DESIGN OF A FULLY CONCENTRATED SOLAR POWERED ELECTRICITY GENERATION PLANT FOR THE UAE

by

Hessa Abbas Ali

A Thesis Presented to the Faculty of the
American University of Sharjah
College of Engineering
In Partial Fulfillment
of the Requirements
for the Degree of

Master of Science in
Mechanical Engineering

Sharjah, United Arab Emirates

September 2018

Approval Signatures

We, the undersigned, approve the Master's Thesis of Hessa Abbas Ali.

Thesis Title: Design of a Fully Concentrated Solar Powered Electricity Generation Plant for the UAE.

Signature **Date of Signature**
(dd/mm/yyyy)

___________________________ _______________
Dr. Mohamed Gadalla
Professor, Department of Mechanical Engineering
Thesis Advisor

___________________________ _______________
Dr. Zarook Shareefdeen
Professor, Department of Chemical Engineering
Thesis Committee Member

___________________________ _______________
Dr. Mehmet Kanoglu
Visiting Professor, Department of Mechanical Engineering
Thesis Committee Member

___________________________ _______________
Dr. Mamoun Abdel-Hafez
Head, Department of Mechanical Engineering

___________________________ _______________
Dr. Ghaleb Husseini
Associate Dean for Graduate Affairs and Research
College of Engineering

___________________________ _______________
Dr. Richard Schoephoerster
Dean, College of Engineering

___________________________ _______________
Dr. Mohamed El-Tarhuni
Vice Provost for Graduate Studies

Acknowledgments

This work would not have been achieved if it were not for the support from all the parties involved. Therefore, I would like to thank my advisor, Professor Mohamed Gadalla, for the time and ongoing guidance he offered throughout the various stages of this thesis. I would also like to thank my friends and colleagues, Adnan Alashkar and Argin Nazari, for their encouragement and continuous support during my work on my thesis. Lastly, I will not forget to thank the University for the Provision of the resources and the software that I used in the accomplishment and the actualization of this thesis through simulation.

Abstract

The increase in the world's demand for electricity and the depletion of the fossil fuels used in conventional power plant systems raises the need for different renewable sources of electricity generation. Concentrated solar panel (CSP) is a leading solar technology, with parabolic trough (PT) collectors being the most efficient and advanced type of CSP. This thesis aims to propose and analyze a viable 50 MWe output CSP-PT plant to be integrated into the grid system of the United Arab Emirates (UAE). The simulation and analysis is performed using the System Advisor Model (SAM) and EnergyPLAN software. SAM is used to model the design of the plant and obtain the profiles of the energy supply throughout the year, which is fed to EnergyPLAN. The designed plant includes a thermal energy storage (TES) system to ensure 24-hour daily electricity generation with a 10-hour generation from direct solar energy and 14-hour generation through the use of energy stored in the TES. Three heat transfer fluids (HTFs) – molten salt, water and Therminol VP-1 – are also compared through modeling two configurations and the most efficient combination is selected. The result of this study is a feasible solar 50 MWe power generation plant that operates 24-hours per day by utilizing a 2 x 8 panel CSP-PT field, each panel being 12 m x 12 m, a two-tank direct TES, each tank being 6,604 m^3 in volume, with molten salt as the HTF and storage fluid, running a Rankine cycle power block with an open feed water heater. Economic analysis of the model is presented and evaluated in detail, using EnergyPLAN. The internal rate of return (IRR) at the end of the project is found to be 21.40%, which is within the typical IRR limits (16-25%), and the project's minimum debt service coverage ratio (DSCR) is 1.42, which is much higher than the least expected minimum value of 1.3. The levelized cost of electricity (LCOE) is 15.60 cents/kWh and the payback period on the monetary investment of this plant is 17.3 years. This study proves the feasibility of the realization of a fully solar-powered electricity plant.

Search terms: ***Concentrated solar power; parabolic trough solar collector; thermal energy storage; heat transfer fluid; Therminol VP-1; molten salt; Rankine cycle power block.***

Table of Contents

List of Figures

List of Tables

List of Nomenclature

Symbols

^oC	Degree Celsius
D	Diffuse radiation
B	Direct beam radiation
CO_2	Carbon dioxide
G_{on}	Extraterrestrial solar radiation
GWh	Gega-watt hour
G	Global horizontal radiation
kg	Kilogram
kJ	Kilojoule
KW	Kilo-watt
kWe	Kilo-watt electricity
kWh	Kilo-watt hour
C_{max}	Maximum concentration ratio
MW	Mega-watt
MWe	Mega-watt electricity
m	meter
m^2	meter squared
m/s	meter per second
R	Radiation deflected
R_d	Reduction factor
$	United States dollars

Greek Letters

θ	Angle of incidence
θ_s	Half angle from the sun’s rays (sun rays’ angle of incidence on the collectors)
τ_{aer}	Attenuation transmission coefficient for aerosol
τ_{cg}	Attenuation transmission coefficient for common gases
τ_{cld}	Attenuation transmission coefficient for clouds
τ_{oz}	Attenuation transmission coefficient for ozone
τ_{sct}	Attenuation transmission coefficient for scattering
τ_{wv}	Attenuation transmission coefficient for water vapour

Abbreviations

ADSCR	Annual debt service coverage ratio
CED	Cumulative energy demand
COE	Cost of electricity
CSP	Concentrated solar power
CSP-PT	Concentrated solar power parabolic trough
DNI	Direct normal irradiance
DSCR	Debt service coverage ratio
EPP	Energy payback period
HFC	Heliostat field collectors
HTF	Heat transfer fluid
IRR	Internal rate of return
LCA	Life cycle assessment
LCOE	Levelized cost of electricity
LFR	Linear Fresnel reflectors

LTHES	Latent heat thermal energy storage
NPV	Net present value
PDC	Parabolic dish collectors
PP	Power plant
PPA	Power purchase agreement
PT	Parabolic trough
PTC	Parabolic trough collector
PV	Photovoltaic
RES	Renewable energy source
RES-E	Renewable energy source electricity generation
SAM	Solar advisory model
TES	Thermal energy storage
UAE	United Arab Emirates

Chapter 1. Introduction

Despite its rank as the seventh largest proved oil reserve in the world in 2012 and in spite of being one of the top 10 oil producers as of 2011 (http://www.eia.gov), the United Arab Emirates (UAE) is in need for searching for alternative solutions for sustainable power generation to satisfy future energy demand and reduce carbon dioxide (CO_2) emissions [1]. The UAE has witnessed a double increase in the consumption of electricity between the years 2000 and 2010 [2]. Furthermore, CO_2 emissions created from natural gas consumption in UAE power stations are expected to double over the coming 30 years [3]. This significant increase in energy demand is mainly due to the increase in population and economic growth [4].

The UAE has several types of renewable energy potential. It has plenty of biomass that can be utilized. The issue with biomass is that its conversion to usable forms of energy, like methane gas or biodiesel, results in the emission of pollutants at an abundant rate. Some industries ignore this pollution by assuming that biomass absorbs pollution throughout its lifetime, and that same amount is emitted so the net emission is zero. The UAE has limited potential for wind electricity generation, since the average monthly wind speed is 3.5 – 4.5 m/s and 4.2 – 5.3 m/s in coastal areas, the least among the countries in the Gulf region [5]. The most promising renewable energy source for the UAE is solar energy, with an average vertical solar irradiance of 2120 $kWh/m^2/year$ [6].

For the UAE, the most promising solar technologies are photovoltaic (PV) systems and concentrated solar power (CSP) systems [7] [8]. The utilization of CSP systems, either with thermal storage systems or with 24/7 operation, is more efficient and more cost-effective than PV systems. The advantages of CSP technology are dispatchability, increased electricity output and reduced CO_2 emissions [1]. There are two main CSP systems, namely parabolic troughs and solar towers. Parabolic trough collectors (PTC) are the obvious choice since they are commercially available and relatively cheap, compared to other solar collectors. This study aims to investigate a 100% renewable energy source and seeks to develop a solar power electricity generation (RES-E) plant, as a pilot power station in the UAE.

1.1. Problem Statement

The aim of this project is to select the most promising renewable energy sources for electricity (i.e. power) generation and develop a strategic plan for 100% RES-E in the UAE. The final goal is to basically establish a hybrid cycle capable of running by means of renewable energy with a storage system for night time operation.

The objectives are to carry out an in-depth literature survey of past 100% RES-E work and find what technologies are suitable for the UAE, based on its resources, in order to select the most promising RES-E technologies in the UAE, based on technical, economic and environmental criteria. It is also the aim of this work to develop a strategic plan for a 100% RES-E penetration in the UAE.

1.2. Significance of the Research

This research is significant because of the increasing demand for energy in the UAE together with the dangers involved in the depletion of natural resources. The increase in the UAE population and its economic growth have resulted in an increase for energy demand, which has made the UAE rank among the countries with the highest levels of carbon footprints and the highest depletion rate of fossil fuel.

To deal with these issues, the UAE government announced its first RES-E policy in 2009, which set a goal that at least 7% of Abu-Dhabi's power-generation capacity will come from RES-E technologies by 2020 [9]. The UAE has also made a commitment to the global carbon agenda in the area of reducing its CO_2 emissions by 30% by 2030 [6].

The significance of this study also lies in the fact that there are no power-generating plants in the UAE that are fueled by 100% renewable energy (solar energy). The UAE has already shown interest in the renewable energy field with the Masdar City project. Masdar City aims to be the world's first city dependent on only solar, wind and other renewable energy sources, and hence it will be a carbon-neutral city. Furthermore, the Shams 1 solar project aims to be a CSP station consisting of parabolic trough collectors that will generate 100 MW [10]. The innovation in this study is that a hybrid plant will be comprised by choosing the best option for each of the components of the plant (i.e. solar technology, power generating cycle, heat transfer fluid (HTF) and thermal storage) after comparing previous works done.

1.3. Scope and Objectives

The scope of this thesis is to study several solar power generations, thermal storage, and power generation technologies and their integration. The main objective is to design and select the best configuration of the three to create a 100% solar power generation plant.

The main research aims are to:

1. Carry out an in-depth literature survey;
2. Investigate different HTF’s for PTC;
3. Investigate different HTF’s for thermal storage;
4. Investigate different power generation cycles;
5. Investigate the integration of PTC, TES, and a power generation block;
6. Study and model different configurations for the combined PTC, TES and power generation;
7. Perform economic analysis; and
8. Select the most efficient and cost effective configuration of the system.

1.4. Research Methods and Materials

Through in-depth literature review, the most efficient solar power generation methods, TES, and power generation cycle are selected. After this, several configurations are adopted. Solar Advisory Model (SAM) is used to model the configurations and evaluate the performance and cost. Finally, EnergyPLAN is used for modes of operation of the solar power generation plant. The steps of how the research is carried out are as the following:

1. Carry out an extensive literature survey of past 100% RES-E works and find what technologies are suitable for the UAE based on its resources

2. Examine the viability (technical, economic and environmental) for realization in the UAE
3. Create recommended configurations for the implementation of a 100% RES power generation plant based on these technologies
4. Collect data on the UAE’s solar energy potential and demand during the day
5. Size the components of the RES power generation plant
6. Model the system on EnergyPLAN and obtain initial results
7. Use EnergyPLAN to optimize the modes of operation of the configurations based on the data collected for the UAE
8. Perform an energy analysis to ensure the system can generate the required output
9. Perform an economic analysis to see if the system is feasible

1.5. Thesis Organization

This thesis is divided into six chapters. Chapter 1 introduces the thesis and provides the problem statement, scope, and objectives. Chapter 2 is an in-depth literature survey covering solar power technology, thermal storage, power generation block, and the integration of the three. Chapter 3 provides the technical inputs of the study and proposed systems while Chapter 4 presents the results and the economic evaluation of the proposed systems. Chapter 5 presents the final design of the plant. Chapter 6 contains the conclusions and recommendations.

Chapter 2. Literature Survey

This literature review presents previous work related to the topic of the project. This will help gather necessary information for creating a 100% renewable electricity generation system in the UAE. The chapter is divided into five parts. First, solar radiation, particularly in Abu Dhabi, is discussed. Then, solar technologies, CSP, and power generation blocks are studied. Finally, literature on the integration of all three is studied.

2.1. Solar Radiation

Solar radiation can be converted to energy and used to generate power for different applications.

2.1.1. The sun. The sun is the only star located at the center of our solar system, with all the planets orbiting it. Radiation from the sun (i.e. solar radiation) provides energy that supports nearly all forms of life on earth by driving natural processes, such as photosynthesis, and regulating the Earth's weather and climate. Furthermore, all forms of energy that we utilize in the world, such as oil, coal, natural gas, and wood, are solar in origin, as they were originally produced by photosynthetic processes, followed by chemical reactions. However, direct use of solar energy is not exploited enough. Fossil fuels have provided most of our energy over the past century because it is cheaper and more convenient to use in comparison with other energy forms; environmental pollution has only recently become a concern. Solar energy is advantageous compared to other forms of energy because it is clean, can be supplied without environmental pollution, and non-depleting [11].

2.1.2. Solar irradiance. Extraterrestrial solar radiation (G_{on}) is the amount of solar radiation at the outer surface of the Earth's atmosphere. The irradiance at the surface of the Earth is less than that outside its atmosphere because the Sun's rays are attenuated as they pass through. Direct radiation is measured at the Earth's surface; it is the difference between the solar irradiance above the atmosphere and the atmospheric losses from to absorption (the way a photon's energy is absorbed by matter) and scattering (deflection of a ray from a straight path due to irregularities in the atmosphere and some are deflected back to Space). This is represented in Figure 1. Figure 2 shows the solar irradiance spectrum, in which it can be seen that the solar irradiance at the top of the Earth’s atmosphere is much greater than at sea level [12]. CSP technologies can only utilize direct radiation.

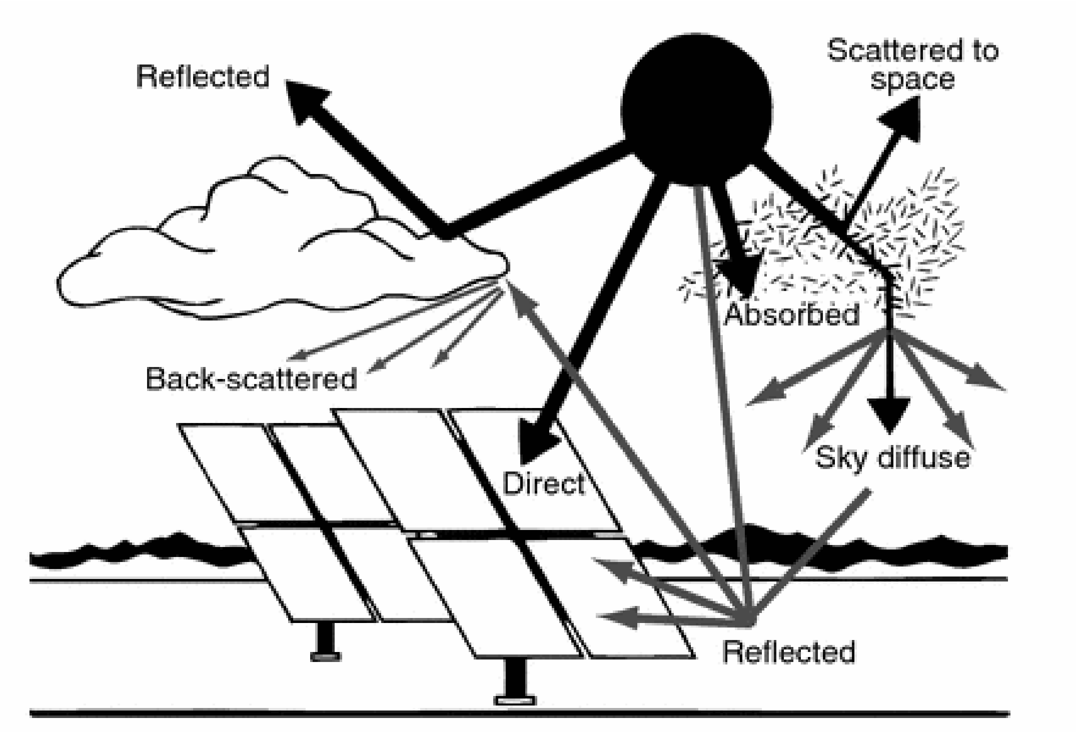


Figure 1: Solar Radiation Components Segregated by the Atmosphere and Surface [13]

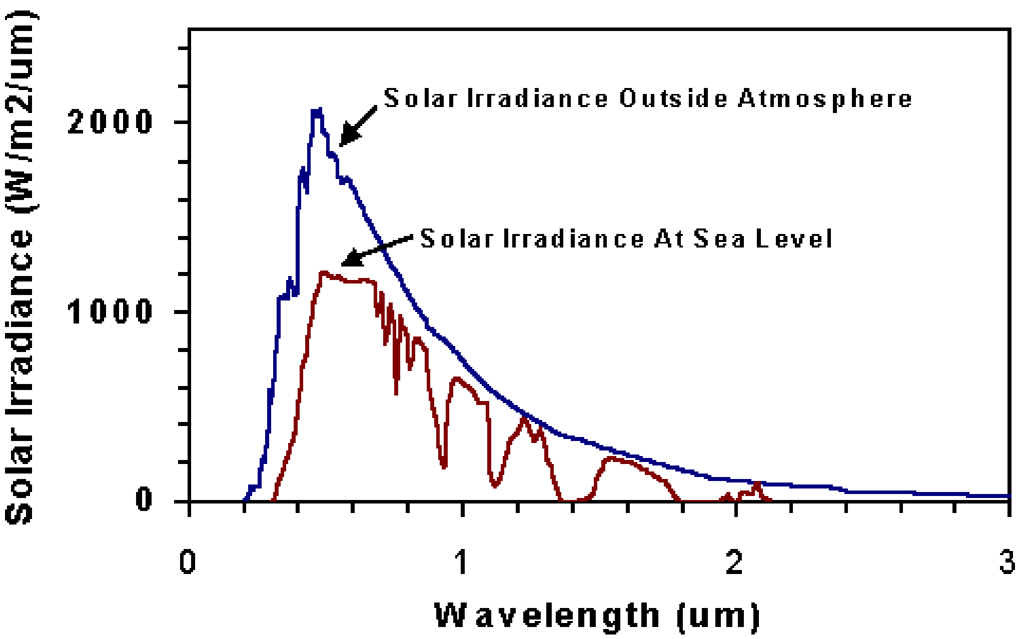


Figure 2: Solar Irradiance Spectrum [14]

Direct radiation is at its greatest level when the sun is perpendicular to the surface; as the Sun moves from this position, the radiation reduces in proportion to the cosine of the angle of incidence [13]. Figure 3 shows this variation.

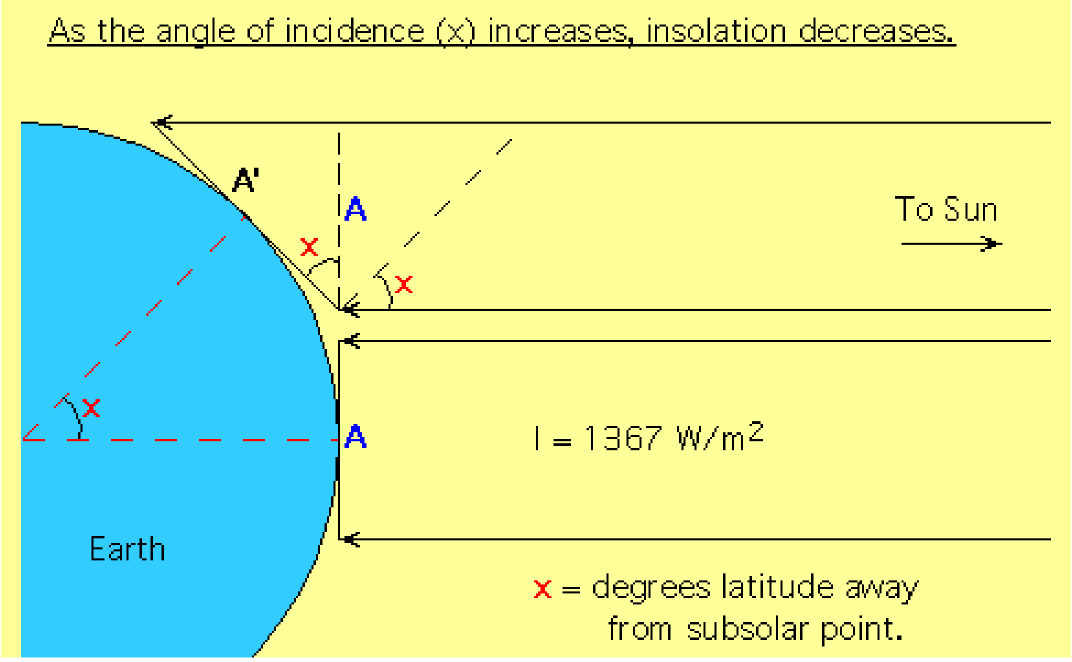


Figure 3: Relationship between Solar Irradiance and Angle of Incidence [15]

For calibrating solar instrumentation, it is fundamental to know the following. The total global horizontal radiation (G), which is the total radiation flux on a horizontal surface after the effects of diffusion and the atmosphere, is:

$$G = \ Bcos\theta + R_d D + R \tag{2.1}$$

where G is shown as A' in Figure 3, B is the direct beam radiation (i.e. A in Figure 3), D is the diffuse radiation on the horizontal surface (shown as sky diffuse in Figure 2), R_d is a reduction factor that accounts for scattering, R is radiation reflected from the ground that hits the tilted surface, and θ is the angle of incidence with respect to the tilted surface (i.e. x in Figure 3) [13].

Furthermore, extraterrestrial radiation varies throughout the year, which has an equally proportional impact on the direct radiation. Figure 4 shows this variation.

2.1.3. Selection of an appropriate site location. Direct Normal Irradiance (DNI), which is the measure of the amount of solar radiation received per unit area by a surface perpendicular to the sun rays, is the best indicator for selecting the best locations for solar plants. On average, the extraterrestrial DNI of the Earth is 1360 W/m2 but is reduced to 1000 W/m2 at the Earth's surface due to the atmosphere. DNI can be found by the following equation [17]:

$$DNI = G_{on} cos\theta \tau_{sct} \tau_{wv} \tau_{oz} \tau_{cg} \tau_{aer} \tau_{cld} \tag{2.2}$$

where θ is the angle between the solar radiation and horizontal surface, and the following are attenuation transmission coefficients for scattering, water vapour, ozone, common gases, aerosol, and clouds, respectively.

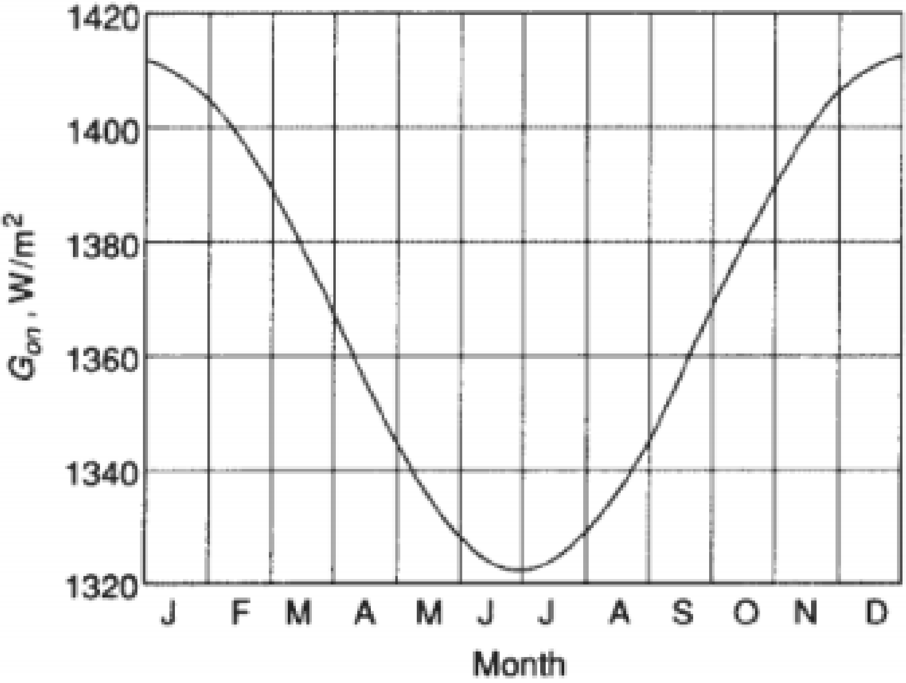


Figure 4: Variation of Extraterrestrial Solar Radiation throughout the Year [16]

The minimum required annual DNI to successfully implement solar thermal technology is 2000 kWh/m^2, while an annual DNI of 2500 kWh/m^2 is considered a location for solar thermal power plants that are competitive with fossil fuel power generation plants [18].

Figure 5 shows the amount of DNI integrated over a year across the world map. Figure 6 shows the regions that are appropriate for having successful solar thermal plants. As can be seen in Figure 6, The Middle East region is appropriate for solar thermal plant integration, and for this work, a location in this region has been selected for possible modeling of solar energy power plant, specifically in Abu Dhabi, UAE.

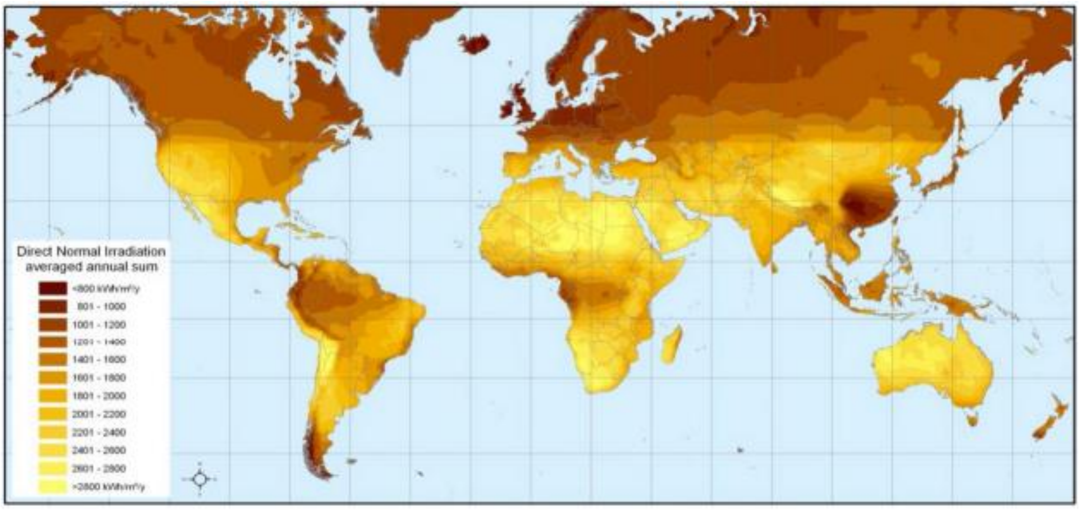


Figure 5: DNI Averages across the World over One Year [18]

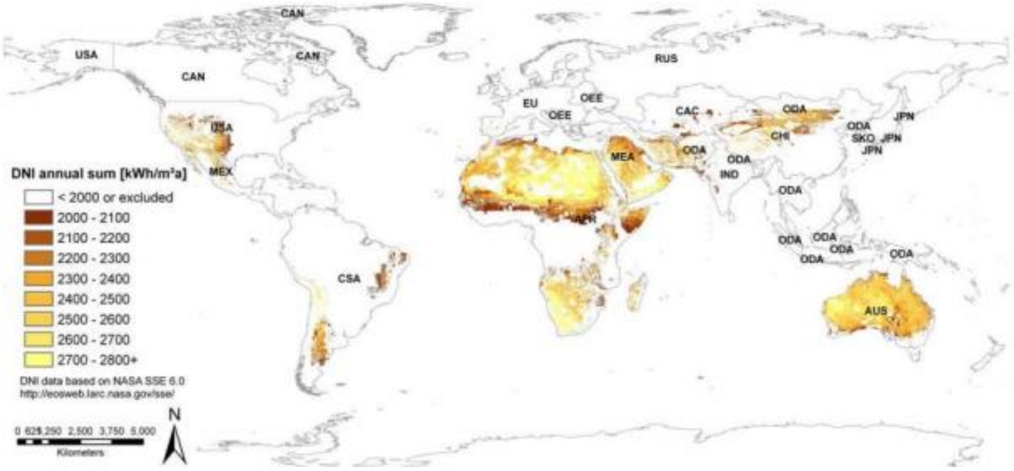


Figure 6: Suitable Regions for Solar Thermal Power Plants [18]

2.1.4. Abu Dhabi. Abu Dhabi, Capital City of the UAE, is sunny and has clear weather for most of the year, making it a potential location for the implementation of a solar power generation plant. Abu Dhabi's dry bulb temperature and rate of DNI should be further investigated to reveal their suitability for solar thermal power generation. Also, it is important to present Abu Dhabi's electricity consumption to see whether having a 100% solar power generation plant is possible.

2.1.4.1. Air temperature. Abu Dhabi's dry bulb temperature for each month during the day is presented in Table 1 [19]. The table shows that the average temperature reaches its maximum at 1 p.m. and the month of August has the highest average temperature. Abu Dhabi has relatively high temperatures, which is beneficial for both CSP plants and steam turbine Rankine cycle plant as less energy is required to get the heat transfer fluid and water to the required temperatures for plant operation.

Table 1: Abu Dhabi average dry bulb temperature during the day for each month [19]

Time of day	JAN Temp. (°C)	FEB Temp. (°C)	MAR Temp. (°C)	APR Temp. (°C)	MAY Temp. (°C)	JUN Temp. (°C)	JUL Temp. (°C)	AUG Temp. (°C)	SEP Temp. (°C)	OCT Temp. (°C)	NOV Temp. (°C)	DEC Temp. (°C)
0	15.651	16.928	19.771	23.336	26.509	28.956	30.754	31.564	29.49	25.535	21.88	17.735
1	15.212	16.314	19.393	22.836	26.067	28.203	30.274	31.248	28.903	25.006	21.193	17.212
2	14.771	15.867	18.977	22.51	25.696	27.843	29.729	30.290	28.45	24.293	20.67	16.725
3	14.154	15.735	18.787	21.976	25.077	27.303	29.348	29.832	27.896	23.693	20.11	16.561
4	13.803	15.035	18.487	21.83	24.919	27.143	29.274	29.564	27.63	23.277	19.57	16.103
5	13.654	14.464	18.141	21.34	24.687	26.803	28.945	29.148	27.303	22.909	19.443	15.767
6	13.267	14.267	17.890	21.71	25.477	28.02	29.319	29.222	27.53	23.132	19.136	15.548
7	14.106	15.407	19.167	24.2	29.106	30.89	31.880	31.661	29.736	25.616	20.853	16.174
8	16.187	17.825	21.145	26.803	32.458	33.743	34.351	34.654	31.91	28.767	23.05	18.241
9	18.277	20.342	23.103	29.03	34.632	35.846	36.780	36.767	33.803	30.758	25.88	20.709
10	20.632	22.789	25.106	30.836	36.471	37.943	38.829	39.129	36.52	33.151	27.873	23.119
11	21.806	24.546	26.396	31.763	37.471	38.846	40.158	40.641	38.196	34.741	29.03	24.616
12	22.58	25.760	26.958	32.7	37.335	39.216	40.693	40.874	38.816	34.683	29.796	25.045
13	22.945	26.196	27.125	32.046	37.054	39.13	40.854	41.354	39.243	34.764	29.89	25.203
14	23.116	25.957	26.851	31.466	36.364	38.966	40.651	40.790	38.6	34.283	29.53	25.054
15	22.661	25.7	26.590	30.886	35.909	37.906	39.567	39.941	37.583	33.158	29.086	24.671
16	22.058	24.596	25.858	29.636	35.048	37.023	38.235	38.571	36	32.129	27.933	23.922
17	20.783	23.253	24.774	28.573	33.629	35.6	36.951	37.290	34.55	30.764	26.726	22.603
18	19.516	21.960	23.367	27.313	31.732	33.856	35.812	36.112	33.516	29.535	25.513	21.377
19	18.751	20.917	22.403	26.456	30.416	32.44	34.516	34.896	32.486	28.371	24.753	20.535
20	17.983	19.878	21.983	25.716	29.635	31.576	33.509	33.9	31.76	27.803	23.833	19.893
21	17.403	18.960	21.074	25.273	28.696	30.753	32.748	33.306	31.006	27.129	23.5	19.212
22	16.7	18.146	20.425	24.626	27.916	30.016	32.138	32.480	30.426	26.412	22.816	18.5
23	16.1	17.664	20.054	23.99	27.212	29.493	31.432	31.980	29.86	25.806	22.403	17.887

2.1.4.2. DNI. When investigating CSP and solar power generation, the most important factor that must be taken into account is the rate of DNI. The average hourly DNI rate for each month of the year for Abu Dhabi is shown in Table 2. The table shows that Abu Dhabi's DNI is relatively high and at its maximum during noon-time [19].

2.1.4.3. Electricity consumption. The UAE has a relatively high electricity consumption per capita when compared to the rest of the world, with the Emirate of Abu Dhabi having the highest electricity demand in the UAE. In 2015, Abu Dhabi's electricity consumption reached a total of 62,979,070 MWh, which marked a consumption increase of 148% since 2005. Figure 7 shows the total electricity power production and consumption levels in Abu Dhabi from the period of 2005 to 2015 [20]. It can be noted that the 2008 economic crisis did not stop the UAE's growth in electricity demand. Moreover, the country's reserves of natural gas have not been sufficient to generate the required electricity demand in recent years. Therefore, it is imperative to find alternative sources for power generation.

Table 2: Average Abu Dhabi DNI per Hour in a Day throughout the Year [19]

Time of day	JAN DNI (W/m2)	FEB DNI (W/m2)	MAR DNI (W/m2)	APR DNI (W/m2)	MAY DNI (W/m2)	JUN DNI (W/m2)	JUL DNI (W/m2)	AUG DNI (W/m2)	SEP DNI (W/m2)	OCT DNI (W/m2)	NOV DNI (W/m2)	DEC DNI (W/m2)
0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	19.6	70.7	66.1	23.5	0	0	0	0	0
7	96.0	141.3	182.3	277.2	332.4	323.5	237.9	222.8	188.3	197.0	211.3	102.9
8	234.5	416.6	371.1	475.6	572.6	576.6	471.2	477.0	507.9	541.9	485.4	367.6
9	543.5	639.9	502.0	596.7	688.2	703.0	611.1	650.6	687.4	728.0	679.9	582.3
10	659.4	726.9	552.5	629.2	771.1	793.7	710.4	749.4	794.1	819.6	754.1	657.6
11	674.6	789.6	577.8	661.7	813.6	854.6	780.7	816.6	856.8	848.4	751.8	670.7
12	722.0	821.0	585.6	648.9	836.5	859.6	794.6	830.4	867.5	833.6	735.8	660.0
13	709.5	809.1	580.8	648.3	834.4	855.1	791.3	825.6	843.6	814.6	735.8	660.7
14	669.0	765.5	583.6	607.8	802.0	816.2	735.8	777.8	779.1	761.4	694.1	617.7
15	605.5	700.2	561.5	546.8	714.8	728.8	644.6	686.0	668.6	634.8	562.2	531.1
16	443.2	583.1	470.3	452.1	574.7	582.5	508.7	506.2	417.6	365.5	308.0	341.0
17	102.0	253.8	234.1	217.7	282.4	288.2	232.9	201.3	101.5	10.8	0	0
18	0	0	0	0	0	10.6	2.8	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0

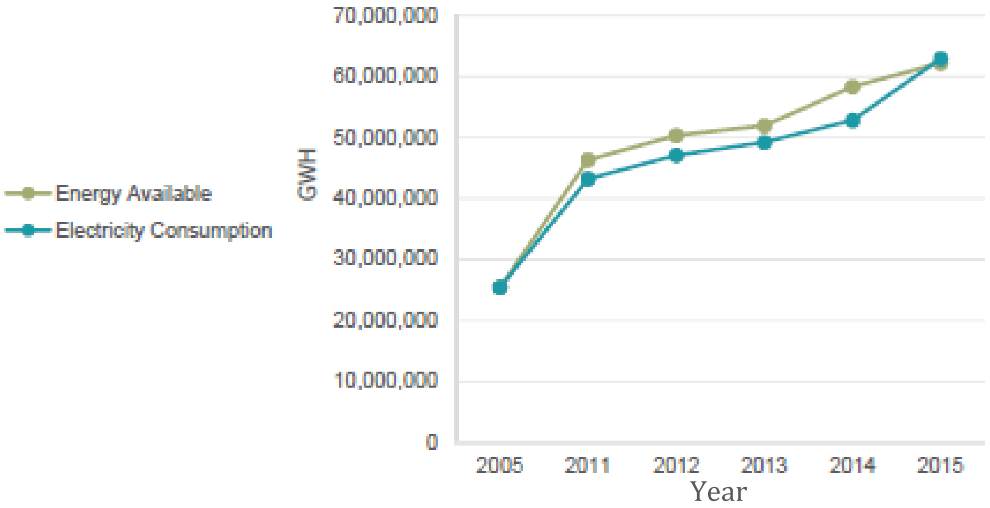


Figure 7: Total Electricity Power Production and Consumption in the UAE [20]

2.1.4.4. Concentrated solar power (CSP) projects in the UAE. There are several solar thermal technologies in the UAE. Shams I, a project done by the Masdar Institute of Science and Technology, is the first thermal power plant in the UAE, utilizing CSP technologies and design with a total output of 120 MWe, making it the largest in the world [21]. The plant consists of 768 solar collector assemblies, made up of a total of 258,048 mirrors that heat oil (i.e. heating fluid) inside the tubes to a range varying from 293°C to 393°C [22]. Oil powers a steam generator that delivers the required thermal input for the plant’s operation. Furthermore, the plant’s overall efficiency is increased by employing a supplementary heater to superheat the steam from 380°C to 540°C, which operates by utilizing fossil fuels that account for roughly 45% of the power generated [23].

Another solar project in the UAE is the ongoing Beam-Down Solar Tower project, in which a new design for solar tower or heliostat field collectors is being investigated. This is a co-venture between Masdar Institute of Science and Technology, Tokyo Institute of Science and Technology and Japan Cosmo Oil [23]. A pilot plant has been built near Masdar City in Abu Dhabi with a capacity of 100 kWe, employing 33 mirrors on the ground with two axis tracking systems. The proposed design includes secondary mirrors in a tower to redirect reflected solar radiation from the mirrors (i.e. heliostats) on the ground towards a collection platform in the system’s base [22].

2.2. Concentrated Solar Power (CSP) Technology

This section presents different CSP technologies available in the market and provides a comparison between CSP and other technologies and the different types of CSP collectors and their advantages.

There are different technologies that convert solar radiation into energy. CSP has proven to be the most efficient of the different solar technologies. It absorbs the solar radiation and reflects it, focusing it on a small area to maximize the amount of captured heat. There are different types of CSP, namely: Fresnel Reflectors, Solar Power Tower, Dish Sterling, and Parabolic Trough Collector (PTC). Based on available literature, PTC is the most researched technology and has proved to be the most efficient.

2.2.1. Solar technologies. There are many studies available in literature that investigate different types of solar technologies. The amount of energy provided by the sun in one hour, if utilized, is greater than the annual required amount of energy for the entire planet [24]. This makes solar energy a viable and obvious solution for an alternative energy source to fossil fuels.

There are two main technologies for converting solar energy into electricity: photovoltaic (PV) and CSP collectors. PV collectors directly convert solar radiation into electricity by utilizing semiconductors and photoelectric effects, whereas CSP collectors absorb solar radiation’s thermal energy by utilizing mirrors and collectors that direct radiation toward a receiver [25]. Among the solar technologies, PV technology is more suitable for areas that are in middle to high latitudes, while CSP technology perform better in arid areas at relatively low altitudes, such as the UAE. This is reflected in both the performance and the levelized cost of electricity (LCOE) generated by the two technologies [26].

Research in the field shows that CSP technology is more advantageous than other technologies in terms of integration with conventional power plants [27]. One paper in particular by Poullikkas and Gadalla [28] studies the possibility of solar electricity production in the UAE on a large scale and investigates the technical, economic and environmental aspects, concluding that CSP is the better technology over PV in terms of the three aspects. Another paper [29] presents six candidate RES-E systems, including a PV system and a parabolic trough CSP with and without thermal storage. The operation of both the PV and parabolic trough CSP systems are simulated; and the electricity unit cost is calculated based on the calculations of the: (a) solar radiation in the plane of the PV or CSP parabolic trough (PT) solar field, (b) electrical energy delivered by the solar plant, (c) system losses, (d) electrical energy delivered to the grid, (e) required area for PV panels or the CSP parabolic trough solar field, (f) required area for the installation of the PV system or CSP parabolic trough power plant, (g) cost of electricity assuming that the initial investment year is year 0 so any inflation is applied from year 1 onwards. The technical and economic parameters of each candidate power-generation technology are taken into account based on a cost function, and the least cost solution is calculated by an equation. The results for the electricity generation over the lifetime of 20 years from the PV and parabolic trough CSP plants examined show that the CSP plant that operates 24/7 has the highest total electricity generation. Furthermore, the cost of CSP technology is much lower than that of PV technology [30].

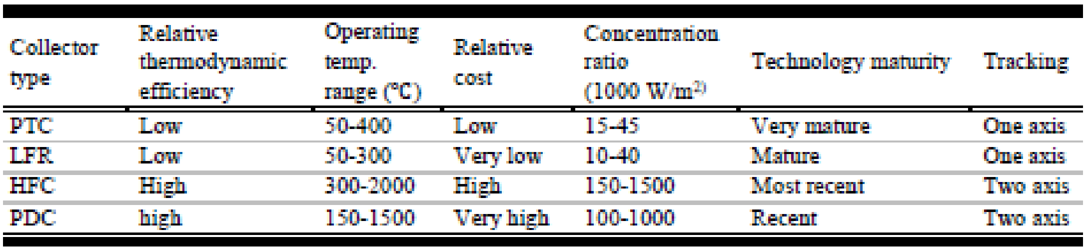
For this study, CSP is the more viable option as 24/7 power plant operation so it is the technology being investigated. CSP can utilize thermal storage as it captures heat for solar radiation, making it possible for the system to produce energy or electricity during night time, when there is no solar radiation. However, PV directly converts solar radiation into electricity, so battery storage would be required for nighttime operation of a power plant, which is not technically or economically feasible [31] [32].

There are different types of CSP systems, categorized by their collector types. The main ones are:

1. Parabolic Trough Collectors (PTC)
2. Linear Fresnel Reflectors (LFR)
3. Heliostat Field Collectors (HFC) i.e. Solar Towers
4. Parabolic Dish Collectors (PDC) i.e. Solar Dishes

Table 3 shows specifications of the four CSP technologies.

Table 3: Specifications of four CSP technologies [24]



Collector type	Relative thermodynamic efficiency	Operating temp. range (°C)	Relative cost	Concentration ratio (1000 W/m$^{2)}$	Technology maturity	Tracking
PTC	Low	50-400	Low	15-45	Very mature	One axis
LFR	Low	50-300	Very low	10-40	Mature	One axis
HFC	High	300-2000	High	150-1500	Most recent	Two axis
PDC	high	150-1500	Very high	100-1000	Recent	Two axis

From the specifications, HFC does have a higher efficiency however it is very expensive and new to the market. PTC has a low efficiency, but it operates at a temperature range that can be acceptable for this project and, is very mature in the current market, making a large amount of information and research surrounding it available.

2.2.2. Parabolic trough collectors (PTC). Parabolic trough technology, shown in Figure 8, will be used in this project, since it is the most proven and the cheapest large-scale solar power technology available. It consists of mirrors that concentrate sun rays on steel tubes that work as heat receivers. The receivers have a special coating that maximizes the energy absorption while minimizing the infrared re-irradiation. They also work in an evacuated gas envelope to avoid heat losses. The operating temperatures ranges from 50°C to 400°C. The heat is then removed by a heat transfer fluid, such as water, molten salt or synthetic oil, which flows through the receiver tubes and get transferred to a steam generator to produce the super-heated steam that runs the turbine [24].

The PTC is a widely used CSP collector for solar thermal power plants around the world. The Solnova Solar Power Station in Spain is a large CSP-PT plant consisting of five power stations, each with a 50 MWe capacity. It operates on a steam Rankine cycle, uses thermal oil as the HTF and has wet cooling. The Alvardo I is another solar thermal power station with an installed capacity of 50 MWe capacity powered by a PT solar plant. The HTF used in this plant is thermal oil and it has a two-tank thermal storage system that uses molten salt [33].

2.2.3. Linear fresnel reflectors (LFC). Fresnel reflector plants, shown in Figure 9, are similar to parabolic trough plants, but they use a long array flat or slightly curved mirrors to concentrate the sunlight toward a linear receiver. The linear receiver is on a tower with a height ranging between 10m to 15m. They are lower in cost and relatively simpler than parabolic trough plants however, they are lower in optical efficiency (i.e. they have higher optical losses). PE1 (Puerto Errado 1) is a 1.4 MW LFR plant in Calasparra, Spain that utilizes hot water and a molten salt thermal storage system. PE2 is a 30MWe solar thermal LFR plant that started commercial operation in 2012 [24].

2.2.4. Heliostat field collectors (HFC) i.e. solar towers. Solar tower plants, shown in Figure 10, are the latest in CSP technology to emerge onto the industry. They use heliostats, which are computer-assisted mirrors, to track the sun individually over two axes and concentrate the sun’s rays onto a single receiver that is mounted on top of a central tower. The height level of the central tower ranges from 75m to 150m; the higher the tower, the higher the heliostat field optical efficiency. Solar tower plants have higher concentration factors than parabolic trough and Fresnel reflector plants, meaning they can achieve higher temperatures so they can be integrated with high temperature thermodynamic cycles such as the gas turbine cycle. However, they have a relatively high capital cost compared to the other CSP technologies [24].

The PS10 (Planta Solar 10) project in Spain is the world’s first commercial CSP solar tower plant that produces electricity with 624 large movable mirrors (heliostats) and has an alumina heat storage system. It is a commercially operational 11 MWe solar central receiver system (CRS) electricity producing plant connected to the power grid. The plant has an annual electricity production of 23 GWh net and costs below

$2,800/KW. After this, the PS20 solar plant was built with a capacity of 20 MWe from 1,255 heliostats [33].

2.2.5. Parabolic dish collectors (PDC) i.e. solar dishes. Solar dishes, shown in Figure 11, are parabolic dish-shaped concentrators that reflect sunlight into a receiver placed in the dish. The receiver can either be an engine or micro-turbine. The advantage of this technology is its high efficiency; however it is not yet commercially deployed [24].

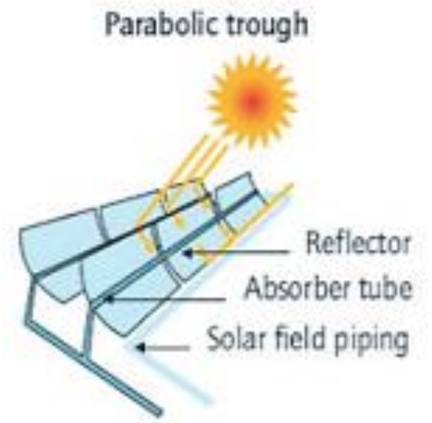


Figure 8: Parabolic Trough Collectors [34]

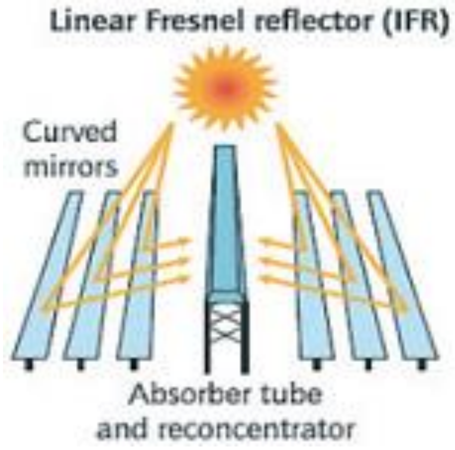


Figure 9: Linear Fresnel Reflector [34]

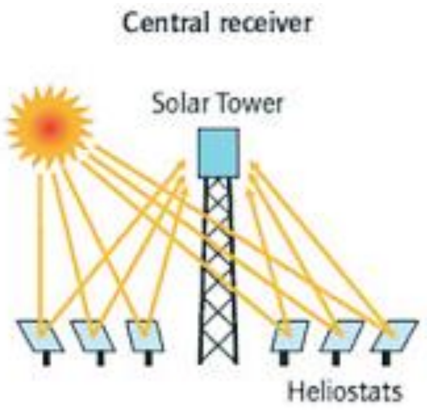


Figure 10: Heliostat Field Collectors [34]

Figure 11: Parabolic Dish Reflector [34]

2.2.6. Selection of optimum CSP technology. After describing the four available CSP technologies, the most appropriate will be selected for implementation in this project. The main difference between the four mentioned CSP technologies are the way the collectors concentrate the solar irradiance. Table 3 also clearly shows the differences between them in terms of efficiency, cost and other factors. Table 4 shows a summary of the comparison between the four solar technologies.

Table 4: Summary of Comparison between different CSP Technologies [35]

CSP Technology	**PTC**	**LFR**	**HFC**	**PDC**
Solar collector	Line focus	Line focus	Point focus	Point focus
Solar receiver	Mobile	Fixed	Fixed	Mobile
Concentration ratio	70-80	>1000	>60	>1300
Working Temperature	Medium	Low	High	Very High
Capacity (MW)	10-300	10-200	10-200	0.01-0.025
Storage System used in existing projects	Indirect or direct 2-tank molten salt	Short term pressurized steam storage	Direct 2-tank molten salt	None; chemical storage being researched
Development status	Commercially proven	Pilot project done only	Commercially viable	Under demonstration

PTC and LFR technologies have a single axis tracking device to accurately follow the sun and linearly concentrate solar rays. For PTC and LFR technologies, the maximum concentration ratio (i.e. the ratio that the collectors can concentrate the sun's rays) is calculated by the following equation [24]:

$$C_{max} = \frac{1}{\sin \theta_s} \tag{2.3}$$

where θ_s is the half angle from the sun's rays and equals 0.27°, resulting in a maximum concentration ratio of 212.

On the other hand, HFC and PDC are single point collectors that focus the sun's rays towards a single point receiver. They have a two-axis tracking mechanism to follow the sun's position and so the maximum concentration ratio is calculated by the following equation [24]:

$$C_{max} = \frac{1}{(\sin \theta_s)^2} \tag{2.4}$$

where θ_S = 0.27°, and a theoretical maximum concentration ratio of 45,000 can be achieved.

As mentioned, HFC and PDC both have very high efficiencies, operating temperatures and concentration ratios however, they are both extremely higher in cost than the other two technologies and are relatively new to the market so experience and literature on them is scarce. PTC and LFR technologies are much lower in cost and are mature in the market. Between PTC and LFR, PTC has a slightly higher efficiency and operating temperature; the operating temperature can power a steam turbine cycle to generate electricity, making PTC the appropriate technology for this project.

2.3. Thermal Energy Storage (TES)

Storage for the thermal energy generated by the solar radiation is necessary if the energy is to be used for 24-hour operation of 100% CSP plants, as there is no solar radiation during night-time. The extended hours of plant operation reduce the cost of electricity produced. The design of the TES system is very important, as it determines how much of the energy collected can be utilized.

There are two types of TES systems: active and passive. In the active TES system, the storage medium is a fluid (i.e. heat transfer fluid) that flows between the storage tanks. In the passive TES system, the storage medium is a solid medium; and the heat transfer fluid (HTF) enters the tanks for charging or discharging. The TES systems available are further classified as the following types: Two-Tank Direct System, Two-Tank Indirect System – both of which are active TES systems – and Single-Tank Thermocline System, shown in Figure 13, which is a passive TES system.

In the two-tank direct system, the same fluid that collects the solar thermal energy is used to store it. The fluid is stored in two tanks: in a cold tank at low-temperature and in a hot tank at high-temperature. Fluid from the cold tank flows through the solar collectors and then into the hot tank for storage. When this thermal energy is needed, the fluid from the hot tank flows through a heat exchanger, in which water flows through as well, generating steam for electricity production. The low temperature fluid exits the heat exchanger and returns to the cold tank. This is shown in Figure 12. Some examples of where the two-tank direct thermal storage system is used are early parabolic trough plants such as Solar Electric Generating Station I, which uses mineral oil as the HTF, and the Solar Two power tower in California, which uses molten salt as the HTF.

The two-tank indirect thermal storage system functions in the same way as the direct system with one main difference: different fluids are used as the HTF and the thermal storage fluid. This requires an additional heat exchanger, to transfer the heat from the HTF coming out of the solar collectors to the fluid that will be stored in the hot tank, which adds cost to the system. This type of thermal storage system is used in many parabolic trough power plants in Spain and is proposed for some in the United States, with organic oil as the HTF and molten salt as the thermal storage fluid.

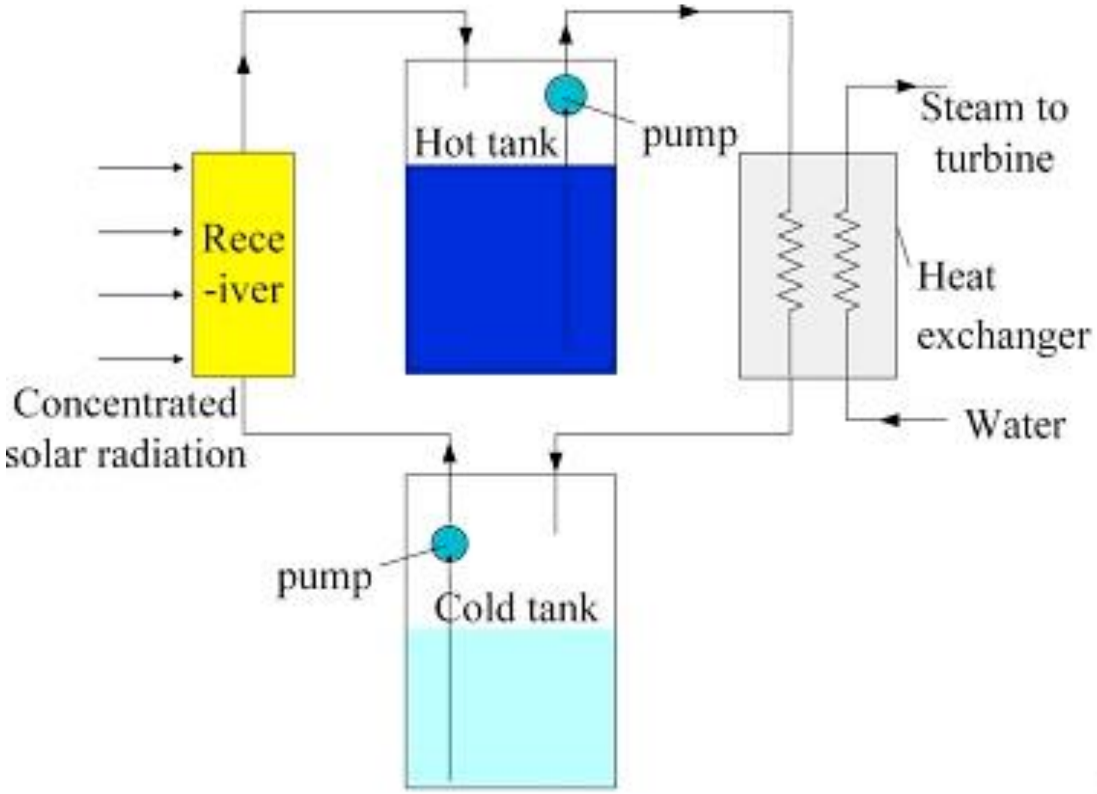


Figure 12: Two-Tank Direct Thermal Storage System

The single-tank thermocline system stores thermal energy in a solid medium, such as silica sand, in a single tank. During operation, a portion of the medium is at high temperature and a portion is at low temperature, with the two regions separated by a “thermocline” or temperature gradient. This is shown in Figure 13. To add thermal energy to the system for storage, the heated HTF flows into the top of the thermocline and exits the bottom at low temperature, thus adding heat and moving the thermocline downward. To utilize the thermal energy from the storage system, the flow is reversed, removing heat from the tank and moving the thermocline upward. The use of a solid medium, and only one tank rather than two for thermal storage, reduces the cost of the system. This type of system is used in the Solar One power tower, where steam is used as the HTF and mineral oil as the thermal storage fluid [36].

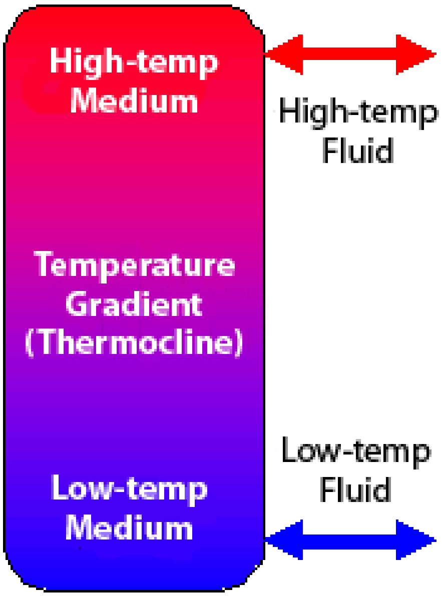


Figure 13: Single-Tank Thermocline Thermal Energy Storage System [36]

Tanks are only one part of the TES storage system; HTF and thermal storage fluid selection is also an important aspect. Both the indirect two-tank and the direct two-tank (represented in Figure 14) storage systems will be studied for this project, because different HTF's will be investigated that each require different type of TES. One study shows that a direct two-tank storage system, where the heat transfer fluid serves as storage medium, is the most advanced method, as heat losses are reduced and is less costly than the indirect, since there is no need for the additional heat exchanger to transfer heat from the HTF from the solar collectors to the thermal storage fluid [37]. However, using the heat transfer fluid as a medium is extremely expensive, so a study on the use of molten salt, which is a cheaper liquid medium, was done; the study shows that the cost is low and the storage can be operated successfully. The use of thermal storage allows for the hours of plant operation to be extended to even when the sun is not up and it also reduces the cost of electricity produced.

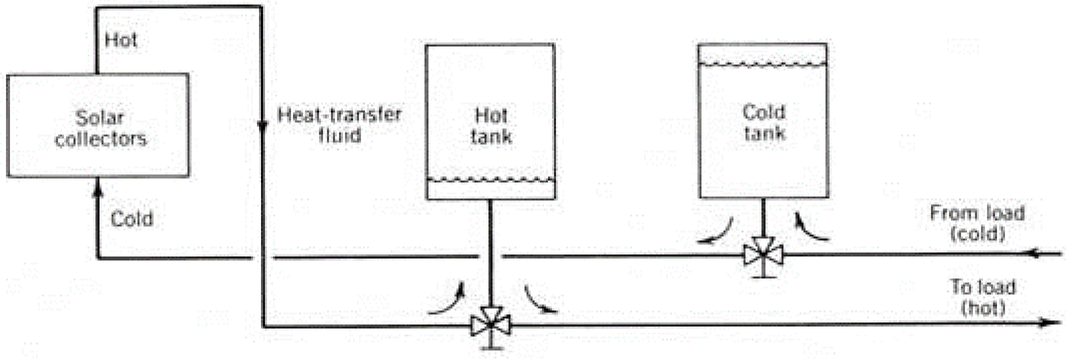


Figure 14: Two-Tank Direct Thermal Storage System [38]

2.4. Heat Transfer Fluid (HTF)

As mentioned in the previous section, HTF is necessary to for realizing a thermal storage system and having night-time operation. Different HTF's are used depending on the type of TES system [39]:

- Direct Storage
  - Thermal oil
  - Molten salt
  - Steam accumulation in pressure vessel
- Indirect Storage
  - Molten salt
  - Concrete
  - Sand with rocks
  - Etc.

Figure 15 summarizes the suitable HTF for the type of TES system. Since a two-tank direct TES system will be used for this study, the HTF will also serve as the storage medium. When selecting the material to use for the HTF, the following requirements must be taken into consideration [40]:

1. Good heat transfer from the HTF
2. Chemical stability and compatibility with the TES system
3. High energy density
4. Low thermal losses

5. Low environmental impact
6. Low cost

As shown in Figure 15, the most suitable HTF's/thermal storage mediums for a direct TES system are thermal oil, water (i.e. steam accumulated in a pressure vessel) and molten salt. Starting with thermal oils, there are two types: synthetic oil and mineral oil. Synthetic oil has a higher thermal conductivity than mineral oil and thus performs better. Therminol VP-1 has been the most common synthetic oil HTF used in PT-CSP plants, but its relatively low thermal breakdown temperature (400°C) limits the power cycle efficiency. Comparing synthetic oils with molten salts, molten salts have a higher temperature capacity and a higher heat transfer rate. Water has the least of these properties in comparison to both thermal oils and molten salt.

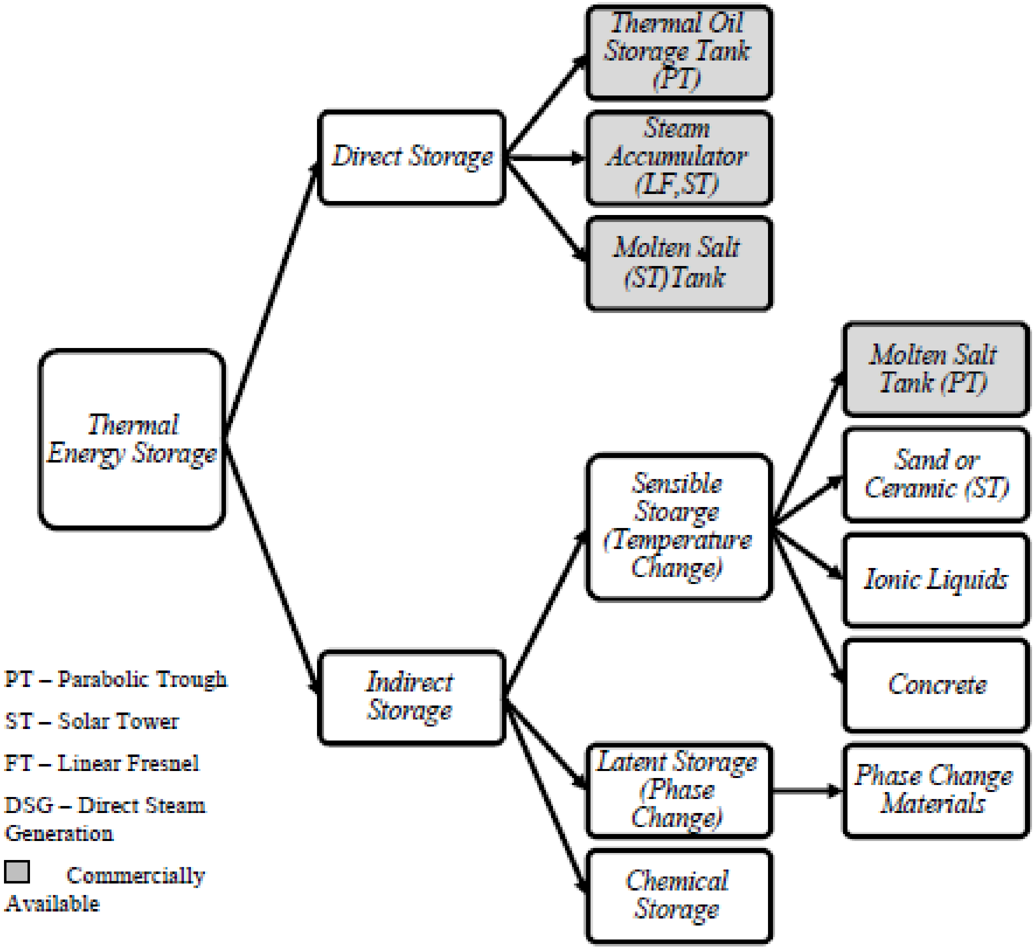


Figure 15: Suitable HTF's for different types of TES Systems

For molten salts, different compositions have been tested to find which can achieve the highest latent hear thermal energy storage (LHTES). Literature shows that the optimum composition, currently utilized at the Andosol Solar Power Station in Spain, is composed for 60wt% NaNO3 and 40wt% KNO3 [41]. Table 5 shows a comparison of the different HTF's that are suitable for CSP plants.

Table 5: Comparison of Heat Transfer Fluids used in CSP Plants [40]

HTF	Max. Temp. (°**C)**	Advantages	Disadvantages
Thermal Oil (Mineral)	<400	Good performance	Inflammable
Thermal Oil (Synthetic: Therminol VP-1)	390	Better performance	• Inflammable • Toxic • Expensive
Water / Steam	-	• Cheap • Environmentally safe	• High temp. • High pressure • High cost
Molten Salt	600	• Simple storage • Good heat transfer • Best performance	• Corrosive • High freezing temp.
Air	-	Cheap	Low performance

2.5. Power Block

In this section, different types of power generation cycles that would make up the power block portion of the solar power generation plant are discussed. The most common power generation cycle used for parabolic trough power plants is the Rankine cycle, which will be used for this project [42]. A Rankine cycle consists of a steam boiler to produce high pressure and high temperature steam. The steam then goes to a steam turbine and is expanded to produce mechanical shaft work that drives and electric generator. The expansion of the steam is performed in stages to increase the overall efficiency of the process. After the final expansion stage, steam goes to a condenser to be converted back to liquid form and then pumped back to the boiler. Power production by Rankine cycle can reach efficiencies of 40%. A solar steam generator will be used instead of a conventional boiler.

2.5.1. Organic Rankine cycle. The heat transfer fluid used in this cycle is organic fluid, such as butane or pentane. They are simpler in design than Rankine cycle and run at lower pressures, reducing the capital cost of the components. They are mostly used for applications with lower resource temperatures and small power plants (ranging from 100 kWe to 10 MWe in size) [43]. Despite the reduced cost and lower pressure and temperature required, the Organic Rankine cycle cannot be used for this project because it generates relatively little power.

2.5.2. Rankine cycle with improved efficiency. An experimental study investigated the performance of a low-temperature solar Rankine cycle with R245fa as the working fluid. The use of this fluid caused the efficiency of the cycle for be lower than the theoretical value due to superheating and subcooling of the working fluid and massive heat loss, making this an impractical option [44].

Using a direct air-cooling condenser has been studied to maximize net power gain. The study showed that even with all air fans on full-load operation, not enough air could be delivered to make a difference in power generation, making this an impractical option [45].

There are two simple options to improve Rankine cycle efficiency, reheating or adding a feed liquid heater (open or closed), as shown in Figures 16, 17 and 18. The reheating option is not viable for this project, simply because the Rankine cycle will operate with a heat exchanger rather than a boiler, with the HTF coming either from the solar field or the TES system, so it will not be practical to have additional water removing more heat. The difference between an open and a closed feed water heater is that mixing does not take place in the closed heater, but this does not add major benefit in the case of this study, so it is more economical to use an open feed water heater. The benefit of having a feed water heater is that steam is extracted from the turbine to heat the fluid returning from the condenser, which will then enter the boiler or (heat exchanger in this case) at a higher temperature [46]. This is crucial since this plant solely relies on HTF heater by solar power to convert water into steam.

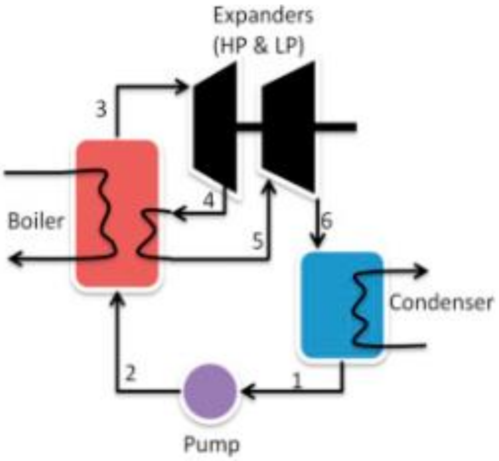


Figure 16: Rankine Cycle with Reheater [46]

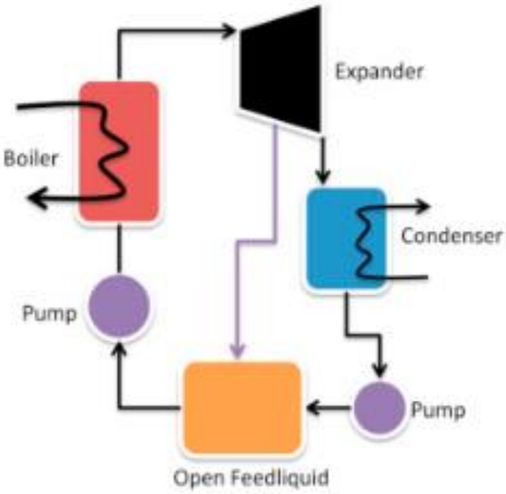


Figure 17: Rankine Cycle with Open Feed Water Heater [46]

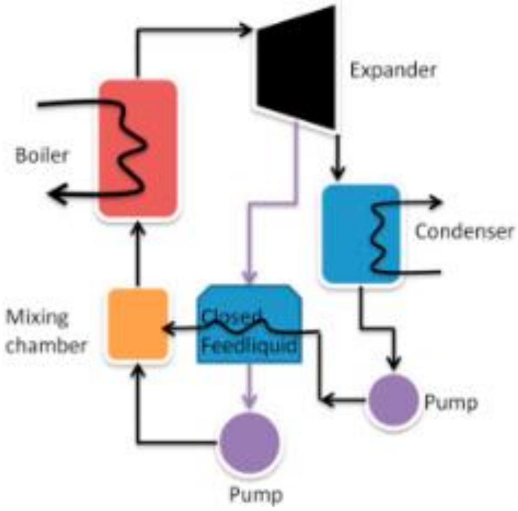


Figure 18: Rankine Cycle with Closed Feed Water Heater [46]

2.6. Integration of Technologies for Renewable Energy Power Generation

In this section, past related research is investigated to understand the drawbacks. This will help in gathering necessary information for creating a 100% renewable energy electricity generation system for the UAE. Three major technological changes are necessary when designing 100% RES, which is important to consider for the UAE's case: energy savings on the demand side [47], efficiency improvements in the energy production [48] [49] and the replacement of fossil fuels by different renewable energy sources [50] [51]. Maintaining the security of energy supply, reducing carbon dioxide emissions and raising export in the energy industry are also targets.

A number of related studies for RES-E were done in Spain. Spain has many 100% solar power generation plants, with the world's first commercial CSP solar tower plant being the PS10. The goal of the PS10 (Planta Solar 10) project is to design, construct and operate commercially a 10 MWe solar central receiver system (CRS) electricity producing plant connected to the power grid [33]. The plant should have an annual electricity production of 19 GWh net and cost below $2800/KW. It is a CSP solar power tower that produces electricity with 624 large movable mirrors called heliostats and has an alumina heat storage system. After this, the PS20 solar plant was built with a capacity of 20 MWe from 1,255 heliostats. There is also the Solnova Solar Power Station, which is a large CSP parabolic trough plant consisting of five power stations each with a 50 MWe capacity. It operates on a steam Rankine cycle, uses thermal oil as the transfer fluid and has wet cooling. The Alvarado I is another solar thermal power station with an installed capacity of 50 MWe capacity powered by a parabolic trough solar plant. The heat transfer fluid used in this plant is thermal oil and it has a two-tank thermal storage system that uses molten salt.

Studies on the hybridization of existing power plants with solar energy have also been done. One paper reviews previous studies for integrating solar thermal energy with conventional and non-conventional power plants [52]. The hybrid solar conventional power plants reviewed are hybrid solar-steam cycle power plants, integrated solar combined-cycle systems (ISCCS) and hybrid solar-gas turbine power plants, and the hybrid solar non-conventional power plants reviewed are hybrid solar-geothermal power plants. The review concludes that the ISCCS is the most successful option due to its technical and economic advantages over the other cycles, which is very useful to know for this project when selecting a power generation cycle for the hybrid system for the UAE.

A study was done by Poullikkas on the integration of pumped hydroelectric energy storage (PHES) plants in small island power systems, specifically in Cyprus [53]. As mentioned in the previous literature studied, there are many renewable sources available, but they are not utilized. The European Union (EU) wants to increase the use of renewable energy sources in power generation (RES-E) to reduce greenhouse gas emissions while meet increasing power demand. The use of PHES systems is necessary because they provide factors for solutions for security of supply, reduce vulnerability, promote rational use of energy and increase the use of RES-E. This work carries out technical and economic analysis of PHES integration. The WASP IV package was used for simulations. The result is calculating the electricity unit cost of the generation system for various scenarios that are investigated.

PHES stores electric energy as hydraulic potential energy by pumping water to high elevation to be stored, then releasing it to pass through hydraulic turbines. There must be a minimum head of 300m to be economical. The electrical storage volume depends on the volume of the reservoirs. Pumping takes place during off-peak periods and power generation takes place during on-peak periods. There are two types of PHES: pure PHES and pump-back PHES (in which a combination of pumped water and natural inflow is used to produce power).

There are several advantages and disadvantages of PHES. The advantages are as follows:

- It is economical because it flattens out the variable load so thermal power stations operate efficiently and it reduces the need to build special plants for only peak demand
- It responds to electrical demand changes quickly without voltage and frequency instability
- It has a high energy storage cycle efficiency of 77%
- The stored water can be used for irrigation, fire-fighting, drinking, etc.
- It has a positive environmental impact

The disadvantages are as follows:

- The reservoirs cause environmental damage
- It has a high capital cost
- It is difficult to find topographically suitable sites with sufficient water capacity to make installation profitable

WASP IV finds an optimal expansion plan for a given power generating system for up to 30 years. The objective function gives the overall cost of the generation system. The optimal allocation procedure is to find two power levels to define the PHES plant operation. Two models are needed: compulsory operation and economic operation.

For analysis, three candidate PHES plants are used: 130 MW, 200 MW and 200 MW. Two groups of scenarios are investigated: the business as usual scenario (BAU) and the increased RES-E scenario. The results show that the power generation system unit cost difference for each scenario when compared with the BAU scenario with or without PHES increased both as the PHES installed capacity increased and as the natural gas projected price increased. This method can be considered for nighttime operation since there is not solar energy available during the day however, storage tanks, discussed in later sections, will be used as they are a more practical solution for this case.

Studies on RES-E in the UAE have also been done. In a paper by Poullikkas and Gadalla, the possibility of solar electricity production in the United Arab Emirates (UAE) on a large scale in technical, economic and environmental terms is investigated. It takes into account the available solar potential mainly for the Emirate of Sharjah. The most promising solar RES-E technologies for the UAE are photovoltaic (PV) systems and parabolic trough concentrated solar power (CSP) systems. Six RES-E candidate system capital costs are identified, including a PV system and a parabolic trough CSP with and without thermal storage at different initial investments and cost per kW. A parametric analysis is carried out by varying each to identify the least-cost feasible option.

Electricity production is relatively cheaper in the UAE since it is an oil producing country, and the bills are heavily subsidized [8]. There are some constraints hindering RES-E development that are due to lack of commercial skills and information, the absence of relative legal and policy framework, the high initial capital costs with lack of fuel-price risk assessment and the exclusion of environmental externalities in the cost [27].

In an analysis previously done, three components for large-scale PV integration into power production were investigated: the estimation of the energy production potential and financial feasibility of a hypothetical PV plant in Abu Dhabi, assessment of the anticipated reductions in greenhouse gas emission and air pollution if the PV plant were constructed and the quantification of the social benefits from the reduced emissions. It was found in the analyses that for the PV plant to be feasible i.e. for there to be a positive net present value (NPV), the selling price of the electricity exported to the grid should be greater than \$0.16/kWh. This highlights the importance of taking into account the economic aspects of solar RES technology integration.

The operation of both the PV and parabolic trough CSP systems are simulated and the electricity unit cost is calculated based on the calculations of the: (a) solar radiation in the plane of the PV or CSP parabolic trough solar field, (b) electrical energy delivered by the solar plant, (c) system losses, (d) electrical energy delivered to the grid, (e) required area for PV panels or the CSP parabolic trough solar field, (f) required area for the installation of the PV system or CSP parabolic trough power plant, (g) cost of electricity assuming that the initial investment year is year 0 so any inflation is applied from year 1 onwards. The simulations for the optimization analysis are done on the IPP v2.1 software tool, which is used for selecting the best least-cost power-generation technology in competitive electricity markets. The technical and economic parameters of each candidate power-generation technology are taken into account based on a cost function, and the least cost solution is calculated by an equation. The financial feasibility indicators are calculated; they are: (a) electricity unit cost or benefit before tax (in US\$/kWh), (b) after-tax cash flow (in US\$), (c) after-tax NPV (the value of all future cash flows, discounted at the discount rate, in today’s currency), (d) after-tax internal rate of return (IRR: the discount rate that causes the NPV of the project to be zero and is calculated by using the after-tax cash flows. Note that the IRR is undefined in certain cases, notably if the project yields immediate positive cash flow in year zero), (e) after-tax payback period (the number of years it takes for the cash flow, excluding debt payments, to equal the total investment which is equal to the sum of the debt and equity [29].

Electricity production from solar RES-E technologies depends on the available solar potential and on the degree of thermal storage integration. The UAE gets a year-round supply of direct normal radiation (DNI) and based on HelioClim database (http://www.helioclim.org), the DNI for the Emirate of Sharjah is 2106 kWh/m2. All parts of the UAE get similar exposure, with a minimum of 8 h in December and a maximum of 14 h in June. The available annual solar potential in hourly intervals used in the simulations and the calculated monthly average DNI are presented in figures in the paper. This analysis assumes the installation and operation of a PV park with a capacity of 50MWp, and the monthly optimal inclination PV panel angle is also presented in a graph. The installation and operation of a 50MWe plant with a typical solar to electricity efficiency of 15% is assumed for the case of the parabolic trough CSP system. This analysis also examines the effect of a two-tank molten salt thermal storage integration by varying thermal storage capacity from 0 h/day (no thermal storage) to 24 h/day (24/7 operation). This has an effect on capital cost (greater solar field is necessary), land area (greater are to accommodate the resulting solar field size is necessary) and electricity production (power production is increased due to increased operating hours).

The results for the electricity generation over the lifetime of 20 years from the PV and parabolic trough CSP plants examined show that the CSP plant that operates 24/7 has the highest total electricity generation. The electricity production from the PV plant is 92 GWh/year and the production from the trough CSP system increases with the thermal storage capacity. When there is no thermal storage, the capacity factor of the PV system and of the parabolic trough CSP system is low. Thermal storage increases the capacity factor of the parabolic trough CSP system (it can reach a value of 86%). Results for reduced CO2 emissions and barrels of crude oil used are also presented, which shows that the transition to sustainable energy production is beneficial to the UAE's economy because the crude oil saved can be exported. For this to be successful, the UAE must develop financial supporting mechanisms because the electricity selling prices are higher than the current UAE electricity tariffs.

In another literature, an optimization analysis is carried out to estimate the optimal power generation expansion strategy using sustainable power generation technologies for the Emirate of Sharjah over a period of 30 years (2013-2042) [1]. Eight alternative configurations of sustainable power generation systems that integrate the technologies within the existing power generation system of the Emirate of Sharjah are examined and compared with the reference (or business as usual, BAU) scenario for a range of natural gas prices; they are listed in the article. Two carbon-capture and storage (CCS) technologies (post- and pre-combustion CCS) integrated to the natural gas combined cycle technology and two solar-based technologies (large PV parks and parabolic trough CSP, chosen for its technological maturity, at different thermal storage capacities) are examined [54]. The Emirate of Sharjah has seven power stations with a total installed capacity of 2576.5 MWe and an annual electricity generation of 10 TWh (http://www.sewa.go.ae). The WASP IV (Wien Automatic System Planning 2006) software package is used for selecting the optimum expansion planning of a generation system; it compares the total cost of the whole generation system for a number of units by applying probabilistic simulation to the production simulation of a one-year period (that can be divided into a maximum of 132 sub-periods). Finally, the electricity unit cost of the power generation system for each scenario is calculated. A sensitivity analysis is also carried out at different natural gas prices. Different considerations are taken into account for the CCS, PV and CSP cases.

Based on the results, the most promising sustainable candidate technologies are the use of the combined cycle integrated with a post-combustion then pre-combustion CCS system, parabolic trough CSP technology with 24/7 operation and to a less extend, the use of a parabolic trough CSP technology with 14.5 h thermal energy storage system. In conclusion, the natural gas combined cycle with integrated CCS and concentrated solar panel systems with 24/7 operation make the best option.

The most recent studies regarding solar power generation plants have been done in India and Libya. The first study was performed to assess the technical and economic feasibility of CSP generation in India. It was found that high DNI is abundant in many locations, and SAM software was used to analyze the potential. It was found that PTC with two-tank TES system is the most efficient and economically feasible to realize the plant [55].

The second study was to investigate the potential of implementing CSP plants in Libya. A topographic study was performed and a thermos-economic simulation of a 50 MW CSP-PT power plant as well. The results were compared with the Andasol-1 plant in Spain as a reference and proved to be both technically viable and economically competitive, especially considering the proposed location is a region where solar DNI is at a minimum compared to the rest of the regions in Libya [56].

An example of a successful realized solar powered electricity generation plant is the Andasol-3 in Spain. This thesis studies a design very similar to that of the Andasol-3, with some changes. The Andasol-3 has a CSP-PT plant with an indirect TES system that utilizes molten salt and has a storage capacity of 7.5 hours. A simple Rankine cycle to generate electricity [57]. In this study, an indirect TES system is utilized with an increased capacity to ensure 24-hour operation. Also, a more efficient Rankine cycle is used for power generation to have a more efficient cycle overall.

Chapter 3. System Modelling

This section presents the proposed configuration and detailed modeling developed for analysis. First, the proposed configuration is discussed, followed by detailed modeling of each component and then the economic model. Simulation requirements are done in SAM software and EnergyPLAN.

3.1. Configuration

Based on the problem statement and literature survey, configurations for a solar energy power generation plant are proposed and one is selected for modelling. The proposed plants all consist of a CSP-PT field, two-tank thermal storage and a power generation block.

The system configurations shown in Figures 19 and 20 were chosen to be analyzed as a 100% solar power generation plant. In the first case, in which the HTFs are Therminol VP-1 and molten salt, the HTF runs through the solar plant and then heat the water to generate steam to run the turbine in the power cycle portion of the plant. In addition, during the day, the heat transfer fluid will also be used for thermal storage. In the second case, in which water is used, water would be turned into steam in the CSP plant and part would be used to power the power block, while another part would be used to heat the molten salt for thermal storage for night-time operation. These systems are chosen due to their efficiencies and conformities to SAM software as well

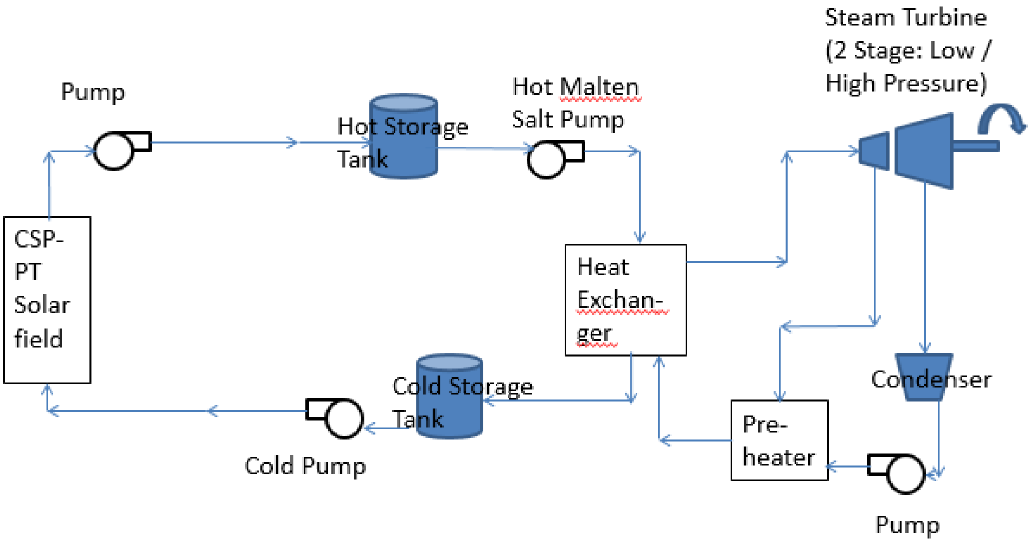


Figure 19: Schematic Diagram of Proposed CSP-PT Power Generation Plant with direct TES Configuration

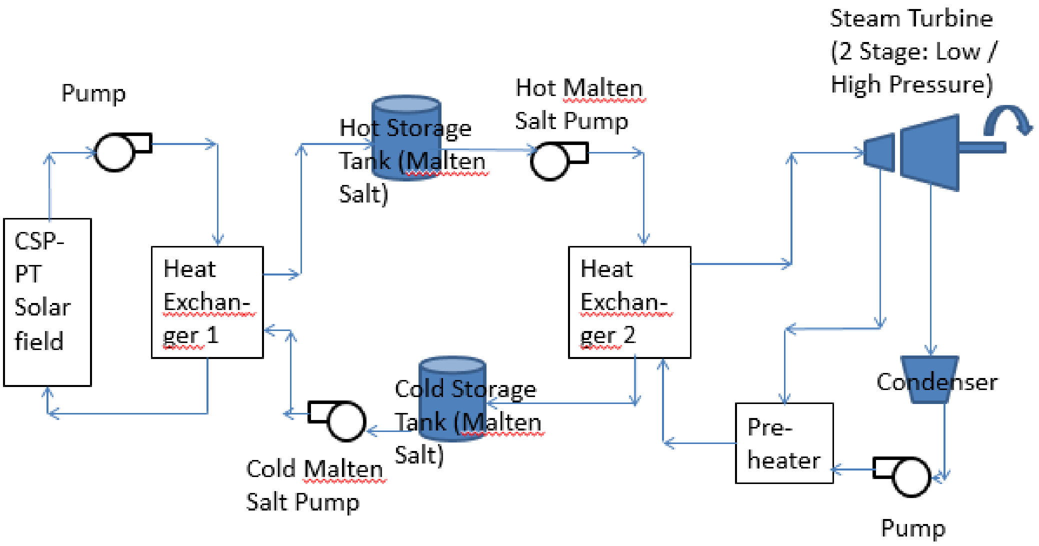


Figure 20: Schematic Diagram of Proposed CSP-PT Power Generation Plant with indirect TES Configuration

3.2. Simulation

The simulation of the proposed CSP-PT plant system is done using SAM and EnergyPLAN.

3.2.1. SAM. SAM (System Advisor Model) is a performance and financial model used to facilitate decision making in the renewable energy industry. SAM makes predicts performance and estimates the cost of energy for grid-connected power projects based on installation costs, operating costs and system design parameters that are input to the model [58].

The first step in SAM is to select a technology and financing option for the project. The input variables are then automatically populated by SAM with a set of default values for the respective type of project. As an analyst, the input data should be reviewed and modified as appropriate for each analysis. Next, information about the project's location, the type of equipment in the system, the installation and operating cost of the system and financial assumptions must be input; the location for this project case is the UAE.

Performance data libraries and coefficients that describe the characteristic of system components such as PV modules, PT receivers and collectors and wind turbines are included in SAM. The appropriate option is selected from a list, and SAM automatically downloads the data and populates the input variable values; the remaining input variables can be kept as default values.

SAM displays simulation results, such as the project's net present value (NPV), first year annual production, detailed annual cash flow, hourly performance data and more, in tables and graphs. The performance models in SAM make hour-by-hour calculations of a power system's electric output and generate a set of 8,760 values representing the system's electricity production. The financial models in SAM use the system's electrical output calculated by the performance models to calculate the series of annual cash flows.

3.2.2. EnergyPLAN. EnergyPLAN software simulates the operation of national energy systems, including electricity, heating and cooling, transport and industrial sectors in an hourly basis. The main purpose of its model is to analyze the energy, economic and environmental impact of various energy strategies [59]. A variety of options are modeled and compared with one another rather than modeling one "optimum" solution based on pre-defined conditions. For this project, three different heat transfer fluids were compared: Therminol VP1, molten salt and water.

Moreover, EnergyPLAN focuses on the future energy system and how it will operate. It optimizes the operation of a given energy system based on the inputs and outputs defined by the user [59].

3.3. CSP-PT Solar Field

Based on the literature survey, the CSP-PT field is the optimum type of solar technology in the current market. The solar collectors are at the optimum tilt angle of 19 degrees for maximum solar irradiance exposure. The results would show the size and configuration of the panels that would provide enough heat to power the plant to produce 50 MWe.

3.4. Thermal Storage and Heat Transfer Fluid (HTF)

The configuration selected will be simulated with three different heat transfer fluids (HTF's): molten salt, water and Therminol VP-1. This is to compare the different HTF's and find the most efficient one for the realization of the 100% RES-E plant. Due to this, both indirect (for the case of water as the HTF) and direct (for the case of Therminol VP-1 ad molten salt as the HTF) thermal storage will be investigated.

The ability of the various HTF's to transfer heat from one body to another depends on their thermodynamic properties. These properties are the information needed to model the HTF portion of the configuration. Details regarding the thermodynamic properties of the three HTF's that will be modelled are presented in the following sub-sections.

3.5.1. Molten salt. The molten salt eutectic mixture that will be used for the proposed configuration is 60% $NaNO_3$ / 40% KNO_3. As mentioned in the literature survey, these salts are widely used as fertilizer and are low in cost and available in large quantities. During solar field operation, its temperature varies from 290 ^oC to 550 ^oC. It is a non-flammable, non-toxic fluid with good heat transfer properties because it has relatively a high coefficient of heat transfer, high heat capacity, high density and low operative pressures. The physical properties of the salts are shown in Table 6.

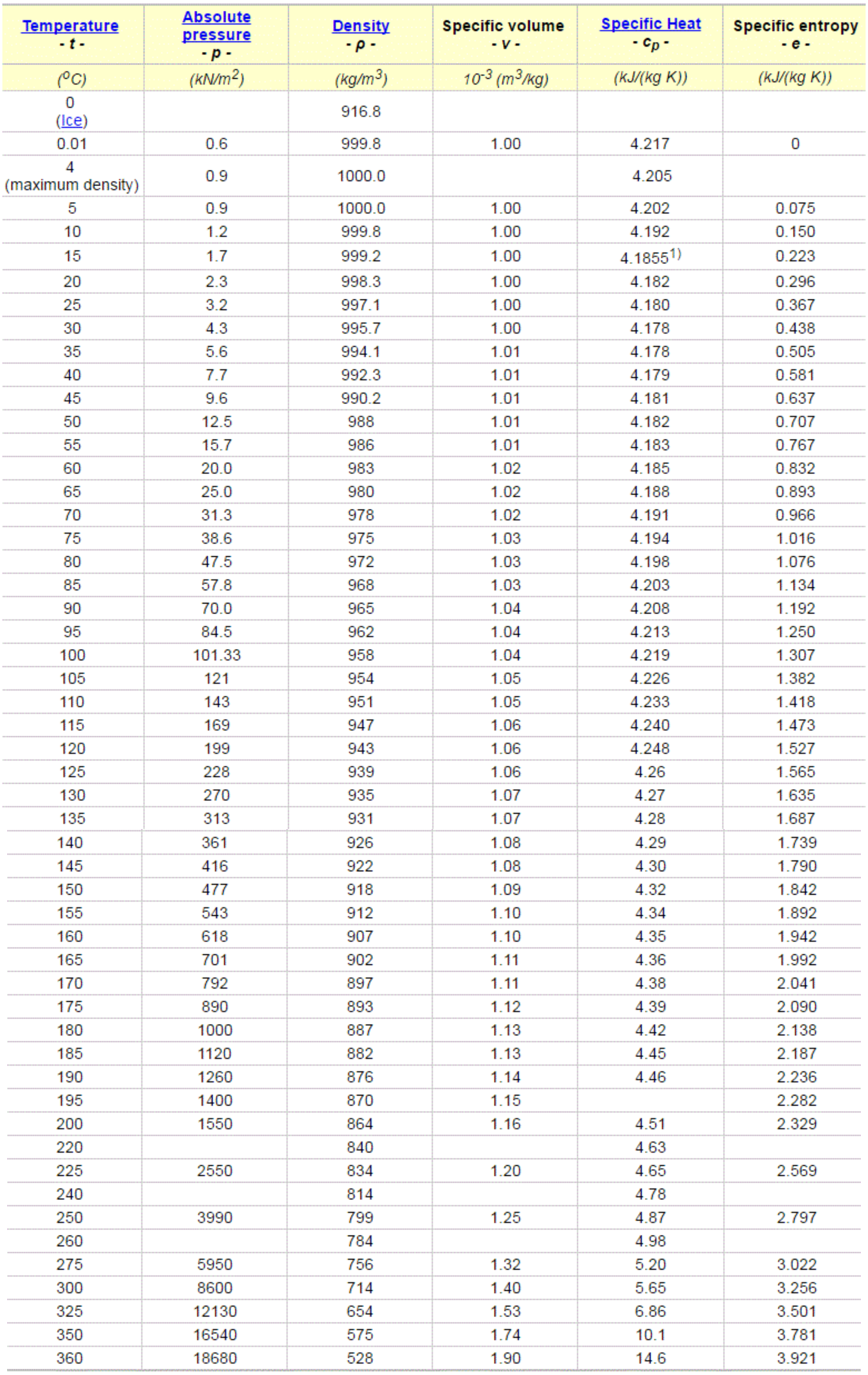
3.5.2. Water. The benefits of water are that it is non-toxic, inexpensive, has a high specific heat, a low viscosity and is easy to pump. The downside is that it has a relatively low boiling point (100 ^oC) and a high freezing point (0 ^oC). Water can also be corrosive if the acidity/alkalinity level (pH) is not maintained at a neutral level. Furthermore, "hard" water, which is water high in mineral content, can cause mineral deposits to form in the solar collector tubing and system piping. Table 7 shows the thermodynamic properties of water at various pressures, up to a temperature of 360 ^oC.

3.5.3. Therminol VP-1. As mentioned in the literature survey, Therminol VP-1 is an HTF designed to meet the demanding requirements of vapour phase systems. The properties used to model the proposed configuration are shown in Table 8.

Table 6: Thermodynamic Properties of Molten Salt

Freezing Temperature	238 ^oC
Melting Temperature	221 ^oC
Heat of Fusion	161 kJ/kg
Volume Change on Fusion	46%

Table 7: Thermodynamic Properties of Water



Temperature - t -	Absolute pressure - p -	Density - ρ -	Specific volume - v -	Specific Heat - c_p -	Specific entropy - e -
(^oC)	(kN/m^2)	(kg/m^3)	10^{-3} (m^3/kg)	(kJ/(kg K))	(kJ/(kg K))
0 (Ice)		916.8			
0.01	0.6	999.8	1.00	4.217	0
4 (maximum density)	0.9	1000.0		4.205	
5	0.9	1000.0	1.00	4.202	0.075
10	1.2	999.8	1.00	4.192	0.150
15	1.7	999.2	1.00	$4.1855^{1)}$	0.223
20	2.3	998.3	1.00	4.182	0.296
25	3.2	997.1	1.00	4.180	0.367
30	4.3	995.7	1.00	4.178	0.438
35	5.6	994.1	1.01	4.178	0.505
40	7.7	992.3	1.01	4.179	0.581
45	9.6	990.2	1.01	4.181	0.637
50	12.5	988	1.01	4.182	0.707
55	15.7	986	1.01	4.183	0.767
60	20.0	983	1.02	4.185	0.832
65	25.0	980	1.02	4.188	0.893
70	31.3	978	1.02	4.191	0.966
75	38.6	975	1.03	4.194	1.016
80	47.5	972	1.03	4.198	1.076
85	57.8	968	1.03	4.203	1.134
90	70.0	965	1.04	4.208	1.192
95	84.5	962	1.04	4.213	1.250
100	101.33	958	1.04	4.219	1.307
105	121	954	1.05	4.226	1.382
110	143	951	1.05	4.233	1.418
115	169	947	1.06	4.240	1.473
120	199	943	1.06	4.248	1.527
125	228	939	1.06	4.26	1.565
130	270	935	1.07	4.27	1.635
135	313	931	1.07	4.28	1.687
140	361	926	1.08	4.29	1.739
145	416	922	1.08	4.30	1.790
150	477	918	1.09	4.32	1.842
155	543	912	1.10	4.34	1.892
160	618	907	1.10	4.35	1.942
165	701	902	1.11	4.36	1.992
170	792	897	1.11	4.38	2.041
175	890	893	1.12	4.39	2.090
180	1000	887	1.13	4.42	2.138
185	1120	882	1.13	4.45	2.187
190	1260	876	1.14	4.46	2.236
195	1400	870	1.15		2.282
200	1550	864	1.16	4.51	2.329
220		840		4.63	
225	2550	834	1.20	4.65	2.569
240		814		4.78	
250	3990	799	1.25	4.87	2.797
260		784		4.98	
275	5950	756	1.32	5.20	3.022
300	8600	714	1.40	5.65	3.256
325	12130	654	1.53	6.86	3.501
350	16540	575	1.74	10.1	3.781
360	18680	528	1.90	14.6	3.921

Table 8: Thermodynamic Properties of Therminol VP-1

Temperature °C	Density kg/m^3	Thermal Conductivity W/m.K	Heat Capacity kJ/kg.K	Viscosity		Vapour pressure (absolute) kPa*	Enthalpy kJ/kg	Latent Heat vap. kJ/kg
				Dynamic mPa.s	Kinematic mm^2/s**			
12	1071	0,137	1,523	5,48	5,12	-	0	419,0
20	1064	0,136	1,546	4,29	4,03	-	12,3	414,7
30	1056	0,135	1,575	3,28	3,10	-	27,9	409,3
40	1048	0,134	1,604	2,60	2,48	-	43,8	403,9
50	1040	0,133	1,633	2,12	2,03	-	60,0	398,6
60	1032	0,132	1,662	1,761	1,707	-	76,4	393,3
70	1024	0,131	1,690	1,492	1,458	-	93,2	388,1
80	1015	0,130	1,719	1,284	1,265	-	110,3	382,9
90	1007	0,129	1,747	1,119	1,111	-	127,6	377,8
100	999	0,128	1,775	0,985	0,986	0,5	145,2	372,7
110	991	0,126	1,803	0,875	0,884	0,8	163,1	367,6
120	982	0,125	1,831	0,784	0,798	1	181,3	362,6
130	974	0,124	1,858	0,707	0,726	2	199,7	357,5
140	965	0,123	1,886	0,642	0,665	3	218,4	352,6
150	957	0,121	1,913	0,585	0,612	5	237,4	347,6
160	948	0,120	1,940	0,537	0,566	7	256,7	342,7
170	940	0,118	1,968	0,494	0,526	9	276,2	337,7
180	931	0,117	1,995	0,457	0,491	13	296,0	332,8
190	922	0,115	2,021	0,424	0,460	18	316,1	327,9
200	913	0,114	2,048	0,395	0,432	24	336,5	323,0
210	904	0,112	2,075	0,368	0,407	32	357,1	318,0
220	895	0,111	2,101	0,345	0,385	42	378,0	313,0
230	886	0,109	2,128	0,324	0,366	54	399,1	308,0
240	877	0,107	2,154	0,305	0,348	68	420,5	303,0
250	867	0,106	2,181	0,288	0,332	86	442,2	297,9
260	857	0,104	2,207	0,272	0,317	108	464,1	292,7
270	848	0,102	2,234	0,258	0,304	133	486,3	287,5
280	838	0,100	2,260	0,244	0,292	163	508,8	282,2
290	828	0,098	2,287	0,232	0,281	198	531,6	276,8
300	817	0,096	2,314	0,221	0,271	239	554,6	271,2
310	806	0,095	2,341	0,211	0,262	286	577,8	265,6
320	796	0,093	2,369	0,202	0,254	340	601,4	259,7
330	784	0,091	2,397	0,193	0,246	401	625,2	253,8
340	773	0,089	2,425	0,185	0,239	470	649,3	247,6
350	761	0,086	2,454	0,177	0,233	548	673,7	241,3
360	749	0,084	2,485	0,170	0,227	635	698,4	234,7
370	736	0,082	2,517	0,164	0,222	732	723,4	227,8
380	723	0,080	2,551	0,158	0,218	840	748,8	220,7
390	709	0,078	2,588	0,152	0,214	959	774,4	213,2
400	694	0,076	2,628	0,146	0,211	1090	800,5	205,3
410	679	0,073	2,674	0,141	0,208	1230	827,0	197,0
420	662	0,071	2,729	0,137	0,206	1390	854,0	188,0
425	654	0,070	2,760	0,134	0,205	1470	867,7	183,3

Chapter 4. Analysis and Discussion

4.1. Sizing of the Equipment of the Configuration through SAM

In this section, the sizing of the three major sections of the proposed configurations – the solar collectors, the thermal storage and the power generation block – is presented. The sizing of the equipment is based on the Rankine cycle power generation block demands – i.e. 50 MWe output with 24-hour operation – with the data of steam and water extracted from the steam tables at the respective temperatures and pressures directly from the SAM software simulator. Initially, the overall design parameters are specified, and then details of each component of the system are specified in separate input pages. Tables 9, 10 and 11 show the sizing of the various components of the configuration for each of the three fluid options: Therminol VP-1, molten salt and water. The input parameters are highlighted in blue.

4.2. HTF Models for Optimum HTF Selection

After sizing the major components of the configuration, the next step is to select the optimum HTF. The proposed solar power generation system is modelled on SAM. Three models distinct by the type of heat transfer fluid are simulated, and from the results obtained, the most viable model is selected and its results used for the remainder of the simulation phases. The following HTF's are simulated:

- Therminol VP1
- Molten Salt (60% $NaNO_3$ and 40% KNO_3)
- Water

Tables 12, 13 and 14 show the results from each of the three models. The results obtained from the simulation for each HTF are: the energy storage, capacity factor, power purchase agreement (PPA) for the first year, PPA price escalation per year, PPA price per KWh, cost of electricity (COE) per KWh, net present value, the internal rate of return (IRR) of the project, the year that the IRR is achieved, the net capital cost and the size of debt.

Table 15 shows a comparison of the monthly output models for Therminol VP-1, molten salt and water for a 50MWe output CSP-PT plant. The outputs are recorded for a “dispatch control period 6” in SAM, which characterizes the time duration from 12:00 am to 6:00 am on weekdays of months January to May and October to December. This period represents the times and seasons of lowest possible DNI, so is therefore reflective of the thermal storage performance of the three plant models, which significantly affects their plant capacities.

Analysis of the results and data obtained from the three simulations shows that molten salt is the preferred option of the three HTF’s. This conclusion is arrived upon by considering the following data:

- The molten salt model has the highest recorded annual production (0.331 TWh), with Therminol VP-1 having the second (0.249 TWh) and water third (0.127 TWh)
- The molten salt model has the highest capacity factor at 75.6%, followed by Therminol VP-1 and water, at 56.9% and 29% respectively
- The molten salt model has the average monthly power output values for the studied period, hence the best thermal storage capabilities
- The levelized cost of electricity (LCOE) for the molten salt model (14.65 ¢/kWh) and Therminol VP-1 (14.12 ¢/kWh) are similar, with a non-significant advantage difference between them, but much lower than the LCOE of water (24.67 ¢/kWh)

Table 9: Size Specifications of Heliostat Field (CSP-PT solar collectors)

PARAMETER	**THERMINOL**	**MOLTEN SALT**	**WATER**
Design DNI	950W/M^2	950W/M^2	………..
Solar multiple	2.4	2.4	………….
Thermal power	324MWt	324MWt	…………..
Heliostat Width	12.2m	12.2m	12.2m
Heliostat Height	12.2m	12.2m	12.2m
Single Heliostat Area	144.375m^2	144.375m^2	144.375m^2
No of Heliostat facets X	2	2	2
No of Heliostat facets Y	8	8	8

Table 10: Specifications of Rankine Cycle Power Generation Block

PARAMETER	**THERMINOL**	**MOLTEN SALT**	**WATER**
Design Turbine Gross output	55.556MWt	55.5555MWt	55.5555MWt
Estimated net conversion factor	0.9	0.9	………….
Cycle thermal efficiency	0.412	0.412	0.404
Cycle Thermal power	135MWt	135MWt	…………
Estimated net output	50MW	50MW	50MW
HTF Hot fluid Temperature	400 °C	574 °C	550 °C
HTF cold fluid temperature	130 °C	290 °C	42 °C
HTF mass flow rate	315.1 kg/s	315.1 kg/s	315.1 kg/s

Table 11: Size Specifications of Thermal Storage Tanks

PARAMETER	**THERMINOL**	**MOLTEN SALT**	**WATER**
Storage tank type	Two tank	Two tank	……
Available HTF volume	13,324m^3	6,273m^3	……
Tank Height	20m	20m	……..
Tank Fluid Minimum Height	1m	1m	……..
Storage Tank Volume	14026 m^3	6604 m^3	……..
Tank Diameter	29.9m	20.5m	

Table 12: Simulation Results of RES-E Plant with Therminol VP-1 as the HTF

Metric	**Value**
Annual energy (year 1)	249,196,464 kWh
Capacity factor (year 1)	56.90%
Annual Water Usage	47,928 m^3
PPA price (year 1)	12.64 ¢/kWh
PPA price escalation	1.00 %/year
Levelized PPA price (nominal)	15.32 ¢/kWh
Levelized PPA price (real)	12.05 ¢/kWh
Levelized COE (nominal)	14.12 ¢/kWh
Net present value	$31,437,272
Internal rate of return (IRR)	11.00%
Year IRR is achieved	20
IRR at end of project	12.59%
Net capital cost	$463,495,680
Equity	$231,546,032
Size of debt	$231,949,664

Table 13: Simulation Results of RES-E Plant with Molten Salt as the HTF

Metric	**Value**
Annual energy (year 1)	331,067,584 kWh
Capacity factor (year 1)	75.60%
Annual Water Usage	79,410 m^3
PPA price (year 1)	13.90 ¢/kWh
PPA price escalation	1.00 %/year
Levelized PPA price (nominal)	15.94 ¢/kWh
Levelized PPA price (real)	12.54 ¢/kWh
Levelized COE (nominal)	14.65 ¢/kWh
Net present value	$45,126,432
Internal rate of return (IRR)	11.00%
Year IRR is achieved	20
IRR at end of project	12.59%
Net capital cost	$663,580,160
Equity	$331,725,408
Size of debt	$331,854,752

Table 14: Simulation Results of RES-E Plant with Water as the HTF

Metric	**Value**
Annual energy (year 1)	127,126,448 kWh
Capacity factor (year 1)	29.00%
Annual Water Usage	44,136 m^3
PPA price (year 1)	20.56 ¢/kWh
PPA price escalation	1.00 %/year
Levelized PPA price (nominal)	26.84 ¢/kWh
Levelized PPA price (real)	21.11 ¢/kWh
Levelized COE (nominal)	24.67 ¢/kWh
Net present value	$29,151,450
Internal rate of return (IRR)	11.00%
Year IRR is achieved	20
IRR at end of project	12.59%
Net capital cost	$428,692,640
Equity	$214,301,536
Size of debt	$214,391,088

Table 15: Comparison if Monthly Output Models for the considered HTFs

FIRST YEAR ENERGY FROM THE SYSTEM BY MONTH FOR TIME OF DAY PERIOD 6 | (KWH)			
	Therminol VP-1	**Molten Salt**	**Water**
Jan	637005	3.98E+06	-54559.9
Feb	2.01E+06	4.44E+06	-49279.9
Mar	1.30E+06	3.94E+06	-54559.9
Apr	1.50E+06	4.27E+06	-52799.9
May	1.18E+06	6.39E+06	-54559.9
Oct	53270.2	5.12E+06	-54559.9
Nov	-130689	4.26E+06	-52799.9
Dec	4489.41	4.01E+06	-54559.9

4.3. Initial Results of the Simulation of the Molten Salt Model's Performance

The plant performance with the selected HTF is simulated on SAM and EnergyPLAN.

4.3.1. Simulation results of the molten salt model's performance. The molten salt model from Section 4.2 is selected. The molten salt makes use of a 60% $NaNO_3$ / 40% KNO_3 mixture as both the heat transfer fluid and the thermal storage fluid. This section presents the data obtained from the EnergyPLAN simulation of the molten salt model from Section 4.2. Analysis and Optimization if the model will be done in the next section using the results obtained from this section.

To meet the United Arab Emirate's electricity demand (92 TWh annually), the total expected energy production by the system above should be 21,000 MW at an assumed plant capacity factor of 50%. Building on the projected required production and the model selected in the previous section, a feasibility study based on the size of investment debt, annual production and capacity factor is carried out using SAM to determine the best way to realize the required capacity. Two systems are hypothesized:

1. Single plant based on the 50 MW molten salt CSP-PT model selected in the previous section, but scaled up to full expected production capacity at 21,000 MW.
2. An integrated system of 420 units of 50 MW molten salt CEP-PT plants to amount to a total capacity of 21,000 MW.

The performance results obtained for both the single plant and integrated plant are compared below to select the more feasible option. The following factors are compared: total investment debt, plant capacity factor and annual production.

Total Investment Debt

Single Plant = \$141,071,712,256

Integrated Plant = \$331,854,368 x 420 units

= \$139,378,834,600

The single plant venture simulates a negative investment debt – its equity is larger than the plant's net capital cost which projects that if actualised the plant would make staggering losses.

Plant Capacity Factor

Single Plant = -0.8%

Integrated Plant = 75.5%

The single plant has a negative capacity factor. This means that it completely fails to generate its expected capacity annually. The integrated model will have a cumulative capacity factor of 75.5% with a projected three quarters of its full capacity realised every year.

Annual Production

Single Plant: As expected, this model has a negative annual production.

Integrated Plant: This is clearly the better of the two with ¾ of its expected annual production according to its very high plant capacity.

Considering the three observations above, the integrated plant model is selected and used to model the system in EnergyPLAN to obtain the initial results.

Results of Simulation of 420 Integrated units of 50 MW Plants

In the analysis of this system, it is assumed that each unit is technically and economically identical and that the cumulative technical and financial data was a function of the number of units integrated to amount to the expected capacity. In this case the number of units is 420. Table 16 presents the data for the single unit.

4.3.2. Plant model's performance results. This section presents the performance results of the proposed plant. The Total Power Availed to Grid vs. Time plot generated from the simulation of the 50 MW plant in SAM is used as the distribution profile for the CSP solar power tab in the electricity supply tab sheet. The initial results are presented in the form of a pre-defined report generated from EnergyPLAN and also electricity balance graphs for the month of January. The results are shown in Figure 21 and Figure 22.

Table 16: Simulation Results of Total Plant Output and Cost in the First Year for One Plant Generating 50 MWe

Metric	**Value**
Annual energy (year 1)	330,846,656 kWh
Capacity factor (year 1)	75.50%
Annual Water Usage	79,392 m^3
PPA price (year 1)	13.93 ¢/kWh
PPA price escalation	1.00 %/year
Levelized PPA price (nominal)	15.95 ¢/kWh
Levelized PPA price (real)	12.55 ¢/kWh
Levelized COE (nominal)	14.66 ¢/kWh
Net present value	$45,126,464
Internal rate of return (IRR)	11.00%
Year IRR is achieved	20
IRR at end of project	12.59%
Net capital cost	$663,579,648
Equity	$331,725,280
Size of debt	$331,854,368

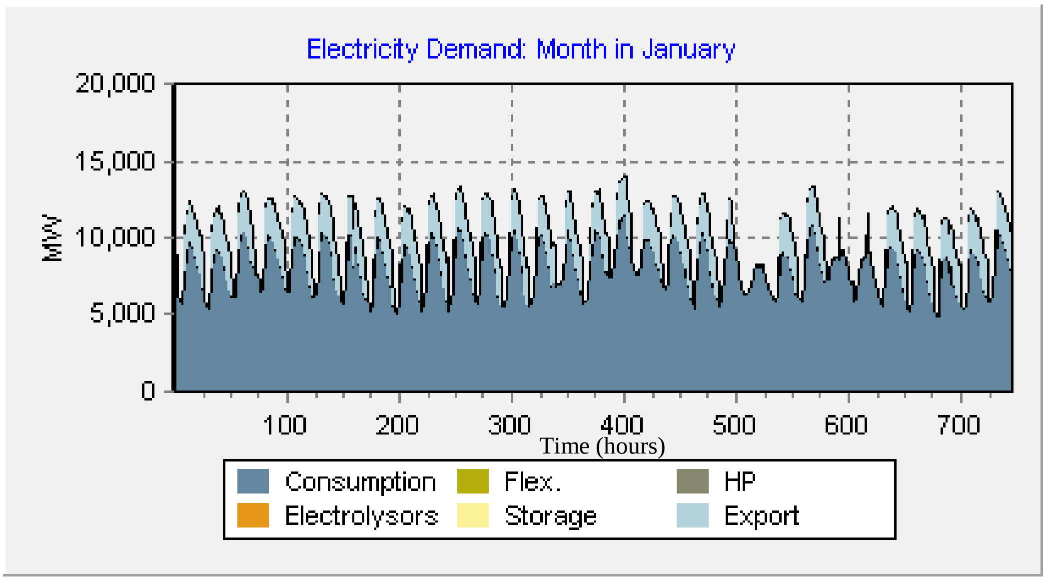


Figure 21: Hourly Electricity Demand in Abu Dhabi for Month of January (MW vs. h)

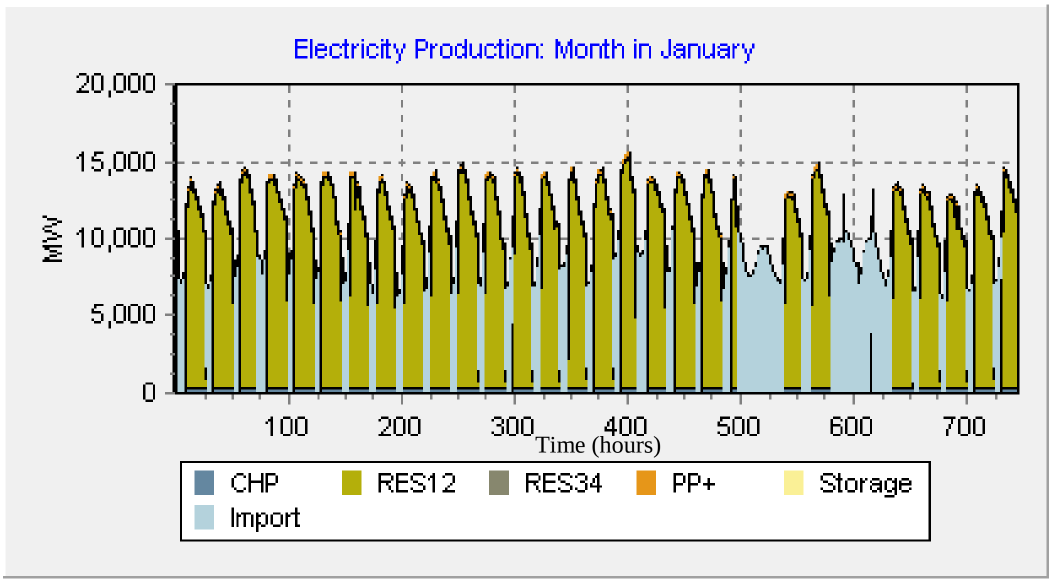


Figure 22: Hourly Electricity Production by the CSP-PT Plant in Month of January (MW vs. h)

Figure 23 presents the remaining electricity demand in Abu Dhabi for the month of January after integrating the 420 units of 50 MWe CSP-PT plants to the grid. The initial results show a great production deficiency by the CSP-PT plant, as the demand is not covered. In the following section, results of the optimization of the system to eliminate this deficiency will be presented.

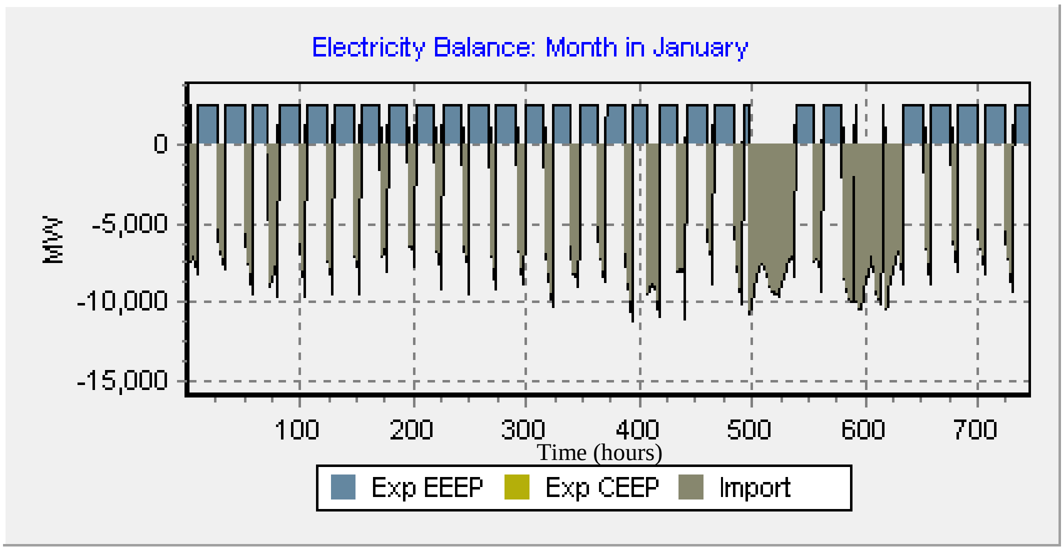


Figure 23: Hourly Electricity Balance in Abu Dhabi for Month of January (MW vs. h) i.e. Remaining Electricity Demand after CSP-PT Plant Integration to the Grid

4.4. Optimization of the Modes of Operation

For optimization of the modes of operation, it is assumed that each of the 420 units of the integrated 21,000 MW CSP-PT plant is operated in the exact same way to produce identical outputs. The optimization process is performed on EnergyPLAN, and is based on analysis of the initial results for the power output profile obtained over a day, for selected days in each of the annual twelve months.

Optimization is based on the dispatch control technique. In this technique, schedule matrices are used to specify the hour and month of a distinct operation period. For each period, a dispatch control variable known as the turbine output fraction is defined and used to scale the turbine's thermal input relative to the design for that specific period. Two schedule matrices are defined: for weekdays and for the weekends.

Production graphs are used to analyse the production in relation with the deficit in order to optimize the production of the plants. In the graphs, the green coloured portions represent the CSP-PT plant's output whereas the light blue coloured portions represent the import. Since EnergyPLAN software automatically simulates an import equal to the deficit, the proportion of the import portions is a direct indicator of the amount of deficit. Hence, the aim of the optimization and thus, its success is gauged by how much the purple coloured portions are reduced. Figures 24 to 35 are the production graphs for the first day of each month:

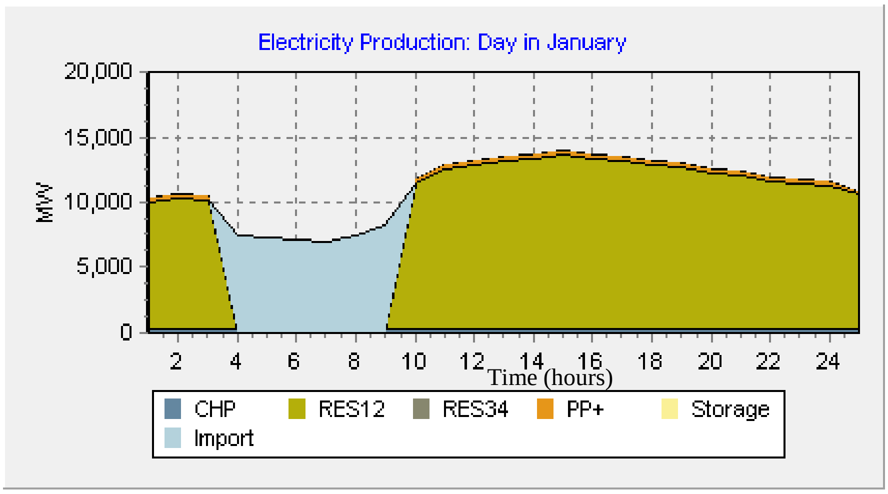


Figure 24: Electricity Supply by the CSP-PT plant to UAE's Grid in Day 1 of Jan.

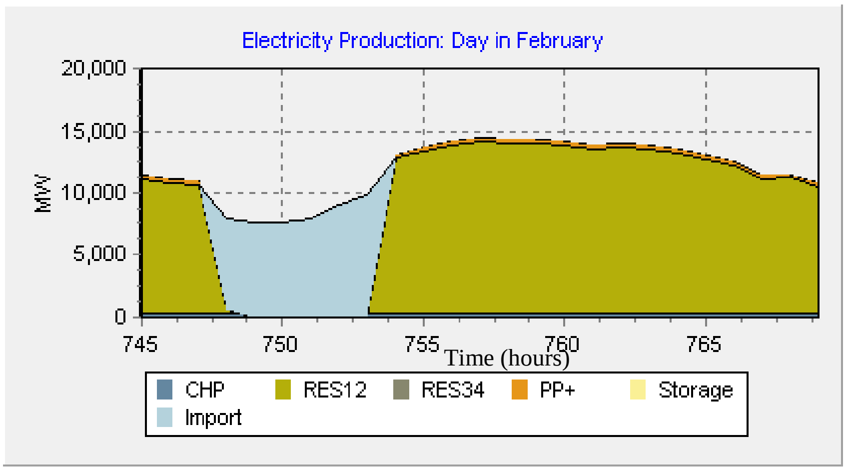


Figure 25: Electricity Supply by the CSP-PT plant to UAE's Grid in Day 1 of Feb.

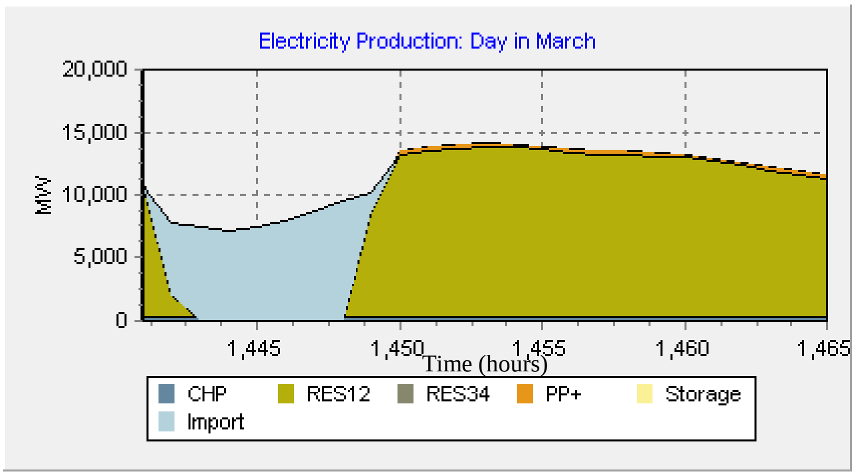


Figure 26: Electricity Supply by the CSP-PT plant to UAE's Grid in Day 1 of March

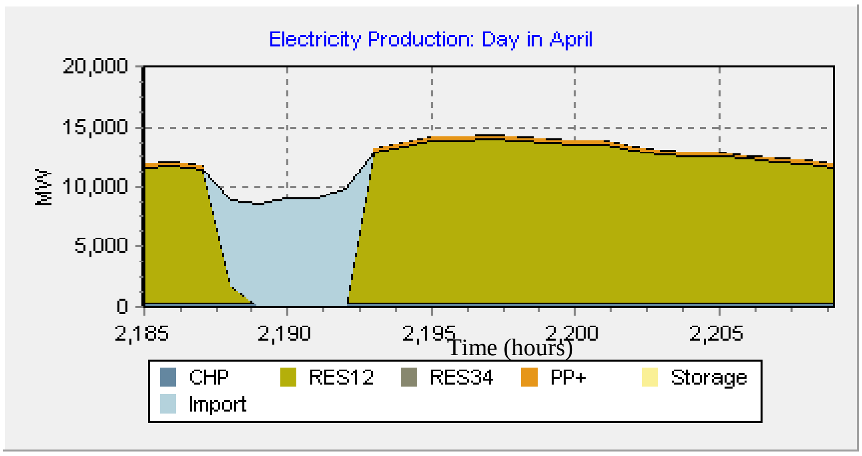


Figure 27: Electricity Supply by the CSP-PT plant to UAE's Grid in Day 1 of April

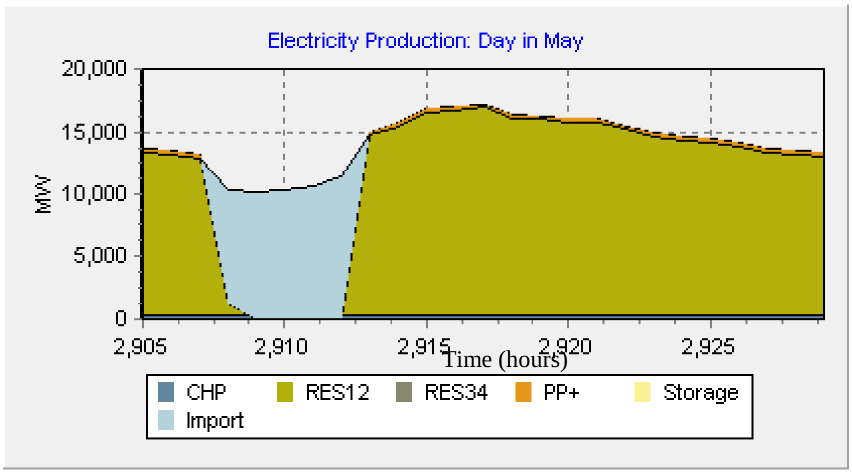


Figure 28: Electricity Supply by the CSP-PT plant to UAE’s Grid in Day 1 of May

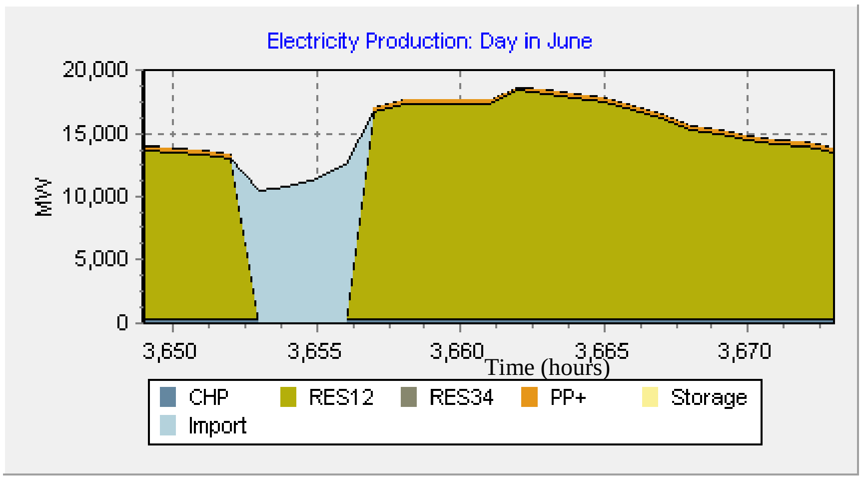


Figure 29: Electricity Supply by the CSP-PT plant to UAE’s Grid in Day 1 of June

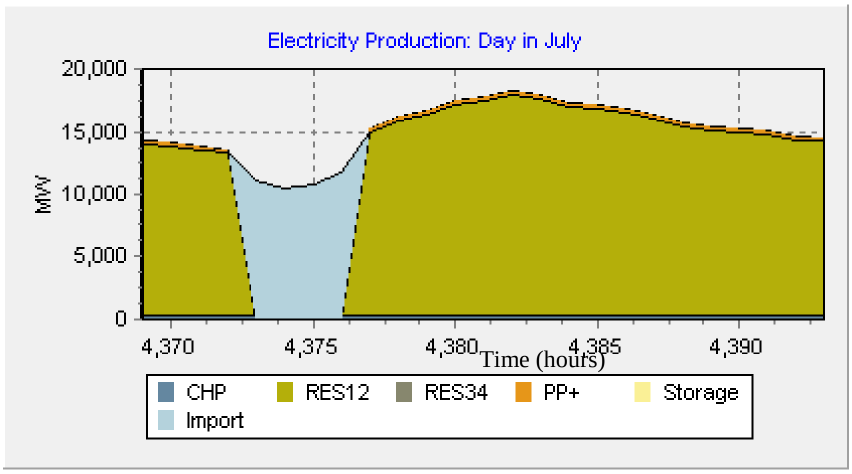


Figure 30: Electricity Supply by the CSP-PT plant to UAE’s Grid in Day 1 of July

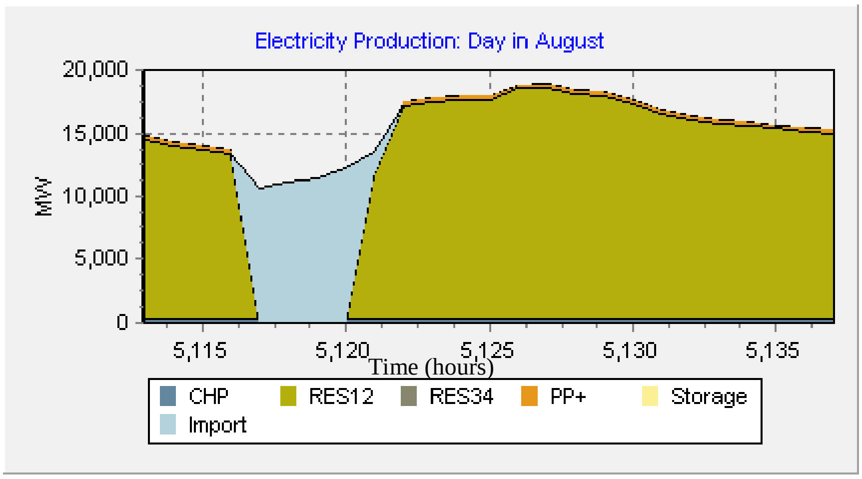


Figure 31: Electricity Supply by the CSP-PT plant to UAE’s Grid in Day 1 of Aug.

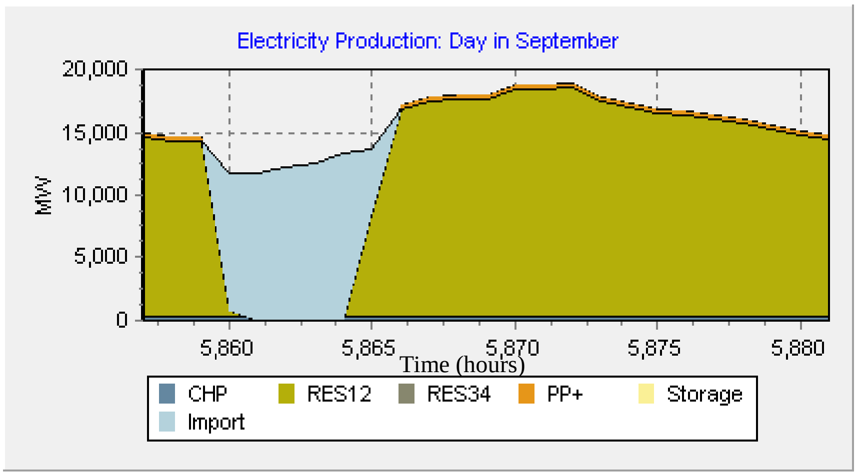


Figure 32: Electricity Supply by the CSP-PT plant to UAE’s Grid in Day 1 of Sept.

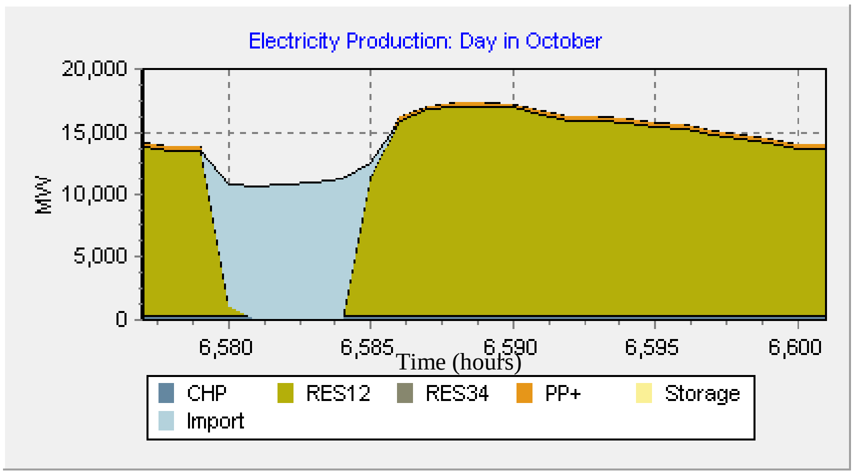


Figure 33: Electricity Supply by the CSP-PT plant to UAE’s Grid in Day 1 of Oct.

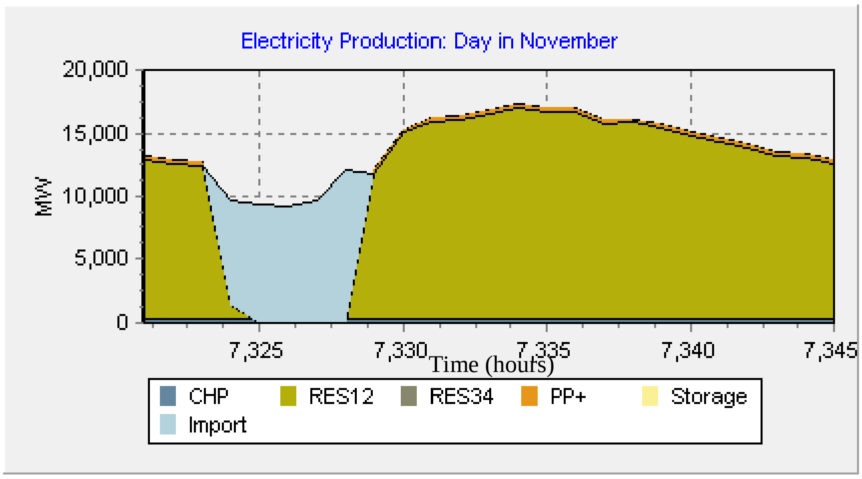


Figure 34: Electricity Supply by the CSP-PT plant to UAE’s Grid in Day 1 of Nov.

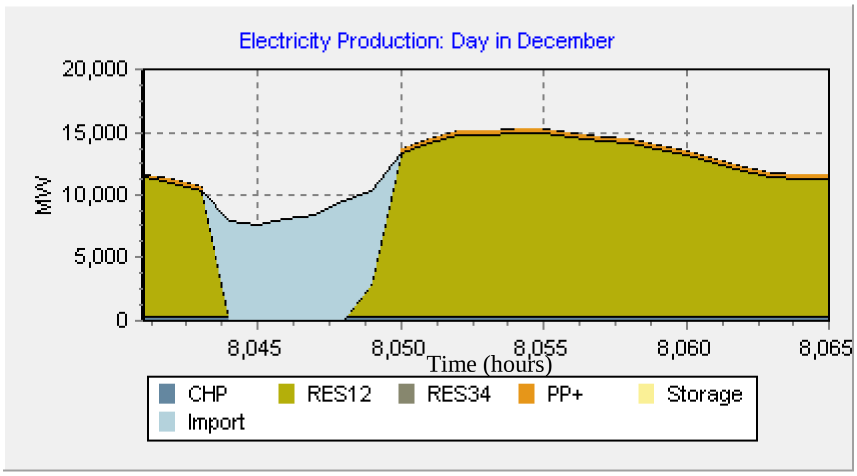


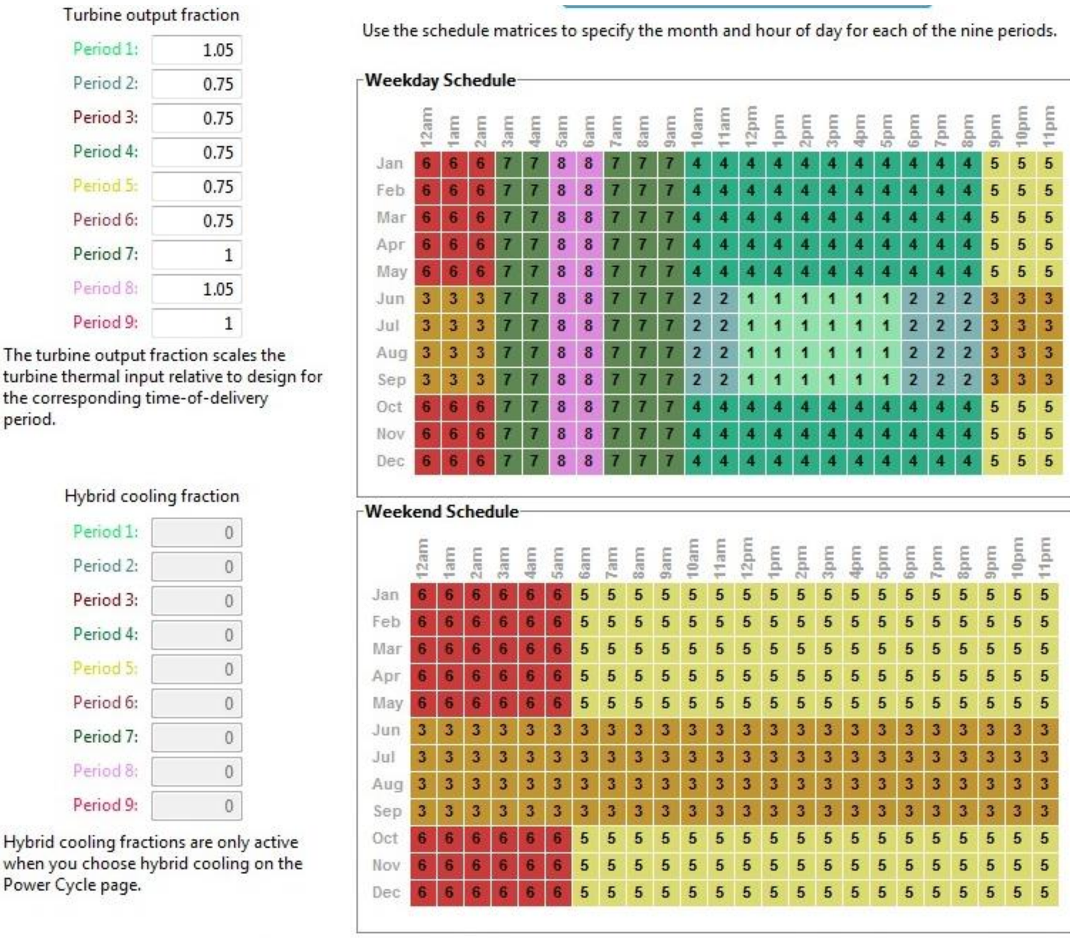
Figure 35: Electricity Supply by the CSP-PT plant to UAE’s Grid in Day 1 of Dec.

From the graphs, it can be seen that the production fully meets the demand except for a section of the day which is consistent with each test day of the twelve months. This section occurs roughly between 3:00 to 9:00 hrs. It can be theorised that there are two causes of this deficiency:

1. The period is at night when there is no insolation.
2. Since the period does not begin at dusk (6pm) but rather 9 hours later, the deficiency is caused by exhaustion of the energy in the thermal storage.

While the issue in the first hypothesis to the problem is inherent in the law of nature and thus virtually unsolvable, optimization measures could be carried out to solve the second issues. The following are the optimization measures effected on the system model and then simulated.

A schedule matrix based on electricity demand profile in the United Arab Emirates is developed. The matrix was built upon the Generic Summer Peak schedule from the System Advisor Model and then modified to take care of the deficiency period. Figure 36 shows the two developed schedule matrices. Mainly, the turbine output factor is increased to cover the periods where there is deficiency.



Turbine output fraction

Period 1:	1.05
Period 2:	0.75
Period 3:	0.75
Period 4:	0.75
Period 5:	0.75
Period 6:	0.75
Period 7:	1
Period 8:	1.05
Period 9:	1

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.

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

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	6	6	6	7	7	8	8	7	7	7	4	4	4	4	4	4	4	4	4	4	4	5	5	5
Feb	6	6	6	7	7	8	8	7	7	7	4	4	4	4	4	4	4	4	4	4	4	5	5	5
Mar	6	6	6	7	7	8	8	7	7	7	4	4	4	4	4	4	4	4	4	4	4	5	5	5
Apr	6	6	6	7	7	8	8	7	7	7	4	4	4	4	4	4	4	4	4	4	4	5	5	5
May	6	6	6	7	7	8	8	7	7	7	4	4	4	4	4	4	4	4	4	4	4	5	5	5
Jun	3	3	3	7	7	8	8	7	7	7	2	2	1	1	1	1	1	1	2	2	2	3	3	3
Jul	3	3	3	7	7	8	8	7	7	7	2	2	1	1	1	1	1	1	2	2	2	3	3	3
Aug	3	3	3	7	7	8	8	7	7	7	2	2	1	1	1	1	1	1	2	2	2	3	3	3
Sep	3	3	3	7	7	8	8	7	7	7	2	2	1	1	1	1	1	1	2	2	2	3	3	3
Oct	6	6	6	7	7	8	8	7	7	7	4	4	4	4	4	4	4	4	4	4	4	5	5	5
Nov	6	6	6	7	7	8	8	7	7	7	4	4	4	4	4	4	4	4	4	4	4	5	5	5
Dec	6	6	6	7	7	8	8	7	7	7	4	4	4	4	4	4	4	4	4	4	4	5	5	5

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	6	6	6	6	6	6	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Feb	6	6	6	6	6	6	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Mar	6	6	6	6	6	6	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Apr	6	6	6	6	6	6	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
May	6	6	6	6	6	6	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Jun	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Jul	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Aug	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Sep	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Oct	6	6	6	6	6	6	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Nov	6	6	6	6	6	6	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Dec	6	6	6	6	6	6	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5

Figure 36: Schedule Matrices for Weekdays and Weekends for the Optimization of CSP-PT Plant based on the UAE's Electricity Demand

The result of the optimization measure above is seen in the production graphs below for the first day in three random months, April, July and November. Pre-optimization graphs are shown for comparison in Figure 37.

Since the deficiency period is observed to begin 9 hours after sunset, the capacity of the storage unit at 10 hours of full load is taken as another limiting factor.

Therefore, a second optimization measure is simulated by increasing the size of the thermal storage unit from 10 hours to 24 hours. The graphs in Figure 38 show the results for the same months taken for Optimization 1.

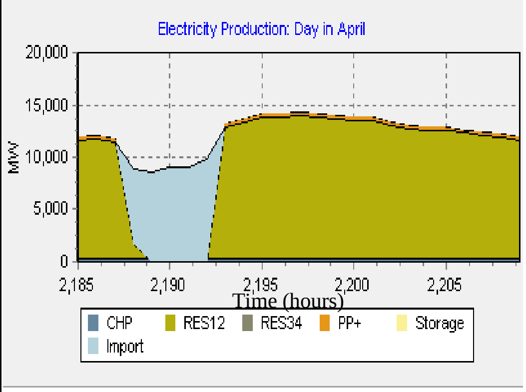
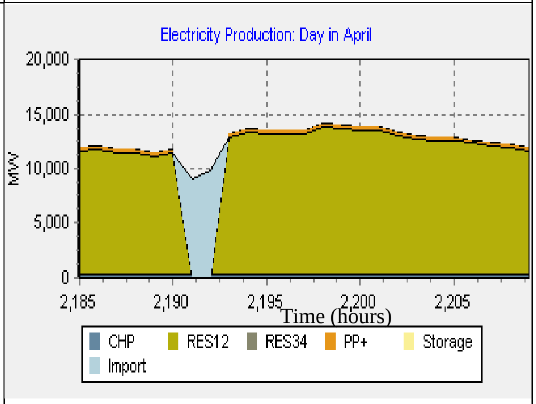
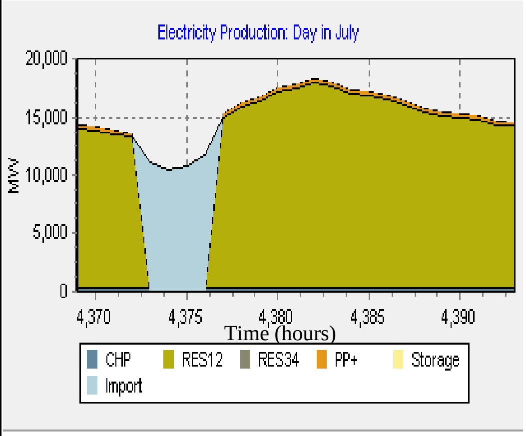
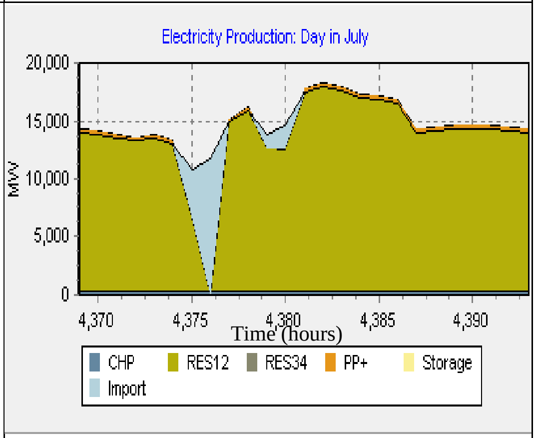
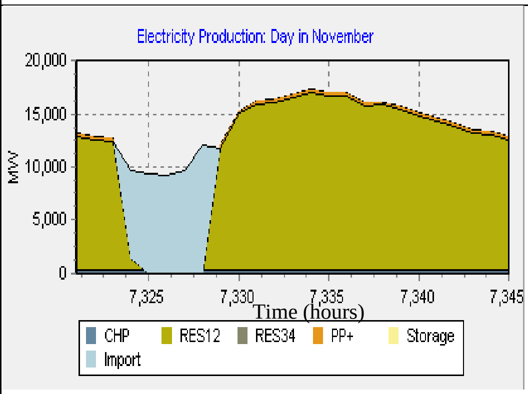
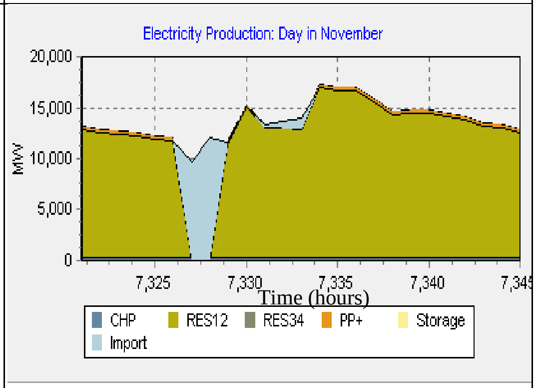
<table>
<tr><th></th><th>Before Optimization 1</th><th>After Optimization 1</th></tr>
<tr><td>Apr</td><td>
</td><td>
</td></tr>
<tr><td>July</td><td>
</td><td>
</td></tr>
<tr><td>Nov</td><td>
</td><td>
</td></tr>
</table>

Figure 37: Electricity Supply to the UAE's Grid from the CSP-PT Plant before and after the First Optimization

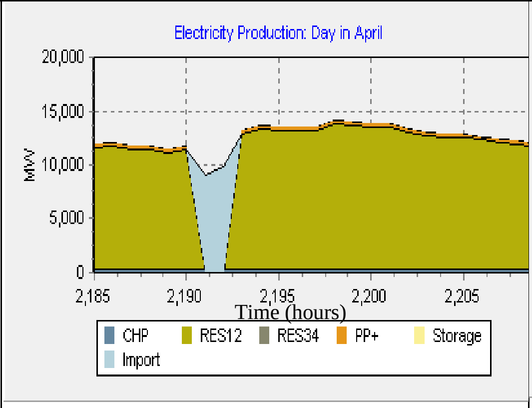
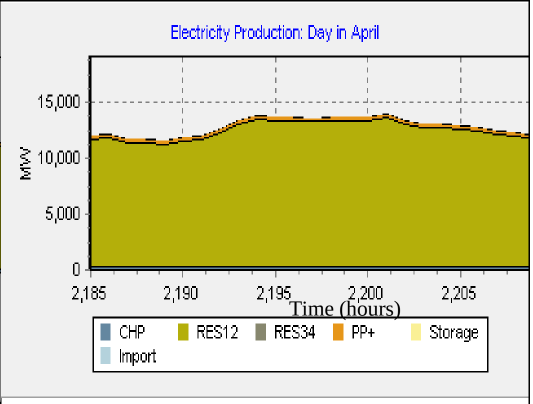
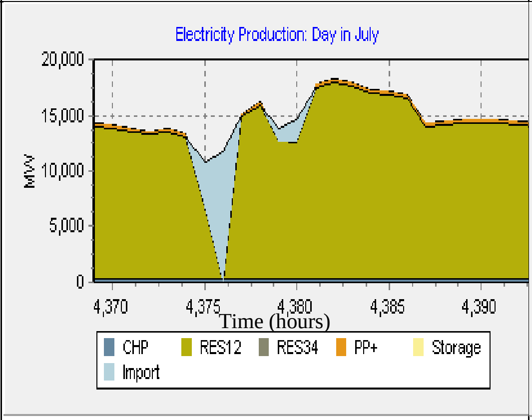
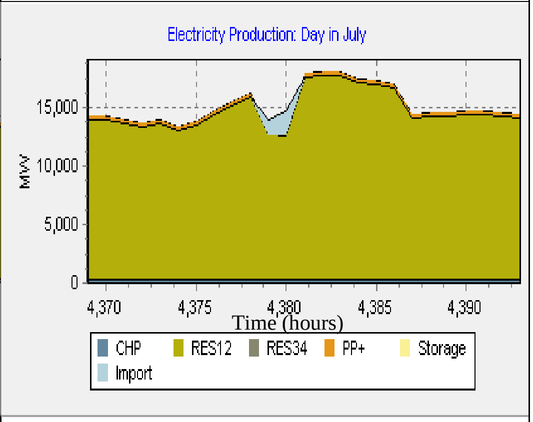
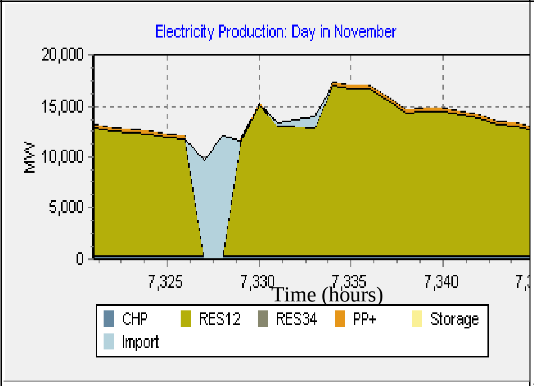
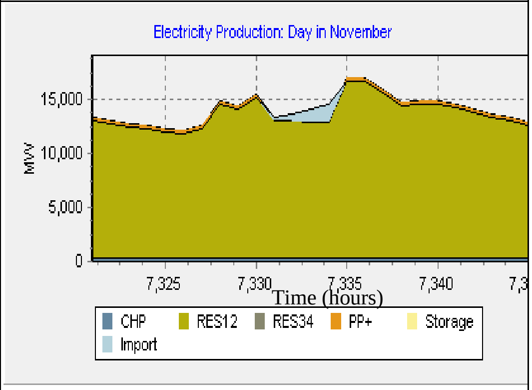
	Before Optimization 2	**After Optimization 2**
Apr		
July		
Nov		

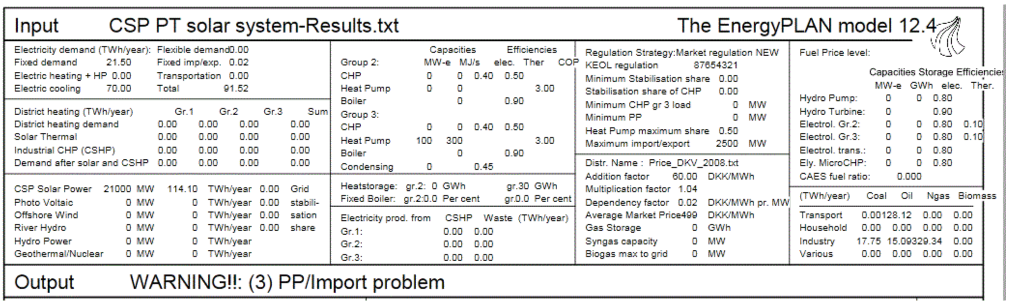
Figure 38: Electricity Supply to the UAE's Grid from the CSP-PT Plant before and after the Second Optimization

The graphs in Figure 38 show that the second optimization greatly reduced the deficiency, but it did not completely eliminate it as seen in the month of November, which is a month of lower DNI in comparison to months in the summer season.

4.5. Energy Analysis Investigating the Sufficiency of the Proposed CSP-PT Plant to the Electricity Demand

The CSP-PT system developed and optimized is modelled in EnergyPLAN and the results are presented in this section. The results obtained are examined to see if the system fully meets the UAE's electricity demand. Measures are then proposed and then simulated on the occasion that the system does not. The results of the first simulation are presented in Figure 39. The integration of the subject CSP-PT's electricity in the simulated model of the UAE energy network reveals one critical error in relation to the production's sufficiency to the demand. In the EnergyPLAN simulator's report, the critical error is dubbed as "PP/Import problem", where PP stands for Power Plant.

According to the EnergyPLAN model, the PP/Import problem manifests if, in one or more simulation hours, the demand deficiency exceeds the maximum transmission line capacity. In an EnergyPLAN simulation, in the event that the hourly production fails to meet the hourly demand, an hourly importation of the deficiency is automatically simulated. Thus, a PP/Import problem simulates a critical situation in which a critical import is needed but is impossible owing to inability of the transmission line to support the load.



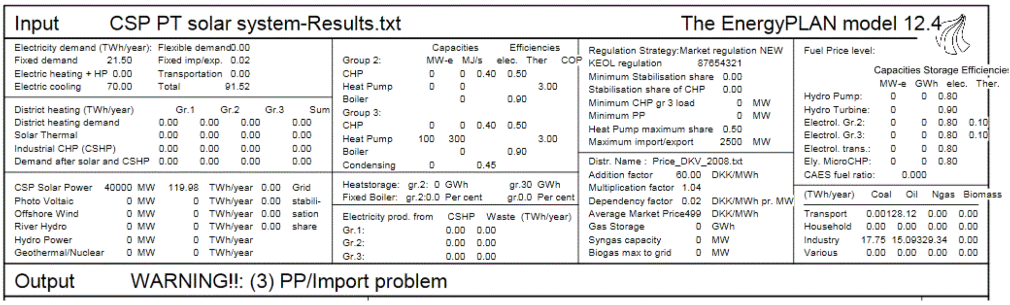
```
Input        CSP PT solar system-Results.txt                    The EnergyPLAN model 12.4

Electricity demand (TWh/year):  Flexible demand0.00
Fixed demand            21.50   Fixed imp/exp.   0.02
Electric heating + HP  0.00     Transportation   0.00
Electric cooling        70.00   Total           91.52

District heating (TWh/year)        Gr.1    Gr.2    Gr.3    Sum
District heating demand            0.00    0.00    0.00    0.00
Solar Thermal                      0.00    0.00    0.00    0.00
Industrial CHP (CSHP)              0.00    0.00    0.00    0.00
Demand after solar and CSHP        0.00    0.00    0.00    0.00

CSP Solar Power    21000  MW   114.10  TWh/year  0.00  Grid
Photo Voltaic          0  MW        0  TWh/year  0.00  stabili-
Offshore Wind          0  MW        0  TWh/year  0.00  sation
River Hydro            0  MW        0  TWh/year  0.00  share
Hydro Power            0  MW        0  TWh/year
Geothermal/Nuclear     0  MW        0  TWh/year

                     Capacities       Efficiencies
Group 2:             MW-e   MJ/s    elec.  Ther   COP
CHP                     0      0    0.40   0.50
Heat Pump               0      0                  3.00
Boiler                         0           0.90
Group 3:
CHP                     0      0    0.40   0.50
Heat Pump             100    300                  3.00
Boiler                         0           0.90
Condensing              0           0.45

Heatstorage:   gr.2:  0  GWh           gr.30  GWh
Fixed Boiler:  gr.2:0.0  Per cent      gr.0.0  Per cent

Electricity prod. from     CSHP   Waste  (TWh/year)
Gr.1:                      0.00   0.00
Gr.2:                      0.00   0.00
Gr.3:                      0.00   0.00

Regulation Strategy:Market regulation NEW
KEOL regulation              87654321
Minimum Stabilisation share    0.00
Stabilisation share of CHP     0.00
Minimum CHP gr 3 load             0   MW
Minimum PP                        0   MW
Heat Pump maximum share        0.50
Maximum import/export          2500   MW

Distr. Name :  Price_DKV_2008.txt
Addition factor       60.00   DKK/MWh
Multiplication factor  1.04
Dependency factor      0.02   DKK/MWh pr. MW
Average Market Price499       DKK/MWh
Gas Storage               0   GWh
Syngas capacity           0   MW
Biogas max to grid        0   MW

Fuel Price level:

                  Capacities Storage Efficiencies
                    MW-e    GWh   elec.  Ther.
Hydro Pump:            0      0   0.80
Hydro Turbine:         0          0.90
Electrol. Gr.2:        0      0   0.80   0.10
Electrol. Gr.3:        0      0   0.80   0.10
Electrol. trans.:      0      0   0.80
Ely. MicroCHP:         0      0   0.80
CAES fuel ratio:         0.000

(TWh/year)     Coal    Oil     Ngas   Biomass
Transport      0.00128.12      0.00   0.00
Household      0.00    0.00    0.00   0.00
Industry       17.75  15.09329.34     0.00
Various        0.00    0.00    0.00   0.00

Output       WARNING!!: (3) PP/Import problem
```

Figure 39: Portion of EnergyPLAN Report of Simulation of Optimized CSP-PT Plant

The occurrence of the PP/Import problem in the simulation of the Optimized Integrated CSP-PT reveals that current system fails, at certain periods of the year, to meet the demand. Two reasons for this critical deficiency are hypothesised as:

1. Insufficiency of the current production capacity (21,000 MW)
2. The residual intermittency of the CSP-PT plant after optimization

In order to verify and rectify hypothesis (1), the number of units modelled in the EnergyPLAN simulation are increased from 420 units to 800 units, which increases the Integrated CSP-PT model’s capacity to a total of 40,000 MW. This change is effected by increasing the CSP solar power capacity in the Intermittent Renewable Electricity tab sheet from 21,000 MW to 40,000 MW. The results of the simulation are presented the report shown in Figure 40.



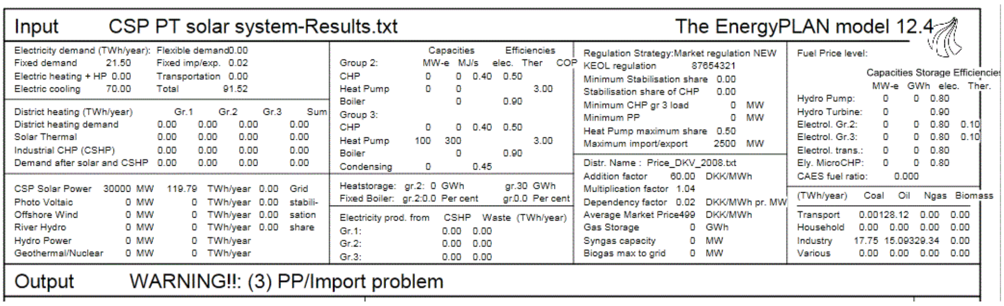
```
Input        CSP PT solar system-Results.txt                    The EnergyPLAN model 12.4

Electricity demand (TWh/year):  Flexible demand0.00
Fixed demand          21.50     Fixed imp/exp.   0.02
Electric heating + HP  0.00     Transportation   0.00
Electric cooling      70.00     Total           91.52

District heating (TWh/year)       Gr.1     Gr.2     Gr.3      Sum
District heating demand           0.00     0.00     0.00     0.00
Solar Thermal                     0.00     0.00     0.00     0.00
Industrial CHP (CSHP)             0.00     0.00     0.00     0.00
Demand after solar and CSHP       0.00     0.00     0.00     0.00

CSP Solar Power    40000  MW   119.98  TWh/year  0.00  Grid
Photo Voltaic          0  MW        0  TWh/year  0.00  stabili-
Offshore Wind          0  MW        0  TWh/year  0.00  sation
River Hydro            0  MW        0  TWh/year  0.00  share
Hydro Power            0  MW        0  TWh/year
Geothermal/Nuclear     0  MW        0  TWh/year

                      Capacities      Efficiencies
Group 2:              MW-e   MJ/s   elec.  Ther    COP
CHP                      0      0   0.40   0.50
Heat Pump                0      0                 3.00
Boiler                          0          0.90
Group 3:
CHP                      0      0   0.40   0.50
Heat Pump              100    300                 3.00
Boiler                          0          0.90
Condensing               0          0.45

Heatstorage:   gr.2:  0  GWh            gr.30  GWh
Fixed Boiler:  gr.2:0.0  Per cent      gr.0.0  Per cent

Electricity prod. from     CSHP    Waste  (TWh/year)
Gr.1:                      0.00     0.00
Gr.2:                      0.00     0.00
Gr.3:                      0.00     0.00

Regulation Strategy:Market regulation NEW
KEOL regulation              87654321
Minimum Stabilisation share      0.00
Stabilisation share of CHP       0.00
Minimum CHP gr 3 load               0   MW
Minimum PP                          0   MW
Heat Pump maximum share          0.50
Maximum import/export            2500   MW

Distr. Name :  Price_DKV_2008.txt
Addition factor        60.00   DKK/MWh
Multiplication factor   1.04
Dependency factor       0.02   DKK/MWh pr. MW
Average Market Price499        DKK/MWh
Gas Storage                0   GWh
Syngas capacity            0   MW
Biogas max to grid         0   MW

Fuel Price level:

                   Capacities Storage Efficiencies
                      MW-e     GWh   elec.  Ther.
Hydro Pump:              0       0   0.80
Hydro Turbine:           0           0.90
Electrol. Gr.2:          0       0   0.80   0.10
Electrol. Gr.3:          0       0   0.80   0.10
Electrol. trans.:        0       0   0.80
Ely. MicroCHP:           0       0   0.80
CAES fuel ratio:          0.000

(TWh/year)     Coal     Oil     Ngas   Biomass
Transport      0.00128.12       0.00      0.00
Household      0.00     0.00    0.00      0.00
Industry      17.75  15.09329.34          0.00
Various        0.00     0.00    0.00      0.00

Output        WARNING!!: (3) PP/Import problem
```

Figure 40: Portion of EnergyPLAN Report of Simulation of 800 units of 50 MW Output Optimized CSP-PT Plant, Generating total Output of 40,000 MW

Analysis of the report in Figure 40 reveals that the PP/Import problem persists even after increase of the total production capacity to 40,000 MW. Also, while the projected annual production of the 40,000 MW model is projected at 252.52 TWh, only 119.98 TWh is realised. This represents a 5.15% increase from the previous annual production at 114.10 TWh. Pitting that with the 90.5% increase in maximum production capacity of the plant it could be seen that at 40,000 MW, the production capacity is overly excess and that the reduced annual production of the 40 GW plant is due to Critical Excess Electricity Regulation Strategy (CEES) of the EnergyPLAN simulator.

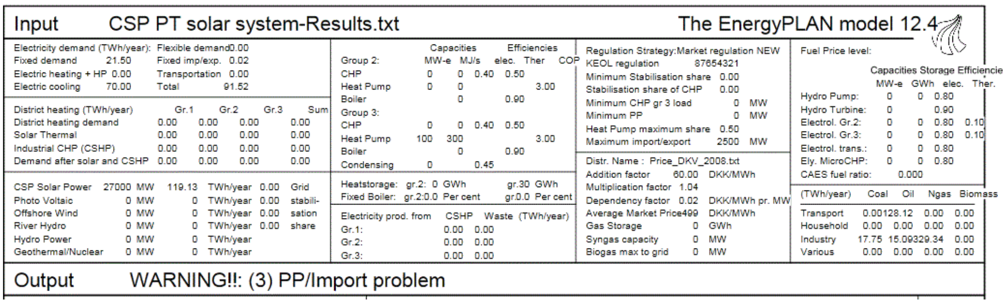
A second simulation is carried out with the production capacity reduced to 30,000 MW. The results of the simulation are presented in the report shown in Figure 41.

Analysis of report in Figure 41 reveals only a slight decrease in the assumed annual optimum production after CEES (i.e. from 119.98 to 119.73). Subsequent simulations with decreasing plant productions are carried out in an attempt to find the optimum production capacity. The optimum integrated plant capacity of 27,000 MW (i.e. 520 units of 50 MW output plants) is reached. Figure 42 presents a report of its simulation.



```
Input        CSP PT solar system-Results.txt                    The EnergyPLAN model 12.4

Electricity demand (TWh/year):  Flexible demand0.00
Fixed demand           21.50    Fixed imp/exp.   0.02
Electric heating + HP  0.00     Transportation   0.00
Electric cooling       70.00    Total            91.52

District heating (TWh/year)      Gr.1    Gr.2    Gr.3    Sum
District heating demand          0.00    0.00    0.00    0.00
Solar Thermal                    0.00    0.00    0.00    0.00
Industrial CHP (CSHP)            0.00    0.00    0.00    0.00
Demand after solar and CSHP      0.00    0.00    0.00    0.00

CSP Solar Power    30000 MW   119.79  TWh/year  0.00  Grid
Photo Voltaic          0 MW        0  TWh/year  0.00  stabili-
Offshore Wind          0 MW        0  TWh/year  0.00  sation
River Hydro            0 MW        0  TWh/year  0.00  share
Hydro Power            0 MW        0  TWh/year
Geothermal/Nuclear     0 MW        0  TWh/year

               Capacities      Efficiencies
Group 2:       MW-e   MJ/s     elec.  Ther    COP
CHP            0      0        0.40   0.50
Heat Pump      0      0                       3.00
Boiler                0               0.90
Group 3:
CHP            0      0        0.40   0.50
Heat Pump      100    300                     3.00
Boiler                0               0.90
Condensing     0               0.45

Heatstorage:   gr.2:  0 GWh           gr.30 GWh
Fixed Boiler:  gr.2:0.0 Per cent      gr.0.0 Per cent

Electricity prod. from     CSHP   Waste  (TWh/year)
Gr.1:                      0.00   0.00
Gr.2:                      0.00   0.00
Gr.3:                      0.00   0.00

Regulation Strategy:Market regulation NEW
KEOL regulation              87654321
Minimum Stabilisation share  0.00
Stabilisation share of CHP   0.00
Minimum CHP gr 3 load        0    MW
Minimum PP                   0    MW
Heat Pump maximum share      0.50
Maximum import/export        2500 MW

Distr. Name :  Price_DKV_2008.txt
Addition factor        60.00  DKK/MWh
Multiplication factor  1.04
Dependency factor      0.02   DKK/MWh pr. MW
Average Market Price499       DKK/MWh
Gas Storage            0      GWh
Syngas capacity        0      MW
Biogas max to grid     0      MW

Fuel Price level:

                   Capacities Storage Efficiencies
                   MW-e   GWh   elec.  Ther.
Hydro Pump:        0      0     0.80
Hydro Turbine:     0            0.90
Electrol. Gr.2:    0      0     0.80   0.10
Electrol. Gr.3:    0      0     0.80   0.10
Electrol. trans.:  0      0     0.80
Ely. MicroCHP:     0      0     0.80
CAES fuel ratio:       0.000

(TWh/year)    Coal   Oil    Ngas   Biomass
Transport     0.00128.12    0.00   0.00
Household     0.00   0.00   0.00   0.00
Industry      17.75  15.09329.34   0.00
Various       0.00   0.00   0.00   0.00

Output       WARNING!!: (3) PP/Import problem
```

Figure 41: Portion of EnergyPLAN Report of Simulation of 600 units of 50 MW Output Optimized CSP-PT Plant, Generating total Output of 30,000 MW



```
Input        CSP PT solar system-Results.txt                    The EnergyPLAN model 12.4

Electricity demand (TWh/year):  Flexible demand0.00
Fixed demand           21.50    Fixed imp/exp.   0.02
Electric heating + HP  0.00     Transportation   0.00
Electric cooling       70.00    Total            91.52

District heating (TWh/year)      Gr.1    Gr.2    Gr.3    Sum
District heating demand          0.00    0.00    0.00    0.00
Solar Thermal                    0.00    0.00    0.00    0.00
Industrial CHP (CSHP)            0.00    0.00    0.00    0.00
Demand after solar and CSHP      0.00    0.00    0.00    0.00

CSP Solar Power    27000 MW   119.13  TWh/year  0.00  Grid
Photo Voltaic          0 MW        0  TWh/year  0.00  stabili-
Offshore Wind          0 MW        0  TWh/year  0.00  sation
River Hydro            0 MW        0  TWh/year  0.00  share
Hydro Power            0 MW        0  TWh/year
Geothermal/Nuclear     0 MW        0  TWh/year

               Capacities      Efficiencies
Group 2:       MW-e   MJ/s     elec.  Ther    COP
CHP            0      0        0.40   0.50
Heat Pump      0      0                       3.00
Boiler                0               0.90
Group 3:
CHP            0      0        0.40   0.50
Heat Pump      100    300                     3.00
Boiler                0               0.90
Condensing     0               0.45

Heatstorage:   gr.2:  0 GWh           gr.30 GWh
Fixed Boiler:  gr.2:0.0 Per cent      gr.0.0 Per cent

Electricity prod. from     CSHP   Waste  (TWh/year)
Gr.1:                      0.00   0.00
Gr.2:                      0.00   0.00
Gr.3:                      0.00   0.00

Regulation Strategy:Market regulation NEW
KEOL regulation              87654321
Minimum Stabilisation share  0.00
Stabilisation share of CHP   0.00
Minimum CHP gr 3 load        0    MW
Minimum PP                   0    MW
Heat Pump maximum share      0.50
Maximum import/export        2500 MW

Distr. Name :  Price_DKV_2008.txt
Addition factor        60.00  DKK/MWh
Multiplication factor  1.04
Dependency factor      0.02   DKK/MWh pr. MW
Average Market Price499       DKK/MWh
Gas Storage            0      GWh
Syngas capacity        0      MW
Biogas max to grid     0      MW

Fuel Price level:

                   Capacities Storage Efficiencie
                   MW-e   GWh   elec.  Ther.
Hydro Pump:        0      0     0.80
Hydro Turbine:     0            0.90
Electrol. Gr.2:    0      0     0.80   0.10
Electrol. Gr.3:    0      0     0.80   0.10
Electrol. trans.:  0      0     0.80
Ely. MicroCHP:     0      0     0.80
CAES fuel ratio:       0.000

(TWh/year)    Coal   Oil    Ngas   Biomass
Transport     0.00128.12    0.00   0.00
Household     0.00   0.00   0.00   0.00
Industry      17.75  15.09329.34   0.00
Various       0.00   0.00   0.00   0.00

Output       WARNING!!: (3) PP/Import problem
```

Figure 42: Portion of EnergyPLAN Report of Simulation of 540 units of 50 MW Output Optimized CSP-PT Plant, Generating Optimum total Output of 27,000 MW

While the PP/Import problem is not solved, a significant improvement on the 27,000 MW model to meet the annual demand, more than the 21,000 MW plant, is seen in the Year Electricity balance graphs generated from corresponding EnergyPLAN simulations shown in Figure 43 and Figure 44.

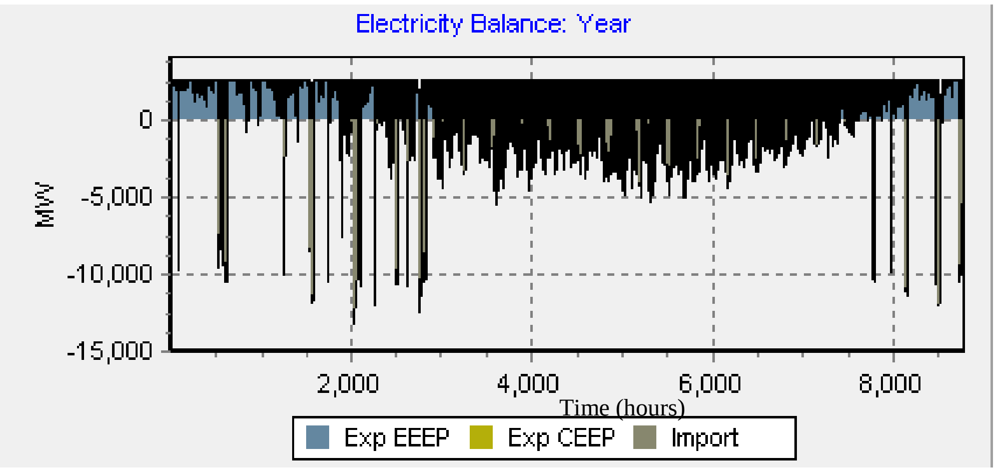


Figure 43: Energy Balance for One Year for Integrated 21,000 MW CSP-PT Plant Production

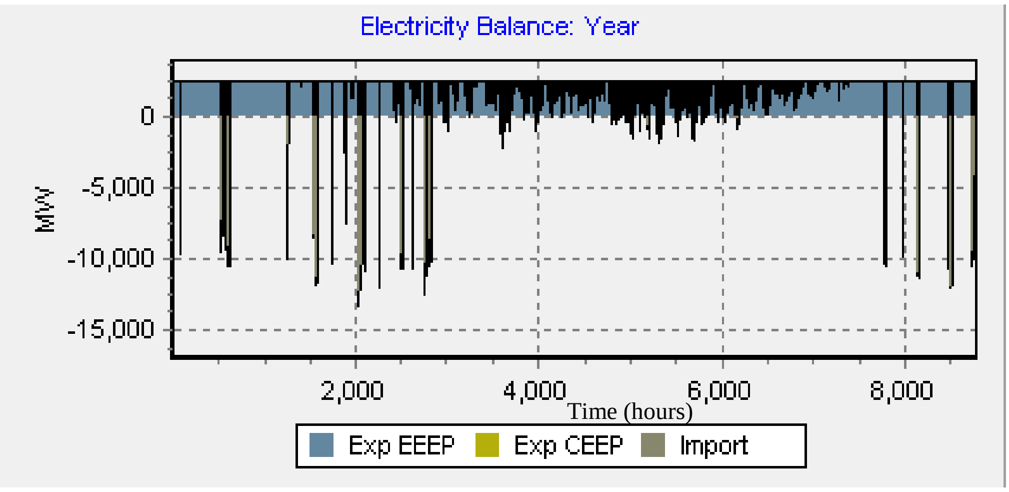
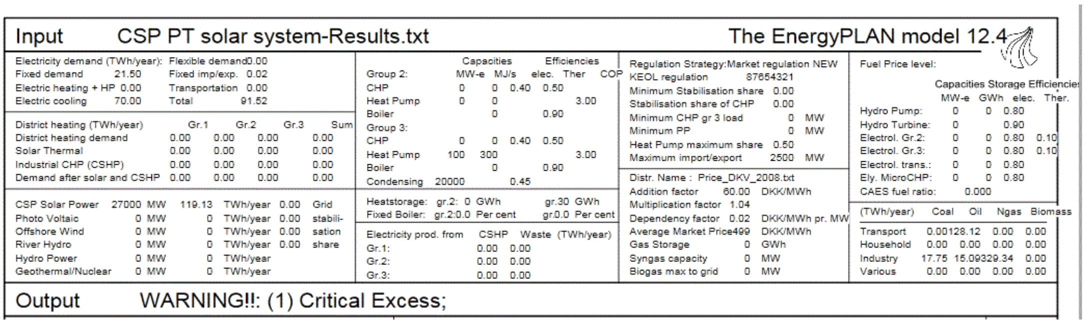


Figure 44: Energy Balance for One Year for Integrated 27,000 MW CSP-PT Plant Production

Analysis of the two graphs in Figure 43 and Figure 44 shows that there is a significant decrease in deficiency periods at 27,000 MW. However, persistence of the PP/Import problem highlights hypothesis (2) as the main contributor to the problem. To verify its validity, an attempted rectification measure is applied using EnergyPLAN. In this step a power plant (PP1) is defined in the in the heat and electricity supply tab sheet by assigning a capacity value to PP1 condensing mode operation input of the Combined Heat and Power input. This allows EnergyPLAN to simulate a situation where if there is an intermittency of the main CSP-PT production that compromises its ability to meet the demand at that time, the PP is prompted to cover the deficiency.

A PP Electric capacity of 20,000 MW is defined and the report in Figure 45 contains results of the simulation. The PP/import problem is eliminated.



```
Input        CSP PT solar system-Results.txt                    The EnergyPLAN model 12.4
```

```
Electricity demand (TWh/year):  Flexible demand0.00
Fixed demand         21.50      Fixed imp/exp.   0.02
Electric heating + HP  0.00     Transportation   0.00
Electric cooling     70.00      Total           91.52

District heating (TWh/year)       Gr.1     Gr.2     Gr.3      Sum
District heating demand           0.00     0.00     0.00     0.00
Solar Thermal                     0.00     0.00     0.00     0.00
Industrial CHP (CSHP)             0.00     0.00     0.00     0.00
Demand after solar and CSHP       0.00     0.00     0.00     0.00

CSP Solar Power     27000  MW    119.13  TWh/year  0.00  Grid
Photo Voltaic           0  MW         0  TWh/year  0.00  stabili-
Offshore Wind           0  MW         0  TWh/year  0.00  sation
River Hydro             0  MW         0  TWh/year  0.00  share
Hydro Power             0  MW         0  TWh/year
Geothermal/Nuclear      0  MW         0  TWh/year
```

```
                     Capacities      Efficiencies
Group 2:            MW-e   MJ/s    elec.   Ther    COP
CHP                    0      0    0.40    0.50
Heat Pump              0      0                    3.00
Boiler                        0            0.90
Group 3:
CHP                    0      0    0.40    0.50
Heat Pump            100    300                    3.00
Boiler                        0            0.90
Condensing         20000           0.45

Heatstorage:   gr.2:  0  GWh            gr.30  GWh
Fixed Boiler:  gr.2:0.0  Per cent       gr.0.0 Per cent

Electricity prod. from    CSHP   Waste  (TWh/year)
Gr.1:                     0.00   0.00
Gr.2:                     0.00   0.00
Gr.3:                     0.00   0.00
```

```
Regulation Strategy:Market regulation NEW
KEOL regulation              87654321
Minimum Stabilisation share     0.00
Stabilisation share of CHP      0.00
Minimum CHP gr 3 load              0   MW
Minimum PP                         0   MW
Heat Pump maximum share         0.50
Maximum import/export           2500   MW

Distr. Name :  Price_DKV_2008.txt
Addition factor         60.00   DKK/MWh
Multiplication factor    1.04
Dependency factor        0.02   DKK/MWh pr. MW
Average Market Price499         DKK/MWh
Gas Storage                 0   GWh
Syngas capacity             0   MW
Biogas max to grid          0   MW
```

```
Fuel Price level:

                   Capacities Storage Efficiencies
                     MW-e    GWh    elec.   Ther.
Hydro Pump:            0       0    0.80
Hydro Turbine:         0            0.90
Electrol. Gr.2:        0       0    0.80    0.10
Electrol. Gr.3:        0       0    0.80    0.10
Electrol. trans.:      0       0    0.80
Ely. MicroCHP:         0       0    0.80
CAES fuel ratio:          0.000

(TWh/year)     Coal     Oil    Ngas   Biomass
Transport      0.00128.12     0.00     0.00
Household      0.00    0.00    0.00     0.00
Industry      17.75   15.09329.34     0.00
Various        0.00    0.00    0.00     0.00
```

```
Output        WARNING!!: (1) Critical Excess;
```

Figure 45: EnergyPLAN Simulation of Additional PP to cover Proposed CSP-PT Plant Deficiency

4.6. EnergyPLAN Analysis to Gauge System Efficiency

This section employs life cycle assessment (LCA) as an energy analysis tool to evaluate the performance of the designed and optimized Integrated CSP-PT facility. The following life cycle metrics are used as the key performance indicators:

1. Cumulative Energy Demand (CED) – This is defined as the amount of primary energy consumed during the life-cycle of a product or a service. It presents the amount of energy invested per energy unit delivered [60]. CED expresses the required amount of primary energy for the manufacturing of the technology's infrastructure (including extraction and transport processes), installation, operation and decommissioning of the plant (over the life time of the plant).
2. Energy Payback Period (EPP) – This measures the time necessary for an energy technology to generate the equivalent amount of primary energy used to produce it i.e. how long it takes for the plant to generate the same amount of energy that was used to construct it.

Primary data used in this analysis is obtained from the simulation results of the model presented in the previous sections of this report. Any other data necessary but unavailable is obtained from a secondary source.

Since the modelled system is an integration of multiple units of smaller and independent 50 MW CSP-PT plants, assumed to be identical and operating at the same exact way, evaluation of the CED and EPT performance indicators was done on the basis of single unit. The performance and efficiency of this 50 MW unit is then taken to reflect the overall efficiency of the 27,000 MW Integrated CSP PT model.

The duration of the life cycle used in this analysis was taken as 25 years assumed to be the life of the modelled plant. All forms of energy are expressed as equivalent electrical energy.

4.6.1. Cumulative energy demand (CED).

The equation for calculating CED is as follows:

$$CED = \frac{Total\ Energy\ Invested}{Total\ energy\ Produced\ throughout\ life\ cycle} \tag{4.1}$$

The **total energy invested** is found as the sum of two distinct energy costs:

i. Capital Energy Costs

Capital costs include the energy requirements to extract and process all raw materials, manufacture and install the capital equipment including any site preparation and grid interconnection [61]. The value for these costs for a typical CSP PT plant is estimated as the median value for capital energy costs of a CSP Tower plant in the secondary data literature. This value is given as **3** kWhe per W_p of nameplate capacity.

Thus, for the 50 MW plant model:

$$Capital\ cost = (50{,}000{,}000\ x\ 3)kWhe = \boldsymbol{150\ GWhe}$$

ii. Operating Energy Costs

Data on operating costs includes energy requirements for maintenance of the system (e.g., washing solar systems, replacing worn parts) including the energy required to build spare parts, energy requirements for operating the systems, such as control systems, or, if necessary, the energy associated with the fuel cycle (including the energy content of any fuel consumed).

The operating energy costs from the secondary data source for the CSP-PT plant are given in units of kWe/kWe as 0.151 kWhe/kWhe generated.

Thus for the 50 MW plant model generating 367,966,944 kWe annually for a life cycle of 25 years, the operating costs are evaluated as:

$$Operating\ Costs = (0.151\ \text{x}\ 367{,}966{,}944\ \text{x}\ 25\ )\text{kWhe} = \mathbf{1389.08\ GWhe}$$

The **total energy produced throughout the plant's life cycle** is given by the annual output multiplied by the lifecycle duration at 25 years. Hence total life cycle output equals:

$$Total\ Energy = (367{,}966{,}944\ x\ 25)kWh = \boldsymbol{9199.2\ GWh}$$

Therefore, CED is found as:

$$CED = \frac{1389.08 + 150}{9199.2} = 0.167$$

4.6.2. Energy payback period (EPP). The EPP is calculated by the following equation:

$$EPP\ (yrs) = \frac{Total\ Energy\ Invested}{Annual\ electrical\ energy\ produced} \tag{4.2}$$

$$= \frac{1389.08 + 150}{367.967} = \mathbf{4.18}\ \boldsymbol{yrs}$$

4.6.3. Analysis of system efficiency. The following conclusions are made after analysis of the obtained performance indicator values.

i. The Cumulative Energy Demand performance of the plant is above average in retrospect to existing CSP-PT plants. Comparison Data obtained from the CED of 0.167 kWe/kWe is slightly below the median mark at 0.18 kWe/kWe. This lower value indicates that the system would perform slightly above the average expected efficiency. The system's CED deviates from best possible CED (0.13 kWhe/kWhe) by about 28% [62].

ii. The system indicates an Energy Payback Period of about 4.18 yrs. This is slightly outside the 50 percentile for existing CSP-PT facilities with lower and higher values at 0.7 and 7.5 years respectively. This is consistent with the result obtained in conclusion (i) above depicting the system's performance within average expectations [63].

iii. Considering the values of the two performance indicators above, the system is predicted to be within average performance and is therefore feasible.

iv. The overall system efficiency, from solar to electricity generation is calculated by dividing the plant output from the turbine with the input from the CSP-PT field, which results in 17.1%.

4.7. Economic Analysis to Determine Feasibility of the Proposed Plant

The economic model of the Designed plant is SAM's PPA-private ownership model. This financing and ownership structure falls within the 'Project Financing' economic structure for power plants. Project financing can be defined as the arrangement of debt, equity and credit enhancement for the construction of a particular facility in a capital-intensive industry, where lenders base credit appraisals on the estimated cash flows from the facility rather than on the assets or credit of the promoter of the facility [64].

The economic analysis done on the system uses two financial metrics to test the feasibility of the project:

1. Annual Debt Service Coverage Ratio (ADSCR) – This is the ratio of pre-finance cash flow after tax to the amount of interest payment and principal repayment for the period [16]. This assesses the project's ability to meet the project's debt financial charges. For feasibility, lenders require that at any stage of the project's life time, the projects' ADSCR should not fall below the minimum value. This minimum ADSCR usually ranges between 1.2 - 1.5.
2. Internal Rate of Return (IRR) - This is discount rate which sets the Net Present Value (NPV) of the project to zero. The IRR financial metric is particularly important for equity investors to gauge the financial feasibility of the project. It is also referred to as the opportunity cost of capital because it describes the return forgone by investing on the project rather than investing on securities (Brealey, 1991). Typical desirable values for this metric usually range between 16 -25 %.

All financial data and their analyses are obtained and done by SAM cash flow analysis tool. Graphs for analysis of the obtained data were also generated using SAM graph tool.

4.7.1. First economic analysis. In the initial financial model, the debt to equity ratio for capital source is set at 50-50. Figure 46 shows the plot of cumulative IRR over 25 years after tax in % vs. the year. Figure 47 shows the plot of the ADSCR pre-tax over 25 years. Figure 48 shows the plot of the debt balance in US Dollars ($) over 25 years.

Study of the three graphs in Figures 46 – 48 reveals that in its present financial model, the project would not be feasible. This is because of the project's Internal Rate of Return (IRR) is 12.589% which falls short of minimum IRR expectations of 16% in the energy market.

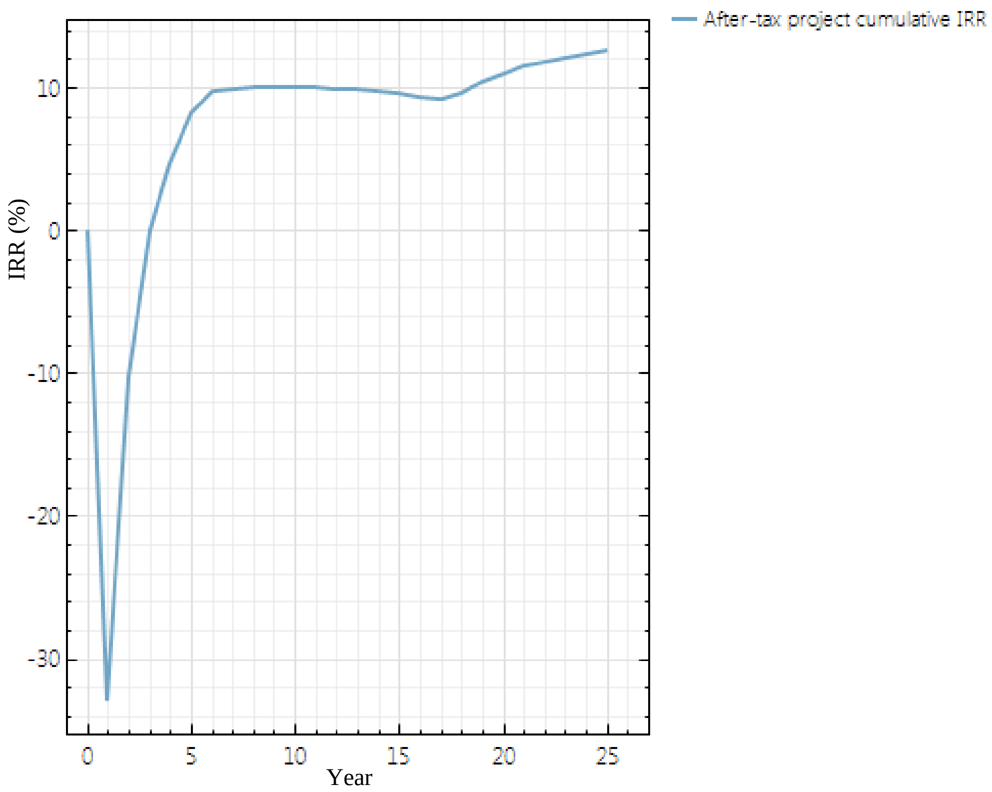


Figure 46: Plot of Cumulative IRR over 25 Years after Tax (% vs. year #)

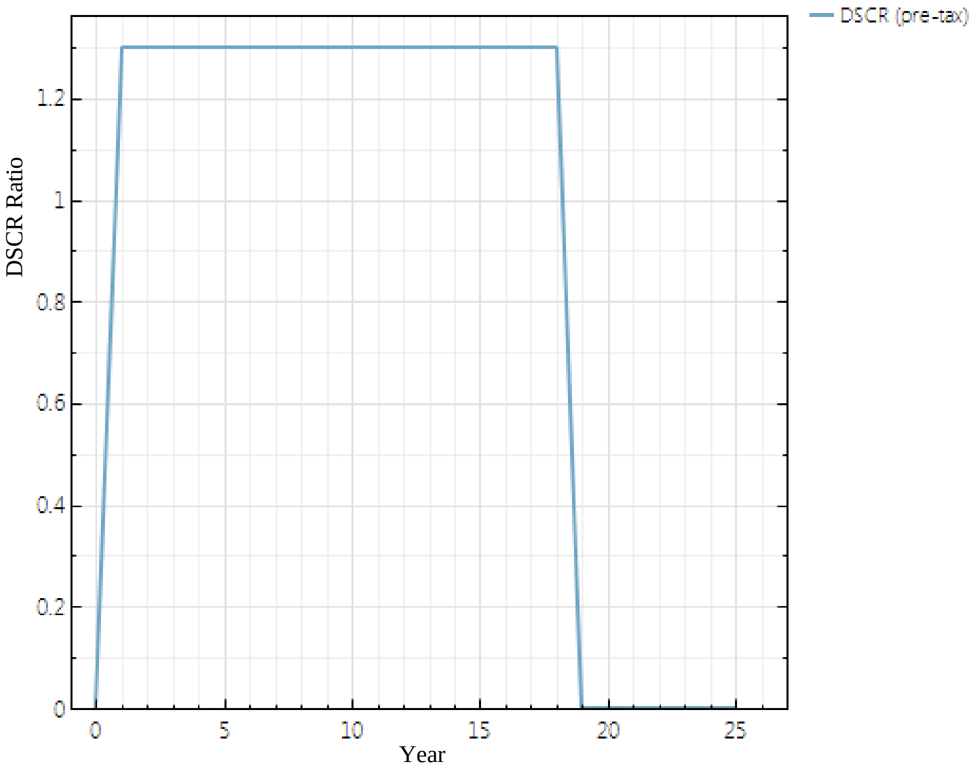


Figure 47: Plot of the ADSCR pre-tax over 25 Years (ratio vs. year #)

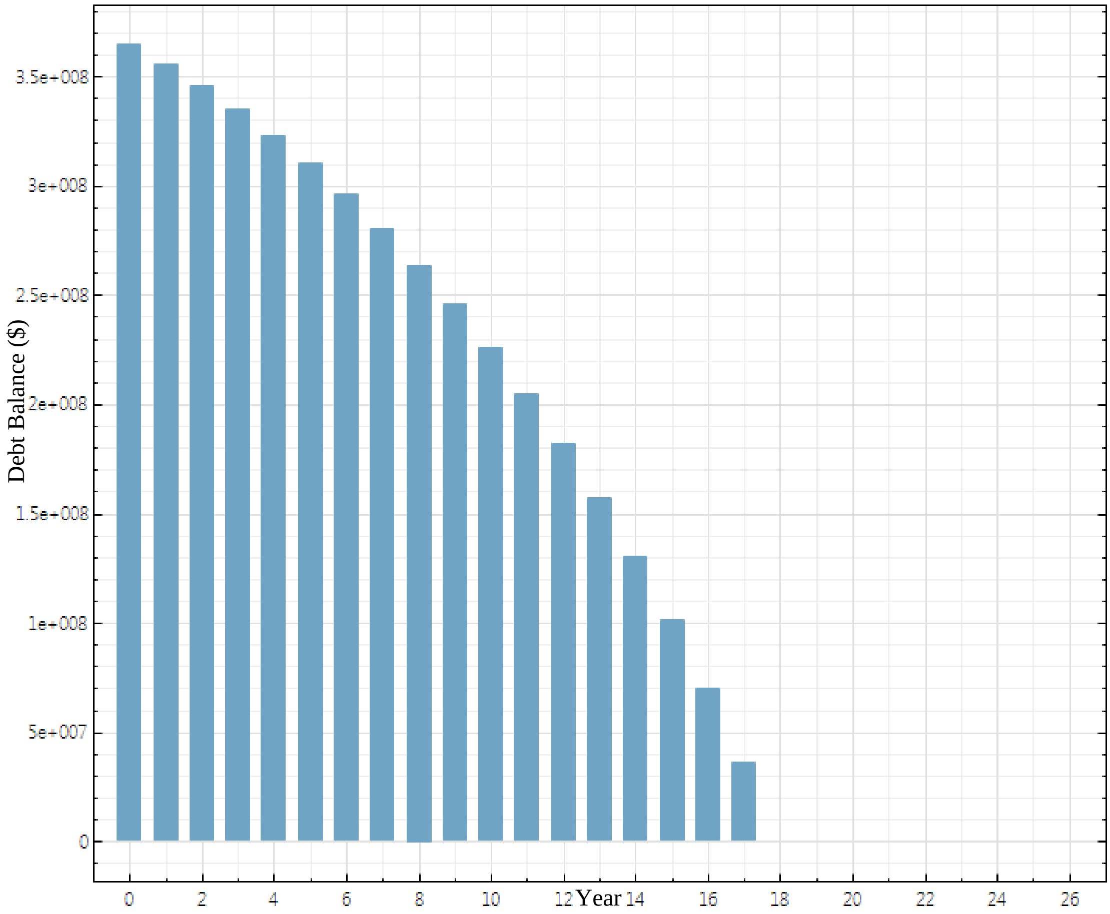


Figure 48: Debt Balance ($ vs. year #)

4.7.2. Second economic analysis. Following the conclusion above, some financial structure adjustments are made on the financial model of the project on SAM. These are:

- The IRR target is set at 20% with the tenth year as the target
- Debt to Equity ratio is adjusted to 55-45

After making the adjustments in section C.2 of EnergyPLAN, the plots in Figures 49 – 51 are generated.

Study of the three graphs in Figures 49 – 51 predicts that at the modified financial model, the project would be financially feasible.

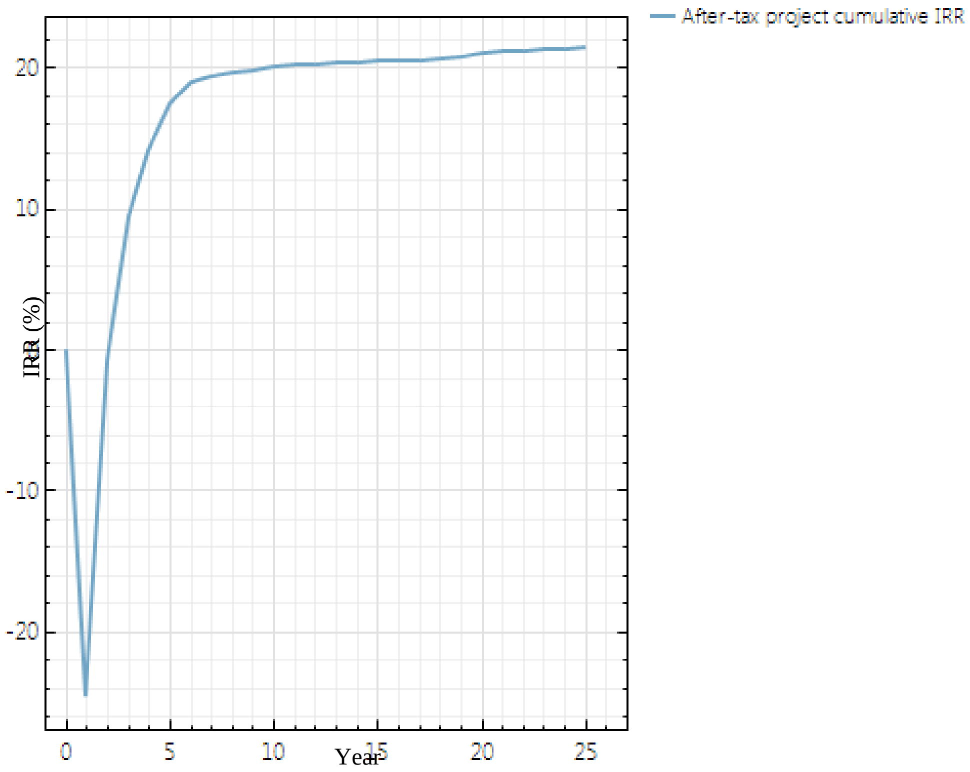


Figure 49: Plot of Cumulative IRR over 25 Years after Tax (% vs. year #)

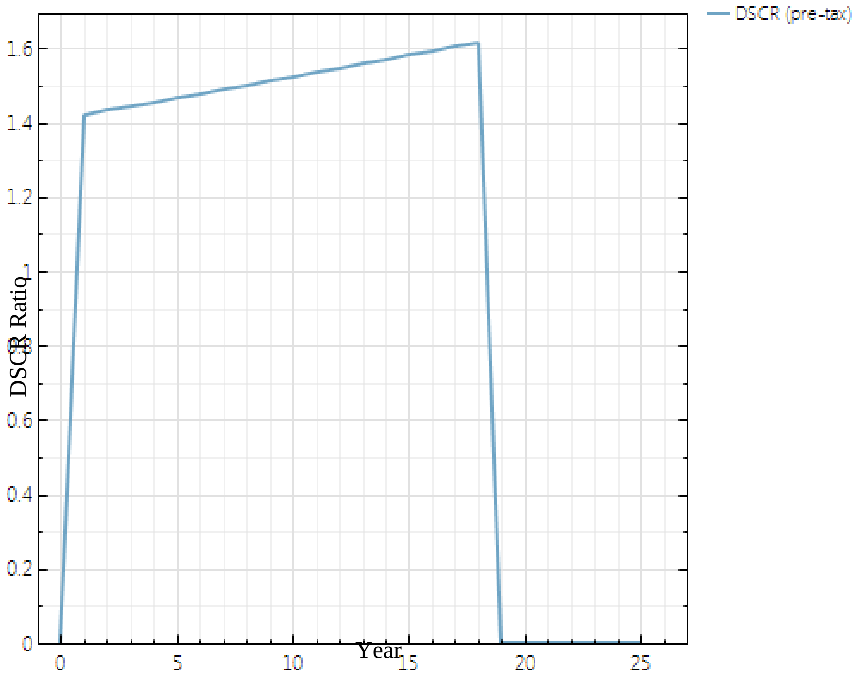


Figure 50: Plot of the DSCR pre-tax over 25 Years (ratio vs. year #)

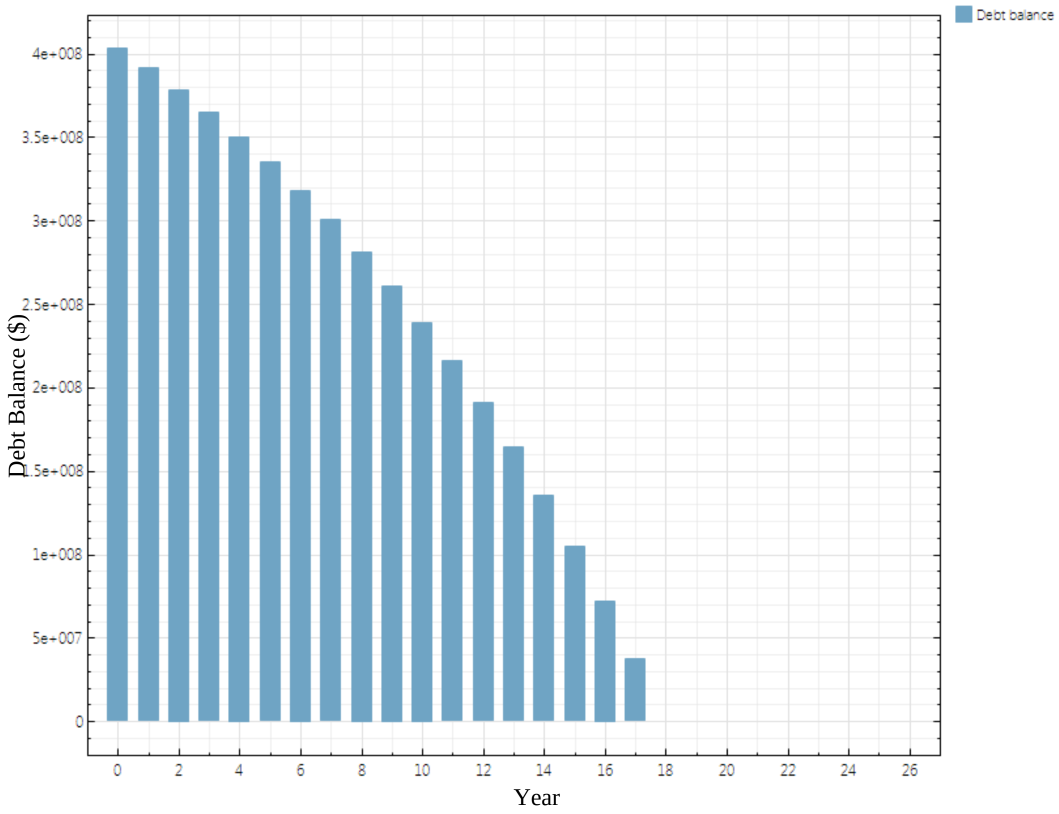


Figure 51: Debt Balance ($ vs. year #)

The following reasons justify the feasibility of the financial model shown in Figures 49 – 51 are observed:

- The Internal Rate of Return (IRR) at the end of the project is found as 21.40%. This represents a lucrative investment opportunity since the IRR value places the project within the above the 50th percentile of the typical IRR limits (16-25%).
- The project's minimum DSCR (1.42) is much higher than the least expected minimum value (1.3) while being within 5% of the highest expected value at 1.5.
- The payback period on the monetary investment of this plant is 17.3 years.

However, the current financial model has brought about an increase in the Levelized Cost of Electricity (LCOE) from 14.34 cents/kWh to 15.60 cents/kWh. While this might be disadvantageous, it does not affect the economic feasibility of the project as the current value still falls within the typical LCOE values for current CSP-PT projects. This is range is typically between 0.139 to 0.196 Euro/kWh as shown in Figure 52 [65].

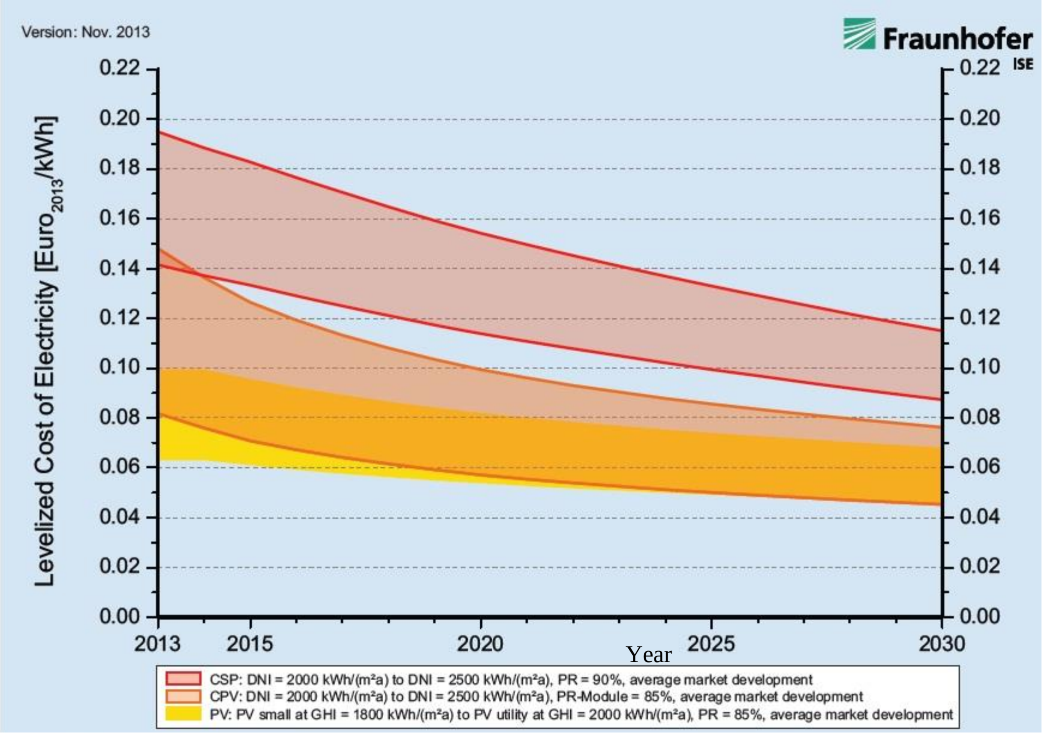


Figure 52: Plot of Levelized Cost of Electricity (cost vs. year) [65]

Chapter 5. Results

The schematic diagram of the CSP-PT 50 MWe output power generation plant for 24-hour operation is shown in Figure 53. The specifications of each component of the proposed RES-E plant are described in this section.

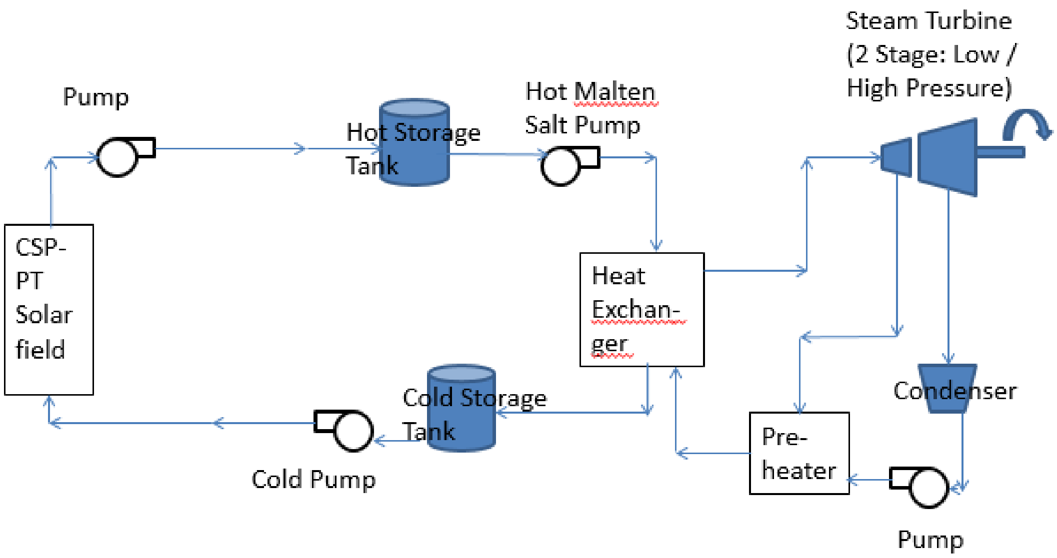


Figure 53: Design CSP-PT 50 MWe power plant

The selected components are as follows:

- Concentrated solar parabolic trough panel field
- Direct two-tank thermal energy storage system
- Molten salt as both the HTF and thermal storage medium
- Heat exchanger between the TES system and the power block, which acts as the boiler to heat the water into steam and power the cycle
- Rankine cycle with extraction at the steam turbine for the power block

Solar Field

The size and details of the solar field are specified in Table 17. The layout is depicted in Figure 54. The field is in operation during daytime hours to heat the HTF.

Table 17: Solar Field Specifications

PARAMETER	**MOLTEN SALT**
Design DNI	950W/M^2
Solar multiple	2.4
Thermal power	324MWt
Heliostat Width	12.2m
Heliostat Height	12.2m
Single Heliostat Area	144.375m^2
No of Heliostat facets X	2
No of Heliostat facets Y	8

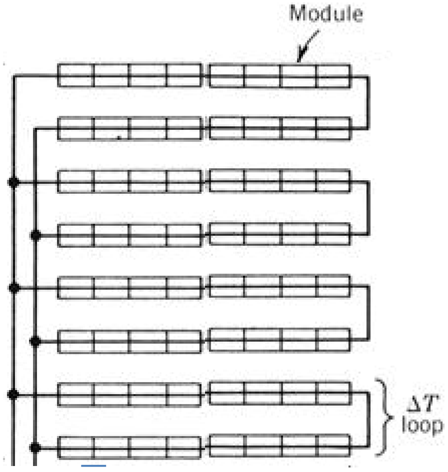


Figure 54: Solar Field Layout

Thermal Energy Storage System

The TES system is direct two-tank, with the sizing and additional details as shown in Table 18. The TES system will store some of the HTF coming from the solar field, which will act directly as the thermal storage medium. During the hours when there is no sunlight, the HTF from the hot tank will flow to power the power generation cycle and return to the cold tank.

Table 18: TES system Specifications

PARAMETER (per tank)	**MOLTEN SALT**
Storage tank type	Two tank
Available HTF volume	6,273m^3
Tank Height	20m
Tank Fluid Minimum Height	1m
Storage Tank Volume	6604 m^3
Tank Diameter	20.5m

Heat Transfer Fluid and Thermal Storage Medium

Molten salt with the composition of 60% $NaNO_3$ and 40% KNO_3 is selected as the HTF and storage medium based on the results of the previous chapter. The percentage efficiency of the solar field for heating the HTF is shown in Table 19.

Table 19: Percentage output power from the Solar Field

	Output powers	Percentage (%)
Specific heating fluid	nuclear efficiency	33
	eff_pp_el	45
Storage Medium	eff_dhp_th	90
	hydro watersupply	0
	hydro pump efficiency	90

The percentage of output power generated from the storage period for specific heating fluid and the storage medium is shown in Table 20.

Table 20: Percentage output power that can be generated from the Storage Medium

	Output powers	Percentage (%)
Heating fluid	nuclear efficiency	37
	eff_pp_el	42
Storage Medium	eff_dhp_th	83
	hydro watersupply	16
	hydro pump efficiency	71

Power Block

Rankine cycle is selected as the power generation block with extraction for reheating in the steam turbine. During the day, part of the HTF comes directly from the solar field into the heat exchanger (which acts as a boiler in this case) to heat the water into steam and power the cycle. When there is no sunlight, the HTF will come from the TES system hot tank instead.

Plant Output

Figure 55 shows the monthly output generated by the plant at optimum efficiency.

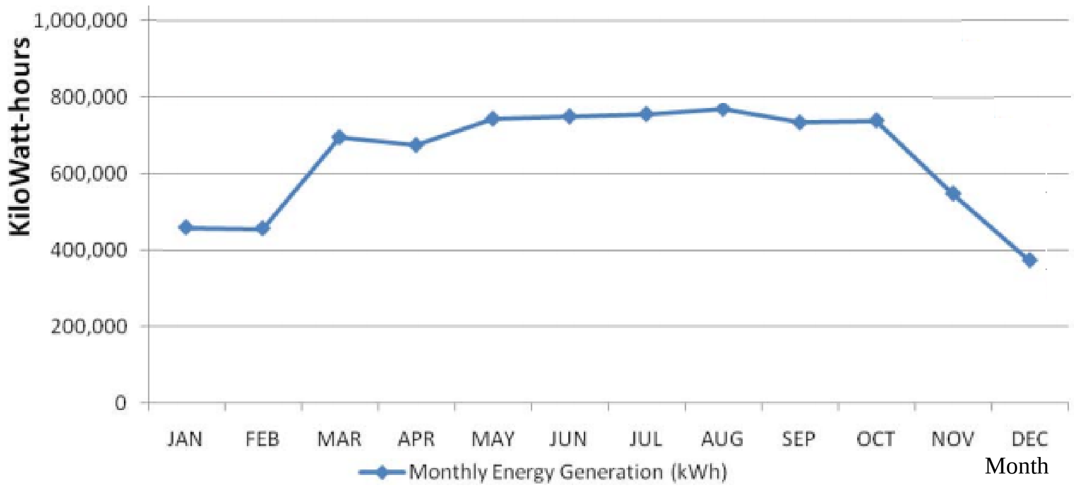


Figure 55: Monthly Power Output of the Plant at Optimum Efficiency

Chapter 6. Conclusion and Recommendations

In this thesis, extensive work is done on the research on the production of 50 MWe using concentrated solar panel – parabolic trough (CSP-PT) technology for a 100% RES-E plant. This work finds its success through the use of simulation software, specifically System Advisor Model (SAM) and EnergyPLAN software. The configuration considered for this thesis is selected through extensive research and also due to the compact nature of SAM software in considering one fluid.

The results show a great success of this work in achieving the desired output of 50 MWe using a purely renewable source of energy. After determining the size of the components of the plant to generate 50 MWe, 24 hours a day, based on the results of a single unit, it is recommended that 540 units are needed in order to power all of the UAE.

6.1. Conclusion

The designed plant consists of a CSP-PT field, with a thermal energy storage (TES) system for 24-hour operation, powering a steam turbine in Rankine cycle configuration to generate 50 MWe. Based on the simulations, molten salt is the optimum heat transfer fluid (HTF) and thermal fluid to use among those studied. The plant utilizes a 2 x 8 panel heliostat field, each panel being 12m x 12m, a two-tank direct TES, each tank being 6,604m^3 in volume, with molten salt composition of 60wt% NaNO3 and 40wt% KNO3 as the HTF and storage fluid running a Rankine cycle power block with an open feed water heater to produce the electricity.

Regarding the economic analysis of the designed plant, the results show that it is economically feasible. With an overall lifecycle of 25 years, the Internal Rate of Return (IRR) is found to be 21.40%, which is within the typical IRR limits (16-25%) and the project's minimum Debt Service Coverage Ratio (DSCR) is 1.42, which is much higher than the least expected minimum value of 1.3. The Levelized Cost of Electricity (LCOE) from this plant is 0.1560 $/kWh, which is higher than the current cost of electricity in the UAE of 0.12 $/kWh but is still acceptable, considering this is a new technology. The payback period is 17.3 years, which is relatively long.

Energy analysis results show that the Energy Payback Period (EPP), which is the time it takes to make up the energy consumed to construct the plant through the energy produced, is 4.18 years, which is within the acceptable range. The overall system efficiency, from solar to electricity generation is calculated by dividing the plant output from the turbine with the input from the CSP-PT field, which results in 17.1%. This percentage is relatively low, especially due to the lack of insolation during night-time operation.

These results show that the design is successful and feasible, but needs improvement to be more energy efficient and competitive in the market.

6.2. Recommendations

This is still a new concept, so more research is required to make it more efficient and economically feasible. Some improvements can be made to the design for more practical application, to increase efficiency and decrease the size of the TES. The following can be applied:

- The molten salt composition of 60wt% $NaNO_3$ and 40wt% KNO_3 is not thermodynamically efficient enough to sustain RES thermal storage for 24-hour operation. This is due to the low thermal conductivity of the salts at the temperature that CSP plants operate at. The answer could be using composite materials (nanoparticles) in the composition [41]. Altering the salt's thermos-physical properties can increase the thermal conductivity, this benefitting its commercial application in this case. Studies have shown that by adding composite materials, such as expanded graphite to the mixture ($NaNO_3$-KNO_3-EG), the thermal conductivity is increased in comparison to that of pure nitrate by 10-20% for a 5wt% addition of EG and 30-40% for a 10wt% addition of EG. Furthermore, research has shown that the use nanoparticles allow for optimal conductive ability due to their abundance of surface area, meaning that it would result in a significant decrease in the size of the TES [66].
- As discussed in the literature review, solar towers can provide higher temperatures, thus reducing the size of the solar field.
- Use of electrolysers and hydrogen storage which can later be used as a fuel for the back-up Power Plant to retrieve the energy [67].

- Use of turbine/pump electricity storage techniques e.g. Compressed Air Energy Storage (CAES) plants where compressed air is pressurised and then stores in an underground cavern – the pressurised air is heated and then used in the expansion cycle of a turbine to retrieve the stored energy [68].

References

[1] A. Poullikkas, A.F. Zueter and M.H. Dirar. "Prospective scenarios for the adoption of sustainable power generation technologies in United Arab Emirates." *International Journal of Sustainable Energy*, vol. 34(1), pp. 23-37, Oct. 2013.

[2] A.M. Kazim. "Assessments of primary energy consumption and its environmental consequences in the United Arab Emirates." *Renewable and Sustainable Energy Reviews*, vol. 11(3), pp. 426-446, Apr. 2007.

[3] H.J. AlFarra and B. Abu-Hijleh. "The Potential role of nuclear energy in mitigating CO2 emissions in the United Arab Emirates." *Energy Policy*, vol. 42(1), pp. 272-283, Mar. 2012.

[4] A.M. Al-Sabounchi, E. Al-Hammadi, S. Yalyali and H.A. Al-Thani. "Photovoltaic-grid connection in the UAE: Technical perspective." *Renewable Energy*, vol. 49(1), pp. 39-43, Jan. 2013.

[5] I.J. Bachellerie. "Prospects for renewable energy in transition in the GCC." Internet: www.eugcc-cleanergy.net, Dec. 1, 2010 [Apr. 20, 2014].

[6] N. AbuAli. "Renewable energy review: United Arab Emirates." Internet: http://www.renewableenergyworld.com/rea/news/article/2012/12/renewable-energy-review-united-arab-emirates, Dec. 26, 2012 [Apr. 22, 2016].

[7] S. Nader. "Paths to a low-carbon economy - The Masdar example." *Energy Procedia*, vol. 1(1), pp. 3951-3958, Feb. 2009.

[8] D. Reiche. "Energy policies of Gulf Cooperation Council (GCC) countries - Possibilities and limitations of ecological modernization in rentier states." *Energy Policy*, vol. 38(5), pp. 2395-2403, May 2010.

[9] T. Mezher, G. Dawelbait and Z. Abbas. "Renewable energy policy options for Abu Dhabi: Drivers and barriers." *Energy Policy*, vol. 42(1), pp. 315-328, Mar. 2012.

[10] "Renewable energy in the United Arab Emirates." Internet: http://www.nortonrosefulbright.com/knowledge/publications/33580/renewable-energy-in-the-united-arab-emirates, Jan. 2011 [Jun. 6, 2016].

[11] S.A. Kalogirou. *Solar Energy Engineering: Processes and Systems*. New York: Elsevier Science, 2009, pp. 1-2.

[12] S.X. Chu and L.H. Liu. "Analysis of terrestrial solar radiation exergy." *Solar Energy*, vol. 83(8), pp. 1390-1404, Aug. 2009.

[13] C.A. Gueymard and D.R. Myers. "Solar radiation measurement: Progress in radiometry for improved modeling," in *Modeling Solar Radiation at the Earth Surface*, 1st ed., vol. 1. V. Badescu, Ed. Berlin: Springer, 2008, pp. 3-6.

[14] "CRISP: Centre for Remote Imaging, Sensing & Processing - Tutorial 01 Optical Remote Sensing." Internet: http://www.crisp.nus.edu.sg/, 2001 [Feb. 12, 2017].

[15] Y. Kushnir. "The Climate System." Internet: http://eesc.columbia.edu/courses/ees/climate/lectures/radiation/, 2007 [Feb. 12, 02 2017].

[16] Y.A. Cengel and M.A. Boles. *Thermodynamics: An Engineering approach*. New York: McGraw-Hill, 2015, pp.73-92.

[17] R. Sandoz. "Thermoeconomic analysis and optimization of air based bottoming cycles for water free hybrid solar gas turbine power plant." M.S. thesis, Ecole Polytechnique, Sweden, 2012.

[18] F. Trieb, F. O'Sullivan, T. Pregger, C. Schillings and W. Krewitt. "Charecterisation of Solar Electricity Import Corridors from MENA to Europe." Internet: https://www.dlr.de/, Jul. 2009 [Feb. 12, 2017].

[19] "National renewable energy laboratory: Typical meteorological year." Internet: http://apps1.eere.energy.gov/buildings/energyplus/, [Dec. 5, 2016].

[20] "Statistics Centre Abu Dhabi: Energy and Water Statistics 2015." Internet: https://www.scad.ae/, Nov. 1, 2016 [Feb. 2, 2017].

[21] V. Poghosyan and M.I. Hassan, "Techno-economic assessment of subtituting natural gas based heater with thermal energy storage system in parabolic trough concentrated solar power plant." *Renewable Energy*, vol. 75(1), pp. 152-164, Mar. 2015.

[22] A. Mokri, M.A. Ali and M. Emziane. "Solar Energy in the United Arab Emirates: A Review." *Renewable and Sustainable Energy Reviews*, vol. 28(1), pp. 340-375, Dec. 2013.

[23] I.J. Bachellerie. *Renewable energy in the GCC countries: Resources, potential, and prospects*. Dubai, UAE: Gulf Research Center, 2012, pp. 161-202.

[24] D. Barlev, R. Vidu and P. Stroeve. "Innovation in concentrated solar power." *Solar Energy Materials and Solar Cells*, vol. 95(10), pp. 2704-2720, Oct. 2011.

[25] V. Bosetti, M. Catenacci, G. Fiorese and E. Verdolini. "The Future prospect of PV and CSP solar technologies: An Expert elicitation survey." *Energy Policy*, vol. 49(1), pp. 308-317, Oct. 2012.

[26] J. Hernandez-Moro and J. Martinez-Duart. "Analytical model for solar PV and CSP electricity costs: Present LCOE values and their future evolution." *Renewable and Sustainable Energy Reviews*, vol. 20(1), pp. 119-132, Apr. 2013.

[27] K. Patlizianas, H. Doukas and J. Psarras. "Enhancing renewable energy in the Arab states of the Gulf: Constraints & efforts." *Energy Policy*, vol. 34(18), pp. 3719-3726, Dec. 2006.

[28] A. Poullikkas and M. Gadalla. "Assessment of solar electricity production in the United Arab Emirates." *International Journal of Sustainable Energy*, vol. 32(6), pp. 631-642, Aug. 2013.

[29] A. Poullikkas. "A Decouple optimization method for power technology selection in competitive markets." *Energy Sources*, vol. 4(2), pp. 199-211, Apr. 2009.

[30] C.S. Lai and M.D. McCulloch. "Levelized cost of electricity for solar photovoltaic and electrical energy storage." *Applied Energy*, vol. 190(1), pp. 191-203, Mar. 2017.

[31] J. Hoppmann, J. Volland, T.S. Schmidt and V.H. Hoffman. "The Economic viability of battery storage for residential solar photovoltaic systems - A Review and simulation model." *Renewable and Sustainable Energy Reviews*, vol. 39(1), pp. 1101-1118, Nov. 2014.

[32] Y. Ru, J. Kleissl and S. Martinez. "Storage size determination for grid-connected photovoltaic systems." *IEEE Transactions on Sustainable Energy*, vol. 4(1), pp. 68-81, Jan. 2013.

[33] P.J. Catania, B. Golchert and C.Q. Zhou. "PS10: A 10MW Solar tower power plant for southern Spain," in *Energy 2000: The Beginning of a new Millennium*, 2000, pp. 386-399.

[34] U. Herrmann, B. Kelly and H. Price. "Two-tank molten salt storage for parabolic trough solar power plants." *Energy*, vol. 29(6), pp. 883-893, May 2004.

[35] A.C. Fernandez. "Economic study of solar thermal plant based on gas turbines." M.S. thesis, Lund University, Lund, 2013.

[36] A.D. Monde, A. Shrivastava and P.R. Chakraborty. *Applications of Solar Energy*. Singapore: Springer, 2017, pp. 131-162.

[37] Y. Wang. "Solar Thermal Storage." Internet: https://www.mtholyoke.edu/~wang30y/csp/thermal%20storage.html, 2008 [Aug. 10, 2015].

[38] P. Palenzuela, G. Zaragoza, D.C. Alarcon-Padilla, E. Guillen, M. Ibarra and J. Blanco. "Assessment of different combinations for combined parabilic-trough (PT) solar power and desalination plant in arid regions." *Energy*, vol. 36(8), pp. 4950-4958, Aug. 2011.

[39] H. Fath. "Technical assessment of solar thermal energy storge technologies." *Renewable Energy,* vol. 14(4), pp. 36-41, Aug. 1998.

[40] S. Kuravi, J. Trahan, D. Goswami, M. Rhaman and E. Stefanakos. "Thermal energy storage technologies and systems for concentrating solar power plants." *Progress in Energy and Combustion Science*, vol. 39(4), pp. 285-315, Aug. 2013.

[41] Q. Peng, X. Yang, J. Ding, X. Wei and J. Yang. "Design of new molten salt thermal energy storage material for solar thermal power plant." *Applied Energy*, vol. 112(1), pp. 682-689, Dec. 2013.

[42] T. Li, Z. Zhang, J. Lu, J. Yang and Y. Hu. "Two-stage eveporation strategy to improve system performance for organic Rankine cycle." *Applied Energy*, vol. 150(1), pp. 323-334, Jul. 2015.

[43] T. Li, Q. Wang, J. Zhu, K. Hu and W. Fu. "Thermodynamic optimization of organic Rankine cycle using two-stage evaporation." *Renewable Energy*, vol. 75(1), pp. 654-664, Mar. 2015.

[44] X.D. Wang, L. Zhao and J.L. Wang. "Experimental investigation on the low-temperature solar Rankine cycle system using R245fa." *Energy Conversion and Management*, vol. 52(2), pp. 946-952, Feb. 2011.

[45] X. Li, N. Wang, L. Wang, Y. Yang and F. Marechal. "Identification of optimal operating strategy of direct air-cooling condenser for Rankine cycle based power plants." *Applied Energy*, vol. 209(1), pp. 153-166, Jan. 2018.

[46] B.F. Tchanche, M. Petrissans and G. Papadakis. "Heat resources and organic Rankine cycle machines." *Renewable and Sustainable Energy Reviews*, vol. 39(1), pp. 1185-1199, Nov. 2014.

[47] H. Lund. "Renewable energy strategies for sustainable development." *Energy*, vol. 32(6), pp. 912-919, Jun. 2007.

[48] K. Blok. "Enhanced policies for the improvement of electricity efficiencies." *Energy Policy*, vol. 33(13), pp. 1635-1641, Sep. 2005.

[49] H. Lund. "Implementation of energy-conservation policies: The Case of electric heating conversion in Denmark." *Applied Energy*, vol. 64(4), pp. 117-127, Sep. 1999.

[50] N. Lior. "Advanced energy conversion to power." *Energy Conversion Management*, vol. 38(13), pp. 941-955, Nov. 1997.

[51] N. Lior. "Thoughts about future power generation systems and the role of exergy analysis in their development." *Energy Conversion Management*, vol. 43(12), pp. 1187-1198, Aug. 2002.

[52] M.S. Jamel, A.A. Rahman and A.H. Shamsuddin. "Advances in the integration of solar thermal energy with conventional and non-conventional power plants." *Renewable and Sustainable Energy Reviews*, vol. 20(1), pp. 71-81, Apr. 2013.

[53] A. Poullikkas. "Optimization analysis for pumped energy storage systems in small isolated power systems." *Journal of Power Technologies*, vol. 93(2), pp. 78-89, Jan. 2013.

[54] A. Poullikkas, I. Hadjipaschalis and G. Kourtis. "The Cost of integration of parabolic trough CSP plants in isolated Mediterranean power systems." *Renewable and Sustainable Energy Reviews*, vol. 14(5), pp. 1469-1476, Jun. 2010.

[55] I. Purohit and P. Purohit. "Technical and economic potential of concentrating solar thermal power generation in India." *Renewable and Sustainable Energy Reviews*, vol. 78(1), pp. 648-667, Oct. 2017.

[56] B. Belgasim, Y. Aldali, M.J.R. Abdunnabi, G. Hashem and K. Hossin. "The Potential of concentrating solar power (CSP) for electricity generation in Libya." *Renewable and Sustainable Energy Reviews*, vol. 90(1), pp. 1-15, Jul. 2018.

[57] F. Dinter and D.M. Gonzalez. "Operability, reliability and economic benefits of CSP with thermal energy storage: First year of operation of Andasol 3." *Energy Procedia*, vol. 49(1), pp. 2472-2481, Dec. 2014.

[58] "National Renewable Energy Laboratory: System Advisor Model (SAM)." Internet: https://sam.nrel.gov/, 2017 [Aug. 6, 2017].

[59] "EnergyPLAN: Advanced energy system analysis computer model." Internet: http://www.energyplan.eu/, 2017 [Aug. 6, 2017].

[60] R. Frischknecht, N. Jungbluth, H.J. Althaus, and G. Doka. "Swiss Centre for Life Cycle Inventories: Overview and Methodology." Internet: https://www.ecoinvent.org/files/dataqualityguideline_ecoinvent_3_20130506.pdf, May 6, 2013 [Jan. 11, 2018].

[61] M.A. Dale. "Comparative analysis of energy costs of photovoltaic, solar thermal and wind electricity generation technologies." *Applied Sciences*, vol. 3(2), pp. 25-337, Mar. 2013.

[62] B. Corona and G.S. Miguel. "Environmental analysis of a concentrated solar power (CSP) plant hybridised with different fossil and renewable fuels." *Fuel*, vol. 145(1), pp. 63-69, Apr. 2015.

[63] B. Corona, G.S. Miguel and E. Cerrajero. "Life cycle assessment of concentrated solar power (CSP) and the influence of hybridising with natural

gas." *The International Journal of Life Cycle Assessment*, vol. 19(6), pp. 1264-1275, Jun. 2014.

[64] W. Short, D.J. Packey and T. Holt. *A Manual for the economic evaluation of energy efficiency and renewable energy technologies*. Colorado, USA: NREL, 1995.

[65] C. Kost, J.N. Mayer, J. Thomsen and N. Hartmann. " Fraunhofer Institut for Solar Energy Systems ISE: Renewable energy technologies study." Internet: https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/Fraunhofer-ISE_LCOE_Renewable_Energy_technologies.pdf, Nov. 2013 [Mar. 6, 2017].

[66] J. Kotyla. "Molten salt composition and composites for improved latent heat thermal energy storage." *PAM Review: Energy Science & Technology*, vol. 4(1), pp. 46-58, Dec. 2017.

[67] M. Karwowska, T. Jaron, K.J. Fijalkowski, P.J. Leszczynski, Z. Rogulski and A. Czerwinski. "Influence of electrolyte composition and temperature on behaviour of AB5 hydrogen storage alloy used as negative electrode in Ni-MH batteries." *Journal of Power Sources*, vol. 263(1), pp. 304-309, Oct. 2014.

[68] G. Venkataramani, P. Parankusam, V. Ramalingam and J. Wang. "A Review on compressed air energy storage - A Pathway for smart grid and polygeneration." *Renewable and Sustainable Energy Reviews*, vol. 62(1), pp. 895-907, Sep. 2016.

Vita

Hessa Abbas Ali was born in 1980, in Abu Dhabi, United Arab Emirates. She received her primary and secondary education in Abu Dhabi, UAE. she received her B.Sc. degree in Mechanical Engineering with a minor in Engineering Management from the American University of Sharjah in 2012. From 2012 to date she has worked at ADNOC Sour Gas and is currently a Senior Reliability Engineer.

In September 2012, she joined the Mechanical Engineering master's program in the American University of Sharjah as a part-time student. During her master's study, she was employed full time as a Mechanical Engineer at ADNOC Sour Gas in the Maintenance System, Policy and Standards Department. Her research interests are in renewable energy and environmentally-friendly power production.