An-Najah National University

Faculty of Graduate Studies

TECHNO-ECONOMIC ANALYSIS OF A HYBRID CSP-PV SYSTEM INTEGRATED WITH THERMAL STORAGE IN PALESTINE

By

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Dedication

I dedicate this work to:

My father and mother,

My wife and children,

My brothers and sisters,

My friends and colleagues.

Acknowledgements

I would like to express my heartfelt gratitude to my supervisor, Dr. Aysir Yasin, for his invaluable guidance, insightful information, and generous support.

Deep thanks to all my teachers at An Najah National University for their dedication and support.

Declaration

I, the undersigned, declare that I submitted the thesis entitled:

TECHNO-ECONOMIC ANALYSIS OF A HYBRID CSP-PV SYSTEM INTEGRATED WITH THERMAL STORAGE IN PALESTINE

I declare that the work provided in this thesis, unless otherwise referenced, is the researcher's own work, and has not been submitted elsewhere for any other degree or qualification.

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Date: 9/10/2024

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TECHNO-ECONOMIC ANALYSIS OF A HYBRID CSP-PV SYSTEM INTEGRATED WITH THERMAL STORAGE IN PALESTINE

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Abstract

This thesis conducts a techno-economic analysis of a hybrid Parabolic Trough Concentrated Solar Power (CSP) and Photovoltaic (PV) system for electricity generation in Palestine. It aims to assess the feasibility, and performance of combining CSP and PV technologies to address Palestine's energy challenges.

The study begins with an assessment of solar power potential in Palestine, adopting the governorate of Jericho as a case study. The hybrid system is aimed to maximize the benefits provided by both CSP and PV, availability of power around the clock, and increased efficiency.

Technical and economic assessments for each technology are performed using the System Advisor Model software to analyze capacity factor, energy production, cost life cycle analysis, and economic parameter analysis including Levelized cost of energy (LCOE), internal rate of return (IRR), and Payback period (PP) for the hybrid system.

The analysis is conducted under two scenarios: supplying a baseload and load following, to measure the system performance and economic flexibility under varying conditions. Assessments of environmental impacts are certainly part of the procedure regarding estimating the avoided carbon dioxide (CO_2) emissions by adopting the hybrid system.

The results show that utilizing a hybrid CSP-PV system has advantages over standalone systems in terms of increased energy output, reliability, and cost. In particular, the inclusion of thermal energy storage in CSP enhances the system's flexibility and reliability which makes it a feasible option for developing clean energy in Palestine.

The economic analysis reveals that the hybrid system achieves an LCOE of 11.72 cent/kWh, an IRR of 13.35%, and a PP of 7 years under the load following scenario, with similar positive outcomes under the base load scenario. Additionally, the hybrid system is projected to avoid approximately 5,011.01 tons of CO_2 emissions annually.

Keywords: Hybrid CSP-PV System; thermal energy storage; parabolic trough; SAM software.

Chapter One

Introduction and Theoretical Background

1.1 Introduction

Renewable energy is increasingly being recognized as a key component of global efforts to achieve energy sustainability and reduce environmental impact. Renewable energy sources, such as solar, wind, hydro, and biomass, provide a sustainable alternative to fossil fuels, helping to reduce greenhouse gas (GHG) emissions and mitigate climate change. These energy sources are renewable by nature and offer the potential for decentralized power generation and enhancing energy security moreover, providing economic benefits.

According to (Renewable Energy Agency, 2024) renewable energy sources account for nearly 43.2% of global electricity generation, Solar energy, the most important element of renewable energy, explains the transformative potential of sustainable energy sources. Using technologies like PV and CSP, solar energy captures the abundant and freely available sunlight to produce electricity and heat.

This renewable resource reduces dependence on limited fossil fuels and contributes significantly to global efforts to mitigate climate change. In recent years, the advanced technology of solar has lowered costs, making solar energy more competitive and widely accessible around the world (Sinha & Chandel, 2015). In regions like Palestine, solar energy is vital due to large electricity shortages and heavy reliance on imports. Using alternative energy sources like solar energy is essential for ensuring a sustainable electricity supply in Palestine. Electricity shortages affect vital services such as healthcare, education, and economic development. However, the widespread use of solar energy in Palestine is hampered by political, economic, technical, and technological challenges (Khatib et al., 2021).

The power supply in Palestine mainly depends on external sources, with most of the electricity being imported. About 93.4% of the entire electrical supply is supplied by the Israel Electric Corporation, making it the primary supplier. The Gaza Electricity Company produces about 4.4% of electricity, while Jordan and Egypt contribute about 1.6% and 0.6% respectively. Palestine receives 3000 sunshine hours annually and an average solar radiation of 5.4 kWh/m^2/day, which indicates significant potential for solar power generation, which will help reduce the dependence on traditional energy sources (Juaidi et al., 2016). According to the World Bank Group, the estimated potential of renewable energy available is about 4,246 megawatts, with solar energy accounting for about 98.3% of this capacity. The remaining part, less than 2%, consists of wind energy, which is limited, and biomass energy, which offers limited opportunities (World Bank Group, 2017). Currently, the total installed capacity for photovoltaics in Palestine is 178,459 kilowatts (kW), divided into 159,512 kW in the West Bank and 18,983 kW in the Gaza Strip (PENRA, 2021).

CSP and PV systems are two essential technologies in solar energy, and each of them has distinct advantages in utilizing solar radiation. CSP systems use mirrors or lenses to concentrate sunlight into small areas, converting it into heat to generate electricity through steam turbines and heat engines (Alami et al., 2023). This technology excels in regions with high direct sunlight and can integrate thermal energy storage for dispatchable power generation, which ensures continuous electricity supply. In contrast, PV systems use semiconductor materials to directly turn sunlight into electricity, like silicon cells. PV technology is diverse, scalable, and ideal for distributed energy generation, and can be used in a variety of settings, from residential rooftops to large-scale solar plants (Kumar & Kumar, 2017).

PV systems are commonly known for their simplicity, low maintenance, and multiple use, and have been widely used while costs have decreased in recent years. The hybrid PV and CSP system combines the strengths of both technologies to the maximum benefits. By integrating thermal energy storage of CSP systems with PV electricity generation, we can get hybrid systems that offer stable and dispatchable power. This combination enhances grid reliability and credibility for energy production, especially in regions with variable sunlight or fluctuating energy demand patterns (Starke et al., 2016). As renewable energy integration continues to develop, hybrid PV and CSP systems are emerging as a promising solution to improve efficiency, flexibility, and sustainability in solar power systems.

This research aims to bridge this gap through the evaluation of the technical and economic feasibility of solar energy systems in Palestine, considering factors such as energy demand patterns, solar resource availability, and environmental impact. The study outcomes will offer essential vision and guidance for policymakers, investors, and stakeholders in the energy sector of Palestine, enabling informed decisions and the promotion of sustainable and economically efficient energy solutions.

1.2 Problem Statement

There is a lack of comprehensive techno-economic analysis on the feasibility and benefits of a hybrid PV and CSP system integrated with thermal energy storage in Palestine.

1.3 Importance of study

This research aims to address the gap in the techno-economic analysis of the CSP-PV hybrid system by conducting a detailed assessment of the technical and economic feasibility of the system, by considering different energy demand patterns, availability of solar energy resources, and local environmental and regulatory conditions.

1.4 Study Hypothesis

Research equation:

1. What is the technical and economic feasibility of incorporating a combined PV and CSP system with thermal energy storage in Palestine?

2. What are the optimal sizing and configuration parameters for the hybrid PV and CSP system to maximize energy production and minimize costs?

3. What is the environmental impact of the hybrid CSP and PV system in Palestine?

4. What are the policy and regulatory barriers and opportunities for the deployment of hybrid PV and CSP systems with thermal energy storage in Palestine?

5. How can the techno-economic analysis results be applied to a specific case study in Palestine to validate the feasibility and benefits of the proposed hybrid system?

Hypotheses:

1. The hybrid PV and CSP system integrated with thermal energy storage will demonstrate technical feasibility by providing a reliable and dispatchable electricity supply that aligns with the energy demand patterns in Palestine.

2. The integration of thermal energy storage will enhance the overall performance and cost-effectiveness of the hybrid system by increasing the system's capacity factor, reducing curtailment, and enabling better matching of electricity generation with demand.

3. The hybrid PV and CSP system integrated with thermal energy storage, will demonstrate a lower LCOE compared to conventional energy generation technologies in Palestine, indicating its economic viability and competitiveness.

4. The environmental impact assessment will show that the hybrid PV and CSP system with thermal energy storage, has lower greenhouse gas emissions, reduced water consumption, and a smaller land footprint compared to conventional energy generation technologies in Palestine.

5. Policy and regulatory analysis will identify existing barriers and recommend necessary improvements, to incentivize and facilitate the integration and deployment of hybrid PV and CSP systems with thermal energy storage in Palestine.

1.5 Objectives

The main objective of this thesis:

1. To perform a thorough literature study of the current research of work, and studies on hybrid PV and CSP systems with thermal storage strategy.

2. Design a model of hybrid CSP and PV system, with thermal energy storage: firstly develop a detailed technical model for a hybrid system integrated with thermal energy storage, and consider the specific conditions and requirements of Palestine. Secondly consider the optimal sizing and configuration of the system components, including solar collectors, PV modules, thermal energy storage systems, and auxiliary equipment.

3. Techno-economic analysis: Evaluate the performance and feasibility of the proposed hybrid system.

1.6 Thesis Structure

The outline of thesis structure provides a brief introduction to the research.

Chapter One: Introduction and Theoretical Background

This chapter provides the general framework of the thesis topic including the overview, the problem of the study, the importance of the study, the hypothesis of the study, and the objectives of the study.

Moreover, an analysis of the available literature and previous studies related to PV and CSP hybrid systems with thermal energy storage concepts is conducted. In addition, the energy status of Palestine and solar power systems.

Chapter Two: Methodology

This chapter deals with the establishment of a comprehensive technical model for a hybrid CSP-PV system with energy storage, focusing on the characteristics and needs of Palestine. Moreover, provides a detailed analysis of a CSP-PV hybrid system from a technology and economic perspective. In addition, The analysis evaluates the system operating parameters, implementation costs, and incentives under different scenarios.

Chapter Three: Result

This chapter provides a result of the technical analysis for each scenario including power generation, levelized cost of energy, and economic analysis including NPV, IRR, LCOE, and PPB. Moreover, environmental impact studies with key performance targets for carbon emissions. In addition, details policy measures to facilitate system adoption.

Chapter Four: Conclusion and Recommendations

This is the final chapter that concludes the research and presents a set of conclusions. It provides a summary of the most important findings of the research and the importance of the PV and CSP hybrid systems. Furthermore, it provides recommendations on policy planning that are practical and feasible.

1.7 Literature Review

Different studies address the challenges with the issues of variability and intermittency of solar PV systems and come out with different ways in which such an effect can be minimized. Utilization of electrical energy storage systems is one of them. Hybridization of CSP and PV technology emerged as one cost-effective solution. Hybrid CSP-PV with TES is economical for a load period duration of more than 16 hours, and for a load period duration of less than 8 hours, it will be economical to supply a PV plant with batteries (Zurita et al., 2018).

These advantages are many, relating to reliability, dispatch, and even costs that could be realized by combining CSP and PV systems. Hybridizing CSP plants with PV systems allows for a reduction in the size of the CSP solar field with high-capacity factors achievable and at lower LCOE. Parametric studies have illustrated that hybrid systems can realize at least a capacity factor of 80% or higher even in relatively small CSP solar fields (Starke et al., 2018).

Another proposed approach is the thermal storage PV-CSP system, where low-cost TES is utilized in the CSP system instead of expensive batteries in the PV system. This integration improves the solar energy utilization though with a slight decline in daily output compared to the stand-alone PV and CSP systems, especially in the conventional dispatch strategy. However, there is an increased annual output in the constant output strategy, therefore means improved utilization of solar energy. Thermal storage PV-CSP system proves to be economically efficient with reduced LCOE compared to standalone PV and CSP systems (Zhai et al., 2017).

In the study of, (Zurita et al., 2021) an in-depth analysis was made to determine how dispatch strategies can affect the optimal designs for solar power plants with storage. They combined a genetic algorithm with a multi-objective optimization method to determine the optimal combination for each of the systems. From this, they inferred that baseload dispatch always yielded the minimum LCOE for all of the technology combinations they considered. On the other hand, LCOEs were considerably lower for those dispatch profiles confined to daytime or early evening hours. Those strategies which considered only evening and night hours had the highest LCOEs. This plant was continuously showing the lowest LCOE solutions, although its ability to ensure energy supply varied upon the dispatch strategy that was considered.

The same operation strategy was proposed for a CSP-PV hybrid system by (Zhai et al., 2018) consisting of a parabolic trough CSP system and a PV system. The objective was to reach an optimal design of such a system through a genetic algorithm and to determine the PV capacity, battery capacity, and thermal storage capacity of the CSP system for the minimization of the cost of power generation. The component ratio of PV and CSP in this system has been optimized according to the results obtained from the genetic algorithm, and further, the LCOE is minimized. This study contributes to the field by providing a method to enhance the design and operation of CSP-PV hybrid systems, considering the specific characteristics of both technologies.

The work by Pan & Dinter. (2017) presented a new design for an optimized PV-augmented central receiver CSP plant for the South African condition. The results of their work showed a significant reduction in both heliostat and thermal energy storage systems costs, thus returning much lower LCOE values when compared to conventional CSP plants of similar ratings. More precisely, the respective LCOE values were within the range of 0.133 to 0.157 $/kWh, demonstrating the cost competitiveness of the given PV-augmented CSP plant design.

Subsequently, Hassani et al. (2021) investigated the design and analysis of a hybrid CSP-PV power plant combined with a solar tower and a photovoltaic system in Oujda city, eastern Morocco. The outcome showed that CSP hybridization with PV in the hybrid plant had delivered lower LCOE of dispatchable energy compared to stand-alone CSP plants. Amongst other things, the hybrid system exhibited an astonishing capacity factor of over 90% and SM of over 3.5. All these confirm how exceptionally advantageous the combination of CSP and PV technologies is in ensuring cost-effectiveness and maximizing energy output.

Expanding the research scope, Sumayli et al. (2023) took it a notch higher to extend the simulation and optimization studies on hybrid CSP and PV systems to Riyadh and Tabuk in Saudi Arabia. The study pointed out a considerable reduction of LCOE in the integration of PV with CSP. In Riyadh, PV integration reduced LCOE by 18%, while in the case of Tabuk, it recorded a reduction of about 7%. Besides that, hybrid systems also enjoyed an extremely high plant capacity factor of 79% compared to pure CSP systems. In addition, PV was useful in generating electricity during the daytime, hence increasing the overall cost competitiveness for hybrid systems. Overall, these findings jointly underline the tremendous potential that hybrid PV-CSP systems offer with regard to achieving high-capacity factors and cost efficiency, enabling the transition towards cleaner, more sustainable sources of energy in the region.

Regarding the environmental impact of these systems, quite a lot of research has been conducted on evaluating their CO_2 equivalent emissions and energy payback times. CPV systems with high concentration usually had a CO_2 equivalent emission below 50 g/kWh while having EPBTs of less than one year. Such findings were echoed by (Lamnatou & Chemisana, 2017) Besides these studies conducted on CSP plants reveal that they tend to have generally low CO_2 equivalent emissions of less than 40 g/kWh with an average EPBTs of one year. The other important GWP is in the 100-year timeframe.

The GWP100 was calculated (Desideri et al., 2013) using the CML 2 baseline 2000 methodology. Their study considered the whole life cycle of the plants, assuming a disposal scenario in which all the components are sent to a landfill. The results showed that the CSP plant had a GWP100 of 29.9 g CO_2 eq/kWh, while the value for the PV plant was higher at 47.9 g CO_2 eq/kWh.

They presented the weighted average GHG emission factor with a baseline (Ullah et al., 2023), accounting for 518 g of CO_2 /kWh for the current energy mix scenario in Pakistan. The GHG emission factors for solar power systems were far lower, typically in the range of 16-40 g CO_2/kWh in most cases. These results further confirm the ecological merits of CPV and CSP systems, with smaller CO_2 equivalent emissions and EPBTs when compared to conventional sources of energy. Solar power system integration will thus help in fighting climate change by promoting sustainable energy utilization.

In general, all these studies have demonstrated the potential of thermal storage systems and hybrid CSP-PV systems to address the challenges in the variability and intermittency of solar energy. These integrated approaches offer cost-effective solutions, increase capacity factors, improve power output stability, and enhance the utilization of solar resources. Additionally, Sumayli et al. (2023) conducted research on a hybrid CSP-PV system for two cities in Saudi Arabia using a baseload dispatch strategy.

Their study also gave very precious ideas about the cost-effectiveness and operational efficiency that hybrid systems could have in a region. Influenced by their work, I will try to perform a similar study in Palestine using two different more suitable dispatch strategies for the region. This research will highlight, through evaluating baseload and alternative dispatch profiles, the most effective approach towards obtaining the highest energy output with the lowest LCOE in the particular solar energy context of Palestine.

1.8 Energy Situation in Palestine

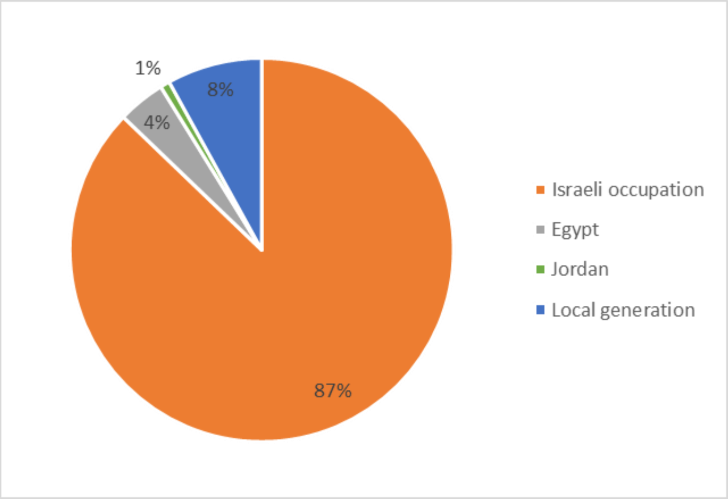
Energy is necessary for pushing economic growth however, there are different ways to keep electricity accessibility across Palestine. Both the West Bank and Gaza encounter massive obstacles in ameliorating their energy landscapes. Characterized by depressed indigenous energy reservoirs, Palestine's heavy reliance on energy imports from Israel increases its energy insecurities. Israel's dominance over the quantity and caliber of energy inflows into Palestine, facilitated by its control over border crossings, constricts trade paths with neighboring nations.

Consequently, Palestine contends with exorbitant energy tariffs dictated by Israel. In light of these exigencies, the imperative of prioritizing renewable energy sources, such as solar and wind power, looms large in Palestine's energy transition effort. A staggering 87% of Palestine's electricity needs are met through imports from the Israeli occupation state, with approximately 5% supplemented by imports from Egypt and Jordan.

The remaining 8% is generated locally in Gaza, including the fuels necessary for Gaza power stations. Consequently, the entirety of Palestine's energy sector operates under the control of the Israeli occupation (Juaidi et al., 2016).

Figure 1.1

Percentage of electricity imports in Palestine



1.9 Solar Energy Potential in Palestine

1.9.1 Introduction

Solar energy is widely accepted as a clean and renewable source of energy and most of the countries have been implementing this energy resource in the provision of power and environmental management. In Palestine, where the energy sector faces significant challenges, such forms of energy such as solar are important. Due to extreme electricity deficits and a lot of electric imports from Israel, Ban should seek other safe means such as Solar energy to be able to provide electricity to Palestine. The impact of electricity shortages extends beyond mere inconvenience, affecting vital services like healthcare, education, and economic development. However, political, economic, technical, and technological challenges hinder the widespread adoption of solar energy.

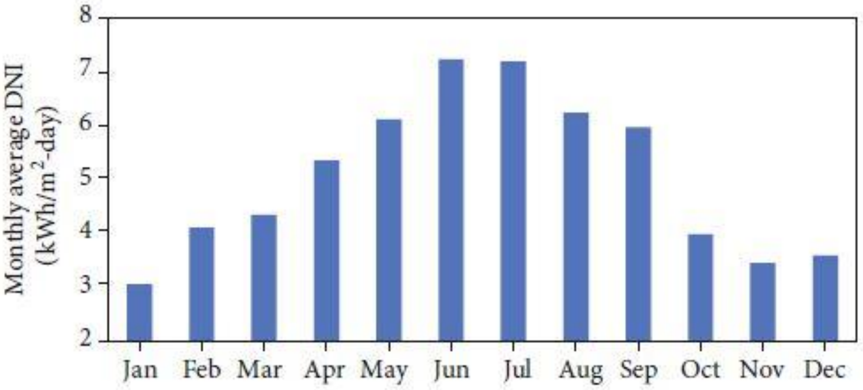
1.9.2 Overview of Solar Energy Potential in Palestine:

Palestine has high solar energy potential, with about 3000 sunshine hours per year and a high annual average of solar radiation amounting to 5.4 kWh/m²/day on horizontal surfaces. However, solar radiation varies between a minimum of 2.63 kWh/m²/day in December to a maximum of 8.4 kWh/m²/day in June (Khatib et al., 2021). Some studies conducted in the year 2010 recorded the monthly average solar radiation in four cities of Palestine which include Salfeet and Tubas situated in the north of West Bank, Ramallah is located in the central region of West Bank, and Hebron in the southern West Bank. The highest annual average of solar radiation was recorded in Salfeet (5.65

kWh/m²/day) followed by Ramallah (5.5 kWh/m²/day), Hebron (5.14 kWh/m²/day), and Tubas (5 kWh/m²/day). Peak solar radiation values were observed in August and June where solar radiation reached Ramallah 8.27 kWh/m²/day, Hebron 7.51 kWh/m²/day, Salfeet 6.86 kWh/m²/day and Tubas 6.15 kWh/m²/day (Juaidi et al., 2016). This data indicates strong potential for applying for a range of solar energy uses, including pumping water, desalinating water, drying crops, heating water, and even powering isolated places that aren't wired into the grid. Studies indicate that using PV systems for rural electrification in Palestine is economically viable and more feasible than diesel generators or extending the high-voltage electric grid, offering a sustainable solution by reducing CO_2 emissions. Figure 1.2 shows the average global solar radiation in Palestine.

Figure 1.2

Monthly Direct Normal Irradiance (kWh/m².mth) in Palestine



Wind energy in Palestine remains largely untapped, despite studies indicating its promising potential. Elevated regions such as Nablus, Ramallah, and Hebron show average annual wind speeds between 4 to 8 m/s, suitable for wind turbines. Hebron, at elevations around 1,000 meters, exhibits wind speeds reaching up to 7.5 m/s. Historical data indicate average wind speeds of 4.3 m/s in Nablus and 5.5 m/s in Ramallah. A comprehensive study by Albisher & Alsamamra; (2019), covering 2000 to 2011, confirmed that areas in the West Bank, especially Hebron, have significant wind energy potential with high annual energy densities. Although the Gaza Strip generally has lower wind speeds averaging about 2.5-3.5 m/s, small-scale turbines could still be viable. With strategic planning and investment, wind energy could become a valuable component of Palestine's renewable energy portfolio, effectively complementing its abundant solar resources and enhancing energy security Figure A.1 (Appendix A) show Wind speed for different cities in Palestine.

1.9.3 Current State of Solar Energy Adoption:

Despite government efforts, the adoption of solar energy in Palestine faces significant challenges. While initiatives promoting solar energy and providing incentives exist, hurdles persist. Nevertheless, ongoing solar projects across residential, commercial, and governmental buildings indicate progress toward energy independence. For instance, the installation of solar panels in schools and healthcare facilities has helped ensure an uninterrupted power supply for essential services (Ibrik & Fadia, 2020).

1.9.4 Challenges and Barriers:

- **Financing**: The financial constraint renders Palestinians unable to afford and access solar energy systems. New financing methods, including microfinance and crowdfunding, can help overcome this barrier.

- **Infrastructure Limitations**: The old grid systems and the limited power transmission capability are obstacles to effective solar energy integration with the current infrastructure. There will be a need to invest in the grid to realize the full benefits of solar energy adoption (Juaidi et al., 2022).

- **Political Instability**: Uncertain political conditions deter investors and create regulatory uncertainties, obstructing the development of the solar energy market. Establishing clear regulatory frameworks and providing political stability are conclusive for attracting investment in solar energy projects (Juaidi et al., 2022).

- **Regulatory Hurdles**: Bureaucratic red tape and unclear licensing processes delaying the implementation of solar energy projects. Streamlining regulations and enhancing transparency in the licensing process can facilitate the deployment of solar energy systems (Juaidi et al., 2022).

1.9.5 Opportunities and Advantages

- **Economic Benefits**: Embracing solar energy stimulates economic growth, creates jobs, and enhances energy security by reducing dependency on imported energy sources. For example, the establishment of local solar energy companies can generate employment opportunities and contribute to economic development (Juaidi et al., 2022).

- **Job Creation**: Providing solar energy creates jobs at every skill set or level, thus promoting economic growth and people's skills development. Training programs and vocational courses can provide local human resources with the relevant carving skills in the expanding solar sector (Juaidi et al., 2022).

- **Energy Security**: By integrating solar energy into the energy mix, there is less reliance on imported fossil fuels, increasing the region's energy security. Local solar power generation reduces exposure to supply disruptions and price volatility in the global energy market (Juidi et al., 2022).

- **Environmental Advantages**: Solar energy helps reduce greenhouse gases and improve air quality and therefore mitigates climate change. Contributing to sustainable development goals. Additionally, utilizing solar energy contributes to protecting the environment for coming generations and conserving limited natural resources (Juaidi et al., 2022; Ajlouni & Alsamamra, 2019).

1.10 Concentrated solar power systems

1.10.1 Introduction

Concentrated solar power is a category of power production technique in which the heat generated from sunlight is converted into high-temp thermal energy, which, in turn, is used to drive an electrical generator and a heat engine. This technology has several subtypes or variations, but they are all based on the same basic principle of generating thermal energy from sunlight. Because it allows for the inclusion of storage, hybridization, and the simultaneous use of thermal and electrical energy, CSP is important for the production of renewable energy. Using mirrors or lenses, CSP systems focus sunlight and transform it into thermal energy, which is used to generate steam that powers a turbine that is connected to a generator to produce electricity. This capacity to produce both electricity and thermal energy utilization distinguishes CSP as a versatile and promising renewable energy technology (Alami et al., 2023).

1.10.2 Types of CSP Technologies

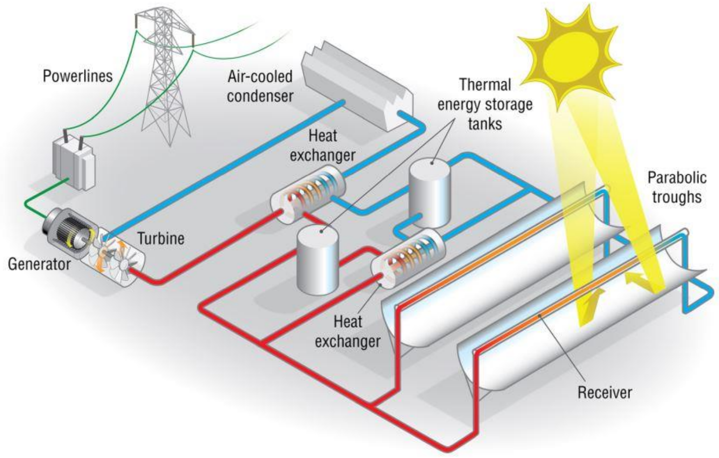
1. Parabolic trough systems

The type of CSP known as parabolic trough system is quite widespread. It comprises a series of long, curved, highly reflective mirrors arranged in a parallel orientation. Long mirrors span more than a hundred meters and focus sunlight directly on receiver tubes that are placed along a line attuned to their focus. These absorbing tubes, generally made out of Stainless steel embedded with a suitable coating, are used to collect the highly concentrated solar energy. In turn, this absorbed heat transfers energy to a heat-transfer fluid circulating in the tubes expanding the temperature of the fluid. After the fluid is heated, steam is produced. This steam powers turbines that are connected to electricity generators to produce electricity. Systems with parabolic troughs are well known for their advanced technology and excellent efficiency. Nevertheless, in comparison to certain other CSP technologies, they are also linked to increased expenses and complexity (Alami et al., 2023; Gauché et al., 2017).

This study selected the parabolic trough CSP system for its well-established reputation as a mature and proven technology. It has demonstrated high efficiency in converting solar energy into thermal energy while requiring relatively low maintenance. Furthermore, its modular design ensures efficient land use, particularly suitable for regions with constrained land availability (Azouzoute et al., 2020).

Figure 1.3

Parabolic Trough System

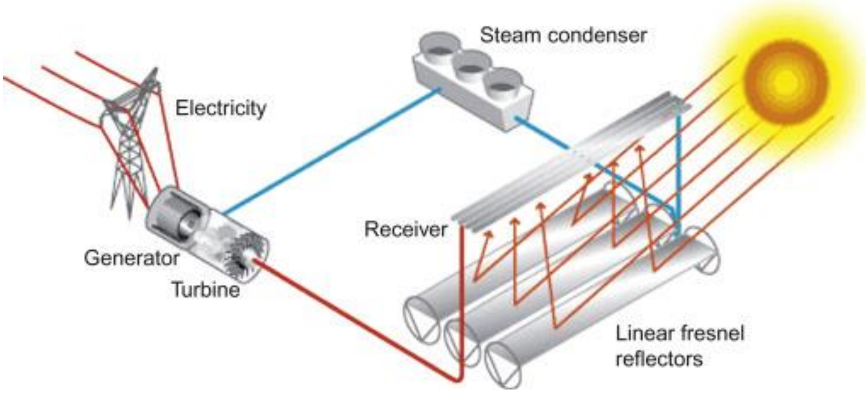


2. Linear Fresnel reflectors (LFRs)

Mirrors are used by linear Fresnel reflectors, such as parabolic troughs, to focus sunlight onto a receiver. But LFRs use linear rows of mirrors to reflect sunlight onto a fixed receiver positioned parallel to the mirror arrays rather than curved mirrors. Compared to parabolic troughs, this fixed receiver design offers simplicity and cheaper investment costs. Nevertheless, parabolic trough systems outperform LFRs regarding solar energy conversion efficiency (Alami et al., 2023; Gauché et al., 2017).

Figure 1.4

Linear Fresnel Reflectors System

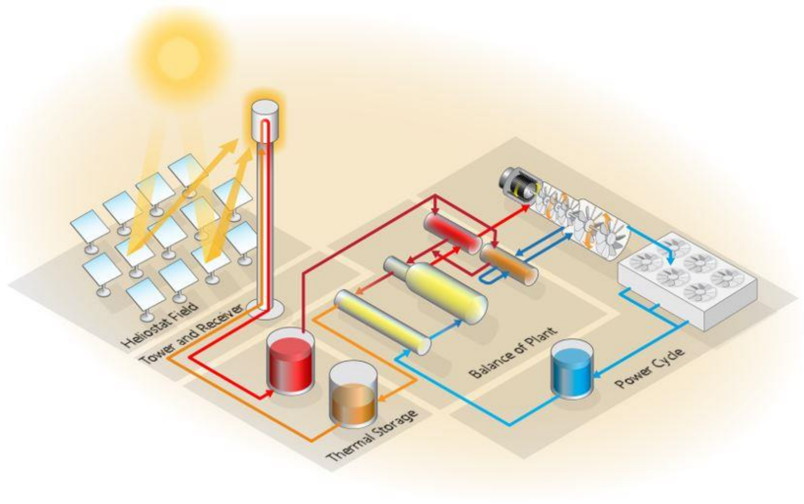


3. Solar towers or central receivers

Thousands of heliostats are used by solar towers, often referred to as central receivers, to focus sunlight onto a central receiver that lies atop a tower construction. By tracking the sun's movements throughout the day, these heliostats make sure that the receiver receives sunlight continuously. Extremely high temperatures can be attained at the receiver from concentrated solar energy, which makes it possible to use molten salt as a heat transfer medium or to directly generate steam for the production of electricity. High-temperature operation is possible with solar towers, making power generation more efficient (Alami et al., 2023; Gauché et al., 2017).

Figure 1.5

Solar Towers or Central Receivers System

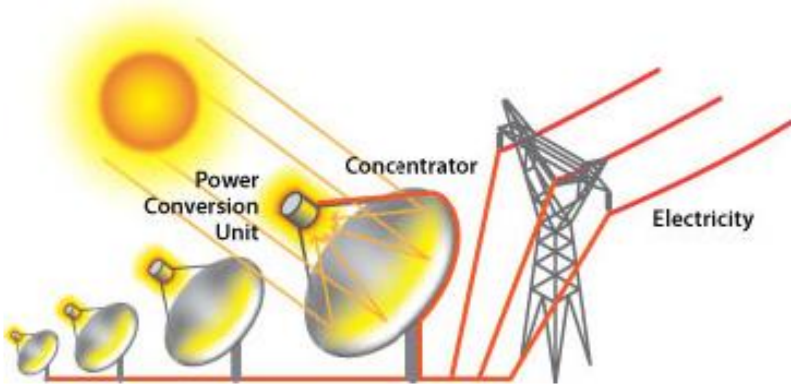


4. Parabolic dish CSP systems

Direct Normal Irradiance (DNI) is focused onto a central receiver at the dish's focal point via a dish-shaped reflector in parabolic dish CSP systems. Stirling engines or micro-turbines positioned at the receiver are usually used in these systems to directly transform concentrated solar heat into mechanical energy. Generators are then used to transform the mechanical energy into electrical energy. In addition to having a high conversion efficiency, parabolic dish CSP systems may directly transform solar energy into electrical power without the use of heat transfer fluids. However, in comparison to other CSP solutions, they might not be as scalable (Alami et al., 2023; Gauché et al., 2017).

Figure 1.6

Parabolic Dish CSP System



1.10.3 Components of parabolic trough System

A PT-CSP system consists of several key components that work together to harness solar energy and convert it into electricity:

1. **Receiver Tubes and Receivers:** Receiver tubes are concentrators used in linear Fresnel reflector and parabolic trough systems that concentrate solar light and transfer that heat to a heat transfer fluid running in the tubes. For different conversion methods, the concentrated solar light is received by a central receiver for solar power towers and a parabolic dish for CSP systems where the sunlight is concentrated.

2. **Solar Field:** The solar field, which has a set of mirrors or reflectors, around the system of fixed receivers or receiver tubes to which the solar radiation is pointed and concentrated. To ensure that the receivers receive the maximum of solar radiation, these mirrors are manufactured to track the movement of the sun.

3. **Power Block:** The most important section of the CSP system which including the turbines and steam generators that are powered by CSP steam. The generators are powered by steam turbines that use the thermal energy from the steam to generate electrical power.

4. **Thermal Energy Storage:** The main component of a CSP system, which use to store excess thermal energy that cannot be utilized during peak solar radiation times. It is helpful to the increase the efficiency and reliability of the CSP unit to use the

heat stored in the CSP unit to heat water, produce steam, and produce power during cloudy seasons or when electrical loads exceed supply.

5. **Heat Transfer Fluid:** The essential part of CSP systems and using for collecting concentrated solar heat and transferring the heat to a generation system. Lubricating oils are a common type of HTF fluid used in applications that do not require high temperatures while molten batteries serve high-temperature applications. HTF fluids are pumped through receiver pipes or fixed receivers that contain solar energy and are used to convert water to steam and operate electricity generation systems.

6. **Schematic layout:** The solar field, power block, and thermal energy storage are often shown in a CSP system's schematic architecture, which also shows how these parts work together to capture solar energy and turn it into electrical power.

1.11 Photovoltaic System (PV)

1.11.1 Introduction

The utilization of PV systems, which can convert solar energy into useful electrical energy, is considered one of the forefront technologies for renewable energy generation. PV was particularly maintained in this position because of high power densities and low maintenance in comparison with others. It likewise assists in global warming reduction and does not emit any pollutants during its operation. PV technology has advantages, but it also has disadvantages, like dust buildup, hail, and variations in operating temperature that can reduce system performance. The surface temperature of PV modules is influenced by exogenous meteorological elements such as wind speed, humidity, ambient temperature, dust buildup, and solar radiation. Also, Efficiency can be negatively impacted by even small increases in surface temperature; for example, an increase of 1°C can result in a 0.5% decrease in efficiency. (Sultan & Ervina Efzan, 2018). Efficiency ratings are normally provided by manufacturers for their photovoltaic modules, which are tested under Standard Test Conditions (STC). These parameters include a cell temperature of 25 °C, an irradiance of 1000 W/m^2, and a spectrum of 1.5 Air Mass (AM). It's important to remember that operational efficiency might change depending on several variables, including location, weather, and the cleanliness and tilt angle of the module (Siecker et al., 2017).

1.11.2 Cell Type

The solar cell, commonly known as the PV cell, is the main part of a photovoltaic power plant. These cells work based on the photoelectric principle, which states that energy from photons causes electrons in semiconductor materials To travel from the conduction band to the valence band. The flow of electrons produces an electric current when a load is connected to form a circuit. There are different types of PV cells:

- Monocrystalline Silicon (Mono-Si): Renowned for having a high efficiency—typically from 15% to 24% (Pastuszak & Węgierek, 2022).

- Polycrystalline Silicon (Poly-Si): Less efficiency compared to monocrystalline cells, averaging from 10% to 18% (Pastuszak & Węgierek, 2022).

- Thin Film PV Cells: With typical efficiencies ranging from 15% to 16%, this category comprises a variety of kinds such as amorphous Silicon, Copper-indium/gallium (CIGS), or Cadmium-telluride (CdTe) cells (Pastuszak & Węgierek, 2022).

After that, PV cells are arranged into panels or modules that may be connected in series or parallel to produce the required output of voltage and power.

1.11.3 PV System Configuration

In general, there are two types of PV systems configuration: standalone and grid-connected.

- **Stand-alone PV Systems**

These systems are appropriate for rural sites or places without grid connection because they run independently of the electric grid. They may have energy-storage components like batteries and are capable of powering DC and/or AC loads. With stand-alone systems, backup power sources like diesel generators can be included for times when there is little sunlight or excessive demand (Lupangu & Bansal, 2017).

- **Grid-Connected PV Systems**

Grid-connected systems allow for the interchange of electricity between the system and the utility grid by operating in parallel. Usually, they come with an inverter to transform the PV array's DC power into AC power for appliances or grid feedback. Grid-connected systems have the benefit of allowing users to sell extra electricity to the grid. They can also include energy storage options to improve power transfer and deal with intermittent problems (Lupangu & Bansal, 2017).

1.12 Hybrid CSP-PV

1.12.1 Introduction

The bet that a hybrid PV and CSP system will make it possible to exploit renewable energy sources more effectively and efficiently is a strong bet. The advantages of both technologies are exploited simultaneously by this hybrid. Solar PV is a traditional and inexpensive technology where electricity generation is available during the day and is available at all times Zurita et al. (2018), however, with solar thermal and its low thermal storage costs, there is solar PV generation during the day and solar PV generation throughout the night. Emerging trends in CSP are diluting the technology's focus on cheaper storage solutions than the combination of solar PV and batteries which reduce the need for energy after sunset. However, even if this has historically been the case with CSP systems being more expensive, their thermal energy storage capabilities also allow them to generate electricity prices comparable to low-cost solar PV systems coupled with DC using the low lifetime system costs of solar PV systems. A viable option is a continuous, cost-effective electricity supply system consisting of a combination of PV and CSP approaches.

1.12.2 Hybrid CSP-PV Project

Hybrid PV and CSP systems, which integrate PV and CSP technology, are being developed in different locations around the world. These projects are strategically existing to take advantage of the unique geographical and climatic conditions that optimize solar energy production, Figure A.2 Solar Power Station 580 MW CSP-PV complex located in the Drâa-Tafilalet region of central Morocco, Figure A.3 Hybrid PV and CSP system with 800 MW in Chile (Appendix A).

Examples of such projects include:

- Copiapó, Chile
- Cerro Dominador, Chile
- Redstone CSP, South Africa
- Bokpoort II, South Africa
- Mendoza, Argentina
- Noor Midelt, Morocco

Chapter Two

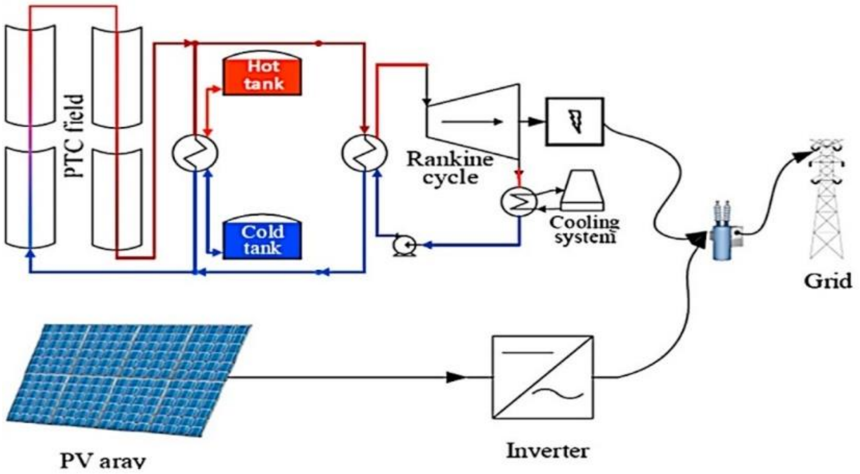
Methodology

2.1 System Description and Configuration

The CSP plant is designed around parabolic trough technology and incorporates Solargenix SGX-1 solar collectors and Schott PTR80 receivers, featuring a two-tank direct thermal energy storage system with HTF Thermoinal VP-1. 293°C and 391°C are the temperatures at the TES system keep the cold and hot tanks, respectively. Emphasizing efficiency, the solar field design optimizes the total aperture reflective area based on the Solar Multiple. The steam Rankine cycle power block of the CSP produces a gross electrical power of 1 MWe with an efficiency of 38%. It works at a maximum designed temperature of 391°C and is designed with a minimum turbine capacity set at 20% of the gross power. Additionally, the integration of a wet-cooled condenser, designed to function efficiently at the ambient temperature of 22.5 C°**,** In addition to the CSP components, the plant integrates a fixed PV field to complement solar thermal generation. For this system, we consider Sun Power SPR-P19-400-COM modules known for their high efficiency and reliability, paired with Huawei SUN2000 inverters.

Figure 2.1

Schematic diagram for Hybrid CSP-PV Plant



2.2 System Design and Modeling

While designing and modeling hybrid systems which included both PV and CSP technologies, it was vital to use an approach that satisfied the technical and economic requirements of the system. Moreover, it becomes very important to find the proper software that can model accurately the intricate interaction that exists between the CSP and PV components along with their respective storage systems. In our study, we choose to use SAM software, due to its durable capabilities in modeling CSP and PV systems. SAM provides extensive tools for analyzing thermal storage integration and optimizing dispatch strategies, offering a comprehensive environment to assess system performance and economic viability, across various operational scenarios. This software choice facilitates a detailed examination of how CSP and PV technologies can enhance energy production efficiency and financial feasibility.

2.2.1 Simulation tools and software used (SAM software)

The SAM software which is built by the National Renewable Energy Laboratory, is a leading tool for evaluating renewable energy systems. It helps users assess the feasibility and performance of solar, wind, biomass, and geothermal projects. SAM aids in making informed decisions by considering factors like resource availability, financial metrics, and environmental impacts. Taking into consideration the easy-to-use interface of SAM and its full functionalities, it is clear that the program helps in promoting the use of renewable energy across the world (National Renewable Energy Laboratory, 2023). SAM, indeed proves it might for modeling a variety of renewable energy systems, however, it is fair to say that there are no simulation options specifically designed for CSP and PV hybrid configurations. On the other hand, SAM does allow modelers to use CSP and PV technologies independently where users can also create and evaluate such models in the software (Sumayli et al., 2023). Users can model hybrid systems combining CSP and PV technologies within SAM by initially simulating the PV plant to determine its load share based on average hourly production. Then, utilizing SAM's dispatch matrix, they can direct CSP to produce a targeted load to compensate for any shortfall in PV production. The dispatch matrix of the system is flexible in that there are nine dispatch states, and the users can have operational strategies for each of the 24-hour periods in each month for different months in a year. Although consistent dispatch schedules throughout the week were chosen in this approach, SAM also provides options for weekdays and weekends. This strategy enhances hybrid renewable energy system operation by effectively coordinating CSP and PV contributions about operating power and energy demand characteristics, Figure A.4 (Appendix A) show the System Advisor Model interface.

2.2.2 Site Analysis and Resource Assessment

To ensure the success of our hybrid PV and CSP system, we conduct a thorough site analysis and resource assessment. Our evaluation considers various factors including solar radiation levels, land availability, slope, water access, infrastructure, and meteorological conditions. These assessments confirm the suitability of the selected location for solar energy projects, supported by favorable environmental conditions such as average ambient temperature, relative humidity, and wind speed.

2.2.3 System Design Parameter

The system design parameters for the PV and CSP components are meticulously selected to optimize efficiency, reliability, and cost-effectiveness. The CSP system utilizes parabolic trough technology with a specified solar multiple, thermal storage capacity, and accurate temperature settings to maximize capture energy and storage. The PV system uses high-efficiency monocrystalline silicon solar cells and inverters to ensure optimal performance under varying temperature conditions. Detailed design parameters for both systems are provided in Table 2.1 & Table 2.2.

Table 2.1

Main design parameter PV system

Table 2.1 otal system capacity	1 MW
Solar cell technology	Mono-c-Si
PV Nominal power	400 W_{dc}
PV Nominal efficiency	19.90%
Temperature coefficient of power	-0.37%/°C
Module area	2.01 m^2
Nominal operating cell temperature TNOCT	46.86 C°
Inverter nominal efficiency	98.69%

Table 2.2

Main design parameter CSP system

CSP technology	Parabolic Trough
Solar multiple	2-4
Design point DNI	950 W/m^2
Collector type	Solargenix SGX-1
Receiver type	Schott PTR80
Cycle thermal efficiency	38%
Net output power nameplate	1MW
Thermal storage capacity	12-18 hour
Loop inlet HTF temperature	293 C°
Loop outlet HTF temperature	391 C°
Land area	18 acres

2.3 Dispatch strategy

Management of the hybrid PV-CSP system requires a dispatch strategy that involves sending energy about the state of charge (SoC) of the TES system and the solar energy received, which has become true for the environment. The dispatch strategy assures the best usage of both PV and CSP aspects hence assuring the efficiency and reliability of the system.

2.3.1 Dispatch Scenarios

- **Scenario A: Supply Baseload 750 kW**

In this scenario, the combined PV and CSP system is designed to produce a constant baseload power output of 750 kW, continuously for 24 hours a day regardless of variations in solar energy availability. This approach ensures disturbance-free operation of the grid and also comprehensively simplifies the strategy, making it particularly useful for remote areas requiring a reliable power supply. It may lead to the waste of energy when there is low demand and potential overuse of the TES system.

- **Scenario B: Supply Power Based on Demand Load**

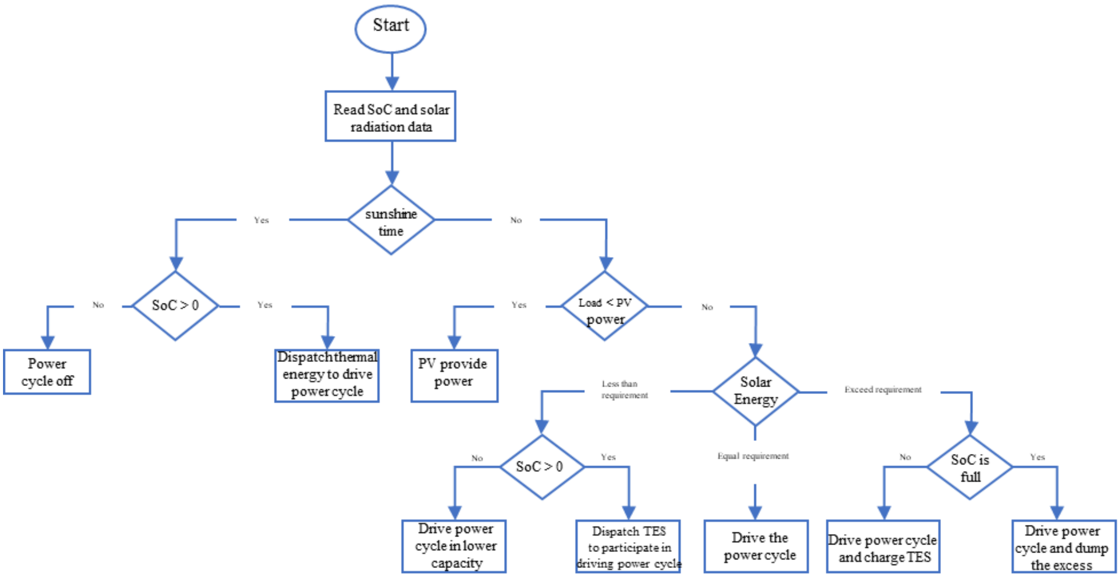
In this scenario, the combined PV and CSP dynamically adjust their power output to match the fluctuating demand load. This approach enhances efficiency by minimizing energy loss and improves grid stability by responding to changes in load requirements. It is especially beneficial in residential and industrial settings with variable demand patterns. However, it requires advanced control and management systems which is increasing operational complexity.

2.3.2 Dispatch Algorithm

The dispatch algorithm works based on the SoC of the TES and the estimated solar radiation data. During sunshine hours, if the solar energy available exceeds the energy required, the system gives priority to the PV output. If the PV system covers the energy demand, its energy is consumed. If not, the CSP system is used. When the SoC of the TES is at its maximum, the CSP system is operated at full capacity with surplus energy being excesses. However, if the SoC is not at maximum, then the excess energy goes to the TES. When the amount of solar energy that can be provided is equal to the amount of energy needed, there is a priority given first to compliance with the SoC. Where the energy demand can be met by the available energy of the PV system, then the resources from the PV system are drawn, and where this is not the case then the CSP system will work. When the SoC of the TES is full, the extra power of the CSP system is used and when the SoC of the TES is not full, the additional energy is charged. In a case where the amount of solar radiation is less than the amount of solar energy needed, the first system under consideration is the output of PV systems. If the PV system can meet the remaining demand, its energy is used. If not, the CSP system and TES are checked. If the TES is not empty, the deficiency is covered by the stored thermal energy; otherwise, the system operates at reduced capacity due to the shortfall in solar energy. During nighttime, when there is no solar radiation, the system relies on stored energy in the TES. The power cycle continues until the SoC becomes empty, ensuring continuous operation as long as stored energy is available. The algorithm of the dispatch system is illustrated in Figure 2.1, providing a visual representation of the system's operation under different solar conditions.

Figure 2.2

Flow chart of dispatch strategy for hybrid CSP-PV system



2.4 Techno-Economic Analysis

2.4.1 Introduction

As with any other field of science and engineering, techno-economic analysis can be defined as the process of critical and holistic assessment of a technology and/or a project considering the technical together with the economic components to establish its acceptability, workability, and impact. This method often includes regular engineering and environmental assessment, economics standards, and emphasizing the interaction of the engineering side and the economy side. In this study, we will perform a techno-economic assessment of the hybrid CSP and PV system in the context of Palestine. However, as part of this investigation, we will focus on the technical performance of the integrated PV and CSP system, including aspects such as capacity factor, and annual energy production. Further economic issues related to the hybrid PV and CSP system in terms of cost analysis, revenue generation potential, and economic viability qualitative assessment will also be carried out. In this research, we attempt to analyze both the economic prospects of the hybrid PV and CSP system as well as its technical feasibility in terms of cost by adding improved technical performance parameters together with the economic factors.

2.4.2 Technical Assessment

The technical analysis is essential for evaluating the performance and efficiency of the hybrid CSP and PV system. This analysis encompasses various aspects, including assessing the annual energy generation and capacity factors.

I. Annual Energy Production:

The annual energy production, which is in MWh, of the combined system of CSP and PV is one of the very important parameters that is affected by many factors. Some of these factors are solar irradiance, which depends on the geographical location and time of year, and the efficiency of the CSP and PV in converting sunlight into electricity. Additionally, the thermal storage capacity in this system which is more associated with the CSP systems makes it possible to produce electricity even when there is little or no sunlight. Factors related to operational performance such as system downtime, maintenance intervals, and even overall system reliability significantly impact energy produced in a year. Accurate estimation demands integrating daily and seasonal solar irradiance changes with the system's performance, highlighting the importance of modeling and data collection, to conduct such comprehensive performance evaluation.

- **Mathematical Equation**

The performance of the CSP system is evaluated using a series of mathematical equations that describe its energy capture and conversion processes (Yasin, 2019). The incident solar power on the aperture area of the collector is expressed as

$$\boldsymbol{Q_{inc} = I_{bn} \times A_{ap,tot}} \qquad (2.1)$$

Here, Q_{inc} represents the incident energy, $I_{bn}$is the direct normal solar irradiation (DNI, W/m²) and $A_{ap,tot}$ denotes the total aperture area of the collector (m^2). The collected energy, accounting for optical losses, is given

$$\boldsymbol{Q_{Collected} = I_{bn} \times A_{ap,tot} \times \mu_{opt}} \qquad (2.2)$$

Where μ_{opt}The optical efficiency of the system accounts for various optical factors, The overall optical efficiency is expressed as

$$\boldsymbol{\mu_{opt} = \mu_{endloss} \times \mu_{shadow} \times \mu_{IAM} \times \mu_{track} \times \mu_{geo} \times \mu_{soil} \times \rho_m \times \mu_{gen}} \qquad (2.3)$$

Where $\mu_{endloss}$ End-loss efficiency, μ_{shadow} Efficiency accounting for shading effects, μ_{IAM} Incidence angle modifier, μ_{track}Tracking efficiency, μ_{geo}Geometric efficiency, μ_{soil} Soiling efficiency,ρ_mThe reflectivity of the mirror, μ_{gen} General efficiency factor.

The thermal energy output is calculated

$$\dot{Q}_{th} = \dot{Q}_{th,des}\left(\frac{I_{bn}}{I_{bn,des}}\right)\left(\frac{\mu_{opt}}{\mu_{opt,des}}\right)\left(\frac{\mu_{therm}}{\mu_{therm,des}}\right) \qquad (2.4)$$

Where $\dot{Q}_{th,des}$ thermal energy at design conditions (W), $I_{bn,des}$ Design direct normal irradiance (W/m^2), μ_{therm} Thermal efficiency of the system, $\mu_{therm,des}$ Thermal efficiency at design conditions.

The power cycle output is determined using the thermal energy and power plant efficiency.

$$\dot{W}_{cycle} = \dot{Q}_{th} \times \mu_{power\ plant} \qquad (2.5)$$

The net power output is given where $\dot{W}_{par}$ Parametric power consumption is (W).

$$\dot{W}_{net} = \dot{W}_{cycle} - \dot{W}_{par} \qquad (2.6)$$

The energy stored in the TES system is expressed as

$$E_{TES} = \frac{\dot{W}_{des} \times \Delta t_{tes}}{\mu_{cycle.des}} \qquad (2.7)$$

Where E_{TES} Energy is stored in TES (Wh), $\dot{W}_{des}$ Design power output (W), and Δt_{tes} Storage time (h), $\mu_{cycle.des}$ Cycle efficiency at design conditions.

II. Capacity Factors

Capacity factors are key performance indicators that measure the ratio of actual electricity generated by the hybrid PV and CSP system to its maximum possible generation capacity over a specific period, typically expressed as a percentage. The capacity factor provides insights into the system operational efficiency and utilization rate, considering factors such as downtime, maintenance periods, and system design limitations. To calculate capacity factors, it analyzes historical electricity generation data which considers variations in solar irradiance, system downtime, and operational constraints. By comparing actual electricity generation to the system's rated capacity, we quantify the system performance relative to its maximum potential. High-capacity factors indicate efficient utilization of available solar resources, while low-capacity factors may suggest operational inefficiencies or design limitations that need to be addressed.

$$\textbf{Capacity factor} = \frac{\textbf{Annual energy generated}}{\textbf{System capacity} \times \mathbf{8760}} \qquad (\mathbf{2.8})$$

2.4.3 Economic Assessment

- **Cost Analysis**

To perform the economic comparison of the hybrid PV and CSP system, cost analysis is an essential part of measuring the financial implications of the project. Cost analysis is more concerned with the various aspects of expenditure related to the PV and CSP systems.

I. Capital Cost

Through capital cost analysis, the amount of money spent to build a hybrid CSP/PV system is determined, by breaking down the costs associated with the CSP and CSP components. For instance, the PV system costs to secure the purchase of basic system components such as PV modules, Inverters, mounting structures, Electrical systems, and Balance of system components such as wiring and junction boxes. These are installation costs and include labor services, rentals for equipment, transport, and site preparation among others. For instance, in the CSP system, the capital cost includes the cost of mirrors, receivers, heat exchangers, thermal storage tanks, and so on, and their accompaniments. The construction cost also includes costs incurred in foundation construction including assembly labor and the use of specialized equipment or tools (Sumayli et al., 2023).

Table 2.3

Capital cost for CSP and PV system

CSP system capital cost	
Site improvements	25 \$/m^2
Solar field	150 \$/m^2
HTF system	60 \$/m^2
Storage	62 \$/kWht
Power plant	910 \$/kWhe
Balance plant	90 \$/kWhe
Contingency	5%
PV system capital cost	
PV module	0.41 \$/Wdc
Inverter	0.1 \$/Wdc
Balance of system equipment	0.2 \$/Wdc
Installation cost	0.17 \$/Wdc
Total indirect cost	0.11 \$/Wdc
Contingency	5%

II. Operation and maintenance cost and land lease cost

The operation and maintenance cost analysis evaluates the ongoing expenses required to ensure the optimal performance and longevity of the hybrid PV and CSP system, expressed in $/W-year. Which includes routine maintenance, cleaning, and inspection of system components, as well as expenses related to replacement parts, labor, and monitoring activities Additionally, the annual land lease cost covers the expenses associated with leasing the land required for system build-out (Sumayli et al., 2023).

Table 2.4

Operation and maintenance cost for CSP and PV system

O&M costs for the CSP system	66 \$/kW-year
O&M costs for PV system	15 \$/kW-year
Annual land least cost	600 \$/year

III. Salvage Value

The salvage value analysis evaluates the market value worth of the hybrid PV and CSP system at the end of its operational life. Defined as the estimated market value of system components and materials post-depreciation, this analysis provides insights into the system's long-term financial implications. By considering factors such as technological advancements and market demand for used components, we estimate the salvage value as a percentage of the initial capital cost. This quantified salvage value, expressed as a percentage of the capital cost, aids in project planning and financial modeling (Sumayli et al., 2023).

Table 2.5

Salvage value of hybrid CSP and PV system

Salvage value for CSP system	5%
Salvage value for PV system	5%

IV. Lifetime of the project

The project lifetime analysis evaluates the expected duration of the hybrid PV and CSP system project from inception to decommissioning, considering the distinct lifetimes of the PV and CSP components. With the PV system expected to operate for 25 years and the CSP system for 25 years, we estimate the project's overall lifespan to understand its long-term sustainability and economic viability (Sumayli et al., 2023).

Table 2.6

Project lifetime for CSP and PV system

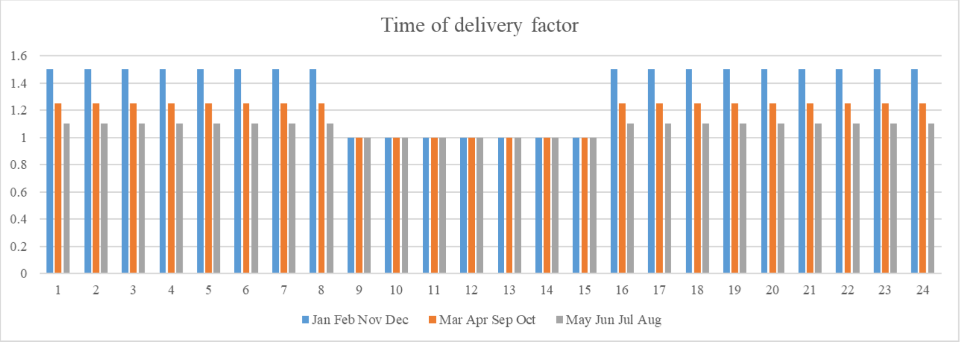
Project lifetime for CSP system	25 years
Project lifetime for PV system	25 years

- **Revenue Analysis**

The revenue analysis of the hybrid PV and CSP system project depends on financial inflows from electricity sales to the grid, significantly influenced by the PPA price. Figure 2.2 shows the proposed PPA agreement. This PPA agreement is structured across four different layers for different months of the year, each affecting revenue based on the timing of electricity delivery. Understanding these tariff implications is crucial, as they allow the system to optimize operations and maximize revenue by generating and storing energy strategically, ensuring both parties benefit from reliable and financially predictable energy transactions.

Figure 2.3

Proposed PPA Agreement



• Economic Analysis

I. Present Value (PV)

Determines the current worth of future cash flows of the generated energy from the hybrid CSP - PV system over time, and considers the time value of money. Indicating how much future cash you will receive after n years and tilting all the concerns over the discounting of the future cash flow to the n defaulting value. Present value provides insights into the project's net economic benefit. A higher evaluation of the present value of future cash flows is positively related to investors' valuation of the investment value. This analysis therefore makes sense to stakeholders to compare the value of future benefits against present costs, helping to allocate available resources and prioritize investments.

$$\boldsymbol{NPV = \sum_{n=0}^{N} \frac{C_n}{(1+d)^n}} \qquad \mathbf{(2.9)}$$

Where:

$C_n: Annual\ project\ cost\ in\ year\ n.$

$d: Discount\ rate.$

$N: Project\ lifetime.$

II. Internal Rate of Return (IRR)

The internal Rate of Return, measures the projects profitability by evaluating the discount rate at which the net present value of cash flows equals zero. It is the gains an investment earns in a year when considered on an annual basis that straddles its investment. It depicts the returns that the project generates over and above the capital employed for the project. A higher IRR implies greater profitability and financial attractiveness, signaling a more favorable investment opportunity This helps stakeholders assess financial viability and compare it with alternative investment options, thus helping determine where to allocate resources.

$$\boldsymbol{NPV} = \sum_{\boldsymbol{n=0}}^{\boldsymbol{N}} \frac{\boldsymbol{C_n}}{(\boldsymbol{1} + \boldsymbol{IRR})^{\boldsymbol{n}}} = \boldsymbol{0} \qquad (\boldsymbol{2.10})$$

Where:

C_n: $Annual\ project\ cost\ in\ year\ n.$

IRR: $Internal\ rate\ of\ return.$

NPV: $Net\ present\ value$

III. Levelized Cost of Electricity (LCOE)

Calculates the average cost of electricity generated by the hybrid PV and CSP system over its operational lifetime, expressed in $/kWh. The project total costs, including capital expenditures and operating cost, are included in the LCOE, maintenance costs, and financing charges, normalized to the total electricity generated. A lower LCOE indicates greater cost competitiveness and economic efficiency, making the project more attractive for electricity consumers and investors. This metric serves as a key benchmark for comparing the economic viability of renewable energy projects and conventional energy sources, guiding policy decisions and investment strategies in the energy sector

$$\boldsymbol{LCOE} = \frac{\sum_{\boldsymbol{n=0}}^{\boldsymbol{N}} \frac{\boldsymbol{C_n}}{(\boldsymbol{1} + \boldsymbol{d})^{\boldsymbol{n}}}}{\sum_{\boldsymbol{n=0}}^{\boldsymbol{N}} \frac{\boldsymbol{Q_n}}{(\boldsymbol{1} + \boldsymbol{d})^{\boldsymbol{n}}}} \qquad (\boldsymbol{2.11})$$

Where:

C_n: $Annual\ project\ cost\ in\ year\ n.$

Q_n: $Electricity\ generated\ by\ the\ system\ in\ year\ n.$

d: $Discount\ rate.$

N: $Project\ lifetime.$

IV. Project payback period

This is the most fundamental non-variation reporting assessment, which estimates the period that the PV and CSP hybrid system can take in recovering initial capital investment through net cash inflows. This analysis entails collecting all the net cash inflows that the system shall produce per year until the net cash flows are equal to the initial expenditure. The short project payback period signifies that the project has a fast return of funds in terms of investment, and this minimizes the risk on the financing and increases the desirability of the project to potential investors or stakeholders in the project. This measurement is useful when carrying out an economic analysis of the project offering a clear timeline for cost recovery. It also enhances decision-making by providing the ends, with the possibility to assess the investment's effectiveness in comparison with other probable projects.

$$\mathbf{PP} = \frac{\textbf{Initial capital investment}}{\textbf{Annual cash inflow}} \qquad (\mathbf{2.12})$$

2.4.4 Case Study

- **Introduction**

Jericho has been identified as an ideal location for the implementation of PT-CSP and PV power systems. Positioned at approximately 31.89°N latitude and 35.46°E longitude, with an elevation of -160 meters, it aligns with specific site requirements and demonstrates favorable solar potential indicators, highlighting its geographical location and supporting the rationale for its selection as a prime site for PT-CSP and PV power system implementation. Figure 2.3 shows the location of Jericho Governorate on the map of Palestine. The region satisfies crucial criteria including solar radiation levels, land availability, slope, water access, infrastructure, and meteorological conditions, solidifying its suitability for solar energy projects. Additionally, Jericho stands out as the most suitable location in Palestine for CSP technology deployment, based on previous feasibility studies (Yasin & Draidi, 2020). With a Direct Normal Irradiance (DNI) of 5.66 kWh/m²/day, Figure A.5 (Appendix A) illustrates the annual beam irradiance – DNI in Jericho. The region provides abundant solar energy for conversion into electricity through PT-CSP and PV technologies. Moreover, its favorable environmental conditions, including an average ambient temperature of 24.5°C, Figure A.6 (Appendix A) showing the monthly average ambient temperature), a relative humidity of 45.5%, and an average wind speed of 2 m/s, underscore its viability as an optimal site for solar energy projects.

Figure 2.4

Location of Jericho governorate on the map of Palestine

2.4.5 Sensitivity Analysis and Optimization

To optimize the planet's operating time and generate electricity at the lowest possible cost, a parametric study was conducted to determine the optimal combination of the solar multiple and heat storage hours for the CSP plant. This study was carried out using the hybrid solar plant's capacity factor and LCOE. The TES size as well as the solar multiple were taken as independent factors for this purpose because of their significant impact on the capacity factor and energy prices. The evaluation range of solar multiple and TES hours was from 1 to 5 and from 3 to 20 respectively to better understand the influence of these design parameters on the LCOE (Starke et al., 2016). Additionally, the study applies to PV plants to find the optimal value of tilt angle in terms of LCOE and annual energy produced.

A. Impact of thermal energy storage capacity on system performance

Increasing the capacity of TES significantly affects the performance of CSP systems, especially in terms of LCOE and capacity factor. As shown in A.7 (Appendix A) , when TES capacity goes from 3 to 9 hours, the capacity factor goes up from 36.86% to 49.18%, and the LCOE goes down from 17.33 cents/kWh to 15.16 cents/kWh, demonstrating improved performance and cost-effectiveness. With a TES capacity of 12 hours, the capacity factor reaches its peak at 53.6%, providing an optimal balance between low LCOE and high-capacity factor, while the LCOE further decreases to 14.89 cents/kWh. Beyond 12 hours, the benefits start to decrease. For a TES capacity of 15 hours, the capacity factor reaches 54.43%, while the LCOE slightly rises to 15.63 cents/kWh. At a TES capacity of 18 hours, the capacity factor stabilizes at around 54.39%, but the LCOE continues to increase to 16.6 cents/kWh. Hence, a TES capacity of around 12 hours offers an optimal balance between low LCOE and high-capacity factor, while higher TES capacities result in diminishing returns and increased costs.

B. Impact of solar multiple (SM) on CSP system performance

Increasing the SM significantly affects the performance of CSP systems, especially the capacity factor and LCOE. As shown in A.8 (Appendix A), when the SM increases from 1 to 2, the LCOE decreases sharply from 32.27 cents/kWh to 17.56 cents/kWh, and the capacity factor increases from 15.48% to 37.85%. The LCOE remains relatively decreed at around 14.89 cents/kWh for an SM of 3, with the capacity factor increasing to 53.62%. For an SM of 4, the LCOE slightly increases to 15.05 cents/kWh, while the capacity factor continues to rise, reaching 61.76%. At an SM of 5, the values remain consistent with an LCOE of 15.89 cents/kWh and a capacity factor of 66.83%. Therefore, an SM value of 3 provides an optimal balance between low LCOE and high-capacity factor, making it a cost-effective choice.

C. Impact of Title Angel on PV system performance

Increasing the tilt angle of PV panels has a significant impact on their performance, particularly about capacity factor and LCOE. As shown in A.9 (Appendix A), the LCOE remains relatively stable and low, around 5.17 cents/kWh, for tilt angles between 20 and 30 degrees. Within this range, the capacity factor reaches its peak at 30 degrees, achieving 28.19%, indicating that this angle maximizes energy production efficiency. However, as the tilt angle increases beyond 32.5 degrees, the LCOE gradually rises, reaching 5.37 cents/kWh at 50 degrees, while the capacity factor steadily decreases to 26.79%. This trend suggests that higher tilt angles lead to diminished performance and increased costs. Therefore, a tilt angle of approximately 30 degrees offers the optimal balance between low LCOE and high-capacity factor, making it the most efficient choice.

Chapter Three

Results

3.1 Introduction

This section describes the results of simulations conducted for the case study with respect to the hybrid PV and CSP system, which is tested under two scenarios: Scenario-A which is aimed at supplying a constant baseload power, and Scenario-B where the power is supplied based on demand load. The study focuses on key indicators of performance to evaluate economic and technological performance.

3.2 Technical Performance

3.2.1 Annual Energy Production

The annual energy production performance of the hybrid system showed a marked difference between the two scenarios. In Scenario-A, the system produces a yearly energy output of 6,298.31MWh which suggests that it always sustains a constant power load. On the other hand, Scenario-B performs better as power production is aimed at meeting demand with a total annual electricity generation of 6,668.46 MWh. This difference highlights the system’s flexibility and potential for improved performance when power generation is aligned with demand fluctuations A.10 (Appendix A) shows the results of annual energy production.

In addition, the monthly energy production breakdown for each scenario is depicted in A.11 (Appendix A). This figure highlights seasonal variations, with peak production observed from May to August. Scenario-B consistently produces more energy during most months, demonstrating its adaptability to seasonal demand patterns. This monthly analysis underscores Scenario-B superior performance in aligning energy production with monthly demand variations and optimizing system utility over the year.

3.2.2 Capacity Factor

The capacity factor further illustrates the system's operational efficiency. In Scenario-A, the hybrid system achieves a capacity factor of 35.9%, reflecting steady energy generation throughout the year. However, Scenario-B sees an increase in the capacity factor to 38.0%, emphasizing the benefits of adjusting power generation according to demand. This higher capacity factor in Scenario-B indicate more effective utilization of the available resources, thus enhancing overall system efficiency, A.12 (Appendix A) illustrates the capacity factor results for each system.

3.3 Economic Performance

3.3.1 Net Present Value (NPV)

The NPV analysis assesses the financial viability of the hybrid system. In Scenario-A, the NPV is $ 3,756,455.00, indicating significant financial returns over the system's operational life. However, in Scenario-B, the NPV is higher at $ 3,934,474.00, reflecting strong financial performance and better adaptability to varying operational conditions. This clear difference demonstrates that tailoring power output to meet demand not only enhances technical performance, but also increases economic benefits. A.13 (Appendix A) presents the NPV results for each scenario.

3.3.2 Internal Rate of Return (IRR)

The IRR values explain the investment potential of the system. In Scenario A, the IRR is 13.12%, indicating good profitability. In Scenario B, the IRR is 13.35% showing even more attractive investment potential. The higher IRR in Scenario B emphasizes that systems designed to adapt to demand variability can provide superior returns on investment, making them more appealing to investors. A.14 (Appendix A) displays the IRR results for each scenario.

3.3.3 Levelized Cost of Energy (LCOE)

The LCOE results demonstrate the cost-effectiveness of the hybrid system in various operational scenarios. In Scenario A, the levelized energy cost stands at 12.37 cents per kWh, which indicates the power configuration cost in terms of a stable constant power supply. Scenario B reported a decrease in the levelized energy cost to 11.72 cents per kilowatt-hour, depicting the increased economic efficiency of the system when the system adjusts power output according to demand. This reduction in LCOE shows that demand-responsive systems can reduce their expenditure on running costs, improving the systems' feasibility. Refer to A.15 (Appendix A) for the LCOE results.

3.3.4 Payback Period (PPB)

The payback period (PPB) is the period over which the initial investment costs are recovered. In Scenario-A, the PPB is 7.2 Years which is reasonable for this Kind of long-term project. In Scenario B, the average PPB is 7 years, providing a sooner return on investment, indicating the financial gain from operating on the demand response system on the generation side. The lower-than-expected PPB rate in Scenario B also confirms the economic benefits of the demand-responsive system. The PPB results are shown below in A.16 (Appendix A).

3.3.5 Cash Flow Analysis

The cash flow analysis provides a comprehensive overview of the financial inflows and outflows associated with the hybrid PV and CSP system project over its operational lifespan. Construction and operating capital as well as revenue collection are accurately calculated, giving a clear description of the project's financial performance. This analysis shows the amount of net cash flows over a specific period within the project time, which enables us to assess the economic feasibility of the project, identify potential risks, and inform strategic financial decision-making. A.17 (Appendix A) shows the cash flow analysis for scenario B.

The most economically and technically efficient hybrid CSP system is compared when its energy production is adjusted to the energy demand (Scenario B). This approach increases the production of energy as well as the capacity factor, maximizes returns on investment, minimizes costs, and reduces the period taken to achieve payback. These results indicate that the implementation of demand response systems in hybrid CSP systems significantly improves performance and economic feasibility.

3.4 Environmental Impact study

3.4.1 Introduction

Traditional power plants such as coal and natural gas-powered ones have remained the main source of electric output around the world. With the advantages, however, comes the disadvantage of generating a lot of negative impacts on the environment.

These plants are sources of greenhouse gases such as carbon dioxide which contributes to climate change. Moreover, polluting power plants release several air pollutants such as So2, NOx, and particulate matter, which are harmful to health and the environment. Furthermore, the extraction, transportation, and combustion of fossil fuels for conventional power generation can lead to habitat destruction, water pollution, and other ecological impacts.

However, solar power generating plants including concentrating solar power systems and PV systems, are greatly beneficial to the environment. The significant mean direct GHG emissions from solar plants come only during the manufacturing of the solar plants those being relatively low. Solar plants, therefore, have lower environmental consequences relative to conventional plants. Water use is also very low for solar plants, especially with dry-cooled systems as compared to fossil fuel-based plants that usually need cooling for the systems that require large quantities of water (Tawalbeh et al., 2021).

Moreover, the establishment of solar power plants has environmental advantages in biodiversity conservation and further land degradation, especially when such plants are established on already degraded lands. In addition, this energy source proves effective in mitigating climate change by increasing the use of renewable energy and decreasing dependence on carbon fuels.

In terms of average emissions, conventional power plants such as coal-fired power plants emit an average total 975.3 g CO_2/ kWh of energy produced, compared to the average of natural gas-fired plants 607.6 g CO/kWh (Talaba et al., 2021). One of the biggest benefits of systems such as CSP and PV is that these plants emit much lower emissions with figures estimated at around 40 g CO_2/kWh for CSP (Guillén-Lambea & Carvalho, 2021) and 46 g CO_2/kWh for PV.

These figures underscore the substantial emission reduction potential of solar energy, compared to conventional fossil fuel-based power generation, highlighting its pivotal role in mitigating climate change and promoting environmental sustainability.

3.4.2 Significant CO_2 Emission Reductions

These technologies help to increase the efficiency of PV and CSP system, using solar PV to reduce CO_2 emissions. In the following sections, the annual CO_2 emissions avoided for each scenario are detailed: Scenario A supplies a constant baseload power, and Scenario B supplies power based on demand load, The system is found to be able to use, in the case of fixed base power for the CSP system, an approximate annual CO_2 emissions reduction of 3248.27 tons of CO_2 emissions per year for the CSP system.

The PV system achieved a total reduction of 1484.60 tons of CO_2 emissions in the year. The integrated PV and CSP system which hybridizes the strengths of both technologies achieves an impressive substantial annual reduction of 4,732.87 tons of CO_2 emissions. These figures reinforce the message of combining CSP and PV technologies in efforts to control carbon emissions while providing a dependable power supply.

In Scenario-B the baseload generation schedule is changed depending on the power demand load and hence the cuts in CO_2 emissions are somewhat moderate. The CSP system in this scenario avoids 3,526.41 tons of CO_2 emissions annually. The PV system contributes to an annual reduction of 1,484.60 tons of CO_2 emissions.

The hybrid PV and CSP system, in as much as all power fluctuation schedules have been completely harnessed, turns on and outperforms by lowering 5,011.01 tons of CO_2 emissions. This case also demonstrates the improvement achieved by the hybrid system in its ability to reduce carbon emissions, through its ability to respond to different levels of energy demand, thus enhancing environmental benefits.

In general, both scenarios demonstrate the promising capability of hybrid PV and CSP systems to contribute towards CO_2 emissions reduction, with Scenario-B demonstrating more reduction because it is more flexible to changing loads. The detailed CO_2 emissions reductions for both scenarios are visually represented in A.18 (Appendix A).

3.4.3 Land Use and Ecological Impact

CSP and PV power plants require extensive land compared to conventional power plants. Securing suitable land for a large CSP plant is critical and must meet specific natural conditions. These areas must be appropriate for constructing solar fields, necessitating verification of factors such as inhabited areas, ground structure, water bodies, land slope, presence of dunes, and compliance with protected or restricted areas, including forests, mountains, and agricultural zones.

PT-CSP systems particularly demand large, flat expanses, with preferred slopes ranging from 1 to 2% (Yasin, 2019). In Jericho, a site with a favorable 1.3% slope was identified, following a meticulous evaluation of available land and consultations with the Jericho municipality's planning department. This selection process ensures optimal conditions for efficient solar power generation. Additionally, our study case requires approximately 90,000 m^2 of land for implementation.

3.4.4 Water Consumption

Water availability stands as a critical determinant for concentrating power plants, particularly those utilizing wet cooling systems. This particular system has proved to be more efficient as well as cost-saving than other alternatives such as the dry cooling system, thus the need for these plants to have constant water sources. In Jericho, a thorough assessment of water availability at the chosen site has been undertaken, drawing upon data from governmental institutions. Its location to sufficient water sources as well as extends to existing water supply mains enhances such power plant (Yasin, 2019). The overall life cycle water consumption coefficient for dry-cooled and wet-cooled PT solar thermal plants is registered as 0.9 and 3.98 m^3 /MWh, respectively. On the other hand, in PV crystalline silicon, the recorded coefficient is 0.33 m^3 /MWh (Ullah et al., 2023b). In this case, the CSP system is estimated to use 18,819 m^3 of water in a year which is using for cooling and washing.

3.5 Political and Regulatory Implications

Since 1995, management of Palestine's energy sector has been overseen by the Palestinian Energy and Natural Resources Authority (PENRA), operating within the jurisdiction of the Palestinian President's Office. PENRA plays a crucial role in regulation, research, and service provision within the energy domain, coordinating with associated institutions. Such centralized rule shows the determination of the government to satisfy the local energy requirements effectively.

PENRA has developed strategies since the year 2011, proposing aggressive targets and goals, policies, and even budgets for the development of renewable energy (RE). However, the realization of these goals encounters significant obstacles stemming from geographical, political, economic, and technical challenges. Despite developments in the use of solar energy, the harnessing of other RE sources remains on hold, with expected investments in biogas yet to be fully realized.

Aside from that, the Palestinian Authority has stated a complete well-coordinated approach to developing green and efficient power generation for sustainable purposes. Such policies in support of solar PV adoption are evident worldwide and are reinforced with policies in Palestine in support of the development and adoption of RE.

On the other hand, such efforts are hampered, among other reasons, by the persistent dependency on energy supplied from Israel, which compromises sustainability and increases the already critical power deficit in the Gaza Strip. There is a need for policy change to improve coordination, reduce bureaucracy, and encourage investment.

However, there is greater potential in the field of solar energy generation capabilities if the Palestinians are allowed to exploit the full potential of their land. The strategies and initiatives promoted by the Energy and Natural Resources Authority, which involve the private sector, seek to increase the use of renewable energy and raise environmental awareness. The incentives approved by the Palestinian Cabinet represent another step towards enhancing the use of renewable energy, indicating a united front to address the energy crisis in Palestine and move the nation towards sustainability (Juidi et al., 2022).

Chapter Four

Conclusion and Recommendations

4.1 Conclusion

1. In the case of Palestine, this study lays out a complete techno-economic model of a hybrid photovoltaic-thermal power system under the two deployment scenarios. Scenario B is identified as the optimal configuration. The analysis demonstrates that it is possible to consider solar energy as an economically sustainable technology that addresses regional energy requirements. This combination of concentrating solar power with PV modules has advantages that are evidenced and offer considerable views on technology performance and economics.

2. The technical evaluation demonstrated the efficiency and reliability of the designed PV and CSP hybrid system rated 2MW with an annual electricity generation of 6,668,461.00 kWh. Integration of CSP and PV technologies has been efficient with a capacity factor of 38% guaranteeing energy availability all year round. Also, this increase in the efficiency of the system due to thermal energy storage ensures that energy is available even when solar radiation is lower.

3. From an economic perspective, the cost analysis makes it easier to identify the costs involved in the components of the hybrid PV and CSP system. As to a detailed analysis of the breakdown of capital expenditures, they amounted to 8,609,899.56 $ including the cost of solar panels, inverters, mounting structures, and infrastructure. Let's assume there is a power purchase agreement in place for the power generated, valued at $0.17 per kWh, and then this means there are revenues that will be sustained.

4. Key financial indicators point to the fact that the system is economically viable. The internal rate of return on investment is 13.35 % and the net present value is 3,934,474.00 $ which makes returns on investment reasonable to expect. Also, each of the cash flow patterns over the period through its analysis illustrates a payback period of 7 years. Based on these results, financial viability and potential profitability are being able to implement a hybrid PV and CSP system in Palestine.

5. In addition, the environmental impact assessment establishes the system's ability to combat climate change through the reduction of carbon emissions. A hybrid CSP system should be expected to result in carbon dioxide reduction by around 5,011.01 tons every year as compared to conventional methods. The establishment of solar power plants supports the achievement of sustainable development and has a small negative impact on the environment.

4.2 Recommendation

1. **Policy**: Investment policies should be developed and implemented through legislative and institutional frameworks. Which includes incentives like investment tax credits, feed-in tariffs, and fast-track permitting processes to facilitate project construction and lure investments.

2. **Infrastructure and Grid Enhancements:** Necessary to invest in improving infrastructure and upgrading the grid. Furthermore, investment in smart grid technology, increasing transmission capacity and improving system resiliency to support the interconnection of renewable energy sources.

3. **International Partnerships**: Making relationships with international organizations, donor agencies, and financial organizations for funding, expertise, and technological assistance. Global partnerships can be used to speed up the execution of the projects as well the access to funding opportunities and the move to sustainable energy transition in Palestine.

List of Abbreviations

Abbreviation	Meaning
PV	Photovoltaic
CSP	Concentrated Solar Power
IEC	Israeli Electricity Corporation
GEC	Gaza Electricity Company
PCBS	Palestinian Central Bureau of Statistics
PENRA	Palestinian Energy and Natural Resources Authority
$kWh/m^2/day$	Kilowatt-hours per square meter per day
MW	Megawatt
kW	Kilowatt
LCOE	Levelized Cost of Energy
SAM	System Advisor Model
GHG	Greenhouse Gas
TES	Thermal Energy Storage
BESS	Battery Energy Storage System
SM	Solar Multiple
EPBT	Energy Payback Time
GWP	Global Warming Potential
CO_2eq	Carbon Dioxide Equivalent
STC	Standard Test Conditions
AM	Air Mass
Mono-Si	Monocrystalline Silicon
Poly-Si	Polycrystalline Silicon
CIGS	Copper-Indium-Gallium-Selenide
NREL	National Renewable Energy Laboratory
DNI	Direct Normal Irradiance
HTF	Heat Transfer Fluid
GHI	Global Horizontal Irradiance
DHI	Diffuse Horizontal Irradiance

O&M	Operation and Maintenance
PPA	Power Purchase Agreement
IRR	Internal Rate of Return

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Appendices

Appendix A

Figures of Study

Figure A.1

Wind speed for different cities in Palestine

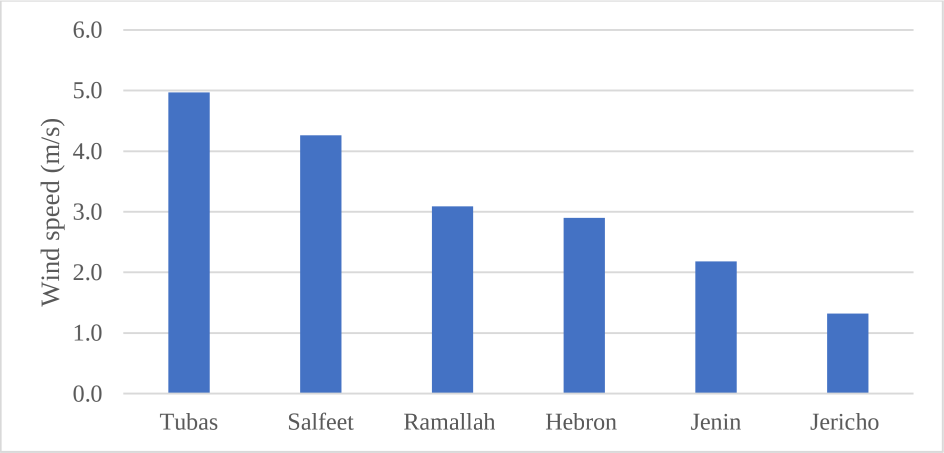


Figure A.2

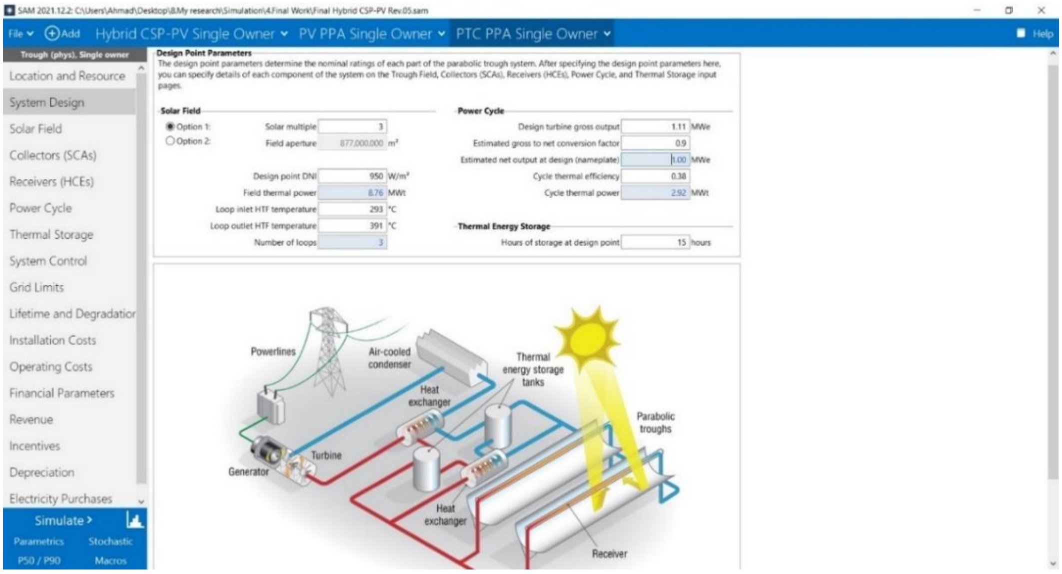
Solar Power Station 580 MW CSP-PV complex located in the Drâa-Tafilalet region of central Morocco

Figure A.3

Hybrid PV and CSP system with 800 MW in Chile

Figure A.4

System Advisor Model (SAM Software)



SAM 2021.12.2: C:\Users\Ahmad\Desktop\8.My research\Simulation\4.Final Work\Final Hybrid CSP-PV Rev.05.sam

Design Point Parameters

The design point parameters determine the nominal ratings of each part of the parabolic trough system. After specifying the design point parameters here, you can specify details of each component of the system on the Trough Field, Collectors (SCAs), Receivers (HCEs), Power Cycle, and Thermal Storage input pages.

Solar Field

● Option 1: Solar multiple 3

○ Option 2: Field aperture 877,000,000 m²

Design point DNI 950 W/m²

Field thermal power 8.76 MWt

Loop inlet HTF temperature 293 °C

Loop outlet HTF temperature 391 °C

Number of loops 3

Power Cycle

Design turbine gross output 1.11 MWe

Estimated gross to net conversion factor 0.9

Estimated net output at design (nameplate) 1.00 MWe

Cycle thermal efficiency 0.38

Cycle thermal power 2.92 MWt

Thermal Energy Storage

Hours of storage at design point 15 hours

Figure A.5

Annual beam irradiance – DNI In Jericho

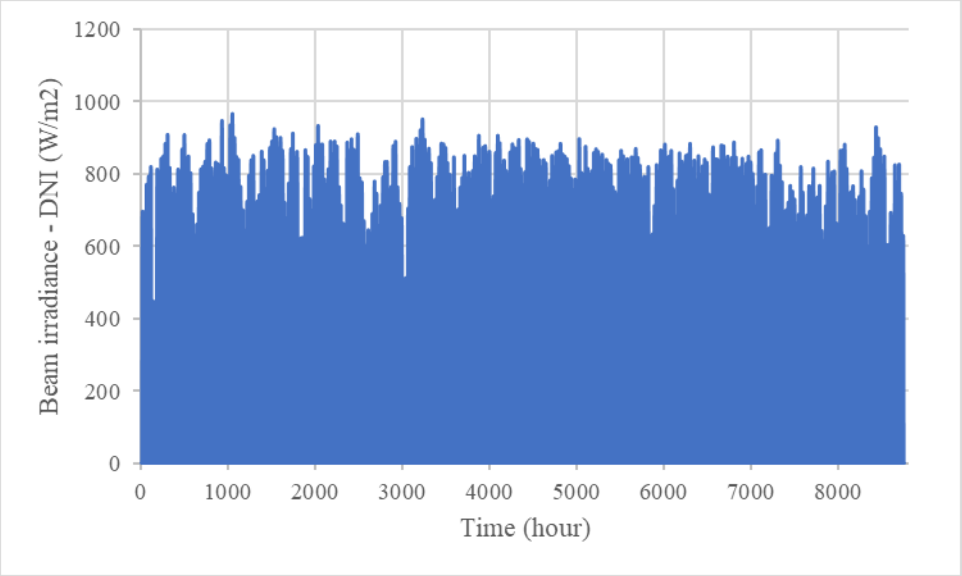


Figure A.6

Monthly Average Air Temperature C°

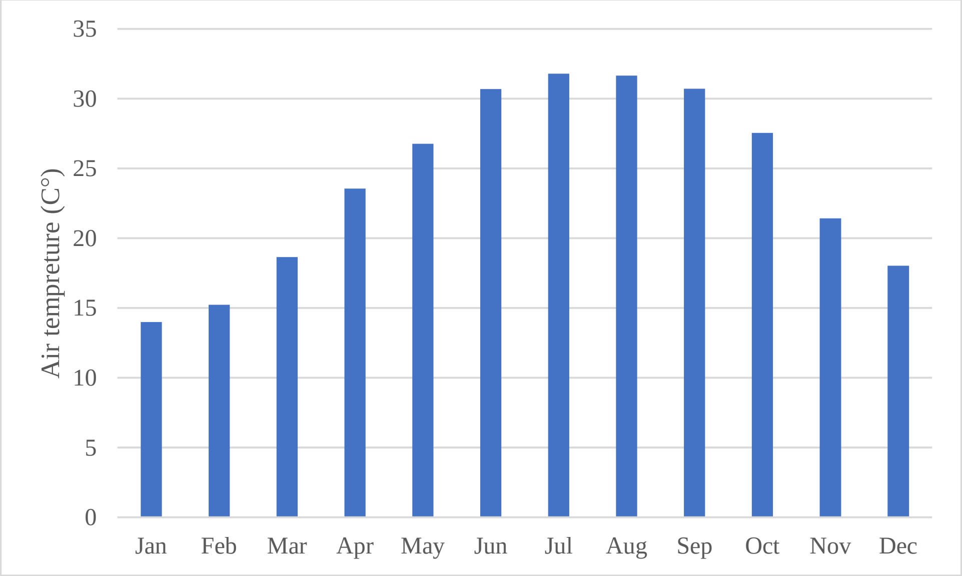


Figure A.7

Impact of TES on capacity factor and LCOE

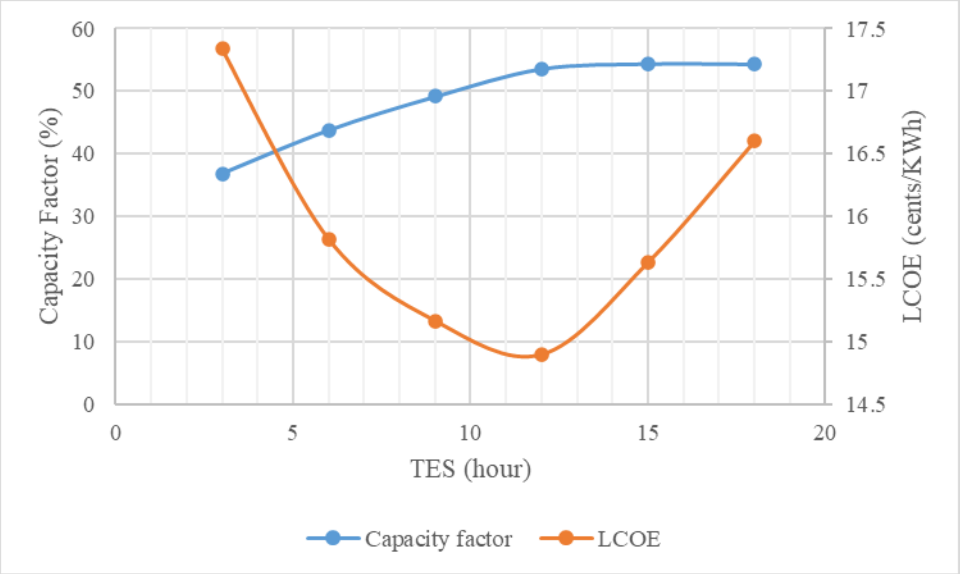


Figure A.8

Impact of solar multiple on capacity factor and LCOE

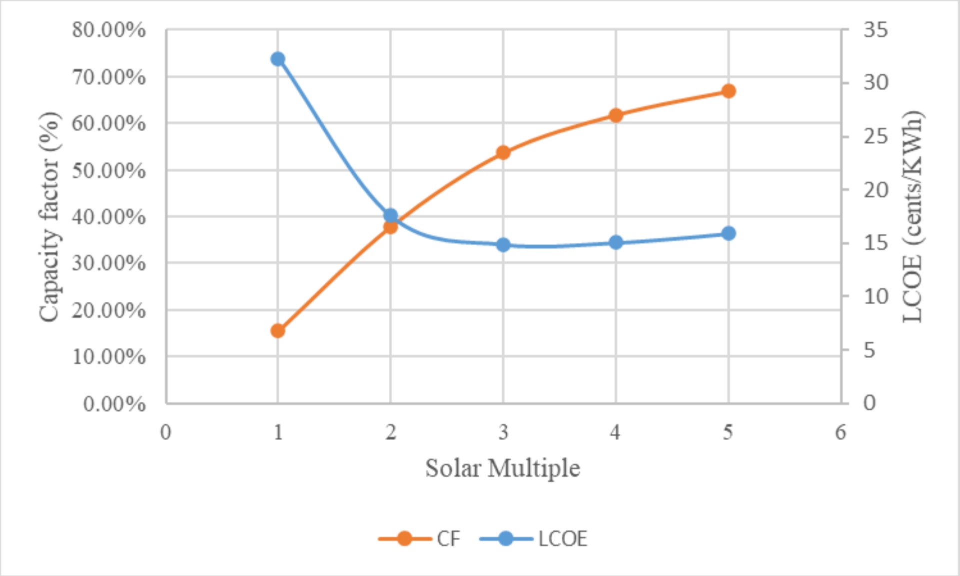


Figure A.9

Impact of title angel on LCOE and capacity factor

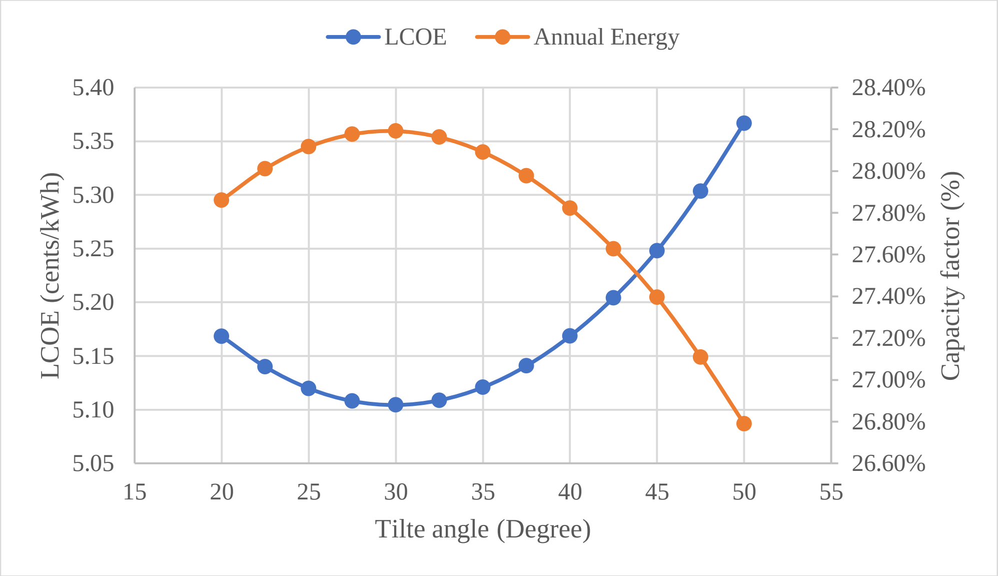


Figure A.10

Annual energy production result for each scenario

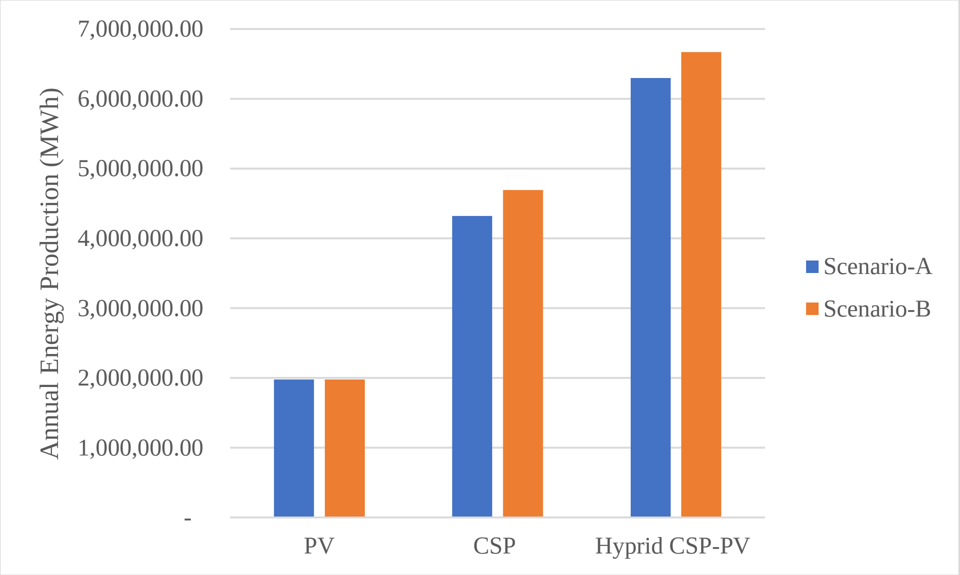


Figure A.11

Monthly produced energy from hybrid CSP-PV in one year

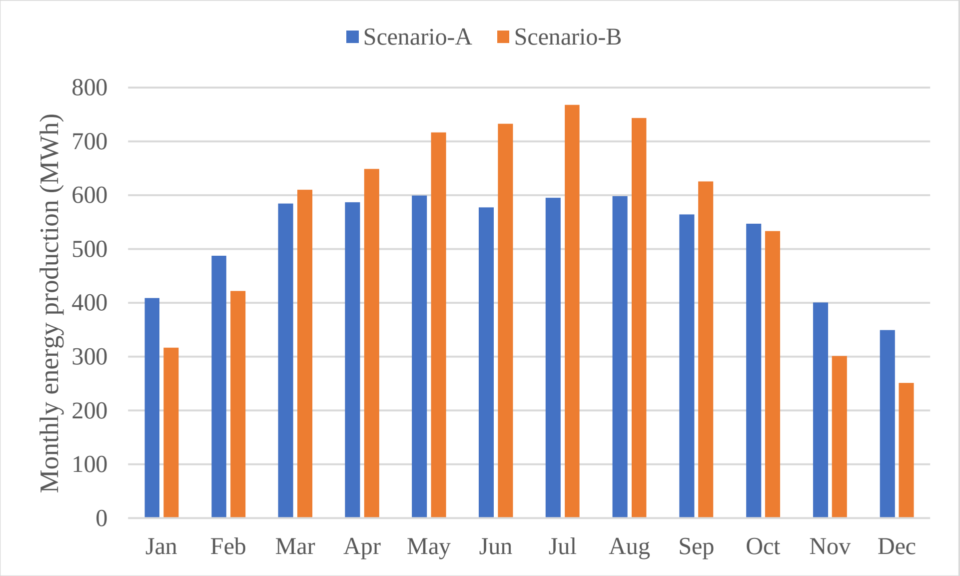


Figure A.12

Capacity factor result for CSP-PV hybrid system

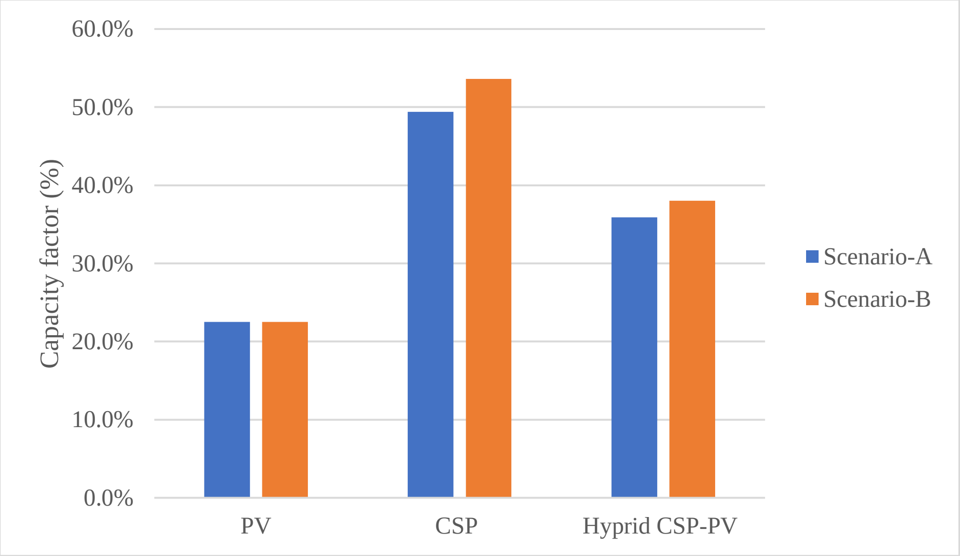


Figure A.13

NPV result for hybrid CSP-PV system

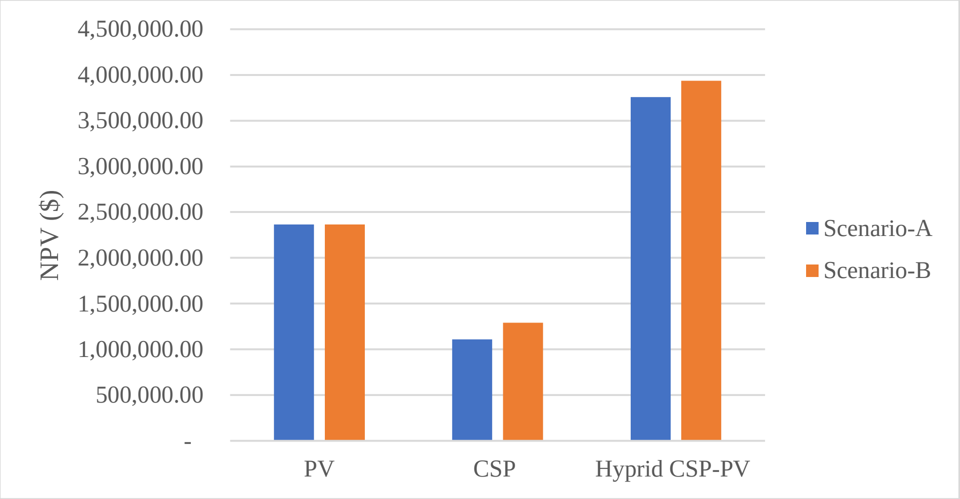


Figure A.14

IRR results for hybrid CSP-PV system

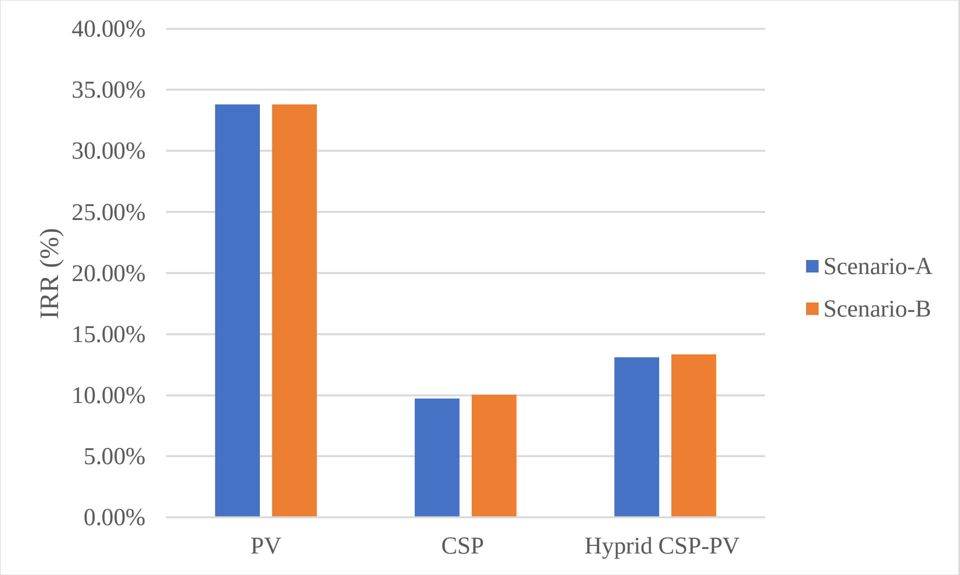


Figure A.15

LCOE results for hybrid CSP-PV system

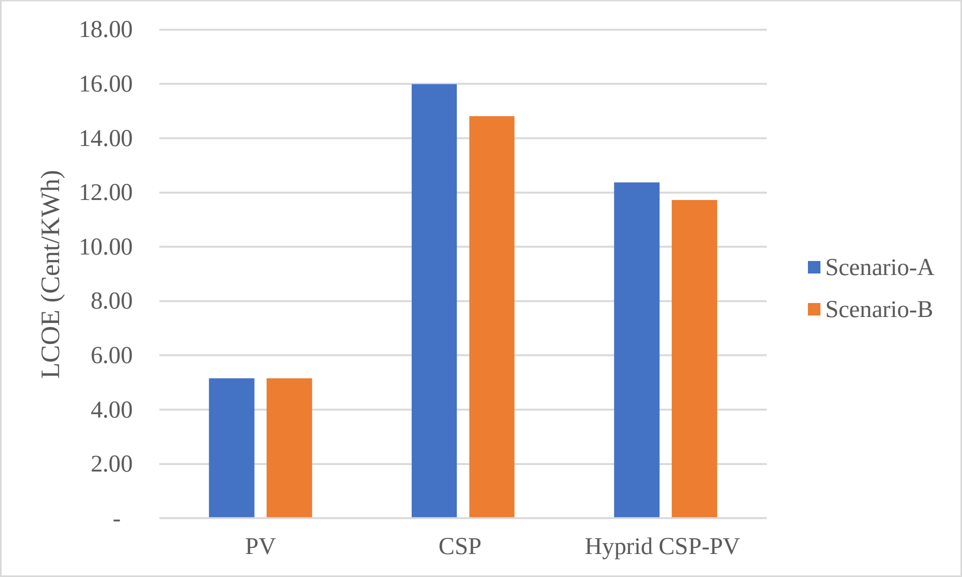


Figure A.16

PPB results for hybrid CSP-PV system

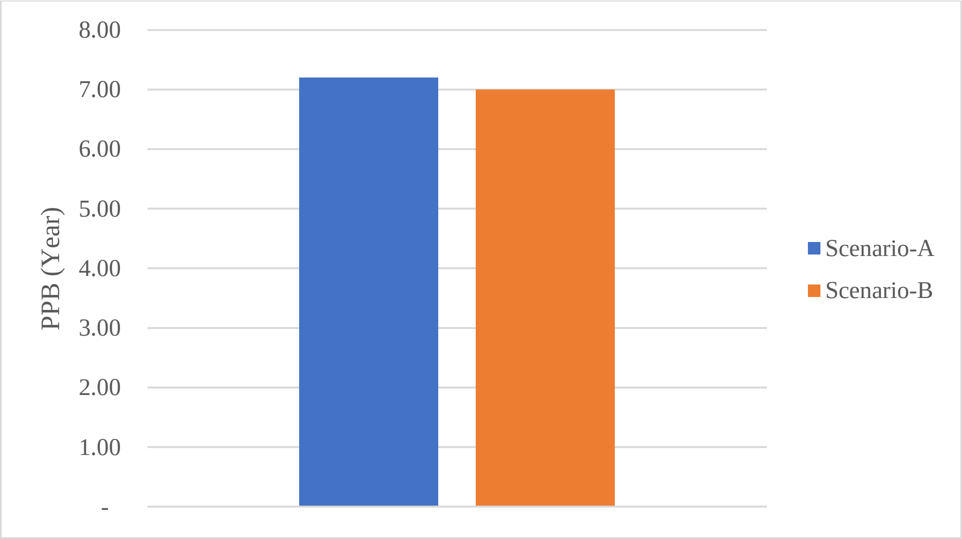


Figure A.17

Cash flow for hybrid CSP-PV system scenario-B

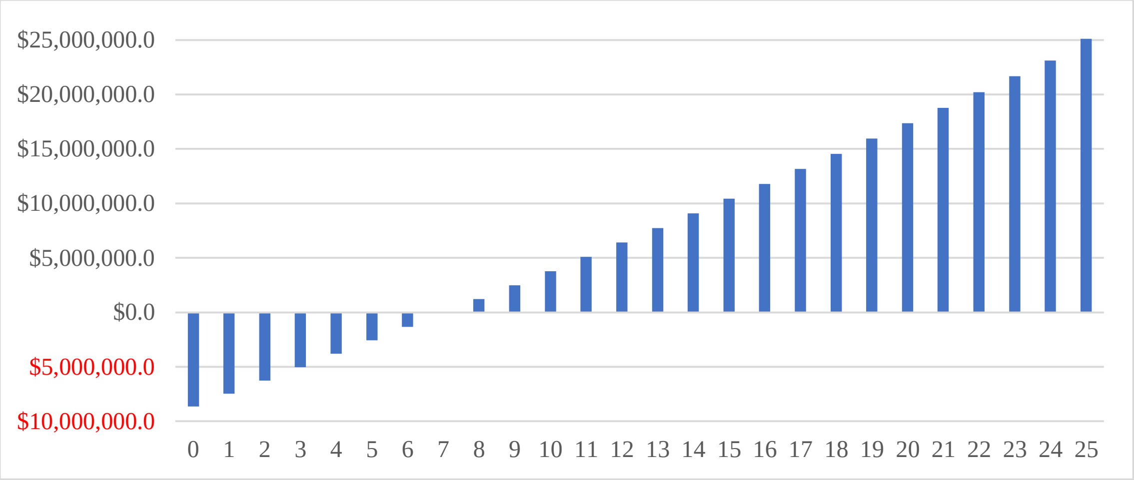
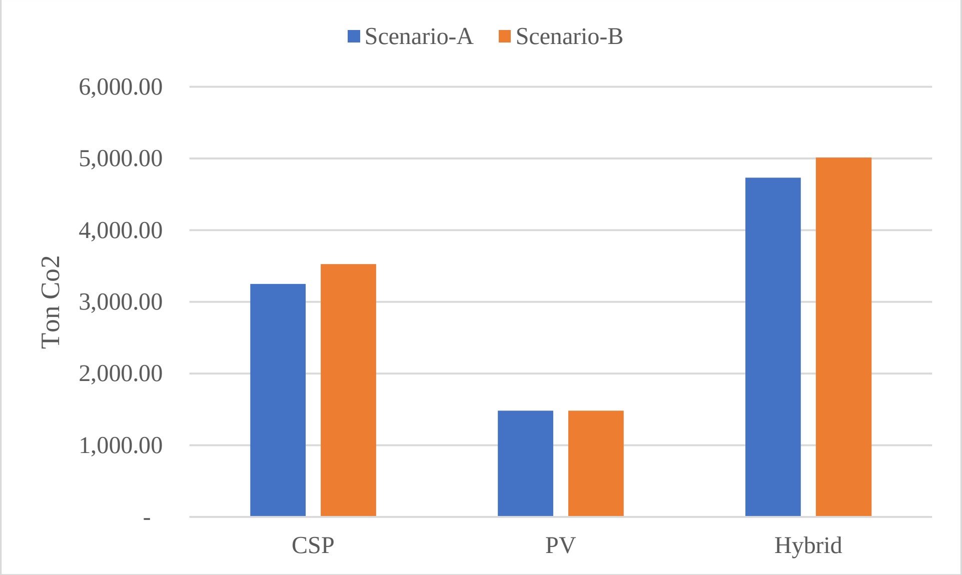


Figure A.18

CO2 emission reductions based on different scenarios

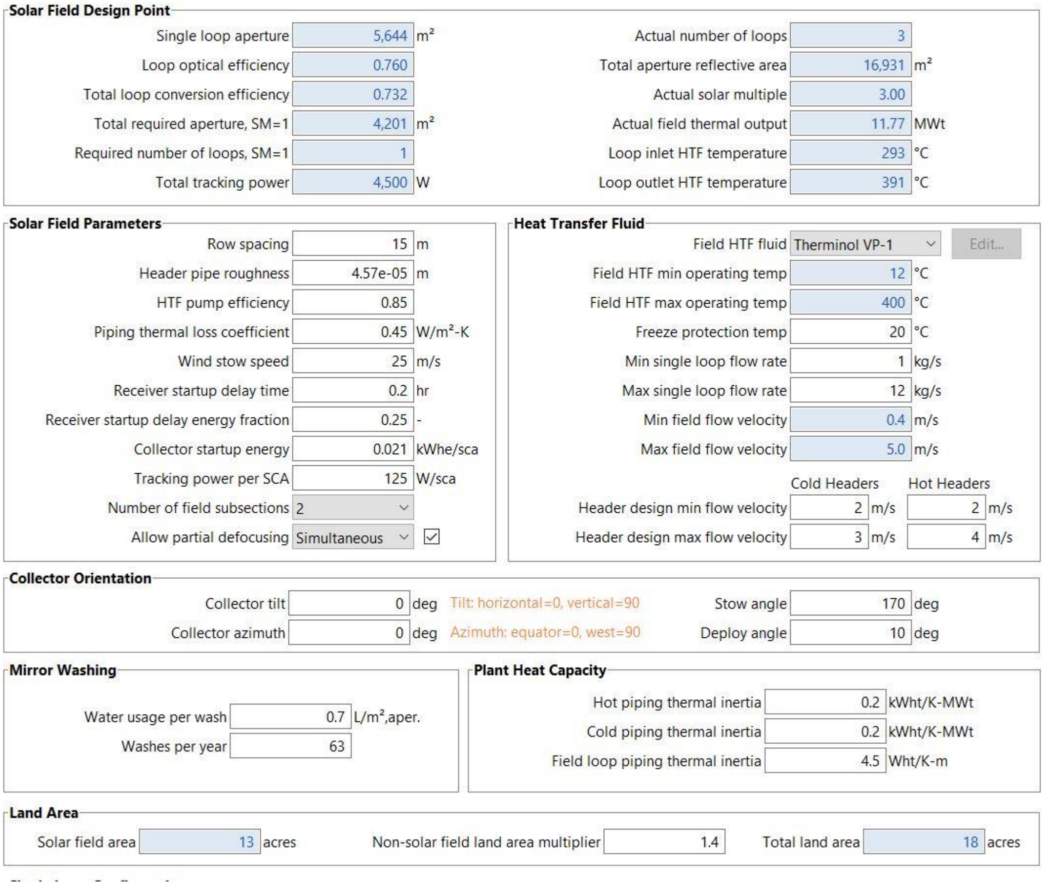


Appendix B

Software Setting

Figure B.1

Screenshot of SAM software for solar field design parameter



Solar Field Design Point

Single loop aperture 5,644 m²
Loop optical efficiency 0.760
Total loop conversion efficiency 0.732
Total required aperture, SM=1 4,201 m²
Required number of loops, SM=1 1
Total tracking power 4,500 W
Actual number of loops 3
Total aperture reflective area 16,931 m²
Actual solar multiple 3.00
Actual field thermal output 11.77 MWt
Loop inlet HTF temperature 293 °C
Loop outlet HTF temperature 391 °C

Solar Field Parameters

Row spacing 15 m
Header pipe roughness 4.57e-05 m
HTF pump efficiency 0.85
Piping thermal loss coefficient 0.45 W/m²-K
Wind stow speed 25 m/s
Receiver startup delay time 0.2 hr
Receiver startup delay energy fraction 0.25 -
Collector startup energy 0.021 kWhe/sca
Tracking power per SCA 125 W/sca
Number of field subsections 2
Allow partial defocusing Simultaneous ☑

Heat Transfer Fluid

Field HTF fluid Therminol VP-1
Field HTF min operating temp 12 °C
Field HTF max operating temp 400 °C
Freeze protection temp 20 °C
Min single loop flow rate 1 kg/s
Max single loop flow rate 12 kg/s
Min field flow velocity 0.4 m/s
Max field flow velocity 5.0 m/s

	Cold Headers	Hot Headers
Header design min flow velocity	2 m/s	2 m/s
Header design max flow velocity	3 m/s	4 m/s

Collector Orientation

Collector tilt 0 deg
Tilt: horizontal=0, vertical=90
Collector azimuth 0 deg
Azimuth: equator=0, west=90
Stow angle 170 deg
Deploy angle 10 deg

Mirror Washing

Water usage per wash 0.7 L/m²,aper.
Washes per year 63

Plant Heat Capacity

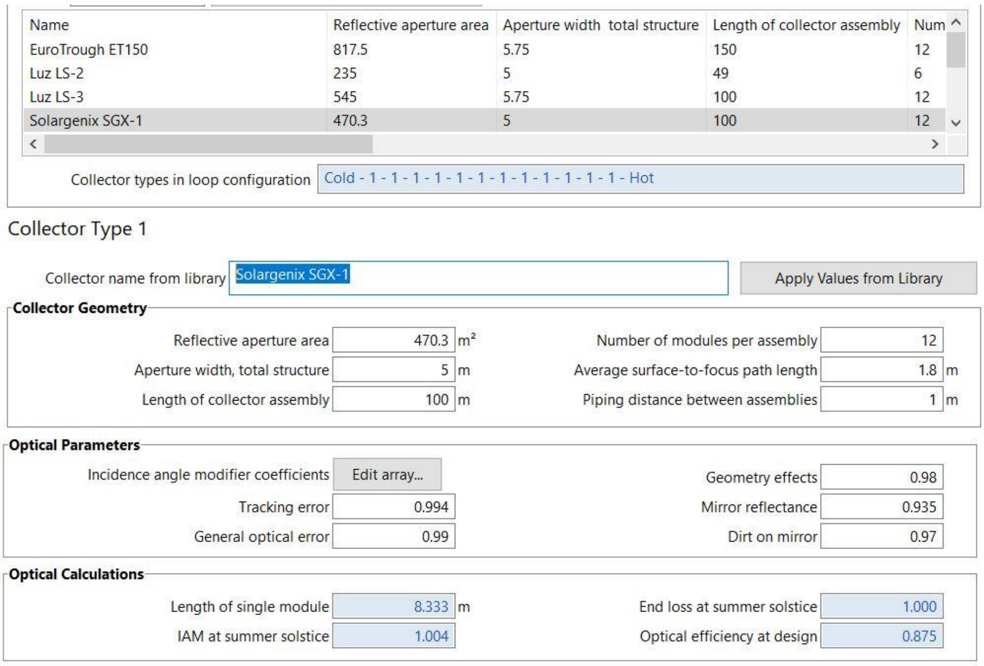
Hot piping thermal inertia 0.2 kWht/K-MWt
Cold piping thermal inertia 0.2 kWht/K-MWt
Field loop piping thermal inertia 4.5 Wht/K-m

Land Area

Solar field area 13 acres
Non-solar field land area multiplier 1.4
Total land area 18 acres

Figure B.2

Screenshot of SAM software for collector design parameter



Name	Reflective aperture area	Aperture width total structure	Length of collector assembly	Num
EuroTrough ET150	817.5	5.75	150	12
Luz LS-2	235	5	49	6
Luz LS-3	545	5.75	100	12
Solargenix SGX-1	470.3	5	100	12

Collector types in loop configuration: Cold - 1 - 1 - 1 - 1 - 1 - 1 - 1 - 1 - 1 - 1 - 1 - 1 - Hot

Collector Type 1

Collector name from library: Solargenix SGX-1

Collector Geometry

Reflective aperture area	470.3 m²	Number of modules per assembly	12
Aperture width, total structure	5 m	Average surface-to-focus path length	1.8 m
Length of collector assembly	100 m	Piping distance between assemblies	1 m

Optical Parameters

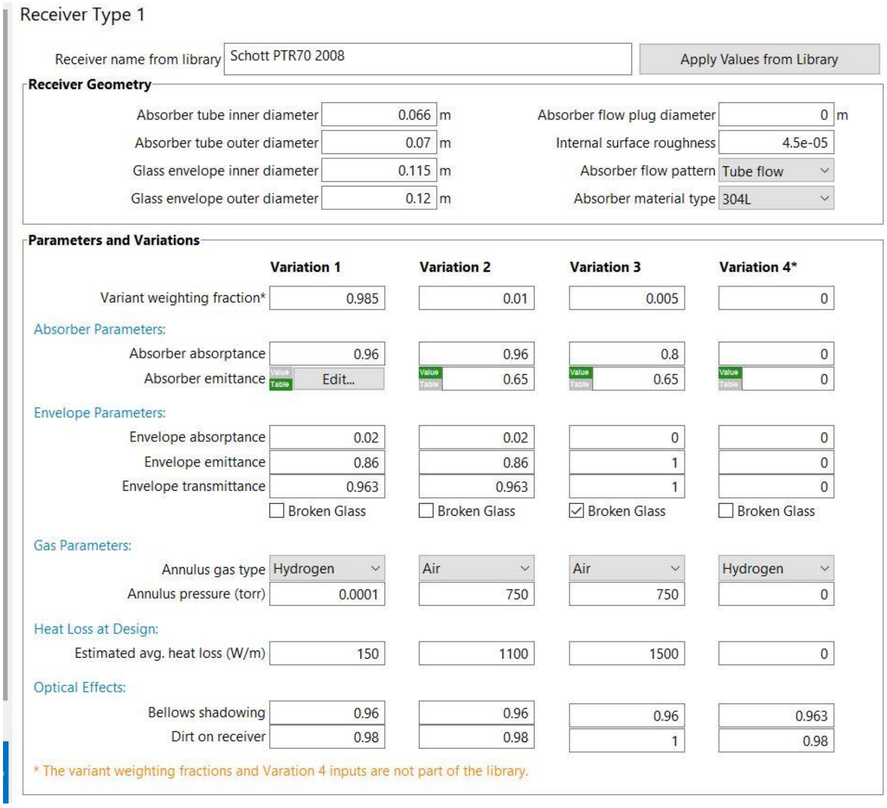
Incidence angle modifier coefficients	Edit array...	Geometry effects	0.98
Tracking error	0.994	Mirror reflectance	0.935
General optical error	0.99	Dirt on mirror	0.97

Optical Calculations

Length of single module	8.333 m	End loss at summer solstice	1.000
IAM at summer solstice	1.004	Optical efficiency at design	0.875

Figure B.3

Screenshot of SAM software for collector design parameter



Receiver Type 1

Receiver name from library: Schott PTR70 2008

Receiver Geometry

Absorber tube inner diameter	0.066 m	Absorber flow plug diameter	0 m
Absorber tube outer diameter	0.07 m	Internal surface roughness	4.5e-05
Glass envelope inner diameter	0.115 m	Absorber flow pattern	Tube flow
Glass envelope outer diameter	0.12 m	Absorber material type	304L

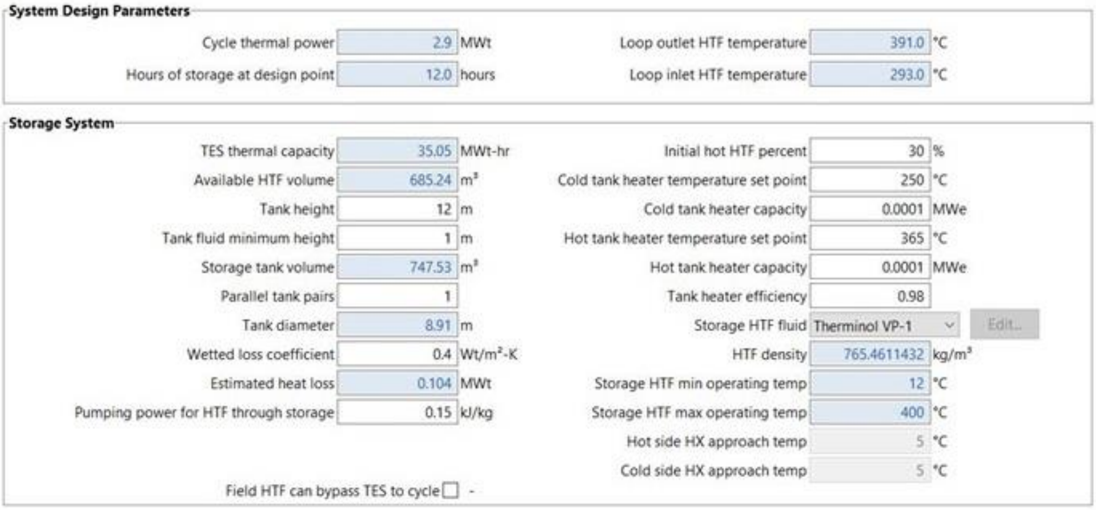
Parameters and Variations

	Variation 1	Variation 2	Variation 3	Variation 4*
Variant weighting fraction*	0.985	0.01	0.005	0
Absorber Parameters:				
Absorber absorptance	0.96	0.96	0.8	0
Absorber emittance	Edit...	0.65	0.65	0
Envelope Parameters:				
Envelope absorptance	0.02	0.02	0	0
Envelope emittance	0.86	0.86	1	0
Envelope transmittance	0.963	0.963	1	0
	☐ Broken Glass	☐ Broken Glass	☑ Broken Glass	☐ Broken Glass
Gas Parameters:				
Annulus gas type	Hydrogen	Air	Air	Hydrogen
Annulus pressure (torr)	0.0001	750	750	0
Heat Loss at Design:				
Estimated avg. heat loss (W/m)	150	1100	1500	0
Optical Effects:				
Bellows shadowing	0.96	0.96	0.96	0.963
Dirt on receiver	0.98	0.98	1	0.98

* The variant weighting fractions and Varation 4 inputs are not part of the library.

Figure B.4

Screenshot of SAM software for thermal storage parameter



System Design Parameters

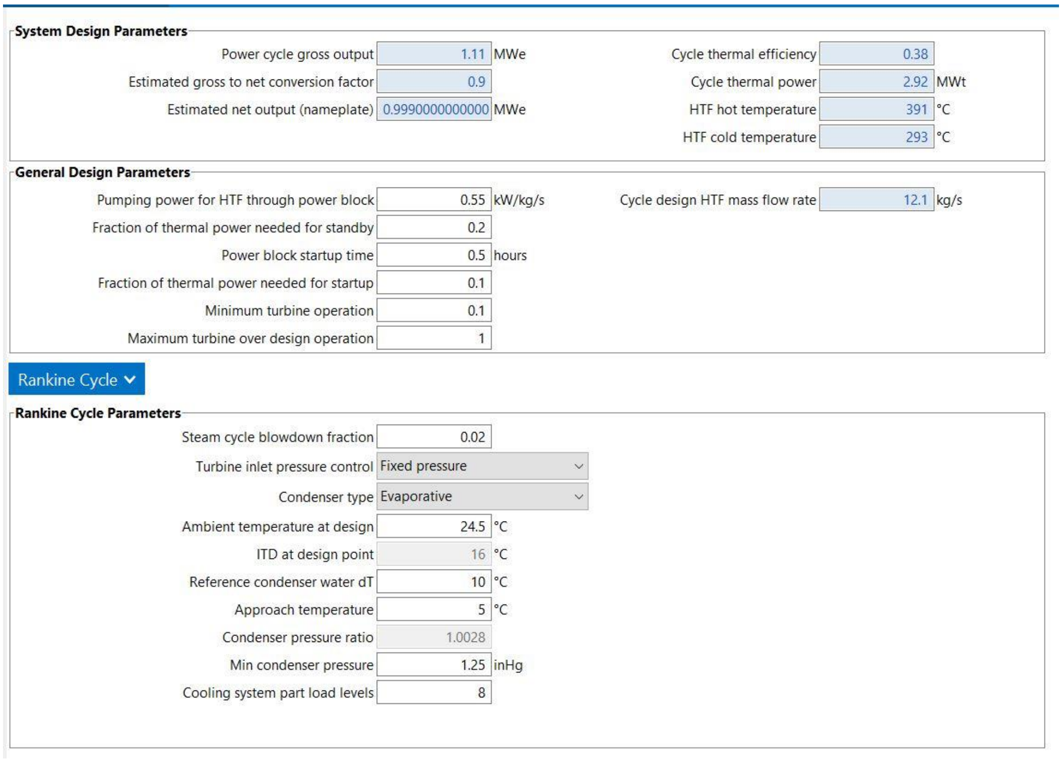
Cycle thermal power 2.9 MWt
Hours of storage at design point 12.0 hours
Loop outlet HTF temperature 391.0 °C
Loop inlet HTF temperature 293.0 °C

Storage System

TES thermal capacity 35.05 MWt-hr
Available HTF volume 685.24 m³
Tank height 12 m
Tank fluid minimum height 1 m
Storage tank volume 747.53 m³
Parallel tank pairs 1
Tank diameter 8.91 m
Wetted loss coefficient 0.4 Wt/m²-K
Estimated heat loss 0.104 MWt
Pumping power for HTF through storage 0.15 kJ/kg
Field HTF can bypass TES to cycle ☐ -
Initial hot HTF percent 30 %
Cold tank heater temperature set point 250 °C
Cold tank heater capacity 0.0001 MWe
Hot tank heater temperature set point 365 °C
Hot tank heater capacity 0.0001 MWe
Tank heater efficiency 0.98
Storage HTF fluid Therminol VP-1
HTF density 765.4611432 kg/m³
Storage HTF min operating temp 12 °C
Storage HTF max operating temp 400 °C
Hot side HX approach temp 5 °C
Cold side HX approach temp 5 °C

Figure B.5

Screenshot of SAM software for power block design parameter



System Design Parameters

Power cycle gross output 1.11 MWe
Estimated gross to net conversion factor 0.9
Estimated net output (nameplate) 0.9990000000000 MWe
Cycle thermal efficiency 0.38
Cycle thermal power 2.92 MWt
HTF hot temperature 391 °C
HTF cold temperature 293 °C

General Design Parameters

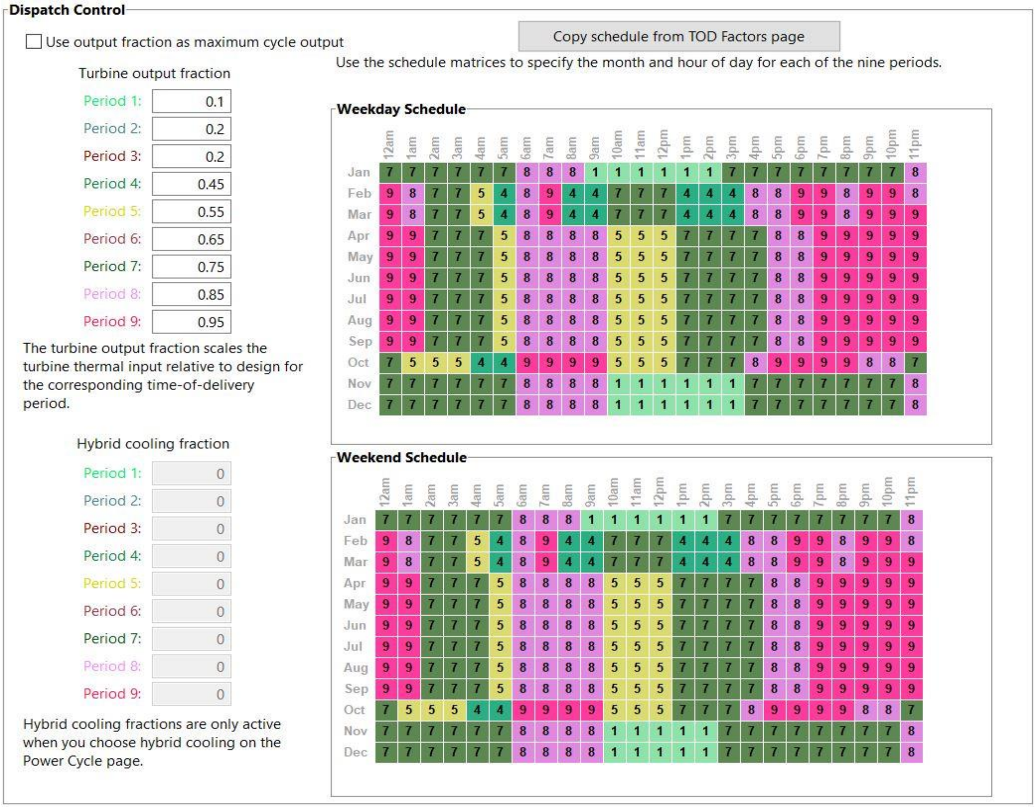
Pumping power for HTF through power block 0.55 kW/kg/s
Fraction of thermal power needed for standby 0.2
Power block startup time 0.5 hours
Fraction of thermal power needed for startup 0.1
Minimum turbine operation 0.1
Maximum turbine over design operation 1
Cycle design HTF mass flow rate 12.1 kg/s

Rankine Cycle Parameters

Steam cycle blowdown fraction 0.02
Turbine inlet pressure control Fixed pressure
Condenser type Evaporative
Ambient temperature at design 24.5 °C
ITD at design point 16 °C
Reference condenser water dT 10 °C
Approach temperature 5 °C
Condenser pressure ratio 1.0028
Min condenser pressure 1.25 inHg
Cooling system part load levels 8

Figure B.6

Screenshot of SAM software for dispatch control setting



Dispatch Control

☐ Use output fraction as maximum cycle output

Use the schedule matrices to specify the month and hour of day for each of the nine periods.

Turbine output fraction

Period 1:	0.1
Period 2:	0.2
Period 3:	0.2
Period 4:	0.45
Period 5:	0.55
Period 6:	0.65
Period 7:	0.75
Period 8:	0.85
Period 9:	0.95

The turbine output fraction scales the turbine thermal input relative to design for the corresponding time-of-delivery period.

Hybrid cooling fraction

Period 1:	0
Period 2:	0
Period 3:	0
Period 4:	0
Period 5:	0
Period 6:	0
Period 7:	0
Period 8:	0
Period 9:	0

Hybrid cooling fractions are only active when you choose hybrid cooling on the Power Cycle page.

Weekday Schedule

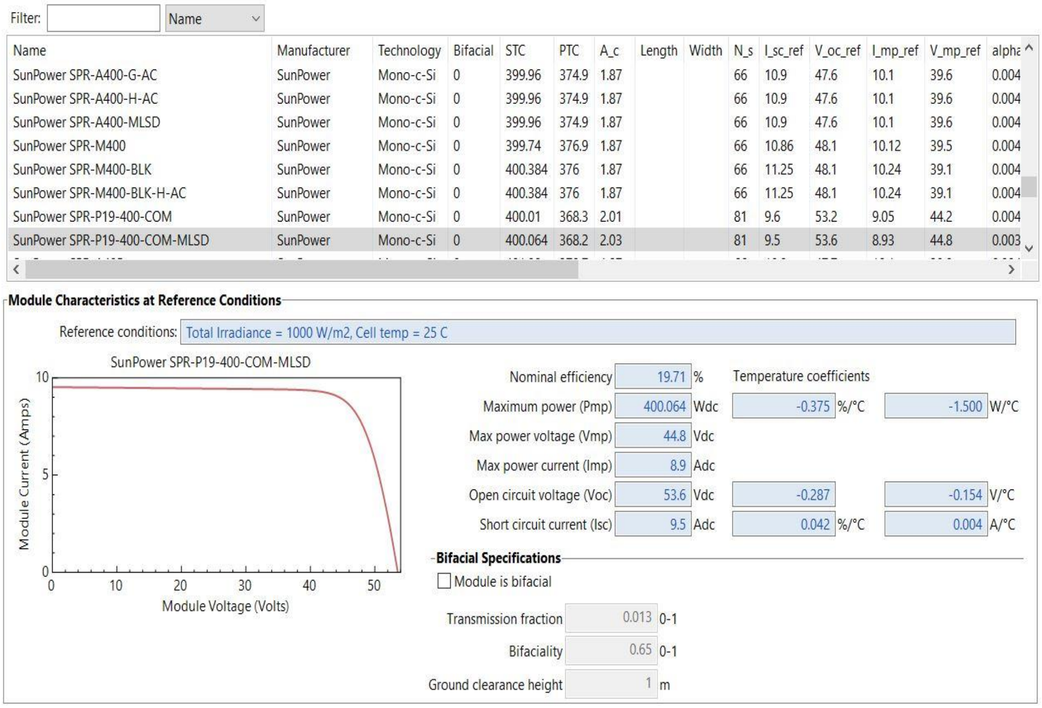
	12am	1am	2am	3am	4am	5am	6am	7am	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm	6pm	7pm	8pm	9pm	10pm	11pm
Jan	7	7	7	7	7	7	8	8	8	1	1	1	1	1	1	7	7	7	7	7	7	7	7	8
Feb	9	8	7	7	5	4	8	9	4	4	7	7	7	4	4	4	8	8	9	9	8	9	9	8
Mar	9	8	7	7	5	4	8	9	4	4	7	7	7	4	4	4	8	8	9	9	8	9	9	9
Apr	9	9	7	7	7	5	8	8	8	8	5	5	5	7	7	7	7	8	8	9	9	9	9	9
May	9	9	7	7	7	5	8	8	8	8	5	5	5	7	7	7	7	8	8	9	9	9	9	9
Jun	9	9	7	7	7	5	8	8	8	8	5	5	5	7	7	7	7	8	8	9	9	9	9	9
Jul	9	9	7	7	7	5	8	8	8	8	5	5	5	7	7	7	7	8	8	9	9	9	9	9
Aug	9	9	7	7	7	5	8	8	8	8	5	5	5	7	7	7	7	8	8	9	9	9	9	9
Sep	9	9	7	7	7	5	8	8	8	8	5	5	5	7	7	7	7	8	8	9	9	9	9	9
Oct	7	5	5	5	4	4	9	9	9	9	5	5	5	7	7	7	8	9	9	9	9	8	8	7
Nov	7	7	7	7	7	7	8	8	8	8	1	1	1	1	1	1	7	7	7	7	7	7	7	8
Dec	7	7	7	7	7	7	8	8	8	8	1	1	1	1	1	1	7	7	7	7	7	7	7	8

Weekend Schedule

	12am	1am	2am	3am	4am	5am	6am	7am	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm	6pm	7pm	8pm	9pm	10pm	11pm
Jan	7	7	7	7	7	7	8	8	8	1	1	1	1	1	1	7	7	7	7	7	7	7	7	8
Feb	9	8	7	7	5	4	8	9	4	4	7	7	7	4	4	4	8	8	9	9	8	9	9	8
Mar	9	8	7	7	5	4	8	9	4	4	7	7	7	4	4	4	8	8	9	9	8	9	9	9
Apr	9	9	7	7	7	5	8	8	8	8	5	5	5	7	7	7	7	8	8	9	9	9	9	9
May	9	9	7	7	7	5	8	8	8	8	5	5	5	7	7	7	7	8	8	9	9	9	9	9
Jun	9	9	7	7	7	5	8	8	8	8	5	5	5	7	7	7	7	8	8	9	9	9	9	9
Jul	9	9	7	7	7	5	8	8	8	8	5	5	5	7	7	7	7	8	8	9	9	9	9	9
Aug	9	9	7	7	7	5	8	8	8	8	5	5	5	7	7	7	7	8	8	9	9	9	9	9
Sep	9	9	7	7	7	5	8	8	8	8	5	5	5	7	7	7	7	8	8	9	9	9	9	9
Oct	7	5	5	5	4	4	9	9	9	9	5	5	5	7	7	7	8	9	9	9	9	8	8	7
Nov	7	7	7	7	7	7	8	8	8	8	1	1	1	1	1	7	7	7	7	7	7	7	7	8
Dec	7	7	7	7	7	7	8	8	8	8	1	1	1	1	1	7	7	7	7	7	7	7	7	8

Figure B.7

Screenshot of SAM software for PV module design parameter



Filter: Name

Name	Manufacturer	Technology	Bifacial	STC	PTC	A_c	Length	Width	N_s	I_sc_ref	V_oc_ref	I_mp_ref	V_mp_ref	alpha
SunPower SPR-A400-G-AC	SunPower	Mono-c-Si	0	399.96	374.9	1.87			66	10.9	47.6	10.1	39.6	0.004
SunPower SPR-A400-H-AC	SunPower	Mono-c-Si	0	399.96	374.9	1.87			66	10.9	47.6	10.1	39.6	0.004
SunPower SPR-A400-MLSD	SunPower	Mono-c-Si	0	399.96	374.9	1.87			66	10.9	47.6	10.1	39.6	0.004
SunPower SPR-M400	SunPower	Mono-c-Si	0	399.74	376.9	1.87			66	10.86	48.1	10.12	39.5	0.004
SunPower SPR-M400-BLK	SunPower	Mono-c-Si	0	400.384	376	1.87			66	11.25	48.1	10.24	39.1	0.004
SunPower SPR-M400-BLK-H-AC	SunPower	Mono-c-Si	0	400.384	376	1.87			66	11.25	48.1	10.24	39.1	0.004
SunPower SPR-P19-400-COM	SunPower	Mono-c-Si	0	400.01	368.3	2.01			81	9.6	53.2	9.05	44.2	0.004
SunPower SPR-P19-400-COM-MLSD	SunPower	Mono-c-Si	0	400.064	368.2	2.03			81	9.5	53.6	8.93	44.8	0.003

Module Characteristics at Reference Conditions

Reference conditions: Total Irradiance = 1000 W/m2, Cell temp = 25 C

			Temperature coefficients			
Nominal efficiency	19.71	%				
Maximum power (Pmp)	400.064	Wdc	-0.375	%/°C	-1.500	W/°C
Max power voltage (Vmp)	44.8	Vdc				
Max power current (Imp)	8.9	Adc				
Open circuit voltage (Voc)	53.6	Vdc	-0.287		-0.154	V/°C
Short circuit current (Isc)	9.5	Adc	0.042	%/°C	0.004	A/°C

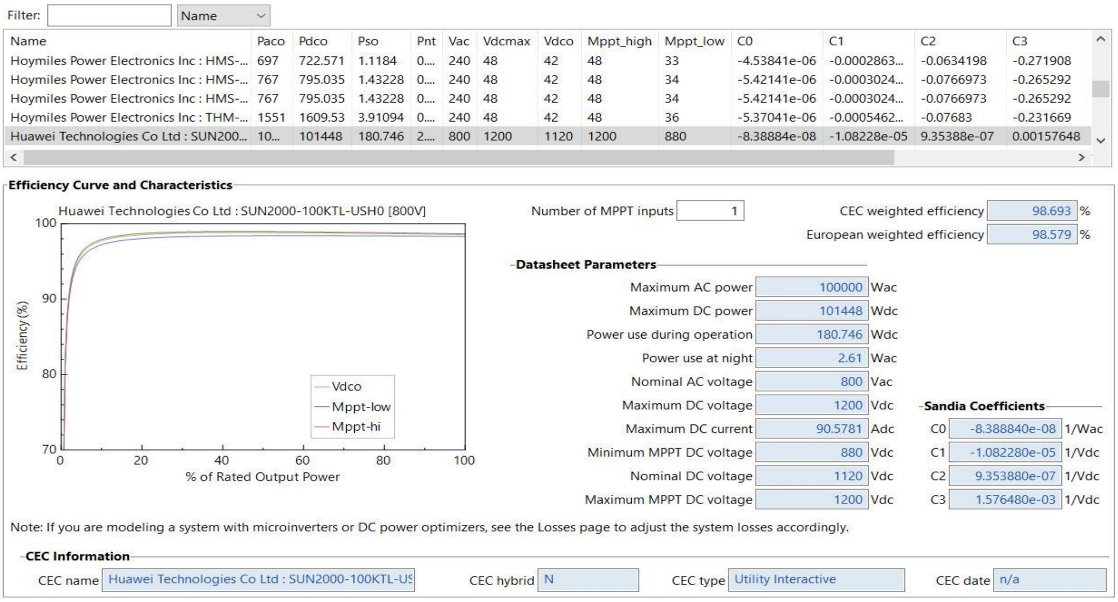
Bifacial Specifications

☐ Module is bifacial

Transmission fraction	0.013	0-1
Bifaciality	0.65	0-1
Ground clearance height	1	m

Figure B.8

Screenshot of SAM software for PV inverter design parameter



Name	Paco	Pdco	Pso	Pnt	Vac	Vdcmax	Vdco	Mppt_high	Mppt_low	C0	C1	C2	C3
Hoymiles Power Electronics Inc : HMS-...	697	722.571	1.1184	0....	240	48	42	48	33	-4.53841e-06	-0.0002863...	-0.0634198	-0.271908
Hoymiles Power Electronics Inc : HMS-...	767	795.035	1.43228	0....	240	48	42	48	34	-5.42141e-06	-0.0003024...	-0.0766973	-0.265292
Hoymiles Power Electronics Inc : HMS-...	767	795.035	1.43228	0....	240	48	42	48	34	-5.42141e-06	-0.0003024...	-0.0766973	-0.265292
Hoymiles Power Electronics Inc : THM-...	1551	1609.53	3.91094	0....	240	48	42	48	36	-5.37041e-06	-0.0005462...	-0.07683	-0.231669
Huawei Technologies Co Ltd : SUN200...	10...	101448	180.746	2....	800	1200	1120	1200	880	-8.38884e-08	-1.08228e-05	9.35388e-07	0.00157648

Number of MPPT inputs 1

CEC weighted efficiency 98.693 %

European weighted efficiency 98.579 %

Datasheet Parameters

Maximum AC power 100000 Wac
Maximum DC power 101448 Wdc
Power use during operation 180.746 Wdc
Power use at night 2.61 Wac
Nominal AC voltage 800 Vac
Maximum DC voltage 1200 Vdc
Maximum DC current 90.5781 Adc
Minimum MPPT DC voltage 880 Vdc
Nominal DC voltage 1120 Vdc
Maximum MPPT DC voltage 1200 Vdc

Sandia Coefficients

C0 -8.388840e-08 1/Wac
C1 -1.082280e-05 1/Vdc
C2 9.353880e-07 1/Vdc
C3 1.576480e-03 1/Vdc

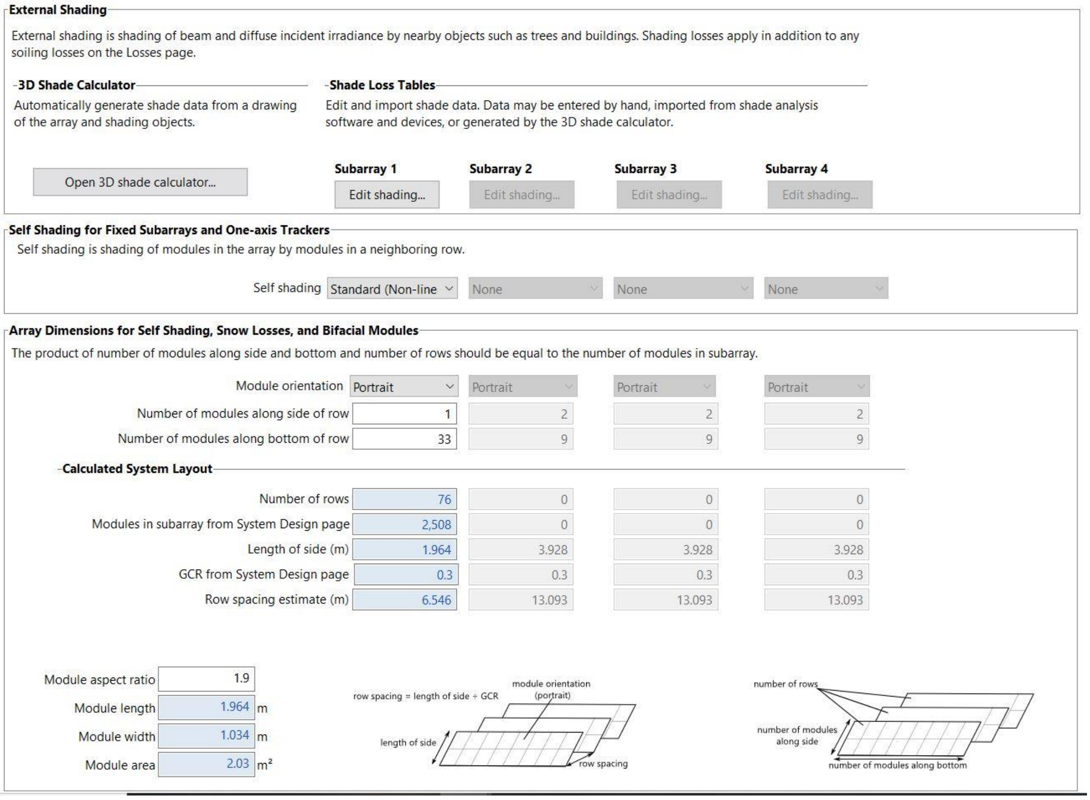
Note: If you are modeling a system with microinverters or DC power optimizers, see the Losses page to adjust the system losses accordingly.

CEC Information

CEC name Huawei Technologies Co Ltd : SUN2000-100KTL-US
CEC hybrid N
CEC type Utility Interactive
CEC date n/a

Figure B.9

Screenshot of SAM software for PV shading analysis



External Shading

External shading is shading of beam and diffuse incident irradiance by nearby objects such as trees and buildings. Shading losses apply in addition to any soiling losses on the Losses page.

3D Shade Calculator

Automatically generate shade data from a drawing of the array and shading objects.

Shade Loss Tables

Edit and import shade data. Data may be entered by hand, imported from shade analysis software and devices, or generated by the 3D shade calculator.

Subarray 1 Subarray 2 Subarray 3 Subarray 4

Self Shading for Fixed Subarrays and One-axis Trackers

Self shading is shading of modules in the array by modules in a neighboring row.

	Subarray 1	Subarray 2	Subarray 3	Subarray 4
Self shading	Standard (Non-line	None	None	None

Array Dimensions for Self Shading, Snow Losses, and Bifacial Modules

The product of number of modules along side and bottom and number of rows should be equal to the number of modules in subarray.

	Subarray 1	Subarray 2	Subarray 3	Subarray 4
Module orientation	Portrait	Portrait	Portrait	Portrait
Number of modules along side of row	1	2	2	2
Number of modules along bottom of row	33	9	9	9

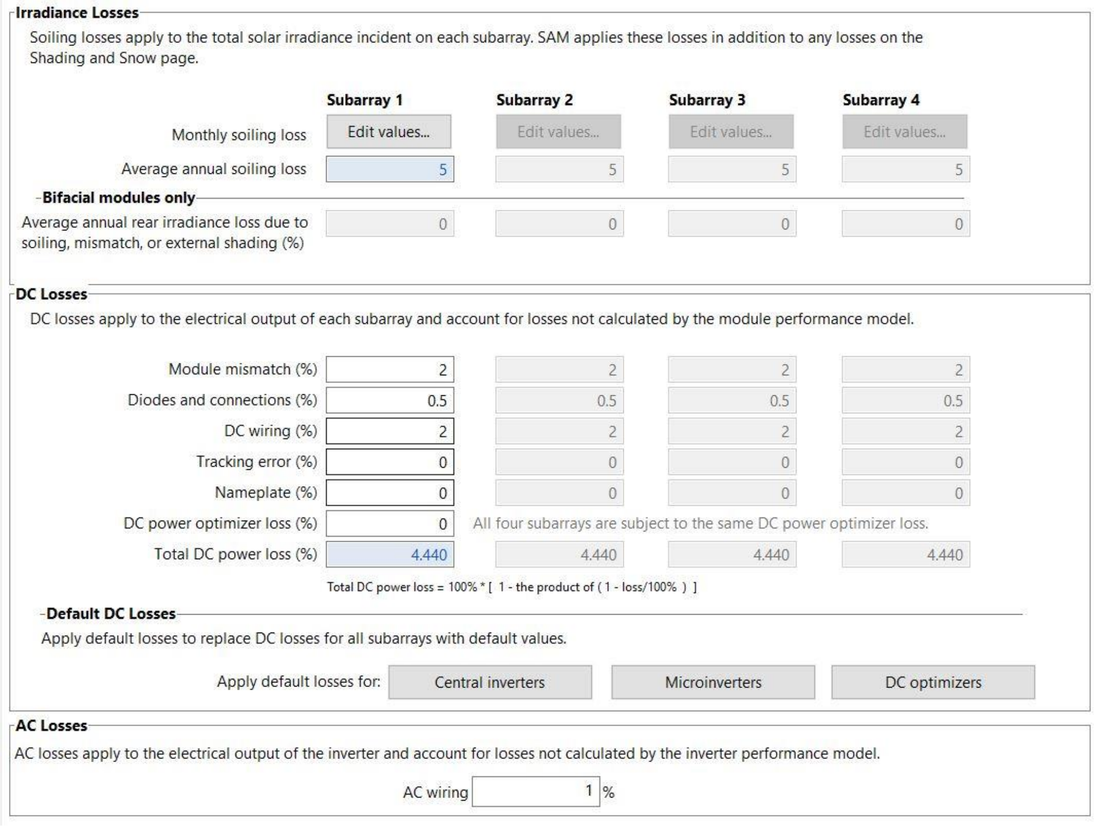
Calculated System Layout

	Subarray 1	Subarray 2	Subarray 3	Subarray 4
Number of rows	76	0	0	0
Modules in subarray from System Design page	2,508	0	0	0
Length of side (m)	1.964	3.928	3.928	3.928
GCR from System Design page	0.3	0.3	0.3	0.3
Row spacing estimate (m)	6.546	13.093	13.093	13.093

Module aspect ratio 1.9
Module length 1.964 m
Module width 1.034 m
Module area 2.03 m²

Figure B.10

Screenshot of SAM software for PV system losses



Irradiance Losses

Soiling losses apply to the total solar irradiance incident on each subarray. SAM applies these losses in addition to any losses on the Shading and Snow page.

	Subarray 1	Subarray 2	Subarray 3	Subarray 4
Monthly soiling loss	Edit values...	Edit values...	Edit values...	Edit values...
Average annual soiling loss	5	5	5	5
Bifacial modules only				
Average annual rear irradiance loss due to soiling, mismatch, or external shading (%)	0	0	0	0

DC Losses

DC losses apply to the electrical output of each subarray and account for losses not calculated by the module performance model.

Module mismatch (%)	2	2	2	2
Diodes and connections (%)	0.5	0.5	0.5	0.5
DC wiring (%)	2	2	2	2
Tracking error (%)	0	0	0	0
Nameplate (%)	0	0	0	0
DC power optimizer loss (%)	0	All four subarrays are subject to the same DC power optimizer loss.		
Total DC power loss (%)	4.440	4.440	4.440	4.440

Total DC power loss = 100% * [1 - the product of (1 - loss/100%)]

Default DC Losses

Apply default losses to replace DC losses for all subarrays with default values.

Apply default losses for:

AC Losses

AC losses apply to the electrical output of the inverter and account for losses not calculated by the inverter performance model.

AC wiring 1 %

Figure B.11

Monthly power generation scenario-A

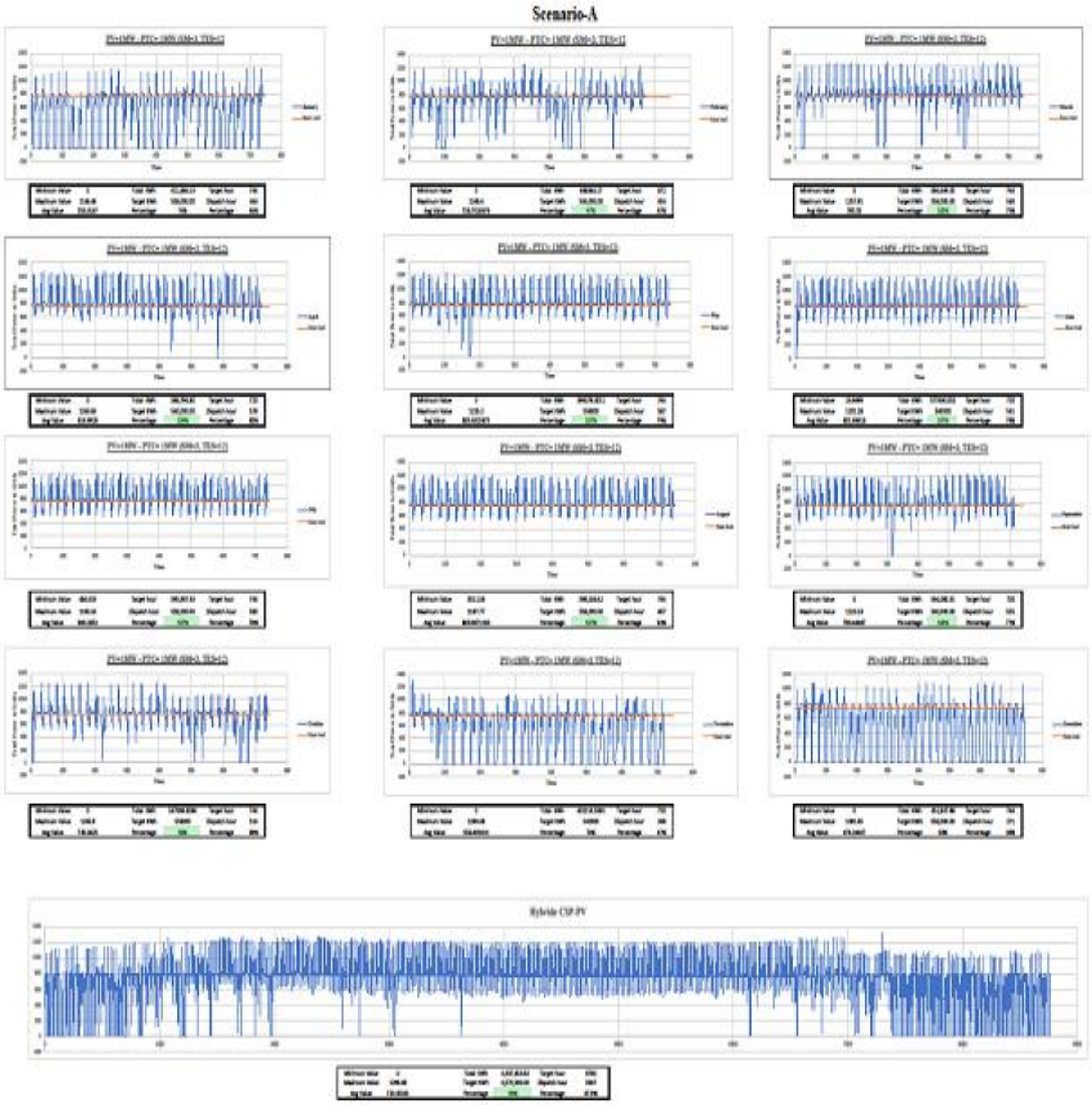


Figure B.12

Monthly power generation scenario-B

جامعة النجاح الوطنية

كلية الدراسات العليا

التحليل الفني والاقتصادي لتوليد الطاقة الكهربائية في فلسطين باستخدام الطاقة الشمسية المركزة والخلايا الشمسية بوجود نظام تخزين حراري

إعداد

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د. أيسر ياسين

قدمت هذه الأطروحة استكمالاً لمتطلبات الحصول على درجة الماجستير في هندسة الطاقة النظيفة وترشيد الاستهلاك، من كلية الدراسات العليا، في جامعة النجاح الوطنية، نابلس– فلسطين.

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الملخص

تهدف هذه الرسالة إلى إجراء تحليل تقني–اقتصادي لنظام هجين يجمع بين تكنولوجيا الطاقة الشمسية المركزة والألواح الشمسية لتوليد الكهرباء في فلسطين. تسعى الدراسة إلى تقييم جدوى وأداء وقابلية الاقتصادية لتكامل تقنيات الطاقة الشمسية المركزة والألواح الشمسية لمواجهة التحديات الطاقة في فلسطين. تبدأ الدراسة بتقييم إمكانيات الطاقة الشمسية في فلسطين، مستخدمة محافظة أريحا كدراسة حالة. تم تصميم النظام الهجين لتحسين الخصائص التكاميلية للنظام الهجين، مما يضمن إمدادًا مستمرًا بالطاقة وزيادة في الكفاءة. تم إجراء التقييمات التقنية والاقتصادية لكلتا التقنيتين باستخدام برنامج نظام المستشار (سام) لتحليل عامل السعة، إنتاج الطاقة، تحليل دورة حياة التكلفة، والتحليل الاقتصادي بما في ذلك تكلفة الطاقة المولدة، معدل العائد الداخلي، وفترة الاسترداد للنظام الهجين. تم إجراء التحليل تحت سيناريوهين: توفير حمل أساسي ومتابعة الحمل، لقياس أداء النظام والمرونة الاقتصادية تحت ظروف متغيرة. تم إجراء تقييمات الأثر البيئي، مع التركيز بشكل خاص على تقييم انبعاثات ثاني أكسيد الكربون المتجنبة نتيجة اعتماد النظام الهجين. تشير النتائج إلى أن نظام الهجين يقدم مزايا كبيرة مقارنة بالأنظمة المستقلة، بما في ذلك زيادة إنتاج الطاقة، الموثوقية، والفعالية من حيث التكلفة. على وجه التحديد، فإن تضمين تخزين الطاقة الحرارية في نظام الطاقة الشمسية المركزة يعزز مرونة واستقرار النظام، مما يجعله حلاً قابلاً للتطبيق لتوليد الطاقة المستدامة في فلسطين. يكشف التحليل الاقتصادي أن النظام الهجين يحقق تكلفة الطاقة المولدة بمقدار 11.72 سنت/كيلوواط ساعة، ومعدل العائد الداخلي بنسبة 13.35%،

وفترة الاسترداد تبلغ 7 سنوات تحت سيناريو متابعة الحمل، مع نتائج إيجابية مماثلة تحت سيناريو الحمل الأساسي. بالإضافة إلى ذلك، يُتوقع أن يتجنب النظام الهجين حوالي5,011.01 طن من انبعاثات ثاني أكسيد الكربون سنويًا.

الكلمات المفتاحية: نظام هجين للطاقة الكهروضوئية والطاقة الشمسية المركزة، تخزين الطاقة الحرارية، حوض مكافئ، برنامج سام.