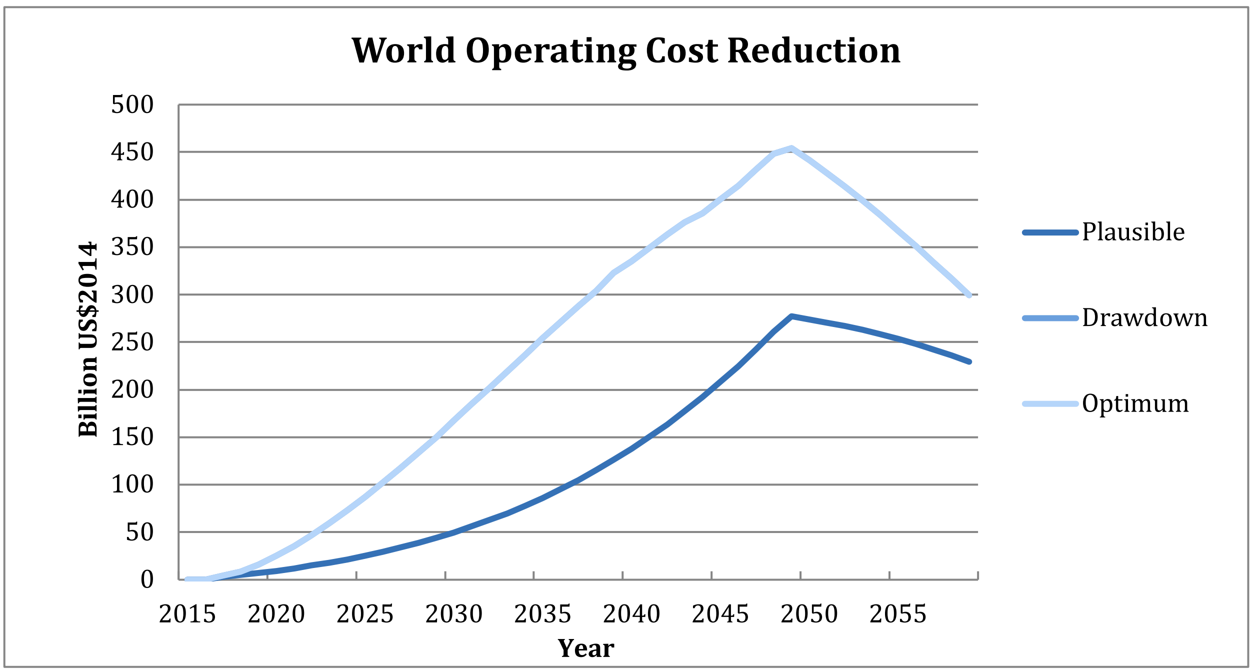

Figure 3.3 World Operating Cost Reduction 2015-2060

4 DISCUSSION

Solar PV has seen unprecedented levels of growth around the world since 2005 due to many factors but primarily gains in technology and declines in costs. Only modest advances in production are needed before distributed PV systems are cost-competitive with fossil fuel generation around the world. As a result, distributed PV is likely to continue its rapid growth in many regional markets and will play an increasingly important role in future global electricity supply, regardless of climate mitigation goals. If distributed solar PV is encouraged through favorable policies, then the world will reap major benefits in terms of GHG emissions reduction, as demonstrated by our results.

The rapid deployment of distributed PV will result in significant reductions in GHG emissions (and corresponding atmospheric concentrations) by displacing emissions associated with coal and natural gas. Solar has an incredibly promising long-term potential, as solar resources are plentiful and widespread, and future advances in both battery and PV technologies should continue to drive the adoption of this technology, even in a world without specific policy interventions.

The financial benefits of rapid distributed PV adoption will also be considerable, and these can help in jumpstarting adoption. There are significant investment costs associated with accelerated adoption, but this is an opportunity to generate wealth and economic growth, as the return on investment is also substantial.

4.1 LIMITATIONS

The accelerated installation of new distributed PV capacity will not be without challenges, however, as traditional electricity markets and grids are in many cases not primed for high penetration of intermittent, renewable energy. There will be economic, policy, and social hurdles to overcome on the pathway set out in PDS scenarios, and some of these will require significant changes to the way it is bought, sold, and even used electricity. But given the significant climate and financial impacts of global distributed PV adoption, it is imperative that the economies take on these challenges in order to reap the benefits.

4.2 BENCHMARKS

Table 4.1 depicts a benchmark of Project Drawdown results for 2050 on the three developed scenarios to other nine publicly available scenarios from IEA (2016b), Greenpeace (2015), IRENA (2017), Ram et al (2017) and IEA (2018). The benchmarked results account mostly for all solar PV electricity generation since results are not available from those sources differentiating utility and distributed solar PV technologies, except Ram et al. (2017).

Table 4.1 Benchmarks

Source and Scenario	Electricity Generation in 2050 (TWh)	Market Share in 2050 (%)
Project Drawdown – Plausible Scenario (PDS1)	**6,235**[7]	**13.7%**
Project Drawdown – Drawdown Scenario (PDS2)	**10,106**[7]	**14.24%**
Project Drawdown – Optimum Scenario (PDS3)	**10,106**[7]	**14.24%**
IEA Energy Technologies Perspectives (2016) – 6DS	2,187[8]	4.24%
IEA Energy Technologies Perspectives (2016) – 4DS	2,703[8]	5.8%
IEA Energy Technologies Perspectives (2016) – 2DS	5,103[8]	12.3%
Greenpeace Energy [R]evolution – Reference Scenario	1,096[8]	2.2%
Greenpeace Energy [R]evolution – Energy Revolution Scenario	9,914[8]	19.9%
Greenpeace Energy [R]evolution – 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	5,845[8]	14.1%
Ram et al. (2017) - 100% RE Scenario	11,912[7]	21.4%

[7] Distributed Solar PV electricity generation.
[8] Total Solar PV electricity generation.

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6 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 customized scenario. 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 CO_2 (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. It is considered a global weighted averages for this input. This is used to estimate the **Replacement Time**.

Building Integrated Photovoltaic system (BIVP) – refers to the photovoltaic components of an electricity generation system which is built into the building envelope (e.g. the roof, walls, cladding etc) during the time of the construction of the building itself. Such a system generates electricity and meets the power requirements of the building to a varying extent.

Building Added Photovoltaic system (BAVP) – refers to the photovoltaic components of an electricity generation system which is not part of the building construction process but which is retrofitted into an already existing building or after its construction is complete (e.g. an solar PV system mounted on the roof of an old building). The objective of this system is to generate electricity and meet the power requirement of the building to a varying extent.

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 takes into account, 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 CO_2e/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 drops 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.