

TECHNICAL ASSESSMENT FOR CONCENTRATED SOLAR POWER

SECTOR: ELECTRICITY GENERATION

AGENCY LEVEL: UTILITIES

KEYWORDS: SOLAR ENERGY, THERMAL ENERGY STORAGE,
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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
- AMPERE – Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates
- A-Si - Amorphous Silicon
- FBOS - Balance-Of-System
- CCS - Carbon Capture and Storage
- Cdte - Cadmium Telluride
- CIGS - Copper Indium Gallium Selenide
- CO₂ – Carbon Dioxide
- CO₂ 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
- DNI – Direct Normal Irradiation
- DOE – Department of Energy (US)
- DS – Degree Scenario
- EIA – Energy Information Administration (US)
- EPBT - Energy Payback Time
- EPC - Engineering, Procurement, and Construction
- EPIA - European Photovoltaic Industry Association
- EROI – Energy Returned on Energy Invested
- ETOI - Energy Return On Investment
- ETP – Energy Technology Perspectives
- EU – European Union
- EV – Electric Vehicles
- GaAs – Gallium Arsenide
- GEM-E3 – General Equilibrium model for Economy, Energy and Environment
- GHG – Greenhouse Gases
- Gt – Gigatons
- GTM - Greentech Media
- GW - Gigawatts
- IEA – International Energy Agency
- IEEJ – The Institute of Energy Economics, Japan
- IMAGE/TIMER – Integrated Model to Assess the Global Environment/The Targets IMage Energy Regional model
- IPCC – Intergovernmental Panel for 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
- LFR- Linear Fresnel Collector
- LUT -Lappeenranta University of Technology
- MESSAGE-MACRO – Model for Energy Supply Strategy Alternatives and their General Environmental impact with macroeconomic feedback
- MIT – Massachusetts Institute of Technology
- MW – Megawatt
- MW_p– Megawatt (Peak)
- NAFU - Net Annual Functional Units
- NAIU - Net Annual Implementation Units
- NO_x - Nitrogen Oxides
- NPV – Net Present Value
- NREL - National Renewable Energy Laboratory (US)
- O&M - Operation and Maintenance
- OECD – Organization for Economic Co-operation and Development
- PD – Project Drawdown
- PDS - Parabolic Dish Systems
- 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
- PTC - Parabolic Trough Collectors
- PV – Photovoltaic
- PVPS – Photovoltaic Power Systems Program (IEA)
- R&D – Research and Development
- REF – Reference Case
- REmap – Renewable Energy Roadmap (IRENA)
- REN21 – Renewable Energy Policy Network for the 21st century
- RES – Renewable Energy Sources
- RPO – Renewable Purchase Obligation
- RRS – Reduction and Replacement Solutions
- SEIA - Solar Energy Industries Association
- SO₂ - Sulfur Dioxide
- SPT - Solar Power Tower
- SPV – Solar Photovoltaic
- STE – Solar Thermal Energy
- TAM - Total Addressable Market
- TES – Thermal Energy Storage
- TWh - Terawatt-Hours
- US – United States

- USD – United States Dollars
- WEO – World Energy Outlook (IEA)

EXECUTIVE SUMMARY

Project Drawdown defines *concentrated solar* as: an electricity generation technology that uses heat provided by direct normal solar irradiance concentrated on a small area, with or without energy storage. Presently, there are four main concentrated solar power (CSP) technologies competing for the electricity market: 1) Parabolic Trough Collectors (PTC); 2) Parabolic Dish Collectors (PDC); 3) Heliostat Field Collectors (Tower); and 4) Linear Fresnel Reflectors (LFR). Though the Parabolic Trough is the oldest and has the most widespread use, the newest (Tower) is the most likely to gain traction, since it is the most economically viable technology that also incorporates storage— an increasing requirement of CSP. This analysis models all CSP technologies, with and without storage.

The total addressable market for *concentrated solar* is based on projected global electricity generation in terawatt-hours from 2020 to 2050, with the current adoption (2018) level estimated at only 0.06 percent of generation. Concentrated solar is particularly promising in regions which receive more than 2,500 kilowatt-hours per meter square per year of sunlight radiation. Such as areas include the southwestern United States, Central and South America, Northern and Southern Africa, the Mediterranean countries of Europe, the Near and Middle East, Iran, and the desert plains of India, Pakistan, the former Soviet Union, China, and Australia (ESTELA, 2016).

Impacts of increased adoption of *concentrated solar* from 2020-2050 were generated 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 levels. Based on an evaluation of the adoption scenarios from five global energy systems models (IEA (2017) Energy Technology Perspectives 2DS and B2DS scenarios; IEA (2018) World Energy Outlook SDS; Advanced Scenario from the Greenpeace Solar Thermal Electricity Global Outlook 2016 (Greenpeace *et al.*, 2016)), the Plausible Scenario follows a medium growth trajectory, capturing 7.4 percent of the market share by 2050. The Drawdown and Optimum Scenarios follow a high growth trend derived from these same models scenarios, reaching 5.9 percent of the electricity generation mix by 2050.

The results for the *Plausible Scenario* show that the net cost compared to the *Reference Scenario* would be US\$486 billion from 2020-2050, with negative US\$371 billion in net operating savings over the same period. Increasing the use of concentrated solar from about 0.06 percent in 2018 to 7.4 percent of world electricity generation by 2050 would require an estimated US\$1.76 trillion in cumulative first costs. With its low greenhouse gas emissions, under the *Plausible Scenario*, CSP could reduce 19.0 gigatons of carbon dioxide-equivalent greenhouse gas emissions from 2020 to 2050. Both the *Drawdown* and *Optimum* Scenarios present higher growth of CSP technologies, with impacts on greenhouse gas emission reductions over 2020-2050 of 24.1 and 23.7 carbon dioxide-equivalent, respectively.

Despite still being in its infancy, concentrated solar has significant potential for helping reverse global warming in an increasingly affordable way. However, the competition and growth of other more mature and less expensive renewable energy sources, such as onshore wind and solar photovoltaic, might delay the short-term adoption of CSP. The main advantages of CSP with storage is the possibility of providing firm and dispatchable power. Nevertheless, when compared to other solar technologies, CSP is heavily dependent on location, due to the size of the projects and the irradiance radiation needed.

The amount of new concentrated solar power capacity is projected to continue growing, but its pace is dependent on policy support schemes, either through stringent greenhouse gas mitigation policies or through financial and regulatory mechanisms for its adoption. Cost reductions will be driven by increasing economies of scale, more competitive supply chains, and technology improvements that will raise capacity factors and/or reduce installation costs.

1 LITERATURE REVIEW

1.1 STATE OF CONCENTRATED SOLAR POWER TECHNOLOGIES

Concentrated solar power (CSP) is an electricity generation technology that uses heat provided by direct normal irradiance (DNI)¹ which is concentrated on a small area. This heat is used to generate steam/hot gases and electricity is produced by using steam/gas to drive a turbine-generator, as in conventional power stations. The distinction is that the energy input comes from solar radiation which is transferred/converted to high-temperature steam or gas (Greenpeace et al., 2016).

Optical elements (e.g. mirrors or lenses) are used to reflect or focus sunlight onto a receiver where the heat is collected by a thermal energy carrier (primary circuit). The generated heat is then carried by a heat transfer fluid (e.g. thermal oil, molten salt, water, air, hydrogen, helium) which drives an engine or turbine according to a specific thermodynamic cycle which in turn drives the electricity generator (Zhang et al., 2013).

One of the main challenges to the widespread use of solar energy is the reduced or curtailed electricity generation when the sun sets or is covered with clouds (US DOE, 2013). In this regard CSP is placed at an advantage since it has the potential to overcome the unsteady nature of solar energy, both within the day (day–night, clouds) and within the year (winter–summer). The key to this is the feature of storage of energy in a medium which can then be used at times when the sun is not shining. If a significant portion of the total energy demand needs to be met by solar energy even when the sun is not shining, then the capture and storage of solar energy becomes critical (Zhang et al., 2013).

Steam was produced using a parabolic mirror to drive the first solar engine by Auguste Mouchout in 1866. Many types of collectors have been developed since then. But, though the principles of concentrating solar radiation to create high temperatures and convert it to electricity have been known for more than a century these have been exploited commercially only after the mid-1980s. The first large-scale concentrating solar power (CSP) stations were built in the Californian Mojave Desert (ESTELA, 2016). After a lull in activity during the 1990s, the technology has received an impetus in the 2000s driven by support policies that resulted in commercial projects in Spain and the United States (US) (IRENA, 2016a).

In regions with a high DNI, CSP is particularly promising. As the financial viability of CSP projects depends on the resource, technology and project costs, the current costs of the technology and constraints on financial support indicate that viable sites need to get at least 2.2MWh of direct normal irradiation per square meter annually. The best sites receive are those that receive more than 2.8MWh/m²/year (World

Bank, n.d.). South-Western United States, Central and South America, North and Southern Africa, the Mediterranean countries of Europe, the Near and Middle East, Iran and the desert plains of India, Pakistan, the former Soviet Union, China and Australia, are the most promising areas of the world (ESTELA, 2016).

The features of the technology depend on four main elements: a concentrator, a receiver, some form of transport media or storage, and power conversion. Different types of systems are possible, some even in combination with other renewable and non-renewable technologies.

Presently there are four main type of CSP technologies: (1) Parabolic trough collectors (PTC); (2) Parabolic dish collectors; (3) Heliostat field collectors (Tower) and (4) Linear Fresnel reflectors (LFR). The oldest type (Trough) is currently the most widespread technology being adopted, but Tower technology is the most likely to play a leading role since it is the most economical technology which incorporates storage – and storage is becoming an increasingly favored requirement of CSP. the remaining two technologies (parabolic dish and LFR) are presently lagging behind since they have yet to achieve more than a few megawatts of installed capacity (HELIOSCSP, 2015).

1.1.1. Parabolic Trough Collectors (PTC)

“A parabolic trough collector (PTC) plant consists of a group of reflectors (usually silvered acrylic) that are curved in one dimension in a parabolic shape to focus sunrays onto an absorber tube that is mounted in the focal line of the parabola” (Llorente *et al.*, 2011).

The first PTC systems were installed in 1912 near Cairo (Egypt) to generate steam for a pump which delivered water for irrigation. This plant was competitive at the time in a region where coal was expensive (ESTELA, 2016). PTC is presently the most mature CSP technology representing more than 90% of the currently installed CSP capacity, particularly in the USA and Spain. Good experience has been gained in engineering procurement and construction (EPC) of these systems and long years of operating experience allows for good confidence levels in operating such systems. As such, projects using parabolic trough technology are considered low-risk investments (Greenpeace et al., 2016).

1.1.2. Solar Power Tower (SPT)

Central-receiver systems such as solar thermal power-tower plants use a field of distributed mirrors (i.e. heliostats) that individually track the sun and targe the sunlight on the top of a tower which contains a heat transfer fluid. By concentrating the sunlight by a factor of 600 to 1000, this technology systems can reach temperatures between 800°C to 1000°C (Kalogirou, 2014). The solar energy is absorbed by the working fluid which in turn is used to generate steam to power a conventional turbine-generator. This conventional portion of the system consisting the steam-turbine and generator is also referred to as the “Power Block” as different from the “Solar Block” which consists of the optical elements like mirrors, lenses, reflectors, etc.,

and the sun-tracking and heat generating and storing sub-systems. Through its use worldwide over the years, power tower plants have shown to be technically feasible in projects using different heat transfer media (steam, air and molten salts) in the thermal cycle and with different heliostat designs (Muller-Steinhagen *et al.* 2003).

When compared to PTC systems, SPT can reach higher-temperature operation. This “*higher temperature can yield higher thermal-to-electric conversion efficiencies in the power block and lower costs for storage*” (Mehos *et al.*, 2016). Power towers use heliostats—reflectors that move to track the sun—to reflect sunlight onto a central receiver (Zhang *et al.*, 2013). According to the International Energy Agency, molten-salt towers are attractive technologies as the high-temperature difference of around 550° C allows reduction of the cost of storage by one third. This is approximately 12% of the total investment cost of PTC with a 7-hour storage. Solar towers also offer the additional advantage of being less sensitive to seasonal variations when compared to linear systems, that have greater optical losses in winter (IEA *et al.*, 2015). Early test plants were built in the ‘80s and ‘90s in Europe and USA. These included Solar II project in California using molten salt as heat transfer fluid and thermal storage medium for night time operation; and the GAST project in Spain using metallic and ceramic tube panels (ESTELA, 2016).

1.1.3. Linear Fresnel Reflector (LFR)

Linear Fresnel Reflectors (LFRs) “*approximate the parabolic shape of a traditional trough collector with long, ground-level rows of flat or slightly curved reflectors that reflect the solar rays toward an overhead stationary linear receiver*” (Zhang *et al.*, 2013). Flat reflectors and fixed receivers lead to lower capital costs as compared to traditional trough-based plants. However, LFR plants tend to be less efficient. Superheated steam up to 500°C has been demonstrated at a pilot scale plant and the first large commercial superheated LFR plants have recently begun their operation (ESTELA, 2016). The investment costs per square meter of collector field using LFRs technology tend to be lower when compared to other technologies due to simpler solar field construction, and use of direct steam generation which guarantees relatively high conversion efficiency and a simpler thermal cycle design. The Fresnel design uses less expensive reflector materials and absorber components. It has a lower optical performance as well as a lower thermal output but this is offset by lower investment and operation and maintenance costs. In addition to electricity generation, linear Fresnel technology can also be deployed for direct thermal applications such as cooling and industrial process heat applications (ESTELA, 2016).

1.1.4. Parabolic Dish Systems (PDS)

Parabolic dish collectors (PDC) concentrate the sunrays on a receiver placed at its focal point and is supported above the center of the dish. The entire system tracks the sun, with the dish and receiver moving

in tandem (Zhang *et al.*, 2013). The concentrated radiation is absorbed into the receiver to heat a fluid or gas (air) to around 750°C. This fluid or gas is subsequently used to produce electricity in a small piston; Stirling engine or a micro turbine, attached to the receiver (ESTELA, 2016).

According to Barlev *et al.* (2011), PDCs offer the highest transformation efficiency of any CSP system, but produce smaller amounts of electricity as compared to other CSP technologies—typically in the range of 3 to 25 kilowatts – this size being optimum for modular use. The two major parts of the system are the solar concentrator and the power conversion unit (US DOE, 2013). PDCs are expensive and have a lower compatibility with thermal storage and hybridization systems (Barlev *et al.*, 2011). Table 1.1 compares the different CSP systems on seven different parameters.

Table 1.1 A Comparative picture of leading CSP technologies (Adapted from Zhang et al., 2013)

	Relative cost	Land occupancy	Cooling water (L/MW h)	Thermo-dynamic efficiency	Operating T range (°C)	Solar concentration ratio	Outlook for improvements
PTC	Low	Large	3,000 or dry	Low	20–400	15–45	Limited
LFR	Very low	Medium	3,000 or dry	Low	50–300	10–40	Significant
SPT	High	Medium	1,500 or dry	High	300–565	150–1500	Very significant
PDC	Very high	Small	None	High	120–1500	100–1000	High potential through mass production

According to IRENA (2016a), the prevalent investment costs for PTC plants were clearer due to its greater deployment, than those of STs. Investment costs for PTC plants without storage in OECD countries, were typically between US\$4,595 to US\$7,991/kW, while in non-OECD countries costs were lower, between US\$3,496 to US\$7,291/kW. CSP plants with thermal energy storage tended to have higher investment costs. For plants with thermal energy storage (4-8 hours), installed after 2007 to 2013, when beneficial support schemes were in place in Spain, in particular, costs ranged between US\$6,792 and US\$12,785/kW. Since 2013, costs reduced in a smaller range of US\$6093 to US\$8,090/kW. The estimated costs for a reference PTC plant with 7.5 hours of storage in 2015 were around US\$5,493/kW and represented the competitive pressures of CSP plants in the market. For the equivalent ST plants, overall installation costs were slightly higher US\$5,693/kW for a reference plant with 9 hours of storage (IRENA, 2016a).

The CSP capacity factors also portrayed important differences for world regions ranging from 19% in Africa to 31% in Europe. Operations and maintenance costs (O&M) for projects on the basis of available, bottom-up, engineering estimates and recent proposed projects, were estimated to range between US\$0.02 to US\$0.04/kWh (including insurance) (IRENA, 2016a).

According to IRENA (IRENA, 2018b), the current investment costs for PTC plants are firmer than those of STs, given their larger deployment. Globally, current investment costs for PTC plants without storage

are typically between US\$2,550 to US\$ 11,265/kW. CSP plants with thermal energy storage tend to have higher investment costs. For plants with thermal energy storage of 4 to 8 hours, the costs were typically between US\$6,050 and US\$13,150/kW. Since 2014, costs have trended down and are in a narrower range of US\$ 2,550 to US\$ 7,000/kW for 'no storage' configuration plants. The estimated costs for PTC and solar tower plants above 50MW size with up to 4 hours of storage built after 2015 were in the range of US\$ 3,500/kW to US\$ 9,000/kW and this again depicts the competitive pressures facing CSP plants in the current market.

Current CSP capacity factors also portray important differences for different technologies and regions. These range from a low of 22% for a large LFR plant to a high of 55% for a large SPT plant with 10 hours of storage (Islam M T., 2018). Similarly, operation and maintenance (O&M) costs also vary a lot. For recent projects on the basis of available, bottom-up, engineering estimates and recent proposed projects, these are estimated to range between US\$0.02 to US\$0.04/kWh (including insurance) (IRENA, 2018b).

1.2 ADOPTION PATH

1.2.1 Current Adoption

Multiple solar thermal power plants have been built over the past few years in regions such as Spain and the south-western United States (US), where there is a high solar resource potential sunlight and large land availability required by these technology. Solar thermal technologies can generate significant amounts of power and can be used with thermal storage options such as molten salts to increase their electricity generation into peak evening hours when the sun is not shining. Contrariwise, solar thermal power plants use more materials (e.g. steel), than other types of solar power such as PV, and thus are more capital-intensive and have higher operation and maintenance (O&M) costs (IEA *et al.*, 2015).

While the first CSP plants were set up in the US in 1985, the sector slowed down in the 1990s due to the oil prices falling and remaining low throughout the nineties stalling the growth of CSP. Secondly, the US energy policy became regressive during this decade and the property tax regime became unpredictable forcing some projects to shut down. It was only by 2004 that the second cycle of CSP activity started and venture capital started to flow into this sector again (Skumanich, 2011).

Though adoption of this technology had started before SPV, it slipped behind due to difficulties involved in installation, operation and maintenance of this system which is a combination of two sub-systems. The first is the conventional power block which is composed of the turbine-generator combine. The second is the solar block which consists of optical elements like mirrors, lenses, concentrators as well as mechanical elements required to focus and track the sun. To this could be added the energy storage system which

generally operates at very high temperatures. The design, installation, operation and maintenance of systems thus requires a higher degree of expertise and experience as compared to SPV systems (WEC, 2016). It was thus not surprising to see CSP losing ground to SPV.

Capacity growth in the CSP market decelerated somewhat in 2015 and 2016. Morocco (160 MW), South Africa (150 MW) and the USA (110 MW) all brought new CSP facilities online in 2015, raising total global capacity by about 10% to nearly 4.8 GW (Helioscsp, 2016). The new facilities use a mix of parabolic trough and tower technologies, and all incorporate TES. Fresnel and parabolic dish technologies have become largely overshadowed. By year's end (i.e. 2015), more CSP capacity was under construction in Morocco (350 MW), South Africa (200 MW), Israel (121 MW), Chile (110 MW), Saudi Arabia (100 MW), China (50 MW) and India (25 MW), reflecting a shift from traditional markets (Spain and the US) to developing regions with high direct normal insolation levels (REN21, 2016). Current adoption¹ for Concentrated Solar Power is estimated at only 0.04 percent (9 terawatt-hours) of total electricity generation (IRENA, 2016).

There has again been a slowdown in the capacity addition of CSP projects worldwide during 2017. Only a little over 100MW capacity was added, almost all of which came from South Africa (IRENA, 2018b). In the traditional countries like US, CSP has been facing competition from sharply falling prices of both solar photovoltaic (SPV) as well as natural gas energy. Moreover, some of the plants which had gone off-stream took a long time to come back online. As a result, the CSP capacity and generation have both been showing fluctuating trends. Though global capacity increased by only 2% in 2017, there still has been a lot of activity in the sector with around 2GW projects being in the pipeline, most of it coming from non-traditional areas like China, the Middle East and North Africa. In 2018 itself a rapid growth of the sector in China was witnessed with three demonstration projects of 200MW capacity coming on-line (CSPFOCUS, 2019). Figure 1.1 gives a picture of the adoption path followed by CSP since 2008.

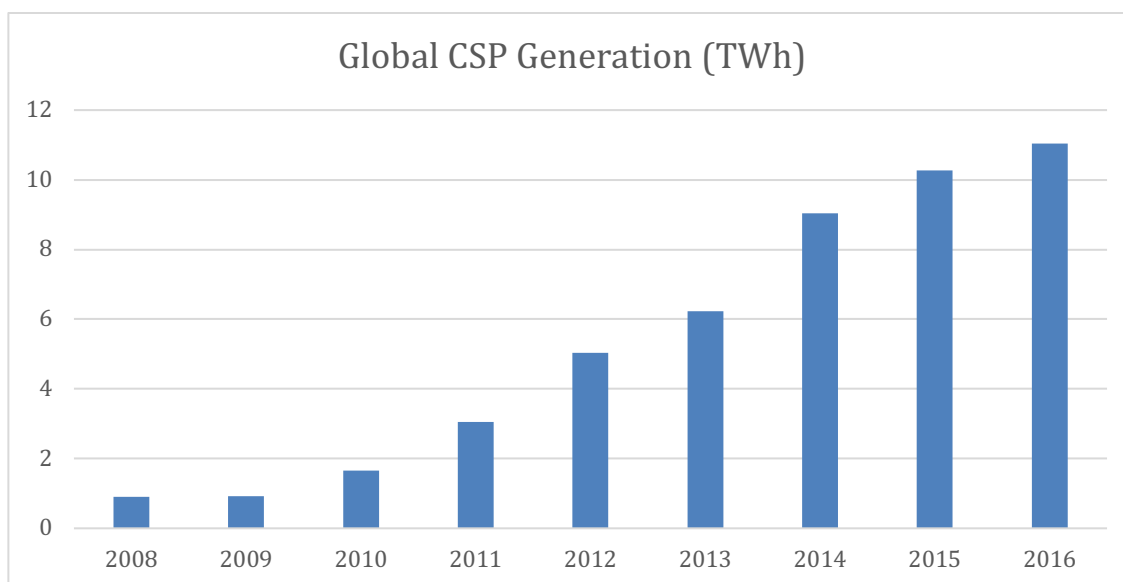


Figure 1.1 Generation from Concentrating Solar Power since 2008 (Source: IRENA, 2018)

1.2.2 Trends to Accelerate Adoption

In its short term forecast for renewable energy technologies, IEA has estimated that globally, CSP will grow by 87% (4.3GW) over the short term 2018-2023. This in itself is a substantial acceleration over the 55% growth rate recorded during the period 2012-2017. Most of this is expected to come from China (1.9GW), Morocco and South Africa (1GW), the Middle East (1GW) and Australia/Chile (300MW) (IEA, 2018c). This trend of moving away from the traditional areas of US and Spain is likely to continue into the future (REN21, 2018). As deployment of CSP plants increases in areas of higher DNI such as the south-western USA, North and South Africa, Chile, Australia and the Middle East, the naturally available solar resources will be used optimally and would help improve the performance and confidence in this technology (IEA et al., 2015).

Stronger adoption of CSP power plants is possible if specific and attractive policies are put in place. These could include preferential tariffs, placing a price on carbon emissions, laying down emissions reduction targets, mandatory sourcing of renewable energy and similar promotion schemes with regulatory support. The roll out of CSP in the regions with high DNI would be further boosted by improvements in the technology and reductions in cost. Larger plants will reduce the per-unit costs due to economies of scale and a larger corpus of plants will result in greater experience (and the resultant confidence) in setting up, operating and maintaining these plants. Some future CSP plants are planned with capacities averaging over 100MW each. The Al Maktoum solar park 700-MW CSP project under implementation in the UAE will be the biggest plant by the time it is set up in 2023 (IEA, 2018c). Apart from economies of scale, cost

reductions and technology improvements would also require enhanced and intensive R&D efforts both by the public sector as well as by the industry.

The unique feature of CSP which gives it a major advantage over SPV is its capacity to store energy. This makes it a source suitable for producing dispatchable power. For utility-scale applications, the thermal storage possible with tower CSP is usually cheaper, more durable, and longer lasting than battery storage thus rivaling the almost limitless recycling capability of pumped hydro systems (HELIOSCSP, 2015). At grid scale, CSP thermal storage often becomes cheaper than deploying batteries. Since 2010, 40% of Spanish plants have included 5-10 hours of storage capacity (ESTELA, 2016), showing that CSP plants have been increasingly including storage. At grid scale, CSP thermal storage is often cheaper than batteries.

Two tower CSP projects in Chile have both battery and thermal storage in order to combine the speedy reaction time of batteries with cheap long-term thermal storage (HELIOSCSP, 2016). Results of a study from Jorgenson et al. (2016) using current capital cost estimates indicate that a combination of PV and conventional gas turbine units provides a lower net cost as compared to both CSP plants with Thermal Energy Storage (TES) as well as to SPV plants with batteries. Some configurations of CSP-TES have shown a lower net cost than SPV plants with lowest cost batteries. In order to derive the dual benefit of the quick reaction time of batteries as well as the low cost of long-term thermal storage, some projects have even started incorporating both batteries as well as thermal storage into their system (HELIOSCSP, 2016).

Solar thermal power plants have shown significant cost reductions in the recent years, even though the deployment levels are currently low. This indicates that there is significant room for further cost reduction based on both volumes of scale and technological improvements. Commercial experience from the first nine CSP plants in California, built between 1986 and 1992 and operating continuously since, shows that power generation costs in 2004 dropped by around two-thirds. The first 14 MW unit supplied power at 0.44 US\$/kWh dropping to less than half at just 0.17 US\$/kWh for their last 80 MW unit (Greenpeace et al., 2016).

In many countries, research and industry are committed to improving CSP performance and reducing its costs. Technology advances of components (mirrors, collectors, piping, etc.) could contribute to about one third of the total cost reduction potential (IRENA, 2016a). Advanced thermal storage, increased plant size and economies of scale, and industrial learning in component production are also important drivers for cost reduction (IRENA and ETSAP, 2013).

Apart from generating electricity, CSP technologies have the added advantage that they can also be used for thermal applications such as process heat for industries that need high heat processes for sterilization,

boilers, heating and absorption chilling for industries such as food, transport, equipment, machinery and textile, etc.

A unique feature of CSP is its suitability for hybridization with other thermal or electricity generating systems. The energy generated from solar energy can be combined with energy from other sources including conventional sources. This offers possibilities of higher system efficiencies as well as reduction in generation costs. The feature of storage of thermal energy makes the intermittent nature of energy dispatchable and places CSP at an advantage when compared to SPV systems. To derive benefits from these varied features, hybridization of CSP is being carried out with conventional sources like coal, natural gas, biomass and also with renewable energy systems like SPV, wind and geothermal energy (Pramanik, 2017).

1.2.3 Barriers to Adoption

Since the technology is based on the level and quality of solar irradiance, it becomes very site specific. Not all countries are equally endowed with this resource. For optimum performance, CSP plants need high direct normal irradiance (DNI) as opposed to diffused horizontal irradiance (DHI). Hence, one of the major barriers to universal adoption of CSP is its heavy dependence on location. Sites need clear and direct sunlight during the daytime hours for optimum performance. Hence, location becomes a barrier.

Secondly is the requirement of land. A typical CSP plant requires 5 to 10 acres of contiguous (and somewhat level) land per MW of capacity in addition to the area required to accommodate the thermal energy storage system. Locating such large tracts of suitable land near the load centers becomes a challenge. The costs associated with acquiring and forming the land profile also becomes a barrier. The desert areas of the tropics offer the dual advantage of both high DNI as well as huge tracts of low cost and largely unutilized land. Hence the move towards these geographical locations is underway.

Thirdly is the requirement of sufficient amount of water. Like thermal power plants based on natural gas, coal and nuclear etc., the CSP systems require access to sufficient quantities of water for cooling, steam generation and for cleaning the collection and mirror surfaces. CSP plants can utilize wet, dry, and hybrid cooling techniques to reduce water consumption and maximize efficiency in electricity generation. Even so, CSP plants need to be sited in areas which have access to sufficient amount of water. In water stressed areas, this becomes a barrier.

Fourthly, due to the size and cost of land required, CSP plants are often located in remote or desert areas, away from urban and population centers. Thus, the need for the creation of suitable infrastructural facilities for evacuating the generated power to the load centers. Hence, the non-availability of adequate access to and the infrastructure of high-voltage transmission lines becomes another barrier (SEIA, 2014).

There are some environmental and social risks associated with CSP plants which could act as a barrier to the large-scale adoption of this technology. Apart from the important issue of extraction of water resources described before, there are some other social as well as technological risks which add to these barriers. Risks to workers and birds due to ambient noise and the interference with visual and recreational resources are a few risks associated with these systems (Otiento, 2016).

Due to these issues, developers have encountered several barriers to building CSP plants. To these could be added insufficient and inaccurate DNI and environmental data; policy uncertainty; difficulties in securing land, water and grid connections; permission issues and expensive financing (IEA et al., 2015). A proactive and supportive policy regime thus becomes necessary to remove or alleviate non-economic barriers such as costly and lengthy permission and connection procedures. In addition, tailored incentive schemes to support the development and deployment of such systems combined with innovative financing schemes to reduce costs of capital and strengthened RD&D efforts to further reduce costs are a pre-condition to the rapid adoption of this solution (IEA et al., 2015).

An additional factor that prevents high uptake of CSP is clearly the competition with technologies (mostly solar PV and wind power) that can hinder the growth of CSP in the short and medium term.

1.2.4 Adoption Potential

Existing long-term scenarios presented in the literature present a limited role for CSP when compared to solar PV systems or wind power systems. In its Energy Technology Perspectives for the year 2017, the International Energy Agency has depicted two scenarios, namely the 2°C Scenario (2DS) and the Beyond 2°C Scenario (B2DS). These scenarios project the level of generation which should come from renewable sources in order to limit the global temperature rise to 2°C (and below for B2DS) by 2050 (IEA, 2017). The 2DS scenario estimates that global CSP power capacity would grow to 720 GW by 2050 in the 2DS (i.e. 2°C) scenario. This would represent 4.8% of total installed capacity and would generate 2,952 TWh. This would account for 6.9% of the electricity generated). Results from the energy system models MESSAGE/MACRO (AMPERE, 2014) presented higher expectations of CSP capacity growth. According to the model's 450ppm scenario, total CSP capacity might reach 1,354 GW. The Advanced Energy Revolution scenario described in Greenpeace (2015) was the most ambitious scenario in terms of its assessment of potential CSP cumulative capacity and generation. This scenario envisaged 14,035 TWh of electricity generated in 2050, representing nearly 21% of the total electricity generation. Their other Energy Revolution scenario was also very ambitious with 8,138 TWh of generation from CSP technologies (i.e. 16% of the total generation) in 2050.

In a different and recent scenario - the Sustainable Development Scenario (SDS) developed separately by the IEA in their flagship document, the World Energy Outlook – 2018, generation from CSP is projected to reach a level of 2,395 TWh by 2050 representing 4.7% of the global generation. But it is the Beyond 2°C Scenario (2BDS) of the IEA:ETP-2017 that is the most ambitious current scenario in terms of its assessment of potential CSP and generation. This scenario envisages 3,895 TWh of electricity to be generated from CSP in 2050, representing nearly 8.8% of the global electricity generation. By comparison, the three-year-old scenarios developed by Greenpeace called the Advanced Energy Revolution and the Energy Revolution scenarios were indeed much more ambitious than even the SDS scenario from IEA in that they projected a generation of 14,035 TWh (i.e. 21% of the total) and 8,138 TWh from CSP technologies (i.e. 16% of the total) respectively by 2050 (Greenpeace 2015).

Figure 1.2 compares the long-term market projections (2015-2050) for CSP electricity generation from several sources by different climate ambition scenarios and where the range of different expectations from CSP deployment can be gauged.

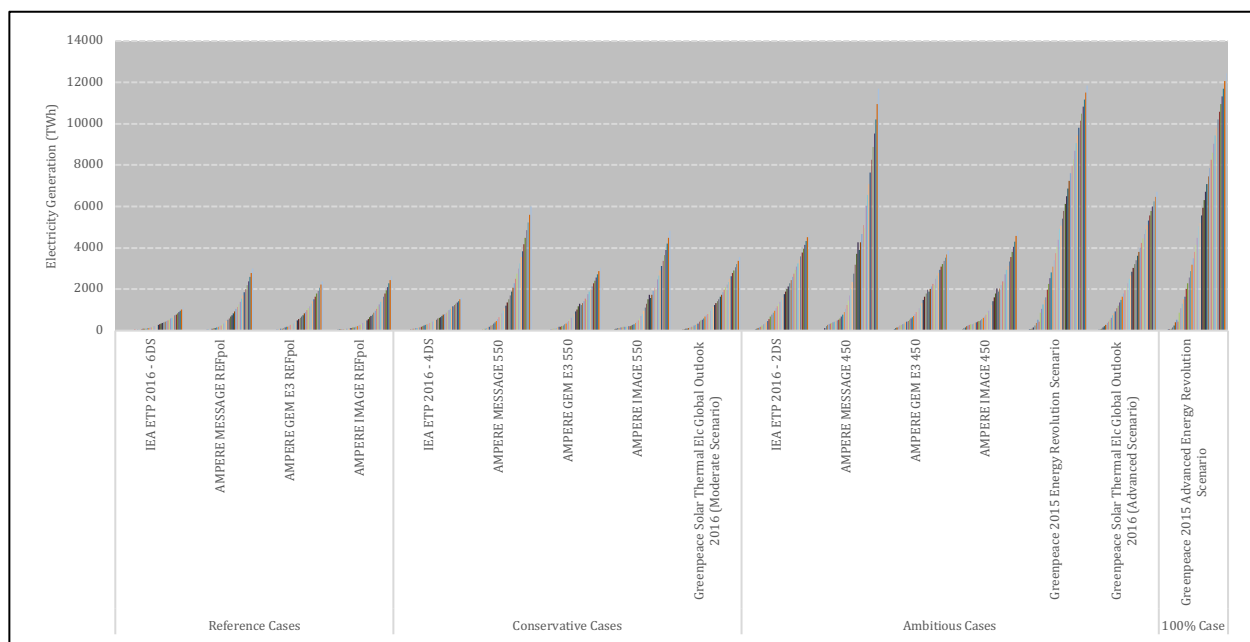


Figure 1.2 A Comparison between several scenarios and sources for the adoption of CSP technologies until 2050

1.3 ADVANTAGES AND DISADVANTAGES OF CONCENTRATED SOLAR POWER SYSTEMS

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 which could be considered as similar/analogous solutions. Solutions similar to solar photovoltaics utility-scale that use the same resource:

i.e. solar energy for electricity generation are considered here. These differ from our solution either in the level of agency (e.g. household or utility-scale level) or in the way the technologies work. These are:

- **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 knocks off electrons from the semi-conducting material. 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 SPV systems, these SPV 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 SPV generation globally. And this share is expected to increase with time and reach over 65% by 2050 (Ram et al., 2017)
- **Rooftop Solar Photovoltaic System:** In fact, the SPV programs started with small scale household and community-based systems and later on grew in scale to utility systems. The underlying technology is the same – the difference being in the scale and the implementing agency (i.e. household or utility). Many countries have mounted and run successful rooftop and decentralized SPV programs like the “Million Roofs Initiative” of the US (Strahs & Tombari, 2006). Rooftop and small community SPV programs still account for a roughly estimated 40% of all global investments in SPV and are the favored solution for providing decentralized and off-grid power to remote habitations and households.
- **Concentrating Photovoltaic Technology (CPV):** Another type of utility-scale PV technology which can be used to generate electricity is the CPV technology. This uses an optical system to focus large areas of sunlight onto 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

Increasing the use of renewable energy systems (RES) like solar PV and wind can create problems for the system peak demand, especially as older fossil plants are being retired and new capacity addition become necessary to maintain system reliability (Jorgenson et al., 2014; Jorgenson et al., 2015). Here, the dispatchability of CSP power becomes its major advantage and gives it an edge over SPV systems which are always generating during sunshine, regardless of whether power is needed or not. For HELIPSCSP (2016), CSP is perfectly suited to smoothing out the increasingly fat “duck curve” of new demand as the load is time shifted by the solar power generated by ever-increasing daytime PV. CSP plants can also contribute to the stability of the system, i.e. maintaining voltage and frequency within required ranges (Greenpeace et al., 2016).

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 CSP, it becomes even more important because though the first costs for CSP may be comparatively 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 CSP 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 CSP projects is growing as these become a favored source for producing “green” energy.

CSP can actively edge fossil fuel power plants off the grid if the price of natural gas is higher, with the consequent advantages on GHG emissions reductions. According to ESTELA (2016) each square meter of CSP concentrator surface, depending on its configuration, is able to avoid 200 to 300 kilograms (kg) of carbon dioxide, each year. The life-cycle assessment of the constituents of CSP systems show that it takes around five months to ‘pay back’ the energy that is used to manufacture and install the equipment. Considering that the plants can last at least 30 years with minimum performance losses, this is a potentially good ratio. Also, the majority of the CSP components are common materials which can be recycled (ESTELA, 2016).

Greenpeace *et al.* (2016) provides additional advantages of CSP technologies adoption, such as the promotion of local industries in growing markets enlarging the supply chain; and where the construction and operation of STE plant can be important for increased employment.

1.3.3 Additional Benefits and Burdens

Contrasting with photovoltaic technology, CSP offers significant advantages from a energy system perspective, due to its built-in thermal storage capabilities (ESTELA, 2016). The collection and conversion of solar energy to thermal energy that power a generator can be stored, and can be used either as providing firm and dispatchable power (such as a natural gas peaking plant), or as a baseload source of electricity commonly done by nuclear and coal power plants. CSP plants can also be installed as a fossil-fuel backup/hybridization allowing that existing fossil fuel projects to run cleaner while operating at the same or lower cost (US DOE, 2016).

The focus of plant design has mostly targeted PT technology, but solar towers are increasingly being used. Additionally, according to Greenpeace *et al.* (2016), mass production and automation will result in lower installation costs and create economies of scale.

Increasing research is being done looking to distributed energy resources, notably, demand response, load-shifting technologies, and stationary, non-CSP storage systems; as a way of meeting system peak in the future, which could potential avoid dispatchable generation as CSP. Table 1.2. presents a comparison of selected pros and cons of the solution with others in the same sector and with the same energy source.

Table 1.2 Solar energy solutions versus conventional electricity generation technologies

Parameter	Conventional Electricity Generation Technologies	Concentrated Solar Power	Solar PV Utility-Scale Systems	Solar PV Rooftop Systems	Concentrating Solar PV Systems
<i>Greenhouse Gas Emissions</i>	Extremely High	Very Low	Almost Zero	Almost Zero	Almost Zero
<i>Land Requirement</i>	Medium	Medium	High	Almost Zero	Medium
<i>Air Pollution</i>	Extremely High	Low	Almost Zero	Almost Zero	Almost Zero
<i>Electricity Generation Flexibility</i>	Very High	Medium	Low	Low	Low
<i>Resource Extractive Drawbacks</i>	Extremely High	Low	Very Low	Very Low	Very Low
<i>End of life Disposal Drawbacks</i>	Very High	High	Medium	Medium	Medium
<i>Water Consumption</i>	Very High	High	Very Low	Very Low	Very Low

<i>Gestation Period</i> ²	Very High	Medium	Low	Low	Low
<i>Modular Scalability</i> ³	Low	Medium	Very High	Very High	High
<i>Environment/Health Benefits</i>	Very Low	High	Very High	Very High	Very High
<i>Operation and Maintenance Costs</i>	High to Very High	Medium	Very Low	Very Low	Very Low

Though there are many benefits to be gained from the adoption of CSP technology, it is not without its drawbacks. As pointed out before, the technology is very site specific and has fairly high up-front costs. To this is added the requirement of availability of large tracts of cheap and suitable land and proximity to high voltage grids for power evacuation. But apart from these drawbacks which have been detailed in this report in the portion on “Barriers”, there are some typical burdens which this technology carries with it which can impede the fast adoption of this technology. In their paper presented in 2016, Otieno and Loosen have analyzed key environmental and social risks associated with CSP projects (Otieno, 2016). They have listed seventeen types of risks associated with these plants. While the risks from these projects could be mitigated by taking appropriate measures, five of them would need careful consideration – the most important ones being the risk of depletion of water resources and risk to safety of workers and birds. This would become critical especially in water stressed and ecologically fragile areas.

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 to implementation units (TW). The adoption of both conventional technologies and the present solution (CSP) 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 concentrated solar power systems. The model used for this analysis constructs both alternative ambitious adoption pathways (PD scenarios) and a Reference scenario (REF) for Concentrated Solar Power. Following project Drawdown methodological assumptions (further description available on the Drawdown RRS Model Framework and Guide), and in order to grasp the total impact of an increased adoption of the solution during the assessed time frame, the REF scenario assumes the future rate of adoption of CSP remains fixed at the current adoption (i.e. 2018) level of the Total Addressable Market (TAM), estimated at 0.06 percent (13.7 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 CSP 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 concentrated solar power, as well as the contribution this adoption can make to annual and cumulative emissions reduction.

2.2. DATA SOURCES

This section presents key data sources utilized in the model to evaluate the adoption of Concentrated Solar Power technologies. Data inputs for the model come from a variety of sources, primarily from peer-reviewed publications and from institutional reports. For all variable inputs, a variable meta-analysis of existing literature was conducted to create low, high, and mean estimates. For each solution variable, a sensitivity analysis of, on average, twenty-five data points reported in the literature was conducted. In some cases, as many as 69 data points were considered. This allowed a robust and reliable analysis of financial, technological and climate parameters. These represent both optimistic and 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 concentrated solar thermal installations (e.g. IRENA, 2016; IRENA 2018; REN21, 2016; REN21 2018; Lazard, 2016; Lazard 2018). It is acknowledged that capital costs for CSP systems can vary significantly by region, but exhaustive regional data were not available to calculate an average cost weighted by installation size. Since only around twenty countries have CSP generation projects, available estimates were concentrated in only a few countries. This reflects the preponderance of present-day CSP installations in traditional areas like the US, Spain etc.

Learning rates for CSP are expected to continue to reduce costs, making the technology more competitive and has the potential to ultimately become cheaper than even conventional sources. Nevertheless, according to IRENA (2012), there is not enough data to identify a robust learning curve. According to Platzer et al (2016). Since the CSP projects are composed of different types of units like the solar field, thermal storage, power block, etc., deriving a simple learning curve becomes a challenge. However, experience from existing low temperature collectors indicates that a learning rate of 20% would be feasible for the solar field whereas for the complete capital costs, this figure would be in the range of 10-15%.

Cost estimates for fixed and variable operation and maintenance (OM) of CSP were collected from many sources (e.g. IPCC, 2014; IRENA, 2016; IRENA 2018; Lazard, 2016; Lazard 2018). These estimates were used to calculate total operating costs of CSP adoption, which, combined with capital costs for installation, represent the total financial costs of adopting this solution in the PD scenarios. Fixed operation and maintenance costs for both renewable and conventional generation technologies can include expenses such as day-to-day preventative and corrective maintenance, labor costs, asset and site management, and maintaining health and safety, among others (Lo, 2014). Average fuel price was calculated considering average prices for coal, oil and natural gas from 2005-2014 using IEA data (IEA, 2016a).

The lifetime of CSP plants (based on the relatively few projects in the market) has been showing an upward trend as the technology matures. According to IRENA (2015), the lifetime of CSP technologies before replacement is 25 3whereas now it is of the order of 35 years; the IPCC (2014) reports 20 years, and Hertwich *et al.*, (2015) have reported a figure of 30 years. Recently, NREL has reported a figure of 30 years based on real life decommissioning of projects (NREL, 2018).

In order to compare capital and O&M costs of CSP system adoption in the PD scenarios with that of conventional generation technologies, the cost data was obtained for fossil fuel-based electricity generating sources from the IPCC 5th Assessment Report (IPCC, 2014) which has conducted its own sensitivity analysis of a number of sources from the literature⁴, and other sources such as OECD (2015), and Lazard (2016). In all, variables for conventional electricity generation sources, data for coal, oil and natural gas (primarily pulverized coal and combined cycle gas turbine technologies) were included and a weighted average obtained. These weights are based on the percentage, for each fuel on the total global electricity generation for 2014 (World Bank, 2015).

In order to calculate the total impacts and benefits of increased solution adoption (for the PDS scenarios), technical data was also integrated, including average annual use, 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 plants efficiency is calculated from several global sources (IPCC, 2014; IEA, 2010), as well as from the U.S. EIA (2015).

Though the average annual use of conventional generating technologies is higher than that of CSP, the range of capacity factors for different conventional generating sources can still vary based on type of technology and location. For this reason, data was collected from a range of different sources (EIA, 2016; IEA, 2016b; Lazard, 2016) that represent most of the regions contained in this analysis. Capacity factor data for CSP was available for the US as well as globally, which enabled calculation of the average annual use of CSP for the world.

The model's analysis of the climate impacts of adoption are primarily derived from the direct emissions factor associated with the replacement of conventional generating technologies with CSP plants. This methodology is explained in greater detail in Drawdown RRS model framework and guidelines. In order to

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).

account for indirect emissions from conventional technologies and CSP systems—primarily those lifecycle emissions associated with manufacturing, transporting, installing and other non-generation activities—peer-reviewed lifecycle analysis (LCA) studies for the different types of CSP technologies available in the market were analyzed. (e.g. Masanet et al., 2013; NTEL, 2013; IPCC, 2014; Hertwich et al., 2015, Norton, 1998; Kommalapati, 2017).

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) 1.5°C degree scenario were considered. The estimated electricity generation for this TAM reaches 70,942 TWh by 2050.

2.4 ADOPTION SCENARIOS

Two different types of adoption scenarios were developed: a Reference (REF) Case which was considered the baseline, where not much changes in the world were expected, 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) case scenario, adoption is fixed at the current adoption⁵ (in percentage terms) of the market. That is, the current percentage of total electricity generation (TWh) provided by Concentrated Solar Power systems has been kept constant throughout the study period to 2050. As the market grows, the total number of CSP plants adopted grows equally to maintain the percent adoption at its starting value in 2018. It is acknowledged that this, in reality, may not be a “business as usual” trajectory considering the changes taking place worldwide, but it allows a sort of measure to evaluate the impact of recent and even more aggressive policies to reverse global warming.

2.4.2 Project Drawdown Scenarios

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

Plausible Scenario

This scenario represents an incremental and plausible growth of renewable energy solutions using medium to high growth trajectories to 2050 depending on the current maturity levels of the technology, and bounded by existing ambitious projections from other global energy systems models. For concentrated solar power systems, this scenario is based on the evaluation of yearly averages of five ambitious scenarios: IEA (2017) Energy Technology Perspectives 2DS and B2DS scenarios; IEA (2018) World Energy Outlook SDS;

⁵ 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

Advanced Scenario from the Greenpeace Solar Thermal Electricity Global Outlook 2016 (Greenpeace et al., 2016); and follows a medium growth trajectory.

Drawdown Scenario

This scenario is optimized to reach drawdown by 2050 using more ambitious projections from existing sources. The scenario projects a 100% adoption of non-fossil fuel-based technologies in 2050; mainly RES but also includes several technologies that are considered transitional solutions (as nuclear energy) (See section 6). For this solution, this scenario follows a high growth trend derived from the abovementioned model's scenario results used in Plausible Scenario.

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 CSP systems follows the same scenarios and high growth trajectory.

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

While being a renewable energy technology, CSP plants do not have direct emissions attributable to combustion of fossil fuels. However, the Project Drawdown modeling exercise considers the analysis of indirect emissions related to the different factors that indirectly contribute to GHG emissions from the lifecycle of CSP systems. In modeling the lifecycle emissions of Concentrated Solar Power adoption in the scenarios, a fixed value (t CO₂-eq per TWh) was used factoring in information from several CSP technologies rather than using a weighted average for different types of CSP systems in use. The climate results would therefore be expected to be more conservative than would have been the case if a decreasing average lifecycle emissions value for CSP systems was assumed.

The values collected in the RRS model show lifecycle GHG emissions for a range of different CSP technologies across different regions and system sizes. The analysis draws from research papers and reports

that have estimated GHG emissions for CSP. The wide span in results for CSP reflects different assumptions around capacity factor, conversion efficiency, operating lifetime and quality of solar resource. As an example, Hertwich et al. (2015) identify for CSP trough 22.7 g CO₂eq/kWh and for CSP tower of 33 g CO₂eq/kWh. NTEL (2013) depicts 49 g CO₂eq/kWh for the lifecycle of this technologies including land use change. IPCC (2014) numbers vary between a minimum of 8.8 and a maximum of 63. A recent paper reports a range from a low of 5 gCO₂-eq/kWh for solar ponds to a high of 213 gCO₂-eq/kWh for a central receiver CSP system (Kommalapati R., 2017). Table 2.1 presents the boundaries of the variable meta analyses on the model and the selected model input.

Table 2.1 Climate Inputs

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Indirect CO ₂ Emissions (Solution)	<i>t CO₂-eq/TWh</i>	5,000 - 114,138	49,904	26	8

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 points⁶.

2.5.2 Financial Inputs

The RRS model constructs PDS adoption scenarios for CSP electricity generation globally and regionally for each year until 2050. It has modelled both the capital costs and the fixed and variable O&M 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 CSP electricity generation, along with first costs (per functional unit), were calculated. A lifetime capacity of 89,741 hours (around years) was calculated depending on the average powerplant annual use.

Estimates in the literature presented for the learning rate of CSP systems vary, but 12 to 20% has been suggested as credible in a slightly conservative range. Learning rates for the solar field, heat transfer fluid, thermal energy storage and the balance of plant will be on the higher side, given they are a more recent and

⁶ 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.

innovative parts of a CSP plant. The power block is based on mature technology and a lower learning rate than the average is expected (IRENA, 2012). Haysom *et al.* (2015) have presented a combined learning rate for CSP technologies of 11%. While previously the CSP learning rates were estimated to be in the range of 10 and 12% (Haysom et al., 2015; Neij, 2008), recent estimates have pegged these figures at above 20% (Lilliestam, 2017). IRENA has reported that if the latest auction results are factored in, then the learning rate for the period 2010-2022 could even reach 30% (IRENA, 2018b).

For the solution (i.e. CSP), 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.

A mean value of the data set range collected is assumed for installation costs of CSP systems which results in a total first cost of US\$ 6,339 per kilowatt⁷. A first cost learning rate of 20.25% percent was considered; and this has the effect of reducing the installation cost to US\$1,510 per kilowatt in 2030 and to US\$947,22 in 2050, compared to US\$1,786 (in 2014) per kilowatt for the conventional technologies (i.e. coal, natural gas, and oil power plants). Additionally, a discount rate is fixed at 9.68 percent appropriate for utility-scale projects and use across all Drawdown electricity generation solutions with this level of agency. Tables 2.2. and 2.3 depict the dataset ranges and the model inputs for the conventional and solution technologies.

Table 2.2 Financial Inputs for Conventional Technologies

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

⁷ All monetary values are presented in US\$2014

Learning Rate Factor (Conventional)	%		2.00%		
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Table 2.3 Financial Inputs for Solution

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
First costs (Solution)	US\$2014/kW	3,491- 9,188	6,339	67	14
Fixed Operation and Maintenance Costs (Solution)	US\$2014/kW	51.96 – 75.37	63.67	11	6
Variable Operation and Maintenance Costs (Solution)	US\$2014/kWh	0 – 0.111	0.046	12	6
Learning Rate Factor (Solution)	%	0.151 – 0.254	20.25%	9	6

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	66,016 – 89,746	77,881	8	8
Average Annual Use (Solution)	hours	1,752 – 3,683	2,717	45	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 adoption data from the different sources are usually given on interval of 5 to 10 years.

To achieve data completeness for the years within the gap, data interpolation was performed using the best fit model amongst 1st, 2nd, and 3rd polynomials. In cases where there are spikes, stepwise interpolation with one or more of the outlier datapoint(s) removed are performed to smooth out the trend, and complete the data for the missing years.

Assumption 2: Most of the scenario sources adopted for this work made assumptions around demographic drivers such as population growth, economic drivers such as GDP, policy drivers such as past policy trends, and the recent Paris Agreement. Other assumptions include international energy prices, exchange rates, international trade and investment, declining costs of renewables, and energy efficiency improvement.

Assumption 3: All currently available Concentrated Solar power technologies with or without storage are considered within the scope of this solution, being Parabolic trough collectors; Parabolic dish collectors; Heliostat field collectors (Tower) and Linear Fresnel reflectors.

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 is available at www.drawdown.org. Those general notes are excluded from this document but may be referred to 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.

The data derived from individual solution models was fed into sector-level integration models to generate the final results for all solutions within a global system. The interlinkage between this sector and all the

others is important, but major interactions of this sector occur with energy demand-side sectors like Transport and Buildings and Cities.

Through the process of integrating concentrated solar power 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

More research and modeling will be necessary to help policy-makers and project developers understand in detail the benefits of adoption on a higher resolution scale, as CSP will not always make economic sense nor fit perfectly into any country's future electricity generation portfolio. In particular, 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.

Global analysis is complicated in many ways by the fact that the technical performance and costs of CSP can vary widely across regions depending on the viability of the solar resource and related factors of production. To account for these differences results were weighted appropriately, but this cannot be done in every case, and due to this limitation, a more conservative estimate for the climate and financial inputs was often selected in order to avoid overstating the potential benefits of adopting CSP.

3 RESULTS

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

3.1 ADOPTION

A comparison of the results from the three modeled scenarios to the Reference Scenario allows an estimation of the climate and financial impacts of increased adoption of CSP systems. As a result of this exercise, the Plausible Scenario (PDS1) projects 7.4 percent of total electricity generation worldwide coming from concentrated solar systems by 2050. In the Drawdown (PDS2) and Optimum Scenarios (PDS3), the market share reaches 5.9 percent. Much of the CSP growth is projected to take place in Asia and Middle East and Africa. Latin America will be the third region, while China and India will potentially outpace the growth of Europe and US in the short term. Below in Table 3.1 are shown the adoptions of the solution in 2050 in functional units and percentage terms. Figure 3.1 depicts the long-term pathway trajectories for the different scenarios of CSP plants.

Table 3.1 World Adoption of the Solution

Solution	Units	Base Year (2014)	World Adoption by 2050		
			Plausible	Drawdown	Optimum
Concentrated Solar Power (CSP)	<i>Electricity Generation (TWh)</i>	9.00	3,385	4,198	4,198
	<i>(% market)</i>	0.04%	7.4%	5.9%	5.9%

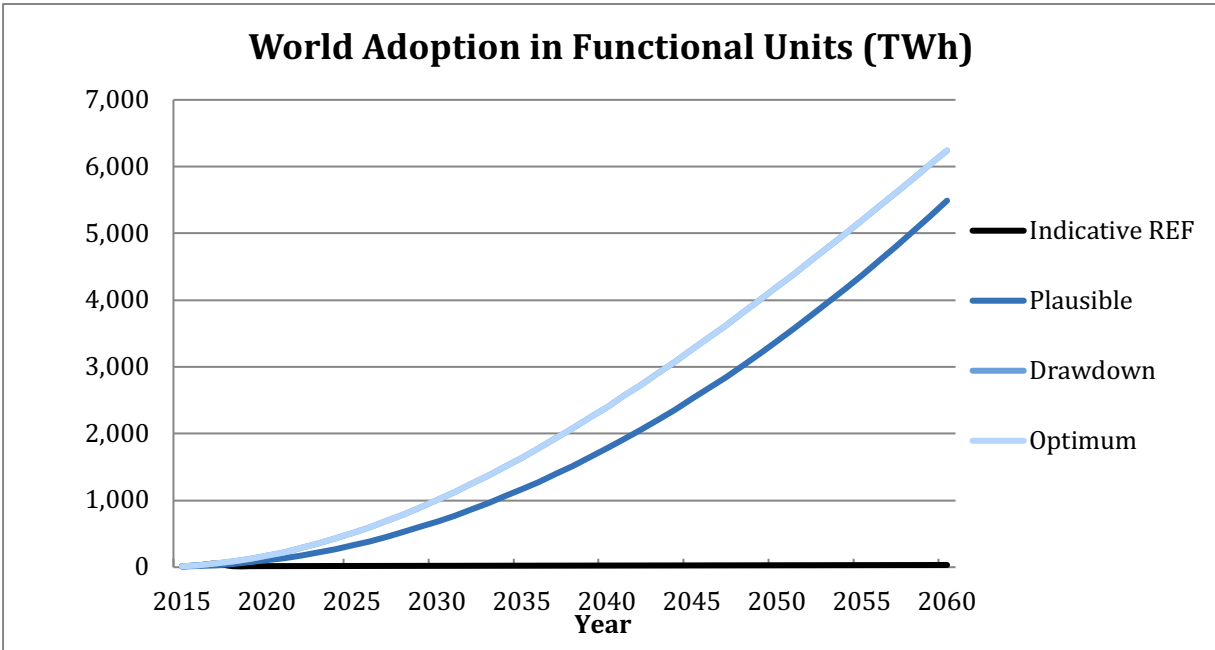


Figure 3.1 World Annual Adoption 2015-2060

Note: Drawdown and Optimum Scenarios have the same global adoption for this solution and therefore the operation costs reduction over time for both scenarios are 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 19.96 gigatons of carbon dioxide-equivalent greenhouse gas emissions between 2020-2050. Both the Drawdown and Optimum Scenarios are more ambitious in the growth of CSP technologies, with impacts on greenhouse gas emissions reductions over 2020-2050 of 26.89 gigatons of carbon dioxide-equivalent. 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	1.53	20.10	1.53

<i>Drawdown</i>	1.90	27.08	1.90
<i>Optimum</i>	1.90	27.08	1.90

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 19.0 gigatons of carbon dioxide-equivalent in the Plausible scenario, 24.1 gigatons of carbon dioxide-equivalent for the Drawdown Scenario and 23.7 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 CO₂-eq

Scenario	GHG Concentration Change in 2050	GHG Concentration Rate of Change in 2050
	<i>PPM CO₂-eq (2050)</i>	<i>PPM CO₂-eq change from 2049-2050</i>
Plausible	1.74	0.13
Drawdown	2.30	0.15
Optimum	2.30	0.15

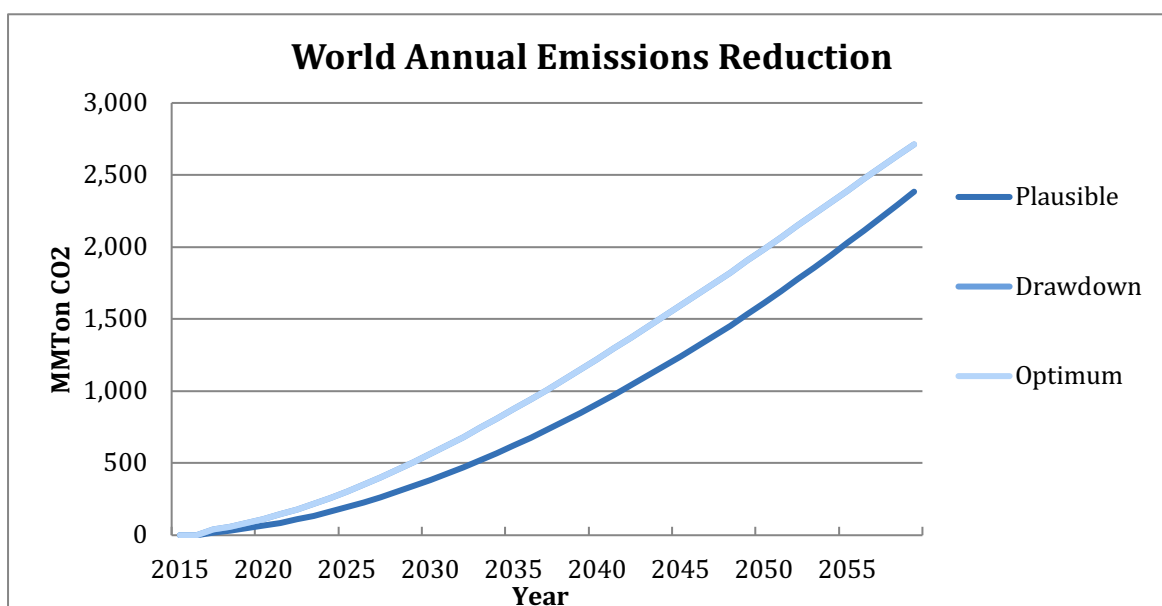


Figure 3.2 World Annual Greenhouse Gas Emissions Reduction (2015-2020)

Note: Drawdown and Optimum Scenarios have the same global adoption for this solution and therefore the operation costs reduction over time for both scenarios are overlaid in the figure.

3.3 FINANCIAL IMPACTS

The financial impacts incurred by replacing conventional grid electricity sources with CSP systems are significant. The Plausible scenario presents US\$486 billion in savings from marginal first costs and negative -US\$371 billions of net operating cost savings are projected over 2020 to 2050. Both PDS2 and PDS3 have similar numbers with near US\$585 billions of marginal first costs and -US\$498 billions of net operating savings over the same period.

The capital costs for PDS adoption of CSP systems will require significant investments in all scenarios, as the cumulative capital costs are over \$1.7 trillion under the Plausible Scenario and just over \$2.1 trillion for the other two more ambitious PD scenarios. 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)
	<i>2015-2050 Billion USD</i>	<i>2015-2050 Billion USD</i>	<i>2020-2050 Billion USD</i>	<i>Billion USD</i>
Plausible	1,758	486	-371	-182
Drawdown	2,169	585	-498	-231
Optimum	2,169	585	-498	-231

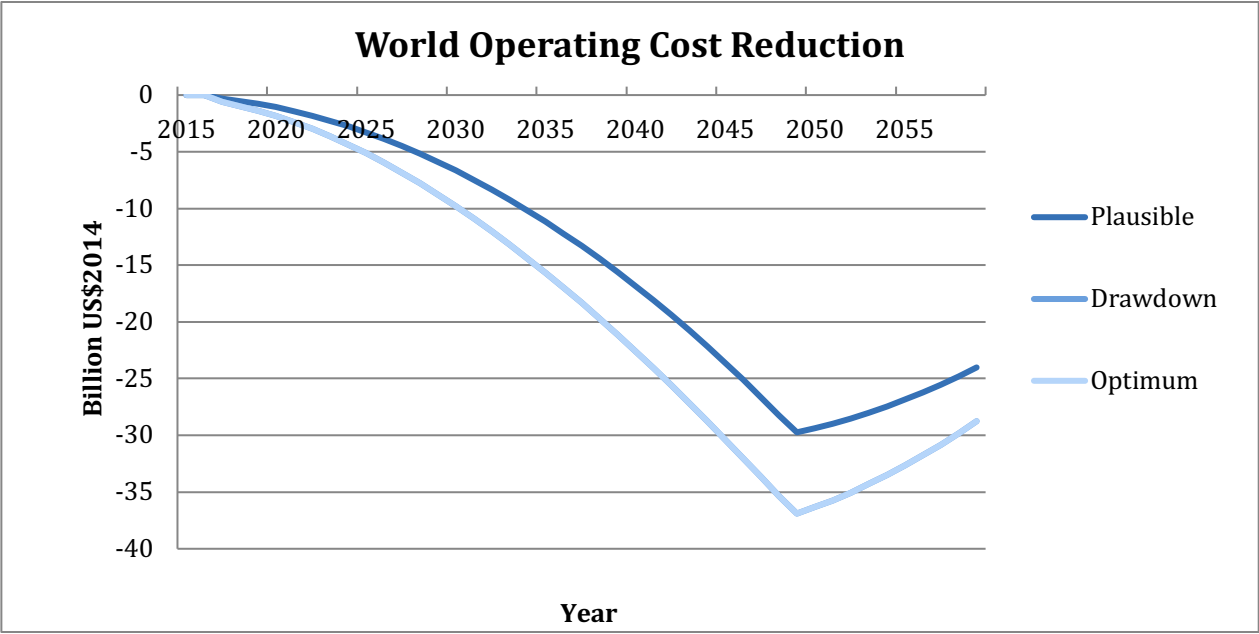


Figure 3.3 World operating cost Reduction (2015-2020)

4 DISCUSSION

High levels of adoption of CSP with combined with storage will enable a stronger and smoother integration of variable RES into the power grid, while providing firm and dispatchable power, or as a baseload source of electricity. Solar photovoltaic systems lack this feature (which to a small extent can be ameliorated by providing large and costly battery back-ups). In the medium term, CSP can also be deployed as fossil-fuel backup/hybridization that allows existing fossil fuel plants to follow a cleaner path while operating at the same or at even lower costs.

The World Energy Council has analyzed that there was hardly any change in the LCOE for CSP projects between 2008 and 2012. However, after 2012, there has been a downward trend in the LCOEs. Of late even where no direct subsidies were available for the projects, the lower LCOEs for CSP plants suggest “that government guarantees and development financing have been able to reduce financing costs for some CSP plants to below 7.5% weighted average cost of capital (WACC)” (WEC, 2016).

One of the most important determinants of adoption of future CSP technologies use will be the cost factor. Cost reductions will be driven by increasing economies of scale with the growth of the number and size of projects, more competitive supply chains and technology improvements that will raise capacity factors and/or reduce installation costs. As more and more plants come on-stream and utilities/operators gain experience of working with the technology, the confidence and familiarity levels will grow thus paving the way for increased future adoption.

The competition and growth of other more mature and currently less expensive RES as onshore wind and solar PV might delay the short-term adoption of CSP, despite advantages that are unique to CSP. Financial and regulatory support could help ensure that CSP technologies continue to come down in prices. Financial and monetary mechanisms such as long-term tax credits and incentives for production and installation have proved to be a boon for SPV and wind sectors. There is no reason to believe that these would not help this sector. The use of CSP would also be supported by adoption of renewable energy and portfolio standards; a price or limit on carbon emissions; and policies or regulations that either limit or place a price on the externality of environmental costs associated with fossil fuels.

A higher adoption of CSP is inhibited by “insufficiently accurate DNI data; inaccurate environmental data; policy uncertainty; difficulties in securing land, water and grid connections; permitting issues and expensive financing”. Policy intervention in these areas would be a key factor in removing and alleviating these non-economic barriers (IEA et al., 2015).

Notwithstanding its land and water use impacts and indirect emissions from the production of the materials for the plants, using CSP for electricity generation to reduce fossil generation brings increased public health and environmental benefits, especially related to reduced air pollution since operation of CSP plants do not produce any GHG or direct polluting emissions.

4.1 LIMITATIONS

First is the limitation set by geography on the deployment of solar technologies. These plants need plenty of sunshine and only areas that receive 2.2MWh of direct normal irradiation per square meter annually can have viable CSP plants. Only twenty countries have set up CSP installations so far (IRENA, 2018). This results in the obvious limitation of experience and confidence in the technology and until its spread increases, it would have to grapple with being looked upon as a risky proposition.

Since there is not much clarity on the investment risks involved, access to project financing also gets limited as the financial institutions themselves do not have long-standing experience of financing CSP projects. The situation would change as more and more countries adopt supportive financial policies to promote CSP and investors gain confidence in the technology and its viability. The experience of other renewable energy technologies like wind and SPV have shown that these are adopted rapidly in countries which have targeted incentives and policies to support them.

The design, installation, operation and maintenance of systems thus requires a higher degree of expertise and experience as compared to SPV systems (WEC, 2016). Lack of experience in installing and maintaining these plants thus becomes another cause for its slow uptake. There is a large variation in the design and configuration of these systems. As there is no standardization of the various sub-components like the solar block and the storage systems, installation costs become high. This results in higher energy costs. The benefits of assembly-line manufacture have not yet been reaped by CSP. There is ample scope for cost-reduction especially in the nascent solar block and storage technologies. For this, greater investments in research and development are necessary by the state as well as the industry.

Lack of experience in operating and maintaining CSP plants results in frequent and long breakdowns. As a result, generation suffers and tends to fluctuate widely with even a few projects going down or coming on-stream. This affects the grid stability and operations.

Another limiting factor is the environmental and social impacts associated with these projects. They are not recommended for water-stressed areas thus adding another limit to the geographical limits set by solar irradiance. As more research is being conducted into this area (Otiento, 2016), more social and

environmental issues are coming to light. Issues of worker health and safety and risks to avian species are some of the issues which could tend to limit its widespread adoption.

4.2 BENCHMARKS

Table 4.1 depicts a benchmark of Project Drawdown results for 2050 on the three developed scenarios to other seven publicly available scenarios from IEA (2017), Greenpeace (2015), IEA (2018), Ram et al (2017). The benchmarked results account for concentrated solar power electricity generation projected for the year 2050.

Table 4.1 Benchmarks

Source and Scenario	Electricity Generation in 2050 (TWh)	Market Share in 2050 (%)
Project Drawdown – Plausible Scenario (PDS1)	3,385	7.4%
Project Drawdown – Drawdown Scenario (PDS2)	4,198	5.9%
Project Drawdown – Optimum Scenario (PDS3)	4,198	5.9%
Greenpeace Energy [R]evolution (2015) – Reference Scenario	3,030	6.05%
Greenpeace Energy [R]evolution (2015) – Energy Revolution Scenario	8,138	16.32%
Greenpeace Energy [R]evolution (2015) – Advanced Energy Revolution Scenario	14,035	20.78%
Ram <i>et al.</i> (2017) - 100% RE Scenario	477	0.9%
IEA Energy Technologies Perspectives (2017) – 2DS	2,866	6.73%
IEA Energy Technologies Perspectives (2017) - Beyond 2DS	3,873	8.74%
IEA World Energy Outlook (2018) - Sustainable Development Scenario	2,395	4.70%

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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. Note that the assumption behind most scenarios is one of growth. If for instance, a solution is one of reduced heating energy usage due to better insulation, then the solution adoption is translated into an increase in the use of insulation. There are two types of adoption scenarios in use: **Reference (REF)** where global adoption remains mostly constant, and **Project Drawdown Scenarios (PDS)** which illustrate the high growth of the solution.

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

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

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

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

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

Discount Rate- the interest rate used in discounted cash flow (DCF) analysis to determine the present value of future cash flows. The discount rate in DCF analysis 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 CO₂e/kWh.

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

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

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

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

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

Learning Rate/Learning Curve - Learning curves (sometimes called experience curves) are used to analyze a well-known and easily observed phenomenon: humans become increasingly efficient with experience. The first time a product is manufactured, or a service is provided, costs are high, work is inefficient, quality is marginal, and time is wasted. As experience 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.

Regrets solution has a positive impact on overall carbon emissions being therefore considered in some scenarios; however, the social and environmental costs could be harmful and high.

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.