# PHOTOVOLTAIC AND CONCENTRATED SOLAR POWER GENERATION AND WATER DESALINATION IN ARID DESERT REGIONS

by

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# ABSTRACT

FAISAL ALSARRAF. Photovoltaic and Concentrated Solar Power generation and water desalination in arid desert countries. (Under the direction of DR. NENAD SARUNAC)

To evaluate the feasibility of solar power plants for both power generation and water desalination in arid desert locations, A Photovoltaic power plant was compared to a Concentrated Solar Power plant at different design capacities in the selected country of Kuwait. Both plants were configured in terms of the country's satellite-based weather data values throughout the year, and their corresponding electrical and thermal power generation capabilities were simulated using the NREL System Advisor Model (SAM) and compared to the country's power grid and RO/MSF desalination plants to explore demand satisfaction. Economic analysis was also performed for both plants and the results were compared in terms of feasibility.

As a result, the PV and CSP systems respectively satisfied up to 0.93% and 2.22% of annual power demand, and up to 133.32% and 162% of RO and MSF energy demand, respectively. It was shown that the PV plants outperformed CSP in most technical performance factors such as energy production and capacity per installation area and fell short against CSP in terms of energy yield and capacity factor. PV systems also outperformed CSP in all factors of economic analysis, ranging from 84.93% to 94.25% in decreased costs when compared to Concentrated Solar Power, deeming the PV option to be favorable for installation in Kuwait and the desert region it is in. Possible issues related to both power plant options such as the effect of high ambient temperature, dust formation, land availability, intermittent operation, and equipment maintenance were discussed along with solutions and mitigations to these problems.

# ACKNOWLEDGEMENTS

This is to acknowledge the aid and supervision of Dr. Sarunac, who has provided me with the knowledge of the operation of energy storage systems for conventional powerplants and their simulations on Ebsilon Professional. Dr. Sarunac has also helped me transition this knowledge into the Solar field and has further helped me narrow down my topic of thesis to the specific issue of using solar power plants to desalinate water as well as to generate power. He has been providing me with the supervision that is required to be able to write this thesis. Acknowledgements and gratitude also go to both Dr. Russell Keanini and Dr. Abasifreke Ebong, who have agreed to supervise the writing and presentation of this paper as well as offer crucial assistance and criticism that were vital to the quality of the topic at hand.

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Special thanks go to my family, who have supported my ambition to help facilitate the presence of renewable energy in my home country, Kuwait. Their support will always be held to my highest appreciation and regards.

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| | |
|---|---|
| PV | Photovoltaic |
| CSP | Concentrated Solar Power |
| RO | Reverse Osmosis |
| MSF | Multiple Stage Flash |
| kWh | Kilowatt Hour |
| TDS | Total Dissolved Solids |
| DNI | Direct Normal Irradiance |
| GHI | Global Horizontal Irradiance |
| DHI | Diffuse Horizontal Irradiance |
| KISR | Kuwait Institute for Scientific Research |
| KFAS | Kuwait Foundation for the Advancement of Sciences |
| MEW | Ministry of Electricity and Water |
| MPW | Ministry of Public Works |
| OPEC | Organization of the Petroleum Exporting Countries |
| b/d | Barrels per Day |
| GW | Gigawatt |
| CCGT | Combined-Cycle Gas Turbine |
| OCGT | Open-Cycle Gas Turbine |
| MCM | Million Cubic Meters |
| MED | Multiple Effect Distillation |
| CPDP | Combined Power and Desalination Plant |
| MIG | Million Imperial Gallons |

| | |
|---|---|
| SAM | System Advisor Model |
| NREL | National Renewable Energy Laboratory |
| MPPT | Maximum Power Point Tracker |
| WDC | Watt of Direct Current |
| DC | Direct Current |
| AC | Alternating Current |
| MACRS | Modified Accelerated Cost Recovery System |
| LCOE | Levelized Cost of Energy |
| TES | Thermal Energy Storage |
| HTF | Heat Transfer Fluid |
| MW | Megawatt |
| MWh | Megawatt Hour |
| TWh | Terawatt Hour |
| IEEE | Institute for Electrical and Electronical Engineers |
| HPV/T | Hybrid PV/Thermal |
| HJT | Heterojunction Technology |

# CHAPTER 1: INTRODUCTION

The countries of the Middle East region, specifically the Arabian Peninsula, are distinctively known for the desert-dominant climate present in the region. The area's climate is among the hottest and driest in the world, with temperatures commonly reaching north of 49 degrees Celsius in regions such as the Saudi Arabian deserts during summer seasons and negligible precipitation values of 14 to 30 inches annually [1]. Kuwait, a small country within the Arabian Peninsula bordering both Iraq and Saudi Arabia, shares the general harsh desert climate conditions of the region, with record temperatures reaching north of 51 degrees Celsius during the summer, and an annual total rainfall averaging below 120mm [2]. Kuwait is also known for being a coastal country overlooking the Persian Gulf and having a limited freshwater source in the form of ground water. Thus, the main source of freshwater in the country is seawater desalination [3].

Although rising and settling dust is a common occurrence in regional weather [4], the conditions present in Kuwait and its neighboring countries make it a viable candidate for the installation of solar power generation, as the country's abundant sun exposure and record temperatures may provide promising energy production using solar power facilities. It also allows for room to explore the water desalination capabilities associated with solar power plants, as this may provide a practical source of power to desalinate saltwater and aid in meeting the country's demands.

## 1.1 Photovoltaic Systems

As for methods of solar power generation considered, there are two main technologies that are to be explored. Photovoltaic (PV) power generation and Concentrated Solar Power (CSP). PV technology consists of utilizing solar cells made of a semiconductor material, typically silicon and conductive metals, to absorb the photons in sunlight using the captured energy to charge electrons that move through the metals carrying electric current [5]. These solar cells are typically arranged into panels, which have the benefit of modularity, as they can be arranged into large arrays with high power productions capacities typically seen in solar farms or plants, or they can be arranged into smaller groups of panels typically placed on rooftops of commercial and residential buildings. These private installations of PV panels are typically integrated directly into the power grid of the consumer, which reduces electrical costs as part of the used power for the building or household is drawn from the PV system.

## 1.2 Concentrated Solar Power

As for CSP, its mean of operation is dependent on the sun’s thermal energy as opposed to its photonic energy. Mirrors are used to concentrate and reflect sun rays into a receiver, which in term heats up a working fluid within the receiver. The heated fluid then flows into a turbine or power generator, converting its stored thermal energy into mechanical energy, which in terms is converted into electrical energy. The fluid then flows into a condenser and is then redirected into the receiver to be heated once again [6]. Since CSP technologies are typically reserved to large scale power plants, they lack the modularity that is possible with PV applications. However, they hold the advantage of multiple possible energy storage options that are often directly integrated into the plants, which would increase the practicality of the plants during the absence of solar exposure [7].

## 1.3 Water Desalination in Kuwait

Although both Reverse Osmosis (RO) and Multiple Stage Flash Distillation (MSF) are viable options for desalination methods to be used in the Middle East, Kuwait has favored the latter option, and has implemented this technology by building multiple MSF desalination plants, which currently supply over 90 percent of the country's freshwater demands [8]. It is noted that desalination using RO requires significantly less energy, where it only requires 5 kilowatt-hour per cubic meter of freshwater produced as compared to the more demanding MSF desalination requiring 18 kilowatt-hours to produce a cubic meter of fresh water. However, the country chooses MSF over RO because of the lack of regional experience with using RO methods at high rates of Total Dissolved Solids (TDS) and high ambient water temperatures as opposed to the well documented and reliable performance of MSF desalination in the region [8].

Desalinating water is a technology that is highly dependent on both thermal energy and electrical power. As of recent studies, it is shown that Kuwait spends a third of its annual oil revenue to generate both electricity and to power the eight major functional water desalination plants in the country [8], which would form an imminent threat to the life expectancy of the finite oil reserves that Kuwait possesses in the coming years. This provides suitable conditions for the integration of solar power generation systems to desalinate water, thus supplying a considerable fraction of the country's freshwater demands efficiently.

Both PV and CSP methods are to be simulated according to the present environmental and economic factors in the country, to determine the efficiency of solar power in providing a solution for both electricity generation and water desalination. This would not only aid in prolonging the depletion of Kuwait's oil reserves, but would also provide for long lasting, renewable energy methods that would eventually take over the country's basic power and water demands as technologies are improved with time. The obstacles with implementing each of the solar methods are also to be discussed, specifically with respect to the factors present in the country. Possible means of improvement are also to be stated to further increase the efficiency and productivity of these technologies when applied to harsh desert regions as that of Kuwait.

# CHAPTER 2: CURRENT RELEVANT FACTORS

To better understand the effectiveness of applying solar energy generation methods in the country, it is crucial to first introduce an inclusive and detailed explanation of all factors related to power and water production that are currently present in Kuwait. These factors are as seen in the following segments.

## 2.1 Environmental Factors

### 2.1.1 Solar Irradiance

Solar irradiance in terms of both Direct Normal Irradiance (DNI) and Global Horizontal Irradiance (GHI) is the primary factor in determining the possible power output by both PV and CSP systems, as both technologies rely on the sun's exposure to be able to convert it to either electrical or thermal energy. As for the sun exposure in Kuwait, the annual DNI and GHI values based on monthly averages for the year 2013 were at 1,982 and 2,086 kilowatt hours per square meter, respectively [9]. A table was prepared by the Kuwait Institute for Scientific Research including the monthly average values for 2013 and is seen as Table 1.

Table 1. Average DNI Values for the year 2013. Steensma, Gilein, Rubén Román, Craig Marshall, Julián Bermejo, Krishnaswamy Iyer, Salem Al-Hajraf, and Ayman Al-Qattan. "Shagaya Renewable Energy Park Project." AIP Publishing. AIP Publishing LLC AIP Publishing, July 25, 2019. https://aip.scitation.org/doi/10.1063/1.5117583.

| | **Daily DNI** | **Monthly DNI** | | | | | |
|---|---|---|---|---|---|---|---|
| | Average ($kWh/m^2$) | Average ($kWh/m^2$) | Yearly share (%) | Minimum | | Maximum | |
| | | | | ($kWh/m^2$) | (%) | ($kWh/m^2$) | (%) |
| Jan | 4.07 | 126 | 6.4 | 83 | -34.1 | 167 | 32.4 |
| Feb | 4.43 | 125 | 6.3 | 90 | -28.5 | 157 | 25.3 |
| Mar | 5.27 | 163 | 8.2 | 113 | -30.5 | 201 | 22.9 |
| Apr | 4.39 | 132 | 6.6 | 98 | -25.3 | 159 | 20.5 |
| May | 4.96 | 154 | 7.8 | 70 | -54.4 | 191 | 24.1 |
| Jun | 7.06 | 212 | 10.7 | 155 | -26.9 | 241 | 13.7 |
| Jul | 7.80 | 242 | 12.2 | 173 | -28.5 | 275 | 13.6 |
| Aug | 7.39 | 229 | 11.6 | 162 | -29.3 | 282 | 22.9 |
| Sep | 6.62 | 199 | 10.0 | 137 | -30.8 | 229 | 15.5 |
| Oct | 5.28 | 164 | 8.3 | 116 | -29.3 | 186 | 13.6 |
| Nov | 4.09 | 132 | 6.2 | 83 | -32.8 | 188 | 53.0 |
| Dec | 3.67 | 114 | 5.7 | 68 | -40.6 | 196 | 72.6 |
| **YEAR** | **5.43** | **1982** | **100.0** | **1813** | **-8.5** | **2090** | **5.5** |

### 2.1.2 Ambient Temperatures

The ambient temperatures within the country also play an important role in determining the power output of renewable systems, as increased surrounding temperatures lead to decreased power outputs for both CSP and conventional powerplants [10]. The ambient temperatures in Kuwait can reach drastic contrasts, typically approaching zero degrees Celsius in peak winter days in January and exceeding 50 degrees Celsius on the hottest summer days of July and August [11]. Simulations are to be run at different ambient temperatures to understand the effect of the varying temperatures on power output. This would in terms simulate the general power output throughout the year on a monthly basis.

### 2.1.3 Sky Clarity and Debris

It is important to note that regions in the Arabian Peninsula such as Kuwait are known for frequent dust conditions, which would impose a significant hindering factor to the amount of sun exposure per year. It not only decreases the amount of sunlight absorbed or reflected by the solar power methods but imposes further issues such as cleaning and maintenance of the PV panels and CSP Mirrors as well as affecting the efficiency of PV inverters and wires [9]. According to research performed by the Kuwait Institute for Scientific Research (KISR) there is a total of 128 hours of dust and sandstorms experienced annually by the country, excluding 405 hours a year of suspended dust. Haze is also a frequent phenomenon in the country resulting from its coastal location, which occurs about 930 hours a year and is also a contributor to the hinderance of sun exposure [9]. Dust deposition is also considered, as the only renewable plant in the country is currently installed in an area of high dust deposition, at about 330-500 tons per square kilometer [9]. This information may be used in the future for the selection of installation areas with less dust disposition. Figure 1 displays the dust disposition rates across different areas of the country.

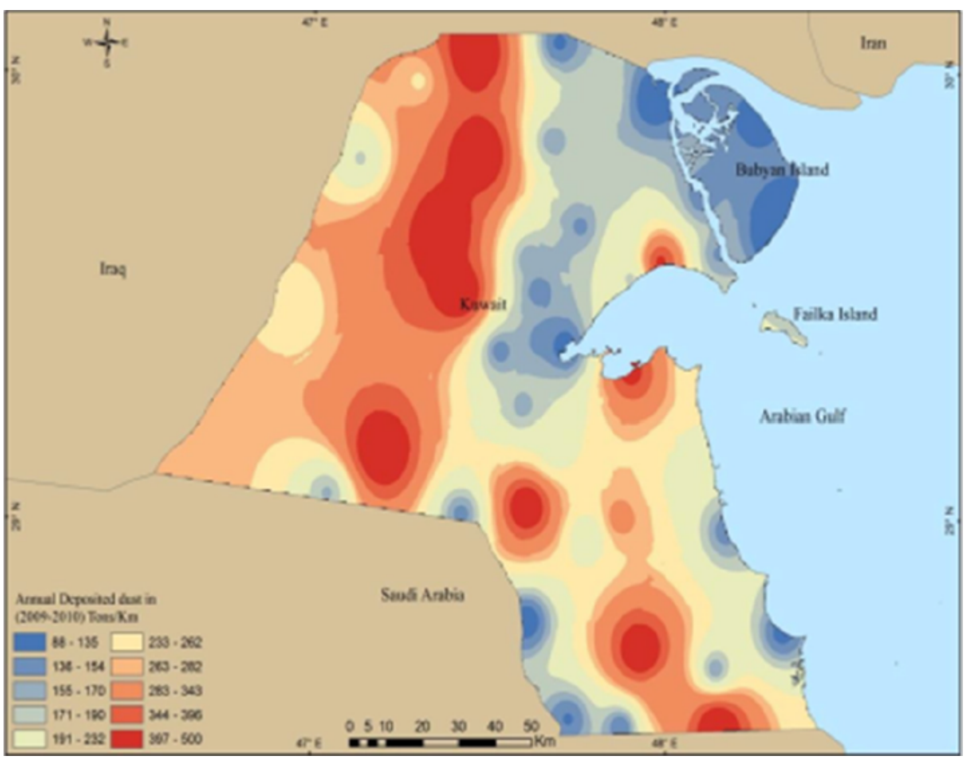


Figure 1. Dust Deposition Values Around Kuwait. Steensma, Gilein, Rubén Román, Craig Marshall, Julián Bermejo, Krishnaswamy Iyer, Salem Al-Hajraf, and Ayman Al-Qattan. “Shagaya Renewable Energy Park

Project." AIP Publishing. AIP Publishing LLC AIP Publishing, July 25, 2019. https://aip.scitation.org/doi/10.1063/1.5117583

### 2.1.4 Land Available for Installation

As opposed to some of the previously mentioned environmental factors that may form a hinderance to solar energy systems, Kuwait has an abundant amount of land area that can be used for the installation of solar collectors. The land in Kuwait is not only almost entirely flat [11], but it is also majorly untouched when compared to the land currently used and populated. There are however two main possible hinderances regarding the installation of renewable (or conventional) plants in these locations.

The first and main issue would be the bureaucratic process of having these installations approved by multiple major entities in the country such as the Ministry of Electricity and Water (MEW) and the Ministry of Public Works (MPW). The second hinderance would be that the mainly populated areas of the country are coastal, which would have large area installation requirements for a solar plant to be installed within proximity to a desalination plant to avoid thermal and electrical losses. This can be explained as observed in Figure 2 [12].

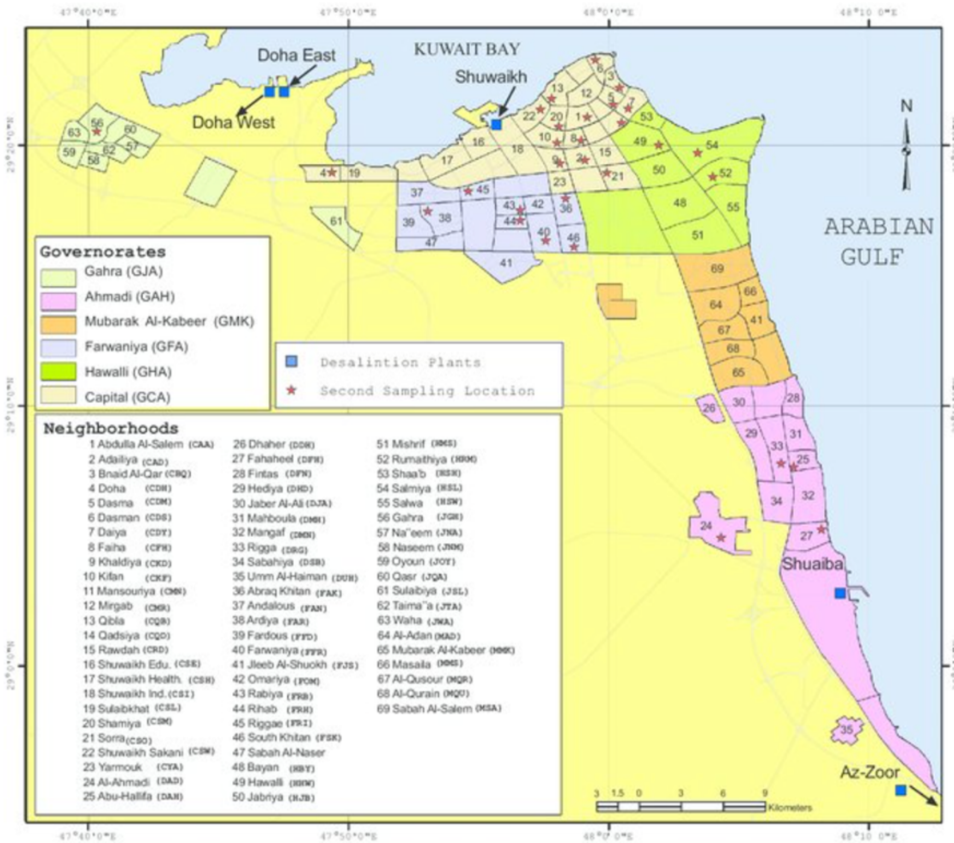


Figure 2. Main Population Distribution and Major Desalination Plants in Kuwait. Al-Mudhaf, Humood F., Abdel-Sattar Abu-Shady, Mustafa I. Selim, and F A Alsharifi. “Survey of Haloacetic Acids in Household Drinking Water Produced from Thermal Desalination in Kuwait.” ResearchGate. Open Environmental Sciences, August 2009. https://www.researchgate.net/publication/228343190_Survey_of_Haloacetic_Acids_in_Household_Drinking_Water_Produced_from_Thermal_Desalination_in_Kuwait.

The PV and CSP simulations are to be performed with the assumption that these hinderances are to be taken care of, which could theoretically be possible by methods such as utilizing the northern coastal area of the country as well as the issuance of governmental grants supported by institutes such as KISR and the Kuwaiti Foundation for the Advancement of Sciences (KFAS).

## 2.2 Oil and Natural Gas Consumption and Power Production Rates

Kuwait’s economy is mainly reliant on crude oil and natural gas production and exports. According to the Organization of the Petroleum Exporting Countries (OPEC), Kuwait has produced an average of 2.438 million barrels per day (b/d) of crude oil, and

12,883 million cubic meters of natural gas as of 2020 [13]. However, these two natural resources are also the two dominant assets currently used for power generation in Kuwait. About 184,000 barrels per day of oil and 37.38 million cubic meters per day of natural was burned in July 2020 to produce power at a capacity of 14.96 Gigawatts (GW) in the country [14], as power demands surge during the summer for air conditioning requirements. As of 2015, 64% of power generating capacity was accredited to using oil, but the country has since pushed to switch its power production and water desalination reliance on natural gas instead [14].

According to the Kuwait Energy Outlook report for power production in the country [15], Kuwait is at a capacity of 18.8 Gigawatts as of 2018. Most of its electricity generation is distributed between steam turbines (Roughly 50% of production) and Combined-Cycle Gas Turbines (CCGT) at 40% production, with some reliance on Open-Cycle Gas Turbines (OCGT) at 8%. There is a presence of renewable energy generation using PV, Wind and CSP methods, but this currently constitutes of less than 1% of total power production in the country. The power plants present in the country as of 2018 accompanied by their power production capacities can be seen in Table 2 [15].

Table 2. Kuwait Power Plants in 2018. "Kuwait Energy Outlook." Kuwait Institute for Scientific Research, 2019. https://www1.undp.org/content/dam/rbas/doc/Energy%20and%20Environment/Arab_Water_Gov_Report/Arab_Water_Report_AWR_Overview.pdf.

| | Technology | Installed Capacity (MW) |
|---|---|---|
| Doha East | Steam turbine (7)<br>OCGT (6) | 1,158 |
| Doha West | Steam turbine (8)<br>OCGT (5) | 2,541 |
| Az-Zour South | Steam turbine (8)<br>OCGT (4) CCGT (15) CCST (4) | 5,806 |
| Az-Zour North | CCGT (5) CCST (2) | 1,540 |
| Sabiya | Steam turbine (8)<br>OCGT (4) CCGT (8) CCST (4) | 5,866 |
| Shuaiba South | Steam turbine (6) | 720 |
| Shuaiba North | CCGT (3) CCST (1) | 875.5 |
| Shuwaikh | OCGT (6) | 252 |
| Shayaga | PV, wind, CSP | 70 |
| Umm Gudair | PV | 10 |
| TOTAL CAPACITY | | 18,838 |

## 2.3 Freshwater Production Rates and Required Power Consumption

As for water desalination, the current eight major water desalination plants in Kuwait have a total production capacity of 3.11 million cubic meters per day (MCM/d) of freshwater [16]. The total estimated net freshwater production across these plants is 717.90 million cubic meters per year (MCM/yr). Most of these plants are based on MSF desalination as opposed to RO [16]. However, there is a push in the country to install more RO plants [17]. The eight major plants, along with their desalination capacities are observed in Table 3.

Table 3. Current major desalination plants and their capacities in Kuwait. "Water Infrastructure in Kuwait." Fanack Water, June 14, 2021. https://water.fanack.com/kuwait/water-infrastructure-in-kuwait/.

| Name of plant | Technology | Commissioning year | Installed capacity MCM/d | Net production of desalinated water MCM/yr |
|---|---|---|---|---|
| **Shuwaikh** | MSF and RO | 1982 | 0.22 | 48.13 |
| **Shuaiba North** | MSF | 2011 | 0.21 | 38.04 |
| **Shuaiba South** | MSF | 1971 | 0.14 | 36.71 |
| **Doha East** | MSF | 1978 | 0.19 | 56.04 |
| **Doha West** | MSF and RO | 1983 | 0.78 | 129.91 |
| **Zour South** | MSF and RO | 1988 | 0.64 | 101.79 |
| **Zour North** | MSF and RO | 2016 | 0.49 | 30.97 |
| **Sabiya** | MED | 2006 | 0.46 | 116.93 |
| | | **Total capacity** | **3.11** | **717.90** |

As for the power required to desalinate water in Kuwait, the data is estimated theoretically using the percentage of water desalinated by each technology and the average power required by each method to produce a given amount of freshwater. As of 2018, MSF plants are expected to produce about three quarters of the country's freshwater supply [16], so 75% will be attributed to MSF for estimation. According to Figure 2, the country's only current Multiple Effect Distillation (MED) produces 116.93 of the 717.90 million cubic meters per year, which would have it at 16.28% of Kuwait's freshwater production. This leaves Reverse Osmosis (RO) to consist of the remaining 8.72% of total freshwater desalination.

Considering that MSF requires approximately 18 kWh to produce a cubic meter of freshwater, whereas 15 kWh/m^3 is used for MED and 5 kWh/m^3 for RO [17], It is estimated that 26,552,466 kWh of power per day is used by MSF plants to maintain their production, as 4,803,046 kWh per day is used by MED plants and 857,546 kWh per day used by RO plants. This yields an estimated total of 32,213,058 kWh of power being used daily to run all desalination plants at their current production rates. The breakdown of water desalination method fractions and power requirements in Kuwait is observed in Table 4.

Table 4. Daily Estimated Water Desalination Methods and Power Demand in Kuwait.

| Kuwait Water Desalination Power Requirements | | | | | |
|---|---|---|---|---|---|
| Annual Total Water Desalination | 717,900,000.00 | m^3 | Daily Total Water Desalination | 1,966,849.32 | m^3 |
| Fraction Contributed by Each Method | | | Total Daily Desalination | | |
| MSF | 0.75 | | MSF | 1,475,136.99 | m^3 |
| MED | 0.16 | | MED | 320,203.07 | m^3 |
| RO | 0.09 | | RO | 171,509.26 | m^3 |
| Power Required for Each Method | | | Total Daily Power Requirement | | |
| MSF | 18.00 | kWh/m^3 | MSF | 26,552,465.75 | kWh |
| MED | 15.00 | kWh/m^3 | MED | 4,803,046.03 | kWh |
| RO | 5.00 | kWh/m^3 | RO | 857,546.30 | kWh |
| | | | Total | 32,213,058.08 | kWh |

## 2.4 Current Examples and Rates for Technical Comparison

### 2.4.1 Photovoltaic Comparison Rates

To understand the specific performance and economical aspects of current power production and water desalination, The selected PV systems are to be modelled and simulated to determine how much of the countrywide power demand, as well as RO desalination power requirements can be satisfied directly using photovoltaic AC power [18]. It was estimated from the previously stated countrywide desalination data that the RO systems in Kuwait require approximately 26,083,700 kWh monthly, or 313,004,400 kWh annually to maintain the mentioned annual water desalination rates. These power demand rates will be used and compared with the annual and monthly electrical power produced by the PV designs according to the simulations.

### 2.4.2 CSP Comparison Rates and Example Plant

As for the CSP simulations, the Shuaiba North Combined Power and Desalination Plant (CPDP) was chosen as a candidate to be examined and compared. This selection was made for the following reasons:

1 The plant is a combined power production and water desalination system, which allows for convenient comparison with a solar power plant.

2 The integrated water desalinated plant is based on MSF solely and has been commissioned relatively recently [16].

3 The chosen CPDP has extensive research and calculated analysis published by Mr. Anwar Bin Amer at the Kuwait Foundation for the Advancement of Sciences (KFAS) [19].

According to the publicized research done by Mr. Bin Amer and KFAS, the Shuaiba North's power generation plant is a combined cycle gas turbine (CCGT), comprising of three gas turbines and one steam turbine. Each gas turbine provides an output of 215.1 MW, whereas the steam turbine produces 215.02 MW, resulting in a total power output of 860.32 MW. The plant's water desalination component comprises of three MSF plants that each desalinate 15 million imperial gallons per day (MIG/d), which requires a total of 170.42 MW. 136.34 MW of that power is derived from the thermal energy provided by the CCGT plant, whereas 34.1 MW is used directly from the CCGT's power output for pumping energy. An additional 4.3 MW is drawn directly from the CCGT's output to power the boiler feed water pump. Accounting for the CCGT's total power output and the fraction of it directly used for the mentioned pumps, the net power output for the Shuaiba North CPDP is equal to 821.77 MW [19]. A complete breakdown of the Shuaiba North MSF plants' thermal and electrical requirements is observed in Table 5.

Table 5. Breakdown of Shuaiba North MSF Plants Power Demand.

| Shuaiba North MSF Power Requirements | | |
|---|---|---|
| Daily MSF Single Plant Production | 15,000,000.00 | Imperial Gallons |
| Daily MSF Single Plant Production, Metric | 68,191.35 | m^3 |
| Number of Plants present | 3.00 | |
| Total daily freshwater production | 204,574.05 | m^3 |
| Percent of Countrywide Desalination | 10.40 | % |
| Power requirement for MSF technology | 18.00 | kWh/m^3 |
| Daily power to cover total desalination | 3,682,332.90 | kWh |
| Annual power to cover total desalination | 1,344,051,508.50 | kWh |
| Total Power Used by the MSF Plants: | 170.42 | MW |
| Thermal Power: | 136.34 | MW |
| Fraction of thermal power to total power used | 0.80 | |
| Thermal power used based on fraction | 1,075,272,753.60 | kWh Annual |
| Electrical power used based on fraction | 268,778,754.90 | kWh Annual |

The Shuaiba North's MSF water desalination capacity is to be used as the main point of interest in determining CSP power desalination, as simulations are to be run to determine the possible fraction of required energy for water desalination that can be satisfied by the modelled CSP plants. Both the thermal energy required for the MSF process, as well as the electrical energy required for plant operations and boiler pumps are to be considered in satisfying these demands.

# CHAPTER 3: METHODOLOGY AND TECHNICAL APPROACH

## 3.1 Simulation Software

The selected software that is used to simulate the outputs of both PV and CSP plants is the System Advisor Model (SAM), created by the National Renewable Energy Laboratory (NREL). SAM was selected for this simulation not only for its inclusive library of currently present PV and CSP component models, but also for its extensive customization properties. SAM provides global satellite data that can be used for GHI, DNI, ambient temperature, sun path, and more environmental factors specific to the location of interest. It also contains the technical specifications of all models within its library, such as power output, working temperatures, reference voltages and currents for PV systems, power storage options, sizing, and costs.

SAM is to be used to simulate the power output for selected PV and CSP systems based on the regional environmental and economic factors in Kuwait, and the yielded simulation results are then used directly with existing water desalination plants to determine overall performance.

## 3.2 Satellite Data

All simulations performed by SAM for both PV and CSP options are based on regional data derived directly from the NSRDB satellite, with a serial code of 2419941. This satellite gathers the environmental factors required to simulate the performance of renewable energy systems in Kuwait, and includes the exact location in terms of latitude, longitude, and altitude, as well as GHI, DNI, DHI, ambient temperature and wind speed values among multiple other factors recorded throughout the entire year of 2019. Some of these factors such as the location and annual calculated averages can be seen in Figure 3.

SAM also provides graphs of weather factors upon inspection of the obtained satellite date weather file, as seen by the DNI/DHI/GHI graph in Figure 4.

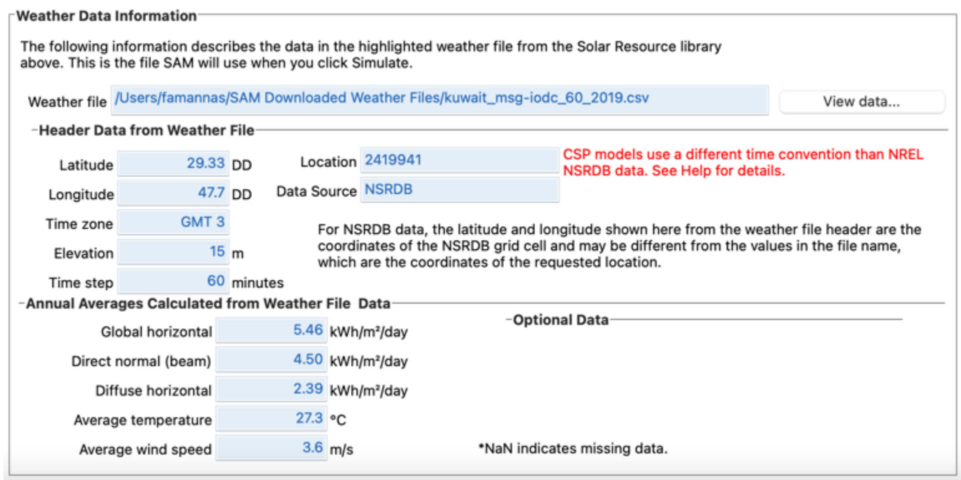


Figure 3. Location and Annual Averages Derived from NSRDB via SAM.

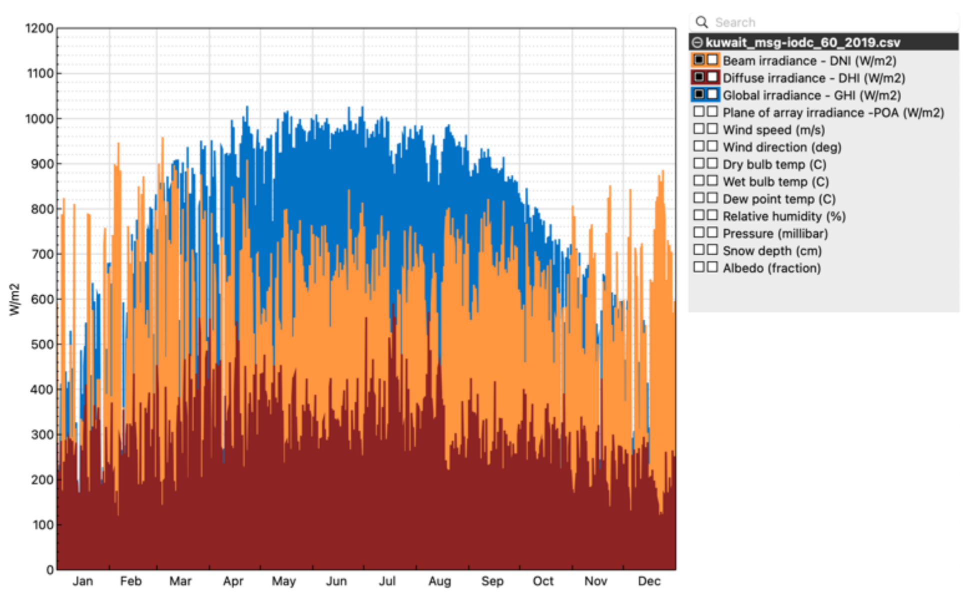


Figure 4. DNI, DHI and GHI Values in Kuwait in the Year 2019 as Derived via SAM.

The data derived the NSRDB satellite for Kuwait in 2019 is to be used for all simulations, which would be performed at timesteps of 60 minutes for a yearly analysis.

## 3.3 Selected PV Design

### 3.3.1 PV Panel Model

The model for all PV capacity simulations was chosen to be the SunPower SPR-E19-310-COM monocrystalline module. The panel was selected based on its performance capabilities in high ambient temperature regions such as that in Kuwait. It has a 1000 Watts per square meter irradiance capacity, a nominal operating cell temperature of 46 degrees Celsius, and a temperature coefficient of -0.386% per degree Celsius, which was deemed a reasonable rate considering the high ambient temperatures reachable in the summertime. The selected panel has 96 cells per module, and a total module area of 1.631 squared meters. Detailed specifications of the chosen PV module are given in Figure 5.

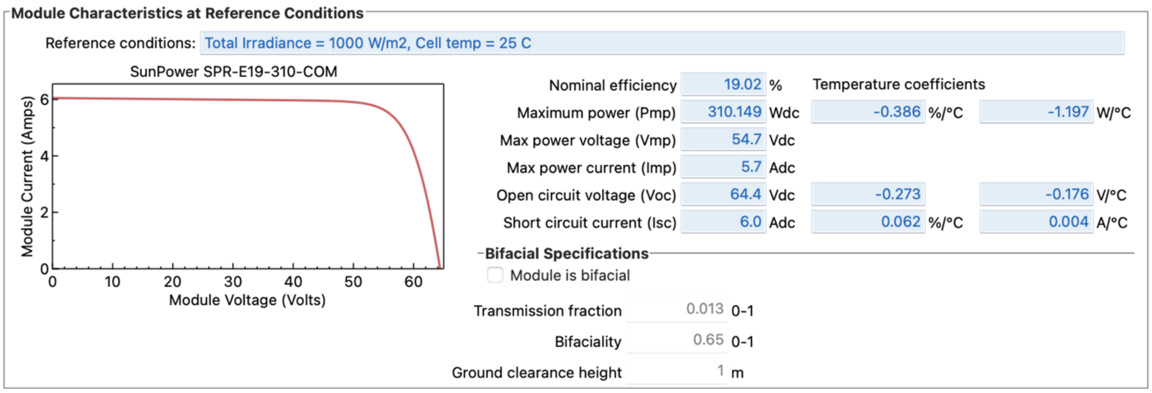

Figure 5. Detailed Specifications of Chosen PV Module, as according to SAM Library.

### 3.3.2 Selected PV Inverter

The inverter for the chosen PV module was selected to be Yakasawa Solectria Solar: SGI 750XTM [380V]. This inverter was chosen for its compatibility with the selected PV module, as well as its relatively high weighted efficiency and maximum operational voltage and power capacities and low MPPT losses. Detailed specifications for the selected inverter are seen in Figure 6.

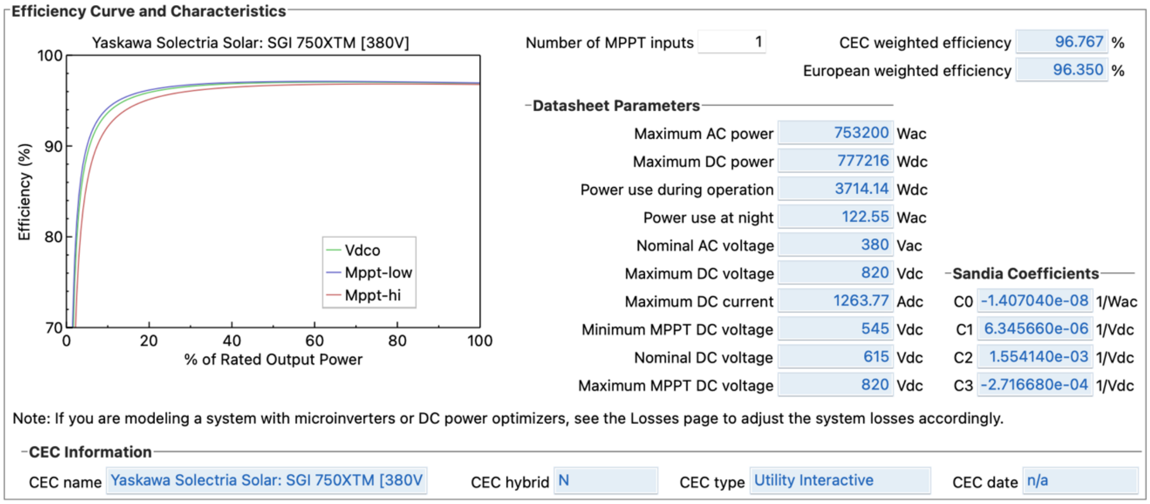

Figure 6. Detailed Specifications for Chosen Inverter, as According to SAM Library.

### 3.3.3 System Design

The PV simulations are to be performed for three cases, at design sizes for two, three and four subarrays each. Each subarray would contain 12 PV modules per string, and 13,435 strings connected in parallel. 50 inverters would be used for each subarray to maintain a DC/AC conversion ratio of 1.33. This would result in a total AC capacity of 75.32 MW for the two-subarray design, 112.98 MW for the three-subarray design, and 150.64 MW of AC power for the four-subarray design.

The mentioned configurations would yield in a total installation area of 281.564 acres for the 2-subarray design, 422.346 acres for the 3-subarray design, and 563.128 acres for the 4-subarray design. All modules in each design would be installed with 2-axis tracking to maximize the possible energy absorption based on the sun's position relative to the region's longitude/latitude. More detailed parameters on the 2-Subarray design can be seen in Figure 7.

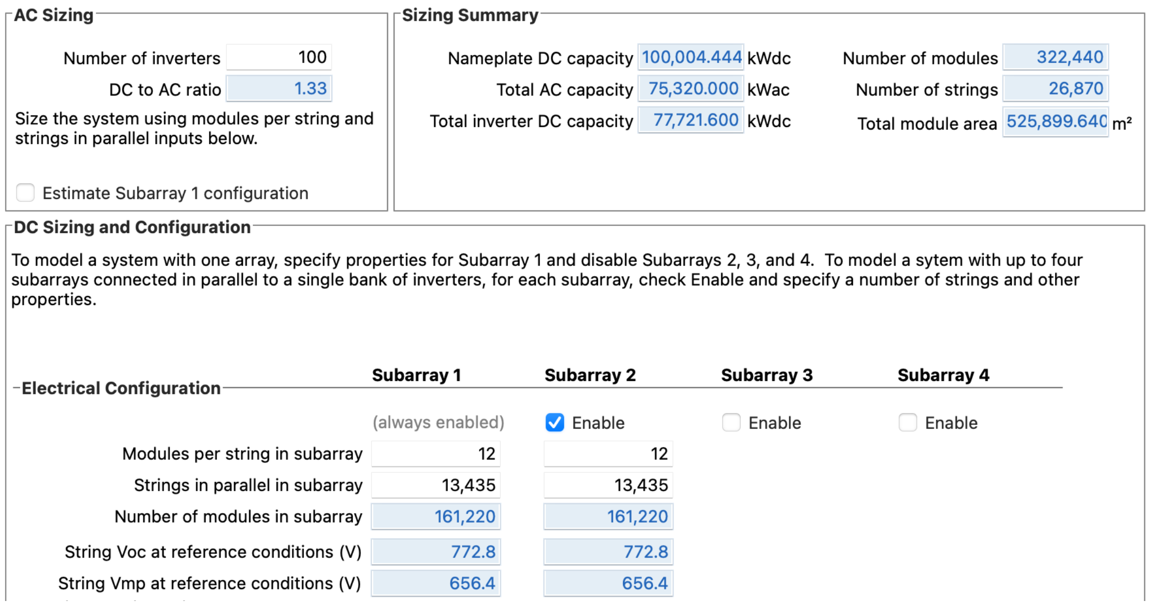


Figure 7. Detailed Parameters for PV 2-Subarray System Design.

### 3.3.4 Losses and Degradation

To obtain more realistic simulation results, power losses were attributed to the designed PV capacities. A 5% annual soiling loss was assumed, as well as 2% for module mismatch, 0.5% for diodes and connections, 2% for DC wiring and an AC wiring loss of 1%. This is applied for each subarray. An annual degradation rate of 0.5% was also assumed to maintain realistic expectations.

### 3.3.5 Financial Parameters

To accurately estimate direct costs, 0.2 dollars per Watt of direct current was assumed for balance of system equipment, as well as 0.11 $/WDC for installation labor, and 0.06 $/WDC for installer margin and overhead, and a 3% contingency of the subtotal including module costs estimates mentioned above. As for indirect costs, 0.01 $/WDC were allocated for permitting and environmental studies, 0.07$/WDC for engineering and developer overhead, and 0.03$/WDC for grid interconnection were allocated.

0.02$/WDC were allocated to land preparation and transmission, which would conclude considerations for total indirect cost.

15 dollars per kilowatt-hour years ($/kWh-yr.) were allocated to operational and maintenance costs, and an annual inflation rate of 2.5% per year was assumed. This yields a nominal discount rate of 9.06% when a real discount rate of 6.4% is assumed. No taxes, debt, or interest was assumed to maintain relative translatability when considering economic factors in regions outside of the United States such as that of Kuwait.

Asset depreciation was also included in the analysis and was calculated using SAM. 90% of assets were allocated as 5-year MACRS properties, 1.5% as 15-year MACRS, 2.5% as 15-year straight-line depreciation, 3% as 20-year straight line depreciation, and the remainder 3% as non-depreciable assets. Finally, 0.1$/W was included as major equipment replacement reserve, with major replacements assumed to be made at 15-year intervals.

## 3.4 Selected CSP Model

### 3.4.1 Parabolic Trough

Upon exploration of multiple possible CSP designs, it was determined that the Parabolic Trough design would be the ideal candidate to be simulated based on factors such as Levelized Cost of Energy (LCOE), annual net energy output, and total installation area. To further illustrate the comparison between a parabolic trough design and that of a solar tower, both layouts have been modelled at a capacity of 100MW and a Solar Multiple value of 4 and have been compared according to the simulation results in Table 6.

Table 6. Parabolic Trough vs. Solar Tower results at 100MW and Solar Multiple of 4.

| CSP Parabolic Trough vs. Solar Tower Design | | | |
|---|---|---|---|
| Plant Design Type | Parabolic Trough | Solar Tower | |
| Plant Capacity | 100 | 100 | MW |
| Annual Net Electrical Energy Production | 358,384,096 | 276,360,192 | kWh |
| Capacity factor | 45.50% | 35.10% | |
| Annual Water Usage | 82,103 | 77,148 | m^3 |
| Levelized COE (nominal) | 84.33 | 99.69 | ¢/kWh |
| Levelized COE (real) | 66.95 | 79.15 | ¢/kWh |
| Net present value | -3,000,605,440 | -2,747,979,776 | $ |
| Total Land Area | 983 | 1,892.04 | acres |
| Net capital cost | $911,390,656 | $742,806,976 | $ |
| Equity | $911,390,656 | $742,806,976 | $ |

As seen in Table 6, the parabolic trough design produces significantly more electrical energy annually at 358,384,096kWh compared to the 276,360,192kWh produced by the solar tower design. It is also noted that the parabolic trough design achieved this output with virtually half of the total land installation area used by the solar tower design. Both nominal and real levelized costs of electricity for the parabolic trough design are lower than that of the solar tower design (84.33 vs. 99.69 cents/kWh nominal, 66.95 vs, 79.15 cents/kWh real) further supporting the decision of selecting the parabolic trough design for simulation. The tower design does have a lower net capital cost of $742,806,976 versus the $911,390,656 of the parabolic trough, but the previously mentioned advantages of the parabolic trough design have deemed it to be the more practical option.

The parabolic trough CSP plant design is to be simulated at intervals of 100MW, 200MW and 300MW plant capacities to observe how much of the country's power and water demand can be satisfied by each design capacity. All plants would share the specifications given below.

### 3.4.2 System Design

The CSP Plants were designed to operate at a solar multiple of 4, as this was found to offer the best LCOE values without further compromising land area and installation costs. This increased the number of loops to 325, 650 and 975 for the 100MW, 200MW and 300MW designs respectively. An estimated gross-to-net factor of 0.9 was chosen, yielding an estimated net output of 90MW, 180MW and 270MW for the 100MW, 200MW and 300MW designs respectively. The cycle thermal efficiency was kept at the default 0.354 and thermal energy storage time was chosen to be 8 hours for all three design capacities. The heat transfer fluid inlet and outlet temperatures were kept at a default 293 and 391 degrees Celsius respectively.

### 3.4.3 Solar Field

The solar field design point and its accompanying parameters were calculated for each design capacity by SAM based on the previously provided design parameters and regional satellite data. It is noted that Therminol VP-1 was chosen as the heat transfer fluid for the plant cycle, as it is the best performing candidate in the SAM library in terms of net power output and adherence to plant and ambient temperature constraints. Row spacing between plant troughs were decreased from 15 to 10 meters, to further maximize the use of land installation without compromising power output and required spacing for heat absorption, maintenance, and operational safety. This resulted in a calculated land installation area of 983, 1,967, and 2,950 acres for the 100MW, 200MW and 300MW designs. All detailed solar field parameters are seen modelled for the 100MW design in Figure 8 and are the same parameters for the 200MW and 300MW designs aside of loop number dependent variables.


Figure 8. Solar Field parameters for 100MW Parabolic Trough Design.

### 3.4.4 Collectors and Receivers

The parabolic trough collector model for the plant designs was chosen to be the Skyfuel Skytrough, with eight modules per assembly and a total reflective aperture area of 656 square meters for each assembly. Each assembly has a length of 115 meters and a width of 6 meters. A piping distance of 1 meter is chosen in between assemblies.

The chosen accompanying receivers were selected to be the Schott PTR80. The receiver tube’s outer and inner diameters were 80mm and 76mm respectively, contained within a glass envelope with outer and inner diameters of 120mm and 115mm respectively. The internal surface roughness of the receiver tube is 4.5E-5, with an absorber material type of 304L.

## 3.4.5 Power Cycle

Based on the given parameters of loop numbers and net output capacities, The cycle's thermal power input for the 100MW, 200MW and 300MW designs was calculated by SAM to equal 280.9MW, 561.8MW, and 842.7MW thermal respectively. The accompanying mass flow rates of each cycle's HTF were found to be 1,167.6 kg/s, 2,335.2 kg/s, and 3,502.8 kg/s respectively. All other power cycle parameters are independent of the plant's size and capacity and can be seen in detail in Figure 9.

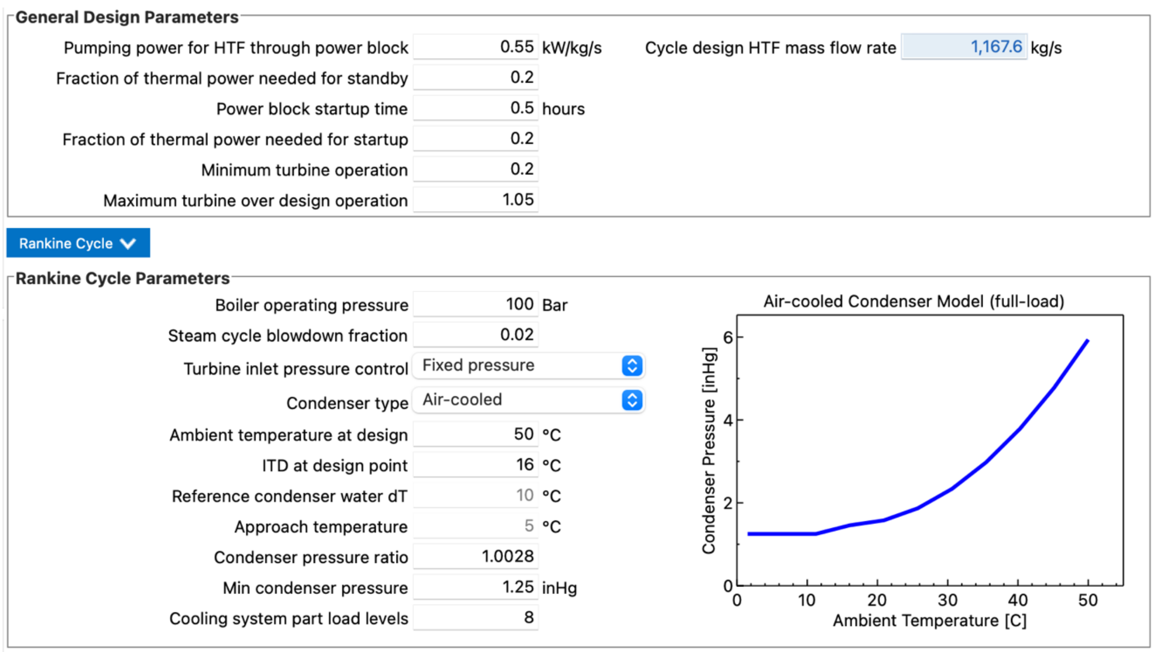

Figure 9. Power Cycle Parameters for 100MW CSP Plant Design.

## 3.4.6 Thermal Storage

The heat transfer fluid chosen for the thermal energy storage (TES) system was Hitec Solar Salt, as molten salt is a reliable source of TES in both conventional and renewable power plant design. All three capacities are designed for 8 hours of thermal storage, and the parameters dependent on the capacity of each design were calculated by SAM and are seen in Table 7.

Table 7. Thermal Storage Values Dependent on Plant Design Capacity.

| Thermal Storage | | | | |
|---|---|---|---|---|
| Plant Capacity | 100 | 200 | 300 | MW |
| Cycle Thermal Power | 280.9 | 561.8 | 842.7 | MWt |
| TES Thermal Capacity | 2,247.19 | 4,494.38 | 6,741.57 | MWt-hr |
| Available HTF Volume | 32690.51 | 65381.03 | 98071.54 | m^3 |
| Storage Tank Volume | 35,662.38 | 71,324.76 | 106,987.13 | m^3 |
| Tank Diameter | 61.51 | 86.99 | 106.54 | m |
| Estimated heat loss | 1.384 | 2.413 | 3.383 | MWt |

The remainder of the thermal storage parameters are independent of the design capacity, and include tank height, HTF operating temperatures, cold and hot tank heat capacities, and initial hot HTF percentages. All independent parameters can be seen in Figure 10 for the 100MW design and are the same for the 200MW and 300MW designs.

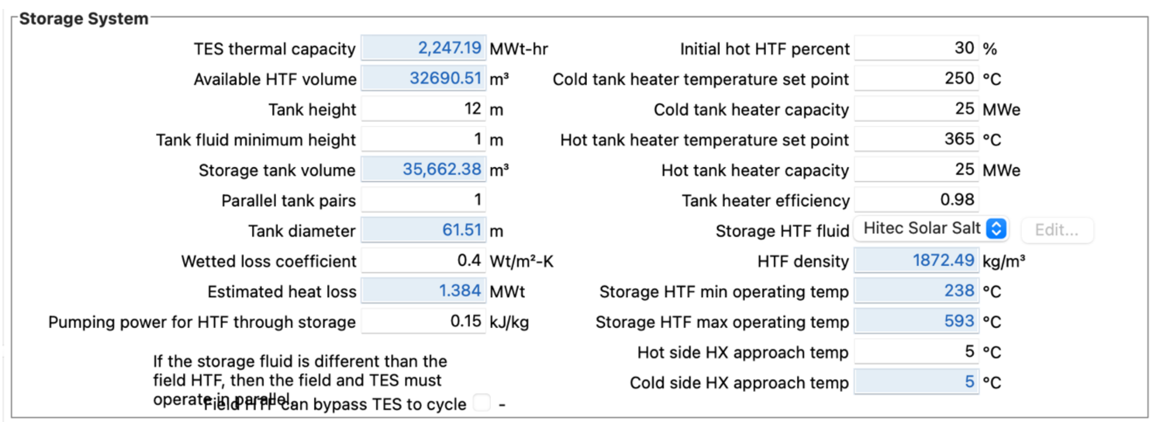

Figure 10. Detailed Thermal Storage Parameters for 100MW plant design.

### 3.4.7 Financial Parameters

All financial parameters were calculated by SAM based on the plant capacities and chosen components, as well as current estimated universal rates. A 7% contingency rate was applied to the total direct cost, and 11% of the total indirect cost was directed to EPC and ownership costs. 10,000$/acre of land was also estimated as a factor of the indirect costs. Fixed operational and maintenance costs were held at 66 $/kW-years, and variable cost by generation was at 4 $/MWh. An annual inflation rate of 2.5% and a real discount rate of 6.4% were applied to cost calculations, resulting in a total nominal discount rate of 9.06% annually as calculated by SAM. Sales taxes, loans and interest rates were not included in this simulation with the assumption that all costs would be paid presently, and to maintain relative consistency with cost regardless of country specific tax regulations. An encompassing financial analysis for each design capacity was performed by SAM and is observed in the Results section.

### 3.5 Power and Water Demand

After simulations are run for the technical performance of both PV and CSP against the weather and environmental factors in Kuwait, direct calculation would be used to determine how much of country's power demand and water desalination would be satisfied by each method both annually and monthly. The power capacity and actual power produced by each plant design would be compared with the countrywide power generation capacity and annual demand, to provide a clear understanding of the actual fractions that would be satisfied by solar generated powers based on the data provided.

As for simulating the solar plants' performances in terms of water desalination demand fulfillment, the thermal and electrical power outputs obtained by the SAM simulations for each plant design would be directly compared to the thermal and electrical power required by their corresponding water desalination methods [20]. For the PV plants, data for the water desalinated by RO systems throughout the country and its appropriate electrical power demand would be used. As for CSP, the thermal power produced would be compared to the thermal fraction required by the three Shuaiba North's MSF desalination plants, and the remaining produced energy would be converted into electrical power to satisfy the desalination plants' electrical power requirements.

# CHAPTER 4: PV RESULTS

## 4.1 Technical Performance Results

The chosen photovoltaic power plant in its three design sizes and selected parameters were simulated using SAM, yielding the technical performance results seen in Table 8.

Table 8. Technical Results for 2, 3 and 4-Subarray PV Plant Design Simulations.

| PV Results | | | | |
|---|---|---|---|---|
| Plant Design | 2.00 | 3.00 | 4.00 | Subarrays |
| Projected Plant Capacity (AC) | 75.32 | 112.98 | 150.64 | MW |
| Annual energy (year 1) | 208,334,096.00 | 312,501,152.00 | 416,668,192.00 | kWh |
| DC capacity factor (year 1) | 0.24 | | | |
| Energy yield (year 1) | 2,765.99 | | | kWh/kW (AC) |
| Performance ratio (year 1) | 0.76 | | | |
| Total Installation Land | 281.56 | 422.35 | 563.13 | acres |

The calculated AC capacity for the 2-Subarray design size was given as 75.32 Megawatts, and it has yielded an annual total of 208,334,096 kilowatt hours. As for the 3-Subarray design, it resulted in an AC capacity of 112.32 MW and an annual production of 312,501,152 kWh. The 4-Subarray design yielded 150.64 MW of capacity, and an annual production of 416,668,192 kWh.

All three design sizes shared the same DC capacity factor of 0.24, an energy yield of 2,765.99 kWh/kW of AC, and a calculated performance ratio of 0.76. The total installation land required was 281.56 acres, 422.35 acres and 563.13 acres for the 2, 3 and 4-Subarray design sizes respectively.

## 4.2 Power Demand Satisfaction

### 4.2.1 Annual Results

The three PV design sizes and their simulation results were compared to the annual countrywide power capacity, as well as the countrywide power demand as per 2015. The results in terms of annual demand satisfaction are seen in Table 9.

Table 9. Annual Power Demand Satisfied by Chosen PV Design Sizes.

| Annual PV Countrywide Power Demand Satisfaction | | | | |
|---|---|---|---|---|
| Design Size | 2.00 | 3.00 | 4.00 | Subarrays |
| Projected Plant Capacity (AC) | 75.32 | 112.98 | 150.64 | MW |
| Kuwait current power generation capacity | | | 18.80 | GW |
| Possible contribution to generation capacity | 0.40 | 0.60 | 0.79 | % |
| Annual energy (year 1) | 208,334,096.00 | 312,501,152.00 | 416,668,192.00 | kWh |
| Annual Electrical Countrywide Consumption (as of 2015) | | | 44.60 | TWh |
| Countrywide demand satisfied by plant production | 0.47 | 0.70 | 0.93 | % |

Since the current power production capacity was deemed to be 18.8 Gigawatts, the 2, 3 and 4-Subarray PV designs and their accompanied AC capacities would yield a possible contribution to the countrywide capacity of 0.40, 0.60 and 0.79 percent each, respectively. As for the satisfaction in terms of actual power produced and consumed, the annual 44.60 Terawatt-hour power demand as of 2015 [15] would be satisfied by 0.47, 0.70 and 0.93 percent by each of the 2, 3 and 4-Subarray systems respectively.

### 4.2.2 Monthly Results

A monthly breakdown of the power demand satisfaction was also simulated to account for the different sun exposure and ambient temperatures throughout the year and is seen in Table 10. The results were further graphed and are seen in Figure 11.

Table 10. Averaged Monthly Power Demand Satisfied by PV Production.

| PV Monthly Countrywide Power Demand Satisfaction | | | | | | |
|---|---|---|---|---|---|---|
| Monthly Power Consumption (Averaged, 2015) | | | | | 3.72 | TWh |
| Design Size | 2 Subarrays | | 3 Subarrays | | 4 Subarrays | |
| Month | AC Power (kWh) | % Satisfaction | AC Power (kWh) | % Satisfaction | AC Power (kWh) | % Satisfaction |
| Jan | 9,659,220.00 | 0.26 | 14,488,800.00 | 0.39 | 19,318,400.00 | 0.52 |
| Feb | 13,528,000.00 | 0.36 | 20,292,000.00 | 0.55 | 27,056,000.00 | 0.73 |
| Mar | 17,745,700.00 | 0.48 | 26,618,600.00 | 0.72 | 35,491,500.00 | 0.95 |
| Apr | 17,527,300.00 | 0.47 | 26,291,000.00 | 0.71 | 35,054,700.00 | 0.94 |
| May | 20,373,500.00 | 0.55 | 30,560,300.00 | 0.82 | 40,747,100.00 | 1.10 |
| Jun | 22,151,600.00 | 0.60 | 33,227,500.00 | 0.89 | 44,303,300.00 | 1.19 |
| Jul | 21,796,200.00 | 0.59 | 32,694,300.00 | 0.88 | 43,592,500.00 | 1.17 |
| Aug | 20,838,000.00 | 0.56 | 31,257,000.00 | 0.84 | 41,675,900.00 | 1.12 |
| Sep | 19,711,700.00 | 0.53 | 29,567,500.00 | 0.80 | 39,423,400.00 | 1.06 |
| Oct | 15,883,400.00 | 0.43 | 23,825,100.00 | 0.64 | 31,766,800.00 | 0.85 |
| Nov | 14,716,000.00 | 0.40 | 22,074,000.00 | 0.59 | 29,432,000.00 | 0.79 |
| Dec | 14,403,300.00 | 0.39 | 21,605,000.00 | 0.58 | 28,806,600.00 | 0.78 |

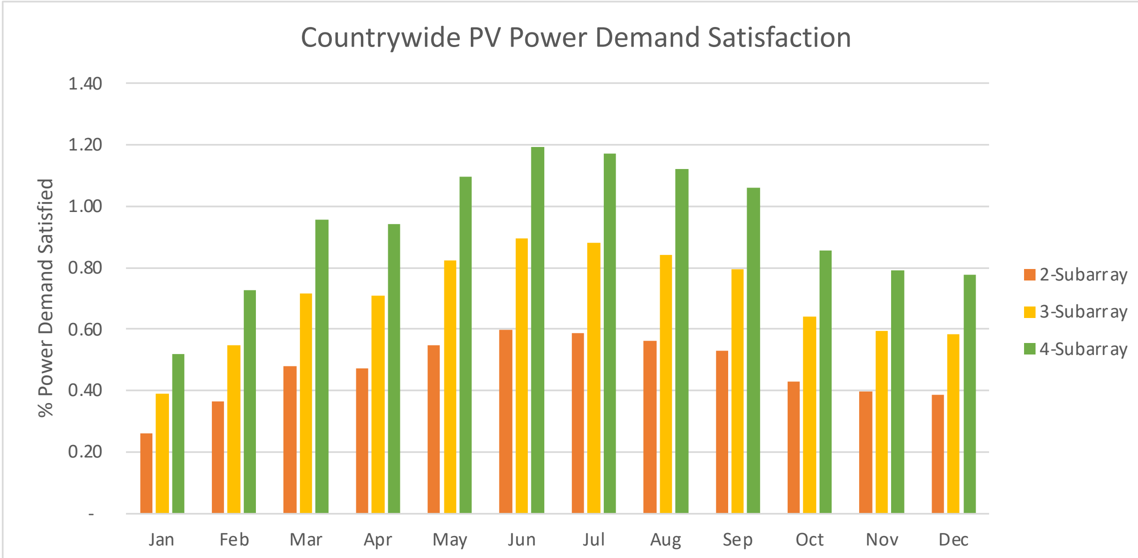


Figure 11. Averaged Monthly Power Demand Satisfied by PV Systems.

The variability of PV power production is observed in Figure 11 above. The PV production peaks in June, with the 2, 3 and 4-Subarray designs producing 22,151,600, 33,227,500, and 44,303,300 kWh respectively, satisfying a total of 0.60, 0.89, and 1.19 percentage of the monthly power consumption as averaged from the annual power demand in 2015.

Production seems to trail downwards in the wintertime, with the lowest PV performance being in the month of January. Plant production values in January were calculated by SAM to be 9,659,220 kWh, 14,488,800 kWh and 19,318,400 kWh for the 2, 3, and 4-Subarray designs respectively, satisfying 0.26, 0.39 and 0.52% of the average monthly power demand.

## 4.3 RO Water Desalination Satisfaction

### 4.3.1 Annual Results

The power produced by the PV systems during their simulations was compared to the power required by the country to desalinate water using it's RO pumps and is seen in Table 11.

Table 11. Annual RO Desalination Requirements Satisfied by PV Designs.

| PV RO Desalination Satisfaction | | | | |
|---|---|---|---|---|
| RO Annual Power Requirement | | | 313,004,400.00 | kWh |
| Design Size | 2.00 | 3.00 | 4.00 | Subarrays |
| Annual energy (year 1) | 208,334,096.00 | 312,501,152.00 | 416,668,192.00 | kWh |
| PV Annual RO Desalination Satisfaction | 66.56 | 99.84 | 133.12 | % |
| Remaining Power to be fed to grid | - | - | 103,663,792.00 | kWh |

When comparing the average annual power produced to the annual power demanded by RO pumps, it is observed that the 2, 3 and 4-Subarray designs could satisfy up to 66.56%, 99.84% and 133.12% of the Countrywide RO Desalination demands respectively, with possibility releasing the remaining electrical power into the country's grid.

### 4.3.2 Monthly Results

The obtained results were more accurate when modelled for monthly analyses, and can be observed in Table 12, and illustrated in Figure 12.

Table 12. Monthly RO Power Demand Satisfied by PV Designs.

| PV Monthly Water Desalination Satisfaction | | | | | | |
|---|---|---|---|---|---|---|
| Monthly RO Power Required | | | | | 26,083,700.00 | kWh |
| Design Size | 2 Subarrays | | 3 Subarrays | | 4 Subarrays | |
| Month | AC Power (kWh) | RO % Satisfaction | AC Power (kWh) | RO % Satisfaction | AC Power (kWh) | RO % Satisfaction |
| Jan | 9,659,220.00 | 37.03 | 14,488,800.00 | 55.55 | 19,318,400.00 | 74.06 |
| Feb | 13,528,000.00 | 51.86 | 20,292,000.00 | 77.80 | 27,056,000.00 | 103.73 |
| Mar | 17,745,700.00 | 68.03 | 26,618,600.00 | 102.05 | 35,491,500.00 | 136.07 |
| Apr | 17,527,300.00 | 67.20 | 26,291,000.00 | 100.79 | 35,054,700.00 | 134.39 |
| May | 20,373,500.00 | 78.11 | 30,560,300.00 | 117.16 | 40,747,100.00 | 156.22 |
| Jun | 22,151,600.00 | 84.93 | 33,227,500.00 | 127.39 | 44,303,300.00 | 169.85 |
| Jul | 21,796,200.00 | 83.56 | 32,694,300.00 | 125.34 | 43,592,500.00 | 167.13 |
| Aug | 20,838,000.00 | 79.89 | 31,257,000.00 | 119.83 | 41,675,900.00 | 159.78 |
| Sep | 19,711,700.00 | 75.57 | 29,567,500.00 | 113.36 | 39,423,400.00 | 151.14 |
| Oct | 15,883,400.00 | 60.89 | 23,825,100.00 | 91.34 | 31,766,800.00 | 121.79 |
| Nov | 14,716,000.00 | 56.42 | 22,074,000.00 | 84.63 | 29,432,000.00 | 112.84 |
| Dec | 14,403,300.00 | 55.22 | 21,605,000.00 | 82.83 | 28,806,600.00 | 110.44 |

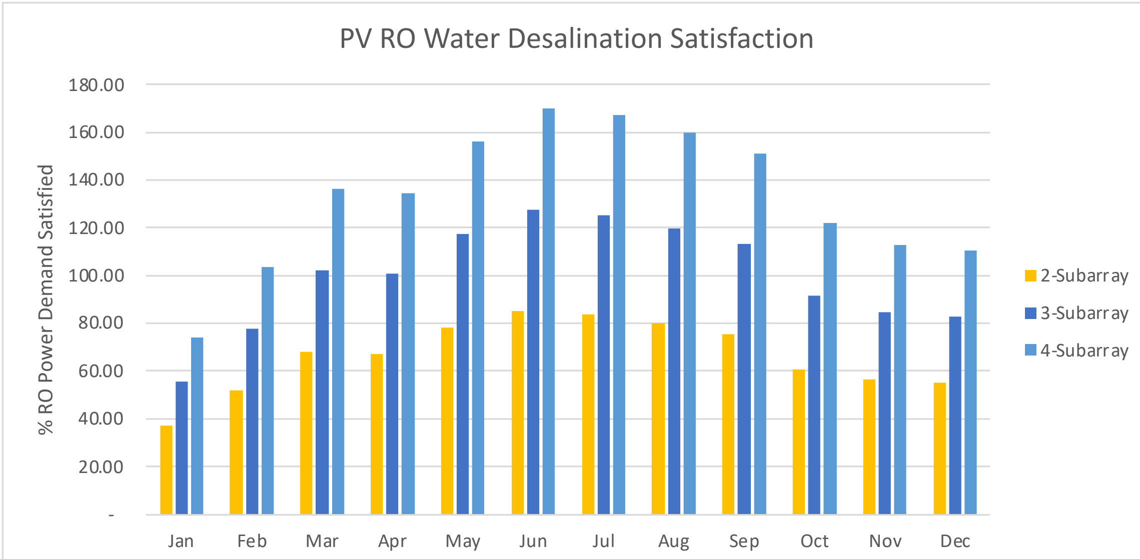


Figure 12. Graph of Monthly RO Demand Percent Satisfied by PV Systems.

As seen in Table 12 and Figure 12. The monthly percent of RO desalination power demand satisfied by the PV designs peaks in June, where 84.93, 127.39, and 169.85 percent of the country's RO power demand could be satisfied by the three PV designs respectively. The least effective month in PV performance would be in January, where only 37.03%, 55.55%, and 74.06% would be satisfied respectively.

The monthly excess power produced by the three and four subarray designs can be seen in Table 13 and Figure 13, and would possibly be released into the country's power grid.

Table 13. Monthly Excess PV Power Available.

| PV Monthly Remaining Power to be Released to Grid | | | | | | |
|---|---|---|---|---|---|---|
| Monthly RO Power Required | | | | | 26,083,700.00 | kWh |
| Design Size | 2 Subarrays | | 3 Subarrays | | 4 Subarrays | |
| Month | AC Power (kWh) | Remaining Power | AC Power (kWh) | Remaining Power | AC Power (kWh) | Remaining Power |
| Jan | 9,659,220.00 | - | 14,488,800.00 | - | 19,318,400.00 | - |
| Feb | 13,528,000.00 | - | 20,292,000.00 | - | 27,056,000.00 | 972,300.00 |
| Mar | 17,745,700.00 | - | 26,618,600.00 | 534,900.00 | 35,491,500.00 | 9,407,800.00 |
| Apr | 17,527,300.00 | - | 26,291,000.00 | 207,300.00 | 35,054,700.00 | 8,971,000.00 |
| May | 20,373,500.00 | - | 30,560,300.00 | 4,476,600.00 | 40,747,100.00 | 14,663,400.00 |
| Jun | 22,151,600.00 | - | 33,227,500.00 | 7,143,800.00 | 44,303,300.00 | 18,219,600.00 |
| Jul | 21,796,200.00 | - | 32,694,300.00 | 6,610,600.00 | 43,592,500.00 | 17,508,800.00 |
| Aug | 20,838,000.00 | - | 31,257,000.00 | 5,173,300.00 | 41,675,900.00 | 15,592,200.00 |
| Sep | 19,711,700.00 | - | 29,567,500.00 | 3,483,800.00 | 39,423,400.00 | 13,339,700.00 |
| Oct | 15,883,400.00 | - | 23,825,100.00 | - | 31,766,800.00 | 5,683,100.00 |
| Nov | 14,716,000.00 | - | 22,074,000.00 | - | 29,432,000.00 | 3,348,300.00 |
| Dec | 14,403,300.00 | - | 21,605,000.00 | - | 28,806,600.00 | 2,722,900.00 |

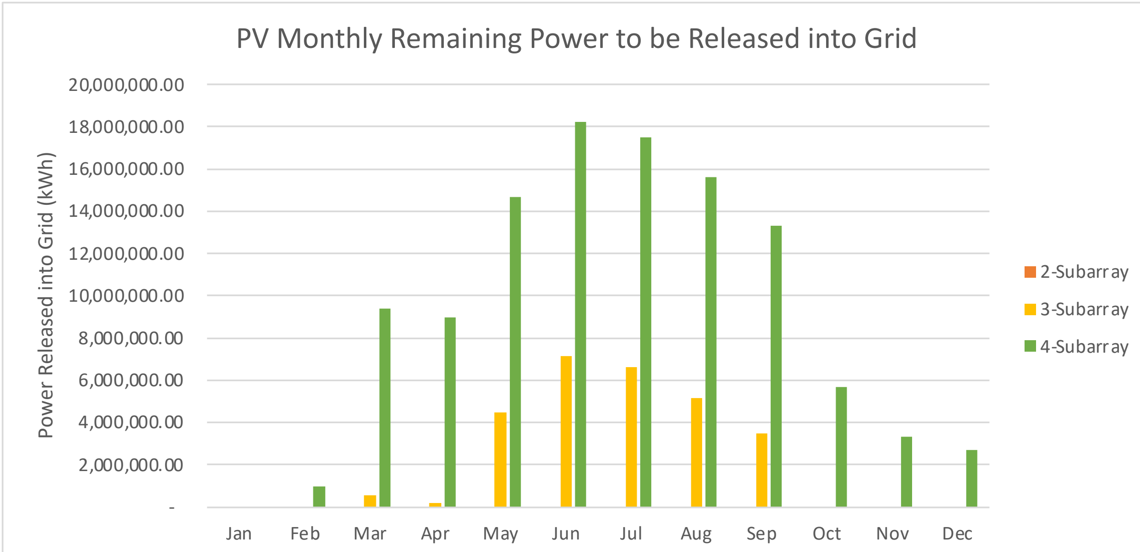


Figure 13. Monthly Excess PV Power Available to the Grid.

## 4.4 Economic Analysis

A financial analysis for all three PV design sizes was performed using the specified financial parameters, and the resulting costs are seen in Table 14.

Table 14. Financial Analysis Results for Simulated PV Design Sizes.

| PV Financial Results | | | | |
|---|---|---|---|---|
| Design Size | 2.00 | 3.00 | 4.00 | Subarrays |
| Total Direct Cost | 85,493,798.80 | 128,240,698.20 | 170,987,597.60 | $ |
| Total Indirect Cost | 13,000,577.66 | 19,500,866.49 | 26,001,155.33 | $ |
| Total Installed Cost | 98,494,376.46 | 147,741,564.69 | 196,988,752.92 | $ |
| Installed Cost per Net Capacity | | 1,289.47 | | $/kW(AC) |
| Levelized COE (nominal) | | | 8.33 | ¢/kWh |
| Levelized COE (real) | | | 6.65 | ¢/kWh |
| Net present value | -142,057,888 | -213,086,816 | -284,115,776 | $ |
| Net capital cost | 102,963,216.00 | 154,444,832.00 | 205,926,432.00 | $ |
| Equity | 102,963,216.00 | 154,444,832.00 | 205,926,432.00 | $ |

The total installed costs were calculated to equal $98,494,376.46 for the 2-Subarray design, $147,741,564.69 for the 3-Subarray design, and $196,988,752.92 for the 4-Subarray design. This results in a total installed cost of $1,289.47 dollars per kilowatt of plant AC capacity for all three plants. The three design sizes also share the same values for nominal and real levelized cost of energy, at 8.33 and 6.65 cents per kilowatt hour each respectively.

Net present values were calculated by SAM to equal -$142,057,888, -$213,086,816 and -$284,115,776 for the 2, 3, and 4-Subarray designs respectively. The three designs had a total capital cost of $102,963,216, $154,444,832 and $205,926,432 respectively as calculated by SAM according to the provided financial parameters.

The results obtained for PV seem to display significant promise in the utilization of the technology to satisfy the country's power and water demands, and it's obtained LCOE values seem to be competitively low and feasible. These results are to be further analyzed and compared with the results obtained from the CSP plant simulations in the Discussion section.

# CHAPTER 5: CSP RESULTS

## 5.1 Technical Performance Results

The yielded annual performance simulation results for the 100MW, 200MW and 300MW designs are observed in Table 15.

Table 15. CSP Technical Performance Results as According to SAM Simulations.

| CSP Results | | | | |
|---|---|---|---|---|
| Plant Capacity | 100 | 200 | 300 | MW |
| Net Capacity | 90 | 180 | 270 | MW |
| Annual Net Energy Production (Set to Electrical) | 358,384,096.00 | 698,401,472.00 | 991,686,272.00 | kWh-e |
| Annual Net Energy Production (Set to Thermal) | 594,478,272.00 | 1,176,486,912.00 | 1,740,520,448.00 | kWh-t |
| Electrical to Thermal Ratio (Conversion Efficiency) | 0.60 | 0.59 | 0.57 | |
| Capacity factor | 0.46 | 0.44 | 0.42 | |
| Annual Water Usage | 82,103 | 163,783 | 245,785 | m^3 |
| Total Installation Land | 983 | 1,967 | 2,950 | Acres |

Each of the 100, 200, and 300 Megawatt designs yielded a net power output capacity of 90, 180 and 270 Megawatts respectively when a Gross-to-Net conversion factor of 0.9 was assumed. The annual net energy produced when the plants were set to electrical power output was calculated to equal 358,384,096 kWh-e, 698,401,472 kWh-e, and 991,686,272 kWh-e respectively. As for the energy output when the plants were set to 100% thermal output, the three designs respectively yielded 594,478,272 kilowatt-hours thermal (kWh-t), 1,176,486,912 kWh-t, and 1,740,520,448 kWh-t of energy. The comparisons between the electrical and thermal outputs of each design capacity yields a conversion efficiency of 0.6, 0.59 and 0.57 for the 100MW, 200MW and 300MW designs, respectively. Capacity factors were also recorded for the three plants, and was observed to equal 0.46, 0.44 and 0.42 respectively.

Important factors such as total installation area and water used by the plants was also recorded, as 983, 1,967 and 2,950 acres of land respectively would be used to install the 100MW, 200MW and 300MW plants and their accompanied thermal storage systems.

The annual water usage for solar collector maintenance and keep-up was found to be 82,103, 163,783 and 245,785 cubic meters for each plant design respectively.

## 5.2 Countrywide Power Demand Satisfaction

### 5.2.1 Annual Results

To illustrate the capabilities of each CSP design capacity in satisfying the countrywide power demand, simulation results were recorded and compared to the nation's power capacity and annual usage, and the results are seen in Table 16.

Table 16. Annual Power Demand Satisfied by CSP Plant Designs.

| Annual Electrical Power Analysis (Plant set to 100% Electrical Output) | | | | |
|---|---|---|---|---|
| Plant Capacity | 100 | 200 | 300 | MW |
| Net Capacity | 90 | 180 | 270 | MW |
| Net Energy Production (Set to Electrical) | 358,384,096.00 | 698,401,472.00 | 991,686,272.00 | kWh-e |
| Kuwait Current Power Generation Capacity | | | 18.80 | GW |
| Possible Contribution to Generation Capacity | 0.48 | 0.96 | 1.44 | % |
| Electrical Countrywide Consumption (as of 2015) | | | 44.60 | TWh |
| Countrywide Demand Satisfied | 0.80 | 1.57 | 2.22 | % |

When comparing the net power output of each plant to Kuwait's total installed power capacity of 18.8 Gigawatts, it can be observed that the 100, 200 and 300 Megawatt plants could theoretically make up for 0.48, 0.96 and 1.44 percent of that total capacity, respectively. As for power production and consumption, the country's 44.6 Terawatt-hours of power usage recorded in 2015 would be satisfied by 0.8, 1.57 and 2.22 percent by the power outputs of the 100, 200 and 300 Megawatt plants, respectively.

### 5.2.2 Monthly Results

As with PV systems, CSP power generation varies cross the year with the varying abundance of sun exposure and ambient temperatures between summer and winter. For this purpose, a monthly analysis was performed to observe the power demand satisfaction that would be possible with the three CSP design capacities. The results are viewed in Table 17, and are illustrated in Figure 14.

Table 17. Monthly Countrywide Power Demand Satisfiable by CSP Designs.

| CSP Monthly Countrywide Power Demand Satisfaction | | | | | | |
|---|---|---|---|---|---|---|
| Monthly Power Consumption (Averaged, 2015) | | | | | 3.72 | TWh |
| Design Size | 100 MW | | 200 MW | | 300 MW | |
| Month | Electrical Energy (kWh) | % Satisfaction | Electrical Energy (kWh) | % Satisfaction | Electrical Energy (kWh) | % Satisfaction |
| Jan | 5,703,210.00 | 0.15 | 11,193,300.00 | 0.30 | 16,768,200.00 | 0.45 |
| Feb | 19,074,800.00 | 0.51 | 37,238,400.00 | 1.00 | 53,910,700.00 | 1.45 |
| Mar | 31,429,100.00 | 0.85 | 61,140,000.00 | 1.65 | 86,767,300.00 | 2.33 |
| Apr | 32,574,000.00 | 0.88 | 63,379,300.00 | 1.71 | 90,494,700.00 | 2.43 |
| May | 41,431,600.00 | 1.11 | 80,825,800.00 | 2.17 | 112,450,000.00 | 3.03 |
| Jun | 46,287,100.00 | 1.25 | 90,271,600.00 | 2.43 | 126,367,000.00 | 3.40 |
| Jul | 43,143,300.00 | 1.16 | 84,228,300.00 | 2.27 | 118,994,000.00 | 3.20 |
| Aug | 41,392,700.00 | 1.11 | 80,559,300.00 | 2.17 | 113,989,000.00 | 3.07 |
| Sep | 40,822,600.00 | 1.10 | 79,576,600.00 | 2.14 | 112,717,000.00 | 3.03 |
| Oct | 24,192,000.00 | 0.65 | 47,136,700.00 | 1.27 | 66,728,800.00 | 1.80 |
| Nov | 17,423,800.00 | 0.47 | 33,846,900.00 | 0.91 | 50,501,000.00 | 1.36 |
| Dec | 14,909,800.00 | 0.40 | 29,005,200.00 | 0.78 | 41,999,000.00 | 1.13 |

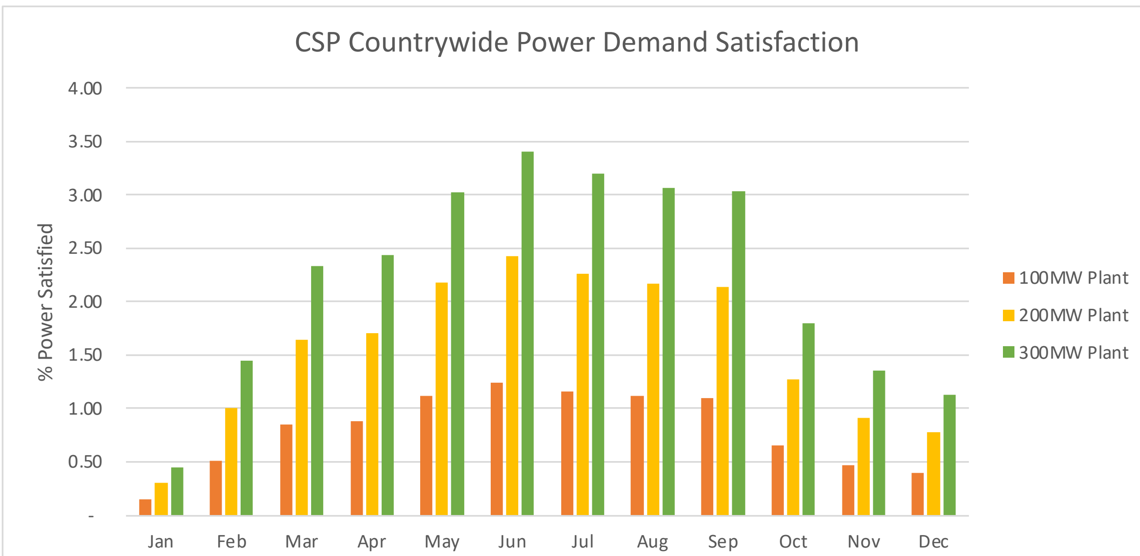

Figure 14. Monthly Power Demand Satisfiable by CSP.

The monthly CSP power demand satisfaction data seems to share an expectedly similar behavior to that of the PV designs, as all three plants seem to peak in production during June. The three plants seem to produce 46,287,100 kWh, 90,271,600 kWh and 126,367,000 kWh of electrical power during June, satisfying a total of 1.25, 2.43 and 3.40 percent of the country's averaged power demand of 3.72 TWh. The minimal operational efficiency seems to lie in the month of January, with only 0.15, 0.30 and 0.45 percent of the average monthly demand being satisfied by the three plants' productions of 5,703,210 kWh, 11,193,300 kWh and 16,768,220 kWh of electrical power.

## 5.3 MSF Desalination Energy Demand Satisfaction

### 5.3.1 Annual Results

As for the CSP plant performance at each design capacity, the plants were set for thermal energy output, and the amount of power produced was used directly to satisfy the thermal power required for the Shuaiba North's MSF plants to desalinate water. An annual analysis was performed and is seen in Table 18.

Table 18.Annual Shuaiba North MSF Desalination Satisfied by CSP Designs.

| Annual CSP MSF Water Desalination Analysis | | | | |
|---|---|---|---|---|
| Plant Capacity | 100 | 200 | 300 | MW |
| Annual Net Energy Production (Set to Thermal) | 594,478,272.00 | 1,176,486,912.00 | 1,740,520,448.00 | kWh-t |
| MSF Thermal Power Requirement | | | 1,075,272,753.60 | kWh |
| MSF Electrical Power Requirement | | | 268,778,754.90 | kWh |
| Fraction MSF thermal requirement fulfilled | 0.55 | 1.09 | 1.62 | |
| Remaining Thermal Energy Output | - | 101,214,158.40 | 665,247,694.40 | kWh-t |
| Converted Electrical Power Output | - | 60,084,065.95 | 379,034,332.39 | kWh-e |
| Fraction of MSF Electrical Requirement Fulfilled | - | 0.22 | 1.41 | |
| Remaining Electrical Energy To be Released into Grid | - | - | 110,255,577.49 | kWh-e |

The fractions of annual MSF thermal power demand fulfilled by CSP thermal power produced seem promising, as 55%, 109% and 162% of the thermal demand was satisfied by the 100, 200 and 300 MW designs respectively. The excess thermal energy available from the 200 and 300 Megawatt plants was converted to electrical energy using each plant's conversion efficiency, and could theoretically satisfy 22% and 141% of the MSF plant's electrical requirement respectively. It was also noted that an average 110,255,577.49 kWh of electricity would be remaining after the MSF plant's electrical demand is satisfied by the 300MW CSP design, which would be released into the country's power grid providing further revenue to the plant.

### 5.3.2 Monthly Results

A monthly analysis to explore the MSF plant's thermal demand was performed, and the results are observed in Table 19 and Figure 15.

Table 19. Monthly Shuaiba North MSF Thermal Demand Satisfied by CSP.

| CSP Monthly Shuaiba North MSF Desalination Satisfaction | | | | | | |
|---|---|---|---|---|---|---|
| Monthly Shuaiba North MSF Thermal Energy Used | | | | | 89,606,062.80 | kWh |
| Design Size | 100 MW | | 200 MW | | 300 MW | |
| Month | Thermal Energy (kWh-t) | % Satisfaction | Thermal Energy (kWh-t) | % Satisfaction | Thermal Energy (kWh-t) | % Satisfaction |
| Jan | 10,236,826.49 | 11.42 | 19,165,258.04 | 21.39 | 26,695,005.00 | 29.79 |
| Feb | 28,137,307.35 | 31.40 | 55,287,149.87 | 61.70 | 80,916,143.87 | 90.30 |
| Mar | 48,998,705.81 | 54.68 | 96,870,027.31 | 108.11 | 143,315,676.81 | 159.94 |
| Apr | 53,342,389.82 | 59.53 | 105,570,327.80 | 117.82 | 156,241,152.50 | 174.36 |
| May | 70,412,767.94 | 78.58 | 139,805,669.37 | 156.02 | 207,701,217.72 | 231.79 |
| Jun | 85,659,195.11 | 95.60 | 170,459,470.63 | 190.23 | 253,703,646.05 | 283.13 |
| Jul | 74,367,802.33 | 82.99 | 147,798,657.46 | 164.94 | 219,680,920.15 | 245.16 |
| Aug | 72,928,171.61 | 81.39 | 144,891,543.19 | 161.70 | 215,322,136.48 | 240.30 |
| Sep | 65,196,699.44 | 72.76 | 129,475,209.56 | 144.49 | 192,283,226.55 | 214.59 |
| Oct | 36,890,895.77 | 41.17 | 72,695,781.74 | 81.13 | 107,043,941.65 | 119.46 |
| Nov | 26,068,937.67 | 29.09 | 51,128,086.01 | 57.06 | 74,843,438.20 | 83.52 |
| Dec | 22,238,630.20 | 24.82 | 43,339,727.51 | 48.37 | 62,773,921.45 | 70.06 |

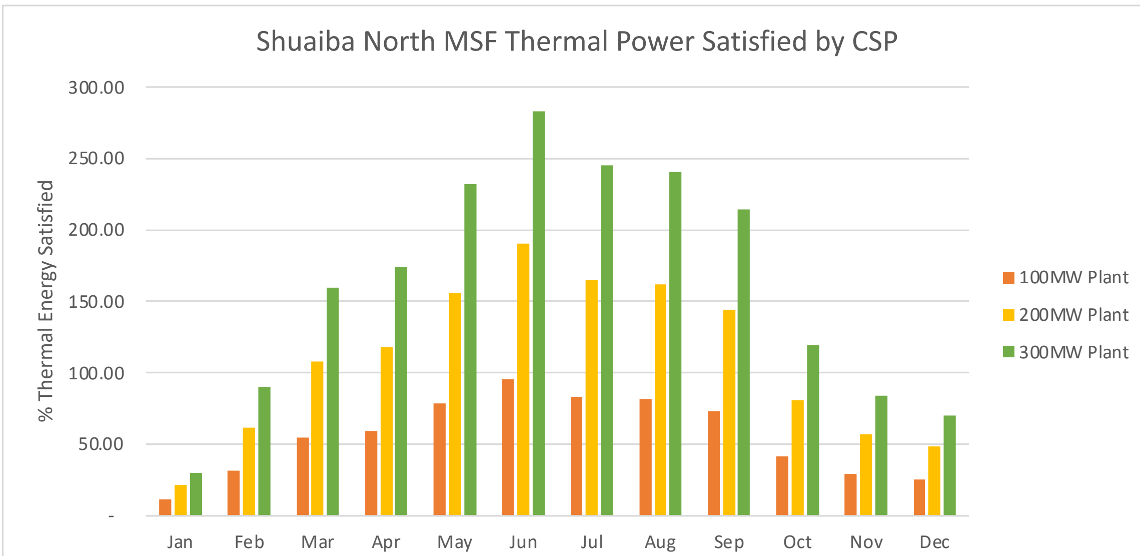


Figure 15. MSF Plant Thermal Power Satisfiable by CSP.

During the CSP Plant's peak performance month of June, an estimated 95.6%, 190.23% and 283.13% of the Shuaiba North MSF Plant's thermal power demand could be satisfied by the 100, 200 and 300 Megawatt designs' thermal outputs, respectively. As for the lowest performance month of January, only 11.42%, 21.39% and 29.79% percent of the desalination's thermal requirement would be fulfilled by the three CSP capacities respectively. Any excess thermal power produced by the 200 and 300 Megawatt capacities was converted into electrical energy and was compared with the MSF plants' electrical requirements to obtain monthly results seen in Table 20 and illustrated in Figure 16.

Table 20. CSP Monthly Remaining Energy to Satisfy MSF Electrical Requirements.

| CSP Monthly Converted Energy To Satisfy Electrical Requirement | | | | | | |
|---|---|---|---|---|---|---|
| Monthly Shuaiba North MSF Electrical Energy Used | | | | | 22,398,229.57 | kWh |
| Design Size | 100 MW | | 200 MW | | 300 MW | |
| Month | Converted Energy (kWh-e) | % Satisfaction | Converted Energy (kWh-e) | % Satisfaction | Converted Energy (kWh-e) | % Satisfaction |
| Jan | | - | | - | | - |
| Feb | | - | | - | | - |
| Mar | | - | 4,312,129.15 | 19.25 | 30,601,816.22 | 136.63 |
| Apr | | - | 9,476,914.75 | 42.31 | 37,966,289.78 | 169.51 |
| May | | - | 29,800,143.77 | 133.05 | 67,286,393.59 | 300.41 |
| Jun | | - | 47,997,252.22 | 214.29 | 93,496,931.20 | 417.43 |
| Jul | | - | 34,545,045.38 | 154.23 | 74,111,999.38 | 330.88 |
| Aug | | - | 32,819,286.38 | 146.53 | 71,628,520.41 | 319.80 |
| Sep | | - | 23,667,641.77 | 105.67 | 58,501,773.91 | 261.19 |
| Oct | | - | | - | 9,935,479.41 | 44.36 |
| Nov | | - | | - | | - |
| Dec | | - | | - | | - |

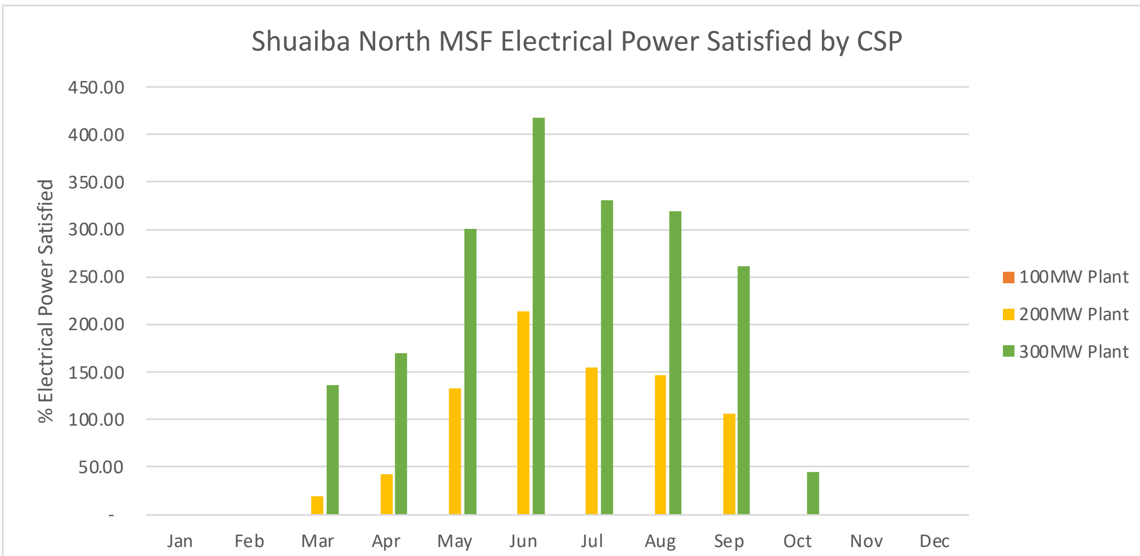


Figure 16. Illustrated MSF Plant Electrical Demand Satisfied by CSP Designs.

The 200 and 300 Megawatt capacities would generate an excess amount of thermal energy between the Months of March and October. In the peak month of June, the two mentioned CSP capacities could satisfy 214.29% and 417.43% of the Shuaiba North MSF plant's electrical requirement, respectively. Any excess energy available after 100% of the MSF plant's electrical requirement is satisfied would theoretically be released directly into Kuwait's power grid and is observed in Table 21.

Table 21. Excess Available Energy to be Released into Grid after MSF Satisfaction.

| Remaining Electrical Energy after MSF Demand Satisfaction | | | |
|---|---|---|---|
| Design Size (MW) | 100.00 | 200.00 | 300.00 |
| Month | Excess Available Electrical Power (kWh-e) | | |
| Jan | - | - | - |
| Feb | - | - | - |
| Mar | - | - | 8,203,586.65 |
| Apr | - | - | 15,568,060.20 |
| May | - | 7,401,914.20 | 44,888,164.02 |
| Jun | - | 25,599,022.64 | 71,098,701.62 |
| Jul | - | 12,146,815.81 | 51,713,769.81 |
| Aug | - | 10,421,056.80 | 49,230,290.84 |
| Sep | - | 1,269,412.20 | 36,103,544.34 |
| Oct | - | - | - |
| Nov | - | - | - |
| Dec | - | - | - |
| Total Annual (kWh-e) | - | 56,838,221.65 | 276,806,117.48 |

## 5.4 Economic Analysis

As done with the PV simulations, SAM was used to provide a thorough analysis for the CSP plants based on the given financial parameters. The financial analysis results for each plant design capacity are seen in Table 22.

Table 22. Financial Analysis for all CSP Design Capacities as According to SAM.

| CSP Plant Financial Analysis | | | | |
|---|---|---|---|---|
| Plant Capacity | 100 | 200 | 300 | MW |
| Total Direct Cost | 684,951,771.69 | 1,369,903,543.37 | 2,054,855,315.06 | $ |
| Total Indirect Cost | 85,178,615.95 | 170,357,231.90 | 255,535,847.86 | $ |
| Total Installed Cost | 770,130,387.64 | 1,540,260,775.27 | 2,310,391,162.91 | $ |
| Installed Cost/Net Capacity | 8,557.00 | | | $/kW |
| Net Capital Cost | 911,390,656 | 1,809,409,152 | 2,732,605,696 | $ |
| Net Present Value | -3,000,605,440 | -5,727,763,968 | -8,969,041,920 | $ |
| Levelized COE (nominal) | 84.33 | 82.65 | 90.86 | cent/kWh |
| Levelized COE (real) | 66.95 | 65.82 | 72.14 | cent/kWh |

The total installed costs, including direct plus indirect costs, were calculated to equal $770,130,387.64 for the 100MW plant, $1,540,260,775.27 for the 200MW plant, and $2,310,391,162.91 for the 300MW plant. This results in a total shared value of $8,557/kW of plant capacity for all plants.

The net capital costs calculated by SAM were equal to $911,390,656, $1,809,409,152, and $2,732,605,696 for the 100MW, 200MW and 300MW plants, respectively. The plants had total net present values of -$3,000,605,440, -$5,727,763,968, and -

$8,969,041,920 for the 100, 200 and 300 Megawatt designs. Finally, both nominal and real levelized costs of energy were calculated for the three plants. Nominal and real LCOE values were found to be 84.33 and 66.95 cents per kilowatt hours respectively for the 100MW design, 82.65 and 65.82 c/kWh for the 200MW design, and 90.86 and 72.14 c/kWh for the 300MW design.

The technical performance analysis for the modelled CSP designs has displayed significant power output and seems to be competitive with conventional power production methods in satisfying the Shuaiba North's MSF plants. However, the economic analysis shows critically high costs that may hinder the implementation of this technology to satisfy the country's power and water demands. A further analysis as well as comparisons with the PV results are given in the following section.

# CHAPTER 6: DISCUSSION

## 6.1 Annual Technical Performance and Demand Satisfaction

Both PV and CSP design selections displayed promising results in terms of technical performance output, with the three PV design sizes ranging in AC capacity from 75 to 150 Megawatts producing an electrical power range of 208 to 417 Gigawatt-hours annually. The three chosen CSP design capacities, ranging between 100 and 300 Megawatts, had outputted an annual electrical power range of approximately 359 to 992 Gigawatt-hours.

The technical performance results obtained from PV and CSP simulations were compared to further understand the advantages and disadvantages of each solar technology. Since the three selected designs of each technology differ in terms of capacity ranges and power output, all differing factors were normalized in terms of comparing these factors to the installation area used by each plant. This allows for the direct comparison between PV and CSP systems of varying capacities, power outputs, and installation areas.

All technical performance results, as well as their capabilities in satisfying Kuwait's power and water desalination demands were compared as seen in Table 23.

Table 23. PV and CSP Results Compared in Terms of Performance and Countrywide Demand Satisfaction.

| PV vs. CSP: Average Annual Technical Performance and Countrywide Demand Satisfaction | | | |
|---|---|---|---|
| Solar Plant Type | PV | CSP | % Difference |
| Net Capacity per Installation Area (MW/acre) | 0.80 | 0.27 | 192.26 |
| Production per Installation Area (kWh/acre) | 2,219,752.15 | 1,055,806.04 | 110.24 |
| Energy Yield (kWh/kW) | 2,765.99 | 3,844.99 | (28.06) |
| Capacity Factor | 0.24 | 0.44 | (45.45) |
| Capacity Contribution per Inst. Area (%/acre) | 0.0042 | 0.0015 | 190.51 |
| Demand Satisfied per Inst. Area (%/acre) | 0.0050 | 0.0024 | 110.24 |
| RO/MSF Desalination Satisfaction (%/acre) | 0.71 | 0.17 | 325.33 |

### 6.1.1 Annual Technical Performance

In terms of technical performance, The PV designs outperformed the CSP plants significantly in the first two comparison criteria. A 192.26% increase was noted for PV over CSP designs for net capacity per installation area, as PV systems averaged 0.8 Megawatts per acre of land used as opposed to only 0.27 Megawatts per acre produced by the CSP systems. Annual PV power production was also noted to be 110.24% higher than that produced by CSP, as approximately 2,219,752 kilowatt-hours of energy per acre were produced by the former option as compared to the 1,055,806 kWh/acre produced by the latter.

However, CSP seems to outperform PV in both energy yield and capacity factor. PV systems showed a decrease of 28% in terms of energy yield, as only 2,765,99 kilowatt-hours per kilowatt of capacity were produced compared to the 3,844.99 kWh/kW produced by the CSP designs. PV also displayed a 45.45% decrease in terms of capacity factor, as the PV plants worked at a capacity factor of 0.24 as opposed to the CSP plant operational capacity factors of 0.44.

### 6.1.2 Power and Water Demand Satisfaction

The photovoltaic designs seem to have outdone the CSP options in the possible contribution to the country's power production capacity per installed area. PV displays a 190.51% increase over CSP in that regard, as the former could contribute an average of 0.0042% of capacity for each acre of installation land. CSP would only contribute 0.0015% of capacity per land used. As for the power produced that would satisfy the countrywide demand, PV was observed to satisfy 0.005% of the annual demand for every acre of land used, displaying a 110.24% increase over CSP which only satisfies 0.0024% of annual demand for each acre of land used.

As for the possible impact on water demand, the PV systems satisfied an average of 0.71% of countrywide RO water desalination per acre of installation used, whereas CSP only satisfied 0.17% of the thermal energy required for the Shuaiba North MSF plants per acre of installation area. It is important to note, however, that the Shuaiba North's MSF water desalination makes up an estimated 10.4% of the countrywide desalination whereas the RO plants cover 8.72% of the country's water desalination demand.

### 6.1.3 Conclusion Based on Technical Performance

In terms of technical analysis, it seems that the PV systems generally outperform CSP designs significantly in most areas. CSP plants however display a higher annual energy yield and capacity factor than those displayed by PV plants, which can be mainly contributed to the abundant regional heat that is captured by the CSP plants.

## 6.2 Economic Analysis

### 6.2.1 PV and CSP Financial Results and Comparison

To analyze how the two energy production systems perform financially in comparison with each other, a table has been prepared that displays all significant economic factors that are involved. Similar to the methodology in the technical performance comparisons, factors involving different design capacities and power outputs were normalized to allow for comparison. However, these normalizations were based on the denominator of net capacity instead of total installation area for more direct results. The economic analysis for PV and CSP systems are viewed in Table 24.

Table 24. PV and CSP Systems Compared in Terms of Economic Analysis.

| PV vs. CSP: Economic Analysis | | | |
|---|---|---|---|
| Solar Plant Type | PV | CSP | % Difference |
| Installed Cost per Net Capacity ($/kW) | 1,289.47 | 8,557.00 | (84.93) |
| Capital Costs per Net Capacity ($/MW) | 4,101,030.98 | 30,299,597.75 | (86.47) |
| Net Present Value per Net Capacity ($/MW) | (5,658,173.84) | (98,379,645.16) | (94.25) |
| Levelized COE - Nominal (cent/kWh) | 8.33 | 85.95 | (90.31) |
| Levelized COE - Real (cent/kWh) | 6.65 | 68.30 | (90.26) |

As per the results in Table 24, PV systems seem to significantly outperform their CSP counterparts in all comparison factors. An 84.93% decrease in installed cost per net capacity was recorded for PV over CSP, as the former requires 1,289.24 %/kW as opposed to the 8,557 $/kW required for CSP plants. PV systems also require 4,101,030.98 dollars of capital cost per Megawatt of capacity, which is 86.47% lower than the CSP capital cost of $30,299,597.75 per Megawatt of capacity. The average net present value for PV systems was calculated to equal -$5,658,173.84 dollars per Megawatt of capacity, which was 94.25% lower than the -$98,379,645.16 per MW of capacity required by CSP designs.

As for the levelized costs of energy, the nominal LCOE for PV systems was calculated by SAM to equal 8.33 cents per kilowatt-hour, which was 90.31% lower than the 85.95 c/kWh of CSP systems. The difference between the real LCOE values was similar, as the PV systems yielded only 6.65 c/kWh in comparison with the 68.30 c/kWh of CSP, resulting in a decrease of 90.26% between the former and the latter options.

### 6.2.2 Conclusion Based on Economic Analysis

Comparing the standardized economic factors between the two plants has shown a distinct favorite, as the PV plants seemed to excel significantly compared to CSP designs in terms of financial feasibility. The averaged costs decreased within a range of approximately 84% to 94% depending on the economic factor of consideration, which would deem the PV plants more likely to be installed and operated in the country for power and water demand satisfaction.

### 6.2.3 Future Cost Reduction

Although photovoltaic plants were deemed favorable as compared to their CSP counterparts based on economic analysis, it is still noted that there is a significant capital cost and LCOE to be considered when installing either technology. These costs however are decreasing rapidly, as Forbes has noted a decrease of 89% in average LCOE costs for Photovoltaics from the year 2009 to 2019 [21]. Forbes has also noted that the average LCOE for PV solar energy is expected to decrease by 74% in an optimistic scenario and 47% in a mid-level scenario by the year 2050 [21].

The current average LCOE for unsubsidized PV solar generation systems is noted to be in the range of 32 to 42 dollars per Megawatt-hours, whereas the subsidized systems range between 31 to 40 $/MWh in LCOE. These numbers are currently lower than those of combined cycle gas plants, which range in average LCOE values between 44 and 68 $/MWh of electrical production [22]. As for CSP Systems, the data is displayed for solar tower systems with accompanied thermal storage and is currently higher than that of CCGT production at an LCOE range of 126 to 156 $/MWh [22]. A graph showing the LCOE of different renewable and conventional energy production is observed in Figure 17 [22].

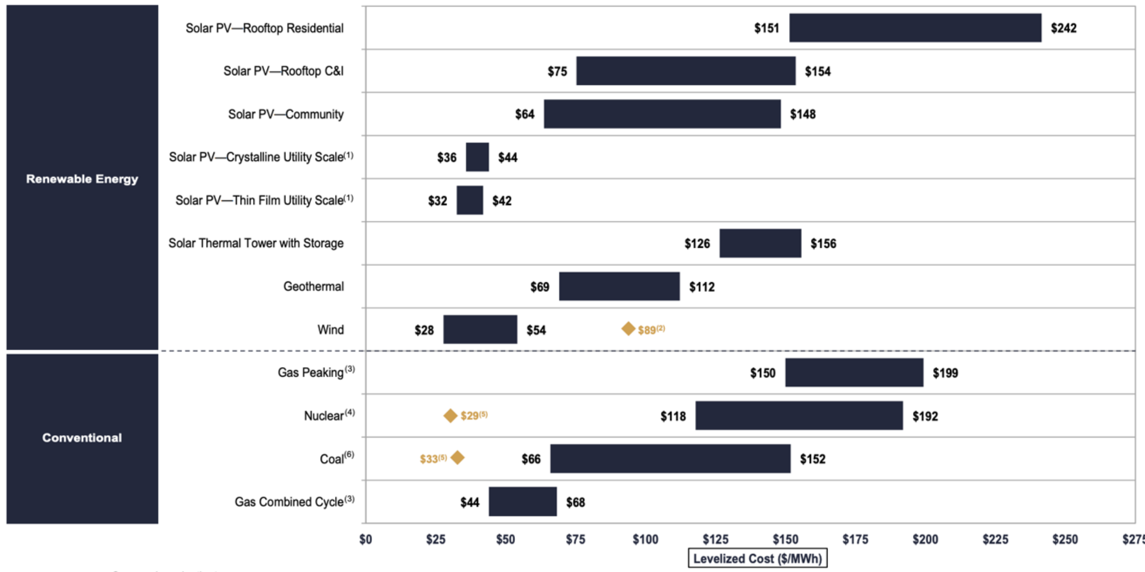


Figure 17. Average LCOE Values for Energy Production Systems As of 2019. "Lazard's Levelized Cost of Energy Analysis—Version 13." Lazard.com. Lazard, November 2019. https://www.lazard.com/media/451086/lazards-levelized-cost-of-energy-version-130-vf.pdf.

## 6.3 Issues and Obstacles to Implementation

Although the simulated solar energy plants displayed adequate potential in satisfying fractions of the power and water desalination demands of Kuwait, their installation on a utility scale still faces obstacles that are to be discussed with their possible mitigation methods addressed. The main issues of consideration are as observed below.

### 6.3.1 Operational Intermittency

The main downfall of solar plants is that these plants are primarily operational during daylight when there is sunlight to be captured and harvested in terms of photonic or thermal energy based on the type of plant installed. These plants currently produce no energy in the absence of the sun, whether that is during evening time or when the sun is obstructed by factors such as clouds or regional dust. According to a research article written for the Institute for Electrical and Electronical Engineers (IEEE), Kuwait has an observed solar insolence value of 7.0kWh/m^2 per day [23], which translates to approximately seven hours a day of absorbed sunlight that is significant enough to produce power.

As with the 8-hour thermal energy storage included in the CSP calculations, it is possible to reduce the intermittency of PV power generation by including an electrochemical energy storage system in the form of lithium-ion batteries. A simulation was made in SAM to include a lithium ion NMC/Graphite battery to the 4-subarray design, with a desired bank capacity and power of 240,000 kWh and 80,000 kW respectively to fit the sizing of the PV plant. The primary comparable results between the inclusion and exclusion of the lithium-ion battery are observed in Table 25.

Table 25. Results for 4-Subarray Plant with and without Battery Storage.

| 4-Subarray PV Plant: Storage vs. No Storage | | | |
|---|---|---|---|
| Energy Storage Included | Yes | No | |
| Annual energy (year 1) | 416,668,192 | 407,936,928 | kWh |
| DC capacity factor (year 1) | 23.8 | 23.3 | % |
| Energy yield (DC) | 2,083 | 2,040 | kWh/kW |
| Levelized COE (nominal) | 8.33 | 10.95 | ¢/kWh |
| Levelized COE (real) | 6.65 | 8.73 | ¢/kWh |
| Net present value | -284,115,776 | -422,991,040 | $ |

With all design and economic factors held constant, the two options have displayed relatively similar technical performance results. However, there is a significant financial disadvantage that is associated with the increase in LCOE and decrease of net present values. This increase in cost is ultimately the cost of minimizing the plant's intermittency and would hopefully continue to decrease as previously projected. Further detailed specifications of the used battery storage system are observed in the Appendix D entry.

### 6.3.2 Plant Cooling

The high ambient temperatures in the region have a significant effect on the performance and lifespan of solar generation methods, with its effects seeming more critical to the performance of the PV plants. This is observed with the nominal operating cell temperatures being close to the ambient temperatures during the summertime, as well as the module's temperature coefficient highlighting the drastic decrease in output at every degree Celsius of increased temperature.

The simulation results were all obtained with no specified cooling parameters, and so it is expected that the inclusion of cooling methods would increase plant power output and life expectancy at a significant increase of capital, operational and general LCOE values. The two main methods of plant cooling are dry air cooling and water cooling and were noted to increase PV power output by up to 50% when applied to the solar panels in the form of Hybrid PV/Thermal cooling systems [24]. Multiple different cooling concepts are being designed such as using HPV/T systems with both water and air as a combined coolant, as well as maximizing natural airflow underneath the solar panels using certain panel placement [25]. Conceptual prototypes are also proposed such as the use of micro-heat pipe arrays for panel cooling as well as including fins in the design of HPV/T systems using air as a coolant to avoid water losses.

The use of more resilient solar panels is also an option to be considered as PV systems continue to decrease significantly in cost with time. Currently, heterojunction technology (HJT) cells are being developed with significantly higher efficiencies such as 24.4% and lower temperature coefficients such as -0.26% per degree Celsius as compared to the -0.386 %/C of the PV cells used in the simulation [26]. These HJT cells show long-lasting capabilities and low sun-related degradation rates and would theoretically offer low LCOE values in the future as they replace the current conventional mono-crystalline cells.

### 6.3.3 Land Usage

Based on the simulation results and as a documented general fact, both PV and CSP systems use adequate amounts of land area to install utility-scale plants with significant output. To provide further perspective on this issue, Kuwait's total land area is at 17,820 square kilometers [11]. When converted from acres to square kilometers, the three simulated PV plant design sizes range between 1.14 to 2.27 square kilometers. This means that a single PV plant could take up between 0.0064% to 0.0127% of the entire country's area depending on the design size used. As for CSP, the simulated designs range between 3.98 to 11.94 square kilometers, which would theoretically occupy 0.022 to 0.067% of the nation's land area.

Although most of the country's land area is uninhabited and provides suitable conditions for the installation of these systems, the area that is favorable for solar plant construction and operation is along the coast of the area. This is to build the plants, particularly the CSP designs, within proximity of the desalination plants to provide the thermal energy directly into the MSF plants with no significant losses. However, this encounters the previously mentioned problem of the population being concentrated along the coast, which leaves availability for these plants to be installed in the northern parts of the country's coast. Figure 18. displays the population density map for Kuwait as of 2019 [27].

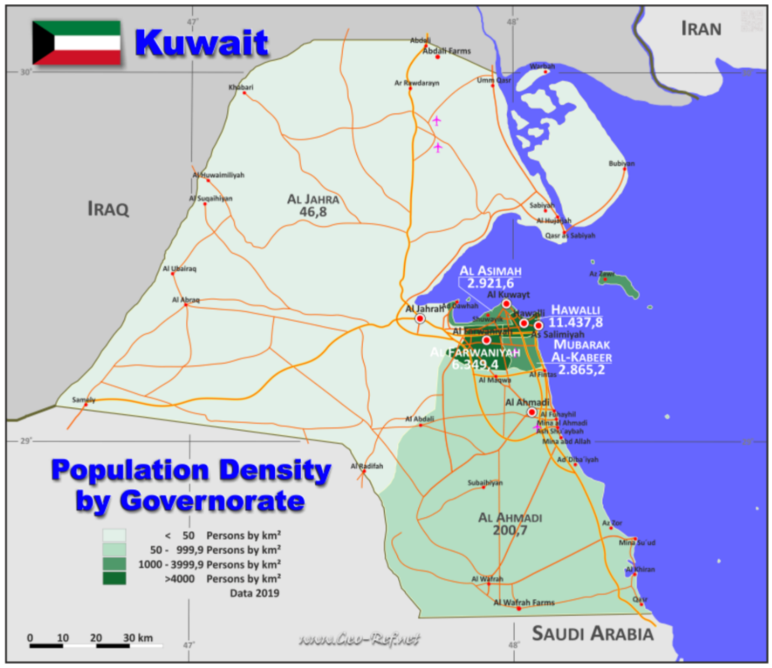

Figure 18. Population Density and Concentration Areas in Kuwait as of 2019. Frommert, Holger. "State of Kuwait." Kuwait Country data, links and map by administrative structure. Accessed April 12, 2022. http://www.geo-ref.net/en/kwt.htm.

As for the PV systems, they are more flexible in terms of installation location as the electrical output can be transmitted directly into the grid and the RO desalination plants using generic high voltage transmission lines with minimal losses.

# CHAPTER 7: CONCLUSIONS

The main objective of the proposed research was achieved, as both Photovoltaic and Concentrated Solar Power were simulated in Kuwait to determine their performances in both power generation and water desalination in arid desert regions. This was achieved by first stating the environmental, economic, and currently present factors in the region that relate to the implementation of solar power plants. The simulations were then run using SAM for three design sizes of each solar plant type. The selected PV plant sizes were to be 2-Subarray, 3-Subarray and 4-Subarray designs yielding approximately 75, 113 and 151 Megawatts of AC capacity. As for the Chosen CSP designs, they were parabolic trough systems configured at capacities of 100, 200 and 300 Megawatts. Both sets of solar plant types were simulated as according to the regional weather data retrieved via satellite, and both technical and economical results were obtained.

As for technical performance, it was noted that the PV systems outperformed CSP in most areas when the results were standardized using output per land installation, and only fell short against CSP in terms of capacity factor and energy yield. Economic analysis however has shown that PV significantly outperformed CSP in all financial parameters, deeming the former option to be more suitable for implementation as of present conditions.

Fractions of countrywide power and water desalination demand were stated, showing promising results for the utilization of both PV and CSP within the country. Obstacles regarding the implementation of both solar power options were addressed along with their possible present and future mitigation methods as the dependence on renewable energies becomes more practical and cost effective with time.

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# APPENDIX

## Appendix A: PV Electrical Losses

The simulations run by SAM include a breakdown of all electrical energy losses for the Photovoltaic plants. Figure A1 displays the losses attributed to the simulated 4-Subarray PV plant.

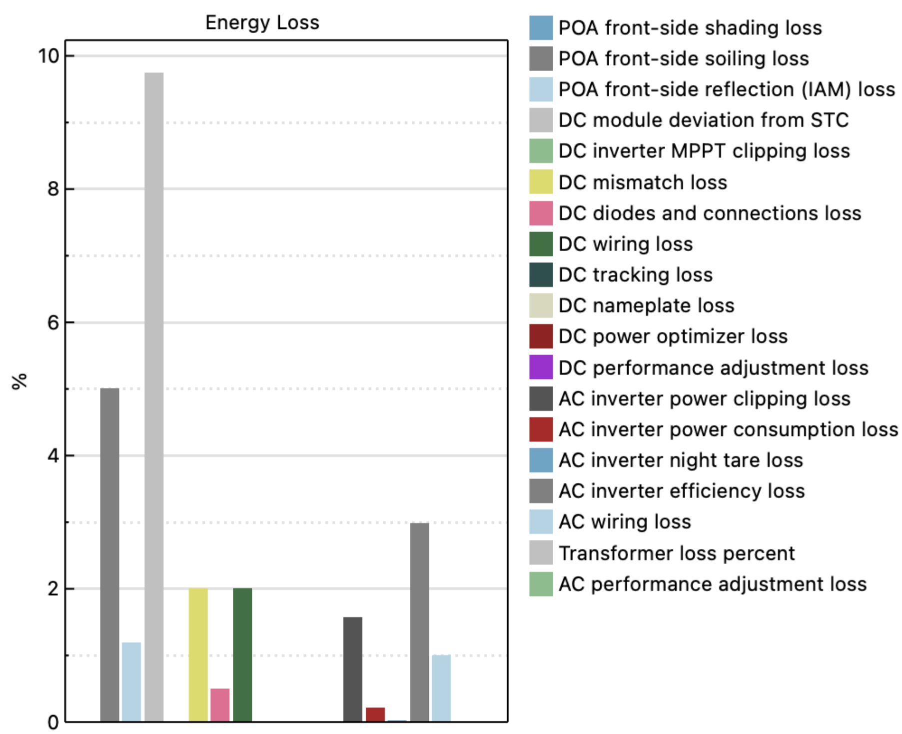


Figure A1. 4-Subarray PV Energy Loss Percentages and Corresponding Contributing Factors.

# Appendix B: Energy Map of 4-Subarray PV System with and without Battery

SAM highlights the operational effect of including an energy storage system by including an energy graph with output power plotted according to a 24-hour axis. The graphs for the 4-Subarray PV design including and excluding the power storage are observed in Figures B1 and B2.

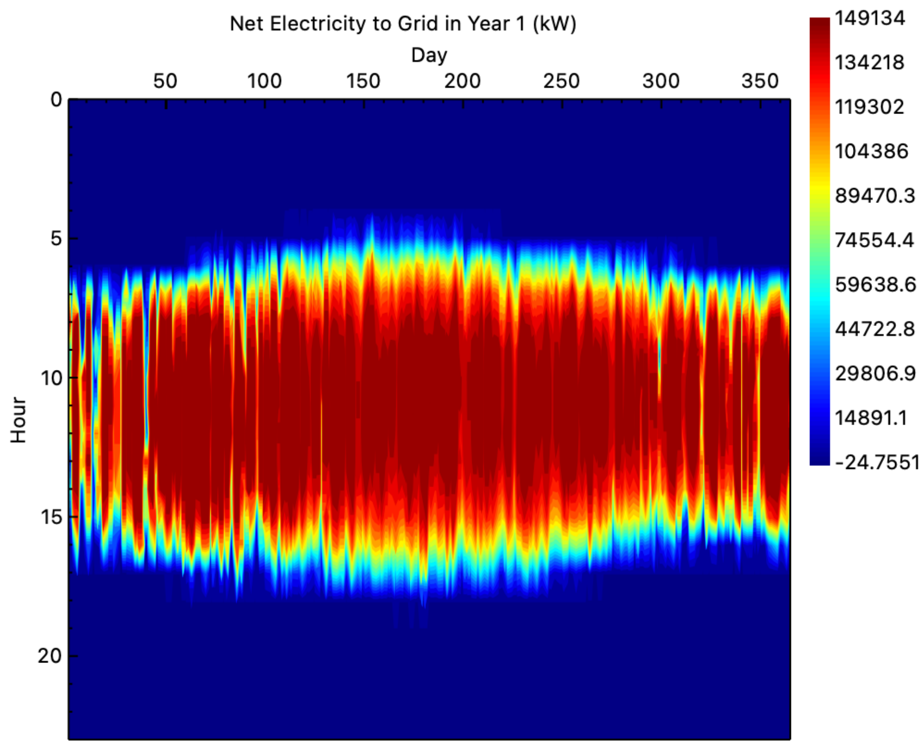


Figure B1. Energy Map of 4-Subarray PV Design with no Energy Storage.

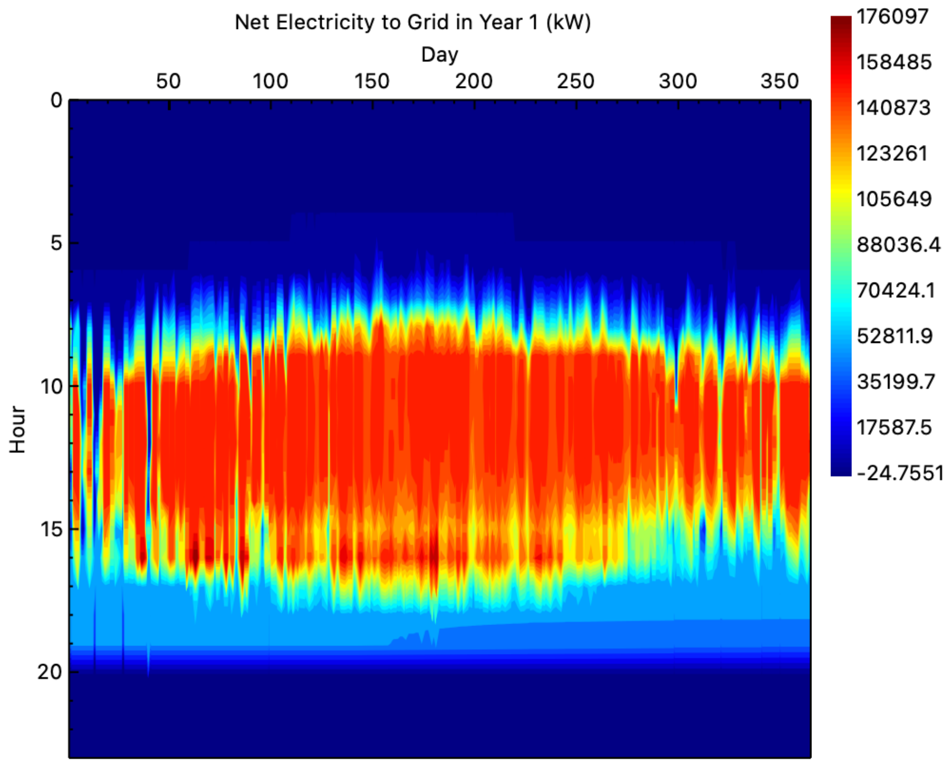


Figure B2. Energy Map of 4-Subarray PV Design with Lithium-Ion Battery Storage.

Appendix C: PV vs. CSP Annual Degradation

SAM has highlighted the significant difference in annual degradation between PV and CSP systems, as PV seems to degrade at a linear rate whereas CSP displays virtually no degradation. This is seen by the annual power output graphs for the 4-Subarray PV design compared to the 300MW CSP plant as observed in Figures C1 and C2.

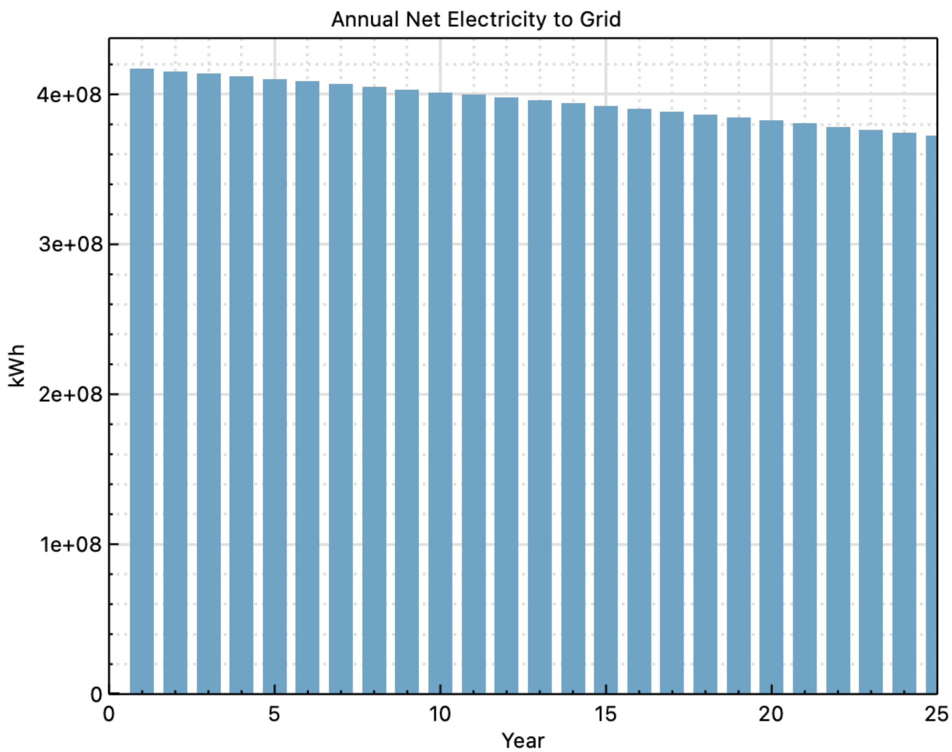


Figure C1. 4-Subarray PV Design Annual Electrical Output.

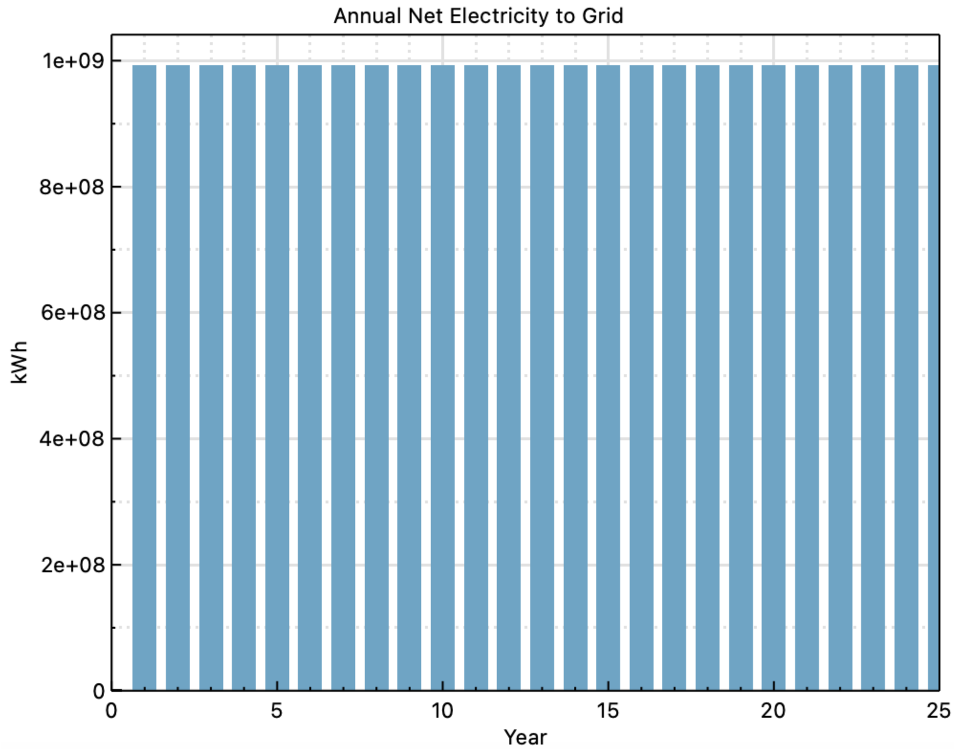


Figure C2. 300MW CSP Design Annual Electrical Output.

# Appendix D: PV Battery Storage Specifications

Detailed specifications of the Lithium-Ion battery storage system used for the 4-Subarray simulations with included energy storage are observed in Figures D1 through D3.

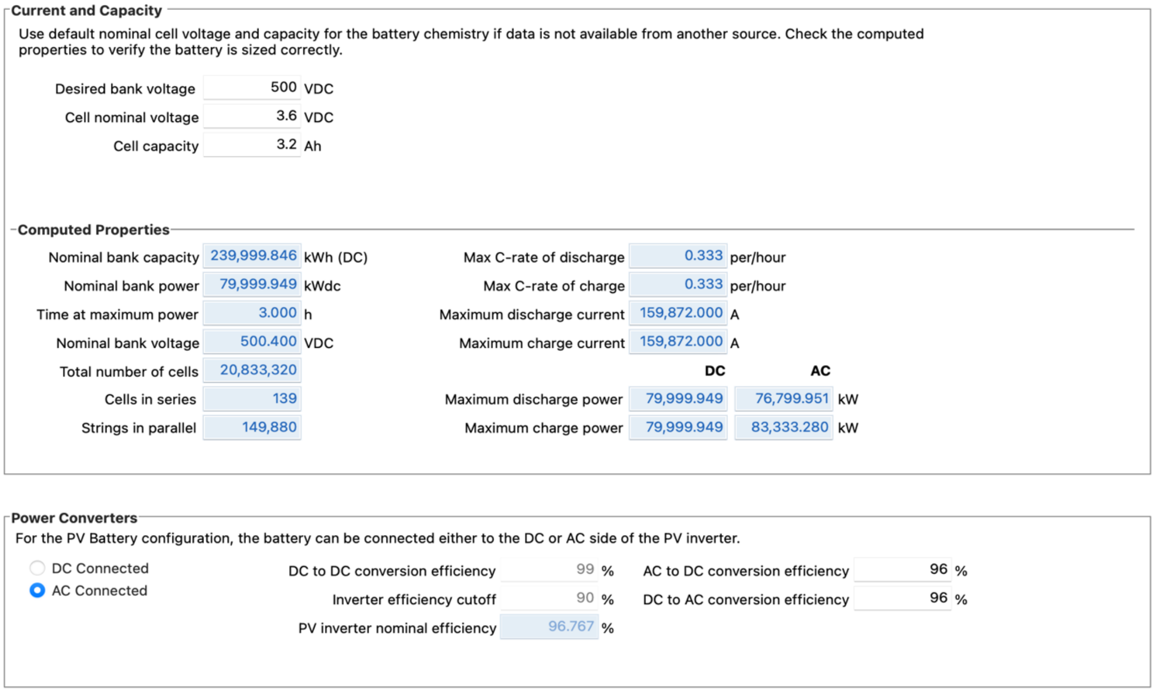


Figure D1. Current, Capacity and Power Conversion Properties of Selected PV Battery.

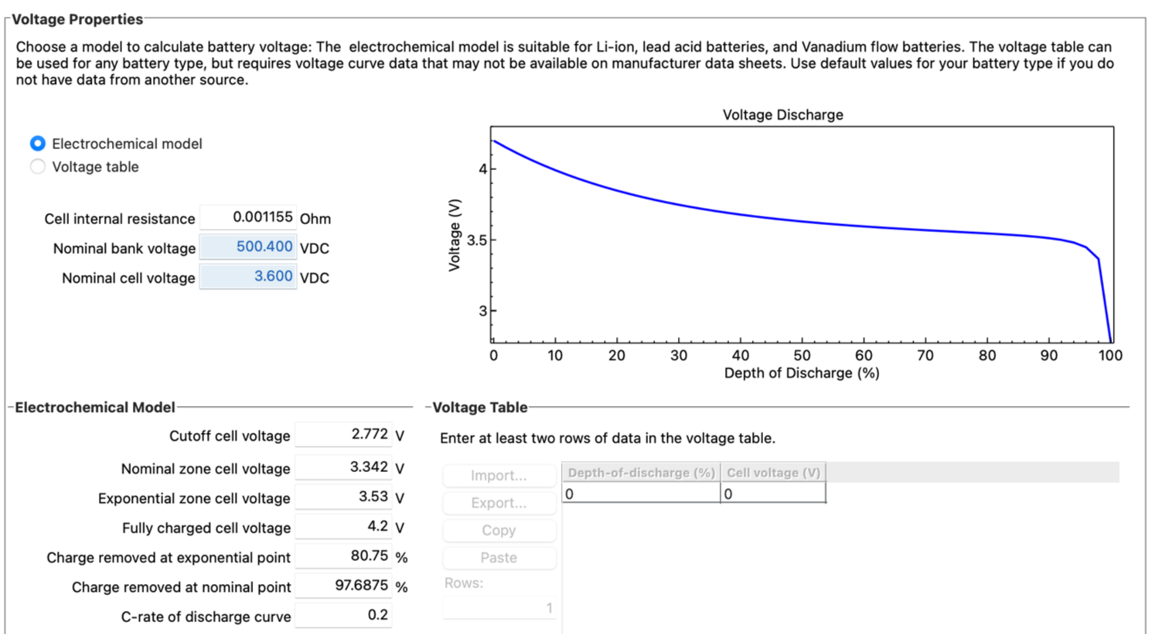


Figure D2. Voltage Properties of Selected PV Battery.

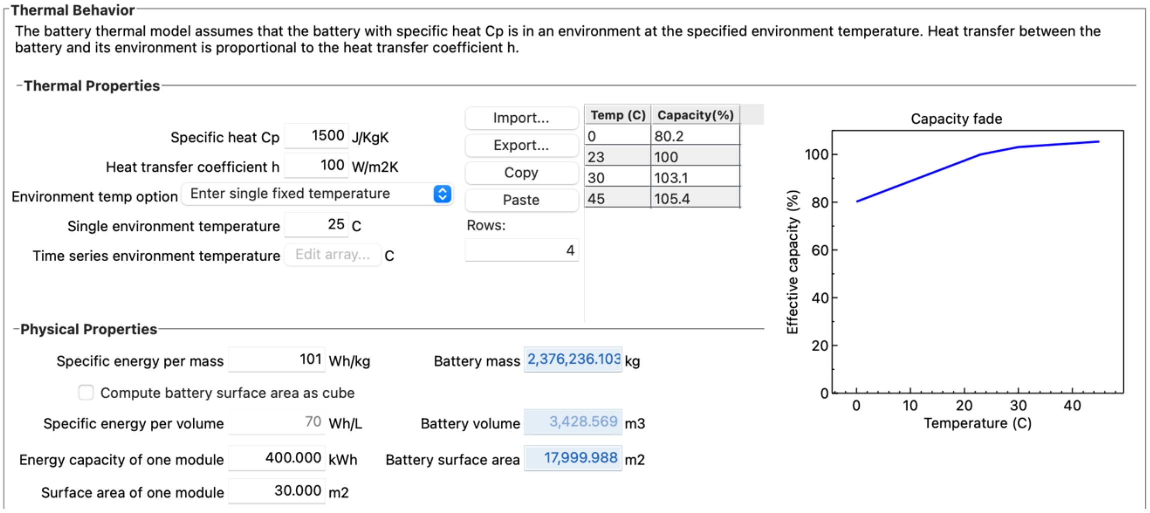


Figure D3. Thermal and Physical Properties of Selected PV Battery.