Modeling of Solar Thermal Tower Power Plants for Climate Condition of Pakistan Using TRNSYS

By

Hamza Ahmad Raza

NUST201463515MCES64114F

Session 2014-16

Supervised by

Asst. Prof. Dr. Majid Ali

A thesis submitted in partial fulfillment of the requirements for the degree of

Masters of Science

In

Energy Systems Engineering (MS ESE)

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THESIS ACCEPTANCE CERTIFICATE

Certified that final copy of MS/MPhil thesis written by Mr. Hamza Ahmad Raza, (Registration No. NUST201463515MCES64114F), of U.S.-Pakistan Center for Advanced Studies in Energy has been vetted by undersigned, found complete in all respects as per NUST Statues/Regulations, is free of plagiarism, errors, and mistakes and is accepted as partial fulfillment for award of MS/MPhil degree. It is further certified that necessary amendments as pointed out by GEC members of the scholar have also been incorporated in the said thesis.

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Certificate

This is to certify that work in this thesis has been carried out by **Mr. Hamza Ahmad Raza** and completed under my supervision in Solar Thermal Laboratory, U.S-Pakistan Center for Advanced Studies in Energy, National University of Sciences and Technology, H-12, Islamabad, Pakistan.

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Dedication

This work is dedicated to my beloved parents and respected teachers.

Acknowledgment

I am thankful to my Creator Allah Subhana-Watala to have guided me throughout this work at every step and for every new thought which You setup in my mind to improve it. Indeed I could have done nothing without Your priceless help and guidance. Whosoever helped me throughout the course of my thesis, whether my parents or any other individual was Your will, so indeed none be worthy of praise but You.

I am profusely thankful to my beloved parents who raised me when I was not capable of walking and continued to support me throughout in every department of my life.

I would also like to express special thanks to my supervisor **Dr. Majid Ali** for his help throughout my thesis.

I would also like to pay special thanks to **Dr. Adeel Waqas** for his tremendous support and cooperation. Each time I got stuck in something, he came up with the solution.

I would also like to thank **Dr. Muhammad Zubair**, **Dr. Emad-Ud-Din** and **Dr. Naseem Iqbal** for being on my thesis guidance and evaluation committee and express my special thanks to research fellows **Sara Sultan**, **Shomaz-Ul-Haq** and **Abdul Kashif Janjua** for their help.

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Abstract

Energy is considered as the backbone for a country's development and the demands are increasing globally. Pakistan is already facing the power shortfall and the energy sector is dominated by fossil fuels. Therefore, it is an intense need to effectively manage the alternative renewable energy resources and implement these technologies on large scale. The objective of this research is to propose an efficient and economical model for solar thermal tower power plant which effectively exploits the abundant solar energy to generate electricity.

TRNSYS software is used to model the solar thermal tower power plant. Three models are developed and analyzed to find the efficient and cost effective option for Bahawalpur, Pakistan conditions. Rankine Cycle based model is developed taking into account the parameters like inlet flow rate, inlet temperature, pressure and the effect of heat transfer fluids is studied. The output power obtained is 1 MWe with 107 heliostats each of area 64 m^2. The Brayton Cycle based model is developed to produce 4 MWe. Third model is the combined cycle system of 2 MWe which uses exhaust gas of Brayton Cycle to run a steam turbine. The numbers of heliostats for each model are optimized and the position of heliostats is specified using System Advisory Model SAM. The cost analysis for all these power plant is done by using RETScreen. As the heliostats were the maximum cost taking component of this system, they are optimized to reduce the overall system cost. It was found that the combined cycle model can efficiently produce enough power with reduced cost and it is feasible for implementation at large scale in Pakistan.

Key Words: *Solar thermal tower power plant, STTPP, System advisory model, Heliostats, Rankine cycle, Brayton cycle, RETScreen, Cost analysis, Siemens Turbine*

List of Figures

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List of Journal/Conference Papers

*Hamza Ahmad Raza, Majid Ali, Adeel Waqas, Sara Sultan, Shomaz-ul-Haq "Modeling of 1 MW solar thermal tower power plant using TRNSYS" [J] under review in International journal of sustainable energy by Taylor and Francis.

**Sara Sultan, Adeel Waqas, Majid Ali, Hamza Ahmad Raza, Saba Aziz, Shomaz-ul-Haq "Modeling of a solar energy driven water desalination system" published in 2016 19^{th} International Multi-Topic Conference (INMIC)

* Attached as Annexure Ⅰ

** Attached as Annexure Ⅱ

List of Abbreviations

GENCO	Generation companies
IPPs	Independent power producers
STTPP	Solar thermal tower power plant
SPTPP	Solar parabolic trough power plant
PDCs	Parabolic dish concentrators
CSP	Concentrated solar power
LFR	liner Fresnel reflectors
HTF	Heat transfer fluids
Rpm	Revolution per minute
TRNSYS	Transient Systems Simulation programs
HRSG	Heat recovery steam generators
ELC	electronic load controller
PMA	Permanent magnet alternator
HP	horse power

CHAPTER 1

Introduction

1.1 Motivation

Depletion of fossil fuels and polluted gases emit during power production are the important factors to think about renewable energy sources.

Energy is the most important and essential factor for the growth, stability and to strengthen the economy of a progressive country. Culture evolves as the amount of energy harnessed per capita per year is increased. Conventional sources of energy oil gas and coal are found to be threating within few years as they are not environment friendly and depleting with the time. Green-house gases effect is hazardous for environment and carbon di oxide is the major gas of this category. Burning of fossil fuel is producing 0.93 metric tons of CO_2 emissions in Pakistan. Pakistan's carbon emissions will reach 400 million tons of CO_2 equivalents (per year) by 2030 if the business-as-usual scenario remains intact [1]. Pakistan would have no reserves of fossil fuels from 2025-2030, if their consumption will continue with this rate [2]. Renewable energy is providing an alternate solution of this massive upcoming problem. Solar energy is found to be a free abundant and ecofriendly source of energy. Due to earth elliptic structure different parts of world receive different amount of sun energy. Pakistan located in Asia is lucky to have high radiations value. Pakistan solar potential is 5-7 kWh/m^2/day and average 10 hours sun shine available. Fossil fuels emit CO_2 during their operation which is an environment hazard gas. 8711 tons of (CO_2) can be saved through installing 4 MWe solar thermal power plants instead of conventional fossil fuels based power plant.

Solar energy use for electricity production can be carried out either through solar photovoltaic panels or by solar thermal power plants. Solar energy has been harnessed through photovoltaic technology since 1950 when first conventional photovoltaic cell was produced. Solar thermal power production started in late 1980s and boosted up by first commercial plants in Spain name as PS10 and PS20. Solar photovoltaic panels generate electricity directly by receiving the solar radiations. Recently, Pakistan has taken an initiative in solar PV power plant installation named as Quaid-E- Azam Solar Power Plant with 1000 MW DC installed capacity [3]. Solar thermal power production has more advantages due to its AC power production instead of DC in solar photovoltaic panels. Solar thermal technology includes solar thermal tower power plant, solar parabolic trough power plant, solar dish system, solar Fresnel lens power system.

Solar thermal tower power plant provides good alternate of conventional fuel plants. In this system sun energy is being reflected by large mirrors knowns as heliostats. Heliostats track the sun all time to get maximum radiation. This reflected light is received on a central receiver called solar receiver. Solar receiver is mounted at the top of a tower which provides support and height to solar receiver. Heat transfer fluid flows inside the tubes of solar receiver and takes its heat. In direct generation system this fluid is converted into steam. Steam strikes to the turbine blades and electrical power is produced. In indirect system, primary fluid transfers its heat to secondary fluid (water) which converts into steam and primary fluid doesn't change its state.

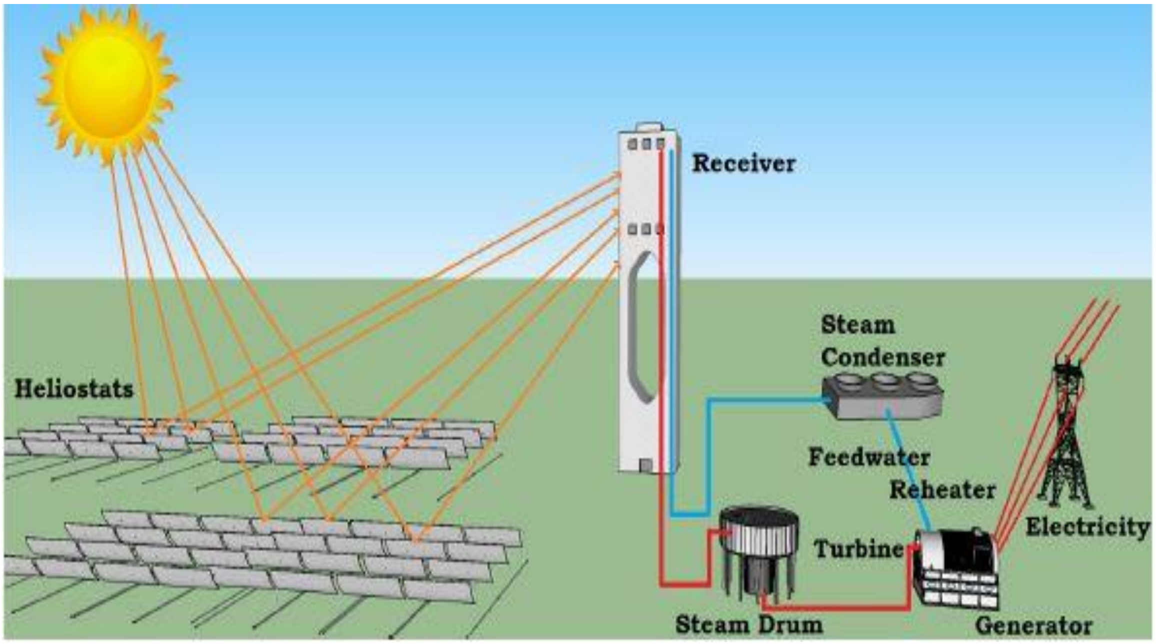

Figure 1: Solar thermal tower power plant [4]

1.2 Research Question

This work addresses the following points

- What are the alternate solutions to produce clean energy?
- What are the advantages of solar thermal tower power plant over others solar thermal technologies?
- What is the high radiation receiving site in Pakistan for installing STTPP?
- How different heat transfer fluids make STTPP performance better?
- What are the important parameters which make STTPP cost effective?
- How the performance of STTPP is affected by changing heat transfer fluid flow rate, pressure and solar receiver area?
- How to optimize heliostats with different input parameters in TRNSYS?
- How the increased number of heliostats affects the cost of STTPP?

1.3 Research Objectives

Objective of this study is to propose a pioneer solar thermal tower power plant for Pakistan and achieve the following agenda

- Simulate the Rankine cycle, Brayton cycle and Combined cycle solar thermal tower power plant models using TRNSYS software
- Analyze the performance of STTPPs by changing the heat transfer fluid parameters like mass flow rate, pressure, temperature and area of solar receiver
- Optimize the number of heliostats to reduce initial cost of system
- Cost analysis of three models to compare and find the efficient system

1.4 Limitations of Study

- TRNSYS does not offer component designing that's why system is not optimized by making individual component efficient.
- Mass flow is fixed to certain value because of turbine input requirement.
- Experimental work is not performed due to high cost of the system

1.5 Methodology of Work

- Learning the basics of thermal power plant operation
- Learning the solar radiation properties and behavior throughout the year in Pakistan
- Learning of TRNSYS and exploring its libraries
- Simulating individual components and making a small model with limited input parameters
- Modeling of different systems and analyzing the results
- Performing the cost analysis on RETScreen and discuss the cost effectiveness of the system

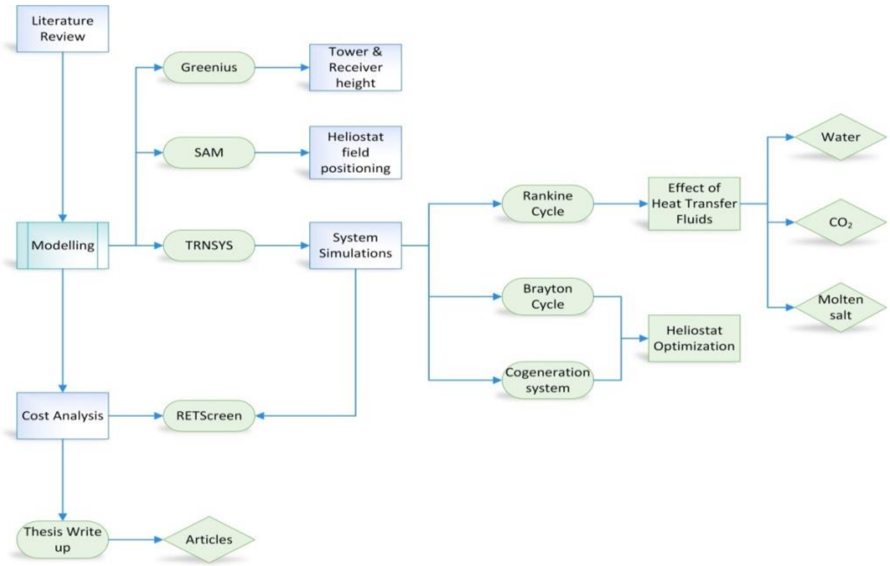

Figure 2: Methodology of work

1.6 Organization of Thesis

This write up is segregated into six main sections as

Chapter 1 gives the answers of initial pre-requisites required for starting research work i.e. motivation, what to do in this work, objectives of work and methodology adopted for current study.

Chapter 2 covers the literature review and describes the solar thermal power plants types and components i.e. heliostats, solar receiver and discusses the working of solar thermal tower power plant.

Chapter 3 presents the TRNSYS based model of solar thermal tower power plant. Three models are presented based on Rankine cycle, Brayton cycle and a Combined cycle system.

Chapter 4 explains the modeling results for three models and shows the effect of different heat transfer fluids in Rankine cycle. It also presents the effect of input parameters variations on heliostats.

Chapter 5 discusses the cost analysis of Combined cycle system which shows the viability of solar thermal tower power plant for Pakistan.

Chapter 6 discusses the basics of hydropower and covers the issues associated with hydro power production and propose the solution and methodology to resolve the problems.

Chapter 7 presents the working of lab scale project at Oregon State University. It describes the behavior of hydro power loop and performance analysis based on different water flow rates.

Summary

This chapter introduces the basic theme of this research work. It discusses the basic research problem and defines the objectives to solve that. Research methodology explains the strategy sequence adopted to achieve the goal

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CHAPTER 2

Literature Review

2.1 World Energy Outlook

Human dependency on machinery demands the continuous production of energy. Hunting the reliable, cheap, and trustworthy source of energy is the basic need of world growing economic nations. According to United States monthly energy review April 2016, US energy production in 1990 was 3037 Tera Wat hour (TWh) while it has been raised up to 4013 TWh in 2013. Demand of energy is rapidly increasing with the growing rate of population. World electricity production in 1995 was 13095 TWh for the population of 574 billion people [1]. The electricity production increased to 20852 TWh in 2010 and world's population increased to 691 billion [2]. Pakistan located in Asia has a strong strategic locality in south Asian countries and to make its impact on the global world it has to become a robust economic power. Pakistan is passing through stressful and devastating circumstances due to economic tumbling. One of the main reasons for economic rise and fall is lack of energy/power production. Pakistan being the 6th largest country of the world according to population has only 43 Watt per capita energy availability which is very low indeed the 1/7th of world average per energy capita due to various reason in which most important is its dependency on oil and gas for electricity production [3]. The Pakistan electricity sector consumed 15 million tons of oil equivalents in 2008 that amounted to 28% of fossil fuels supplied to the country. These fossil fuels not only increase the financial burden on economy but also having a serious impact on environment by emitting the CO_2 [4].

2.2 Pakistan Energy Scenario

Pakistan is producing 60% of its electricity from oil and gas through the thermal power plants and facing a shortfall of 3-4 GW as it is producing 18-20 GW power while its installed capacity is approximate 25 GW [5][6]. Along this, Pakistan has a great potential of renewable energy sources which are abundant and plentiful in nature. Pakistan has a 3000 MW electricity potential from biogas and 5000 MW can be generated from livestock. By producing 18 million cubic meters biogas from these biomass resources 42% electricity generation can be achieved [7]. There is a great potential of electricity generation through Wind in southern areas of Pakistan; especially in coastal areas of Sindh and Baluchistan. Twenty sites located at coastal belt in south shows that 2441 km^2 of area is suitable for production of 11 GW power [8]. Sun is the source of all energy. Pakistan is enriched in solar energy due to its location near equator. Pakistan has a potential of 5-7 $kWh/m^2/day$ solar radiations which is high from other countries. This blessing has been utilized for power production on national level. Solar companies like solar system Pakistan and Shaheen enterprises (Pvt.) Ltd have started to exploit this potential in Pakistan.

2.2.1 Thermal Power Plants in Pakistan

Pakistan power production is highly dependent on thermal power production technologies.

2.2.1.1 Fossil Fuel based

According to power system statistics 2013-2014 five generation companies (GENCO) producing 5458 MW of power through natural gas and oil burning as shown in table below

Table 1: Generation Companies [9]

Power Station	**Location**	**Fuel type**	**Installed capacity (MW)**
GENCO 1	Jamshoro	Gas (Steam Turbine)	850
	Kotri	Gas (Gas Turbine)	144
			Total (994)
GENCO 11	Guddu	Gas (Steam+ Gas Turbine)	2402

	Queta	Gas (Gas Turbine)	35
			Total (2437)
GENCO 111	Muzaffargarh	Gas (Steam Turbine)	1350
	Faisalabad	Gas (Steam+ Gas Turbine)	376
			Total (1726)
GENCO 1V	Lakhra Coal	Coal (Steam Turbine)	150
GENCO V	Nandipur	FO (Gas Turbine)	450

Independent power producers (IPPs) contribute 8793 MW thermal output to the national grid.

Table 2: List of IPPs [10]

No	**Power Station**	**Location**	**Fuel type**	**Installed capacity (MW)**
1	HUBCO	HUB Baluchistan	RFO	1292
2	KOHINOOR	Raiwand(Lahore)	RFO	131.4
3	AES lalpir	Mehmoodkot	RFO	362
4	AES Pak Gen	Mehmoodkot	RFO	365
5	SEPCOL	Raiwand(Lahore)	GAS	135.9
6	Habibula coastal	Queeta	GAS	140
7	Rousch	Abdul hakeem Khanewal	GAS	450
8	Saba Power	Farooqabad sheikhupura	RFO	134
9	Fauji Kabirwala	Kabirwala Khanewal	GAS	157
10	Japan power	Raiwand(Lahore)	RFO	135
11	UUch power	Dera Murad Jamali	GAS	586
12	Altern Energy Limited	Fatehjang Attock	GAS	31

13	TNB liberty power	Dharki	GAS	235
14	Attock Gen Ltd(AGL)	Raealpindi	RFO	165.3
15	Atlas Power	Sheikhupura	RFO	219.2
16	Nishat power	Multan Rd,Lahore	RFO	202.1
17	Orient Power	Baloki	GAS	229.1
18	Engro Energy	Dharki	GAS	233.4
19	Saif power	Sahiwal	GAS	228.5
20	Hubco Norowal	Norowal	RFO	219.2
21	Halmore	Shiekhupura	GAS	228.6
22	Saphire	Muridkey	GAS	228.6
23	Nishat chunian	Multan Rd Lahore	RFO	202.1
24	Libert power Tech	Faisalabad	RFO	202
25	Foundation power	Dharki	Gas	229.8
26	Uch power-ll		Gas	386.2

Pakistan has its own coal and gas reserves but importing a huge amount on imports of crude oil about 68.1% of total crude oil supplies during 2010–2011 were met through imports. The country's expense on crude oil imports during 2010–2011 stood at US$ 4.69 billion.

2.2.1.2 Solar Energy based

Solar energy rich country Pakistan is not currently focused on the plentiful source of free energy. Need of importing oil and huge investment on gas sector can be minimized by making effective energy policy regarding the solar energy. Sun shines through-out the year for average 8 hours a day and 300-400 Watt/m^2/hour radiations available for Pakistan. Radiation data is shown in figure below [11]

Conversion of solar energy directly into electricity is a renowned and commercially applicable technology in the world as-well-as in Pakistan. Quaid-E-Azam solar photovoltaic power plant is the largest in the world with 1000 MW power production Pakistan is far behind from the solar thermal technology on large scale power production. In world there are more or less 60 solar thermal power plants are working. 29 are under construction and 28 have been announced to be completed in next few years [12]. In a solar thermal production unit heavy pressurized steam formed by the solar radiations strikes to the turbine blades and turbine shaft connected with the generator's rotor moves and electricity is being produced

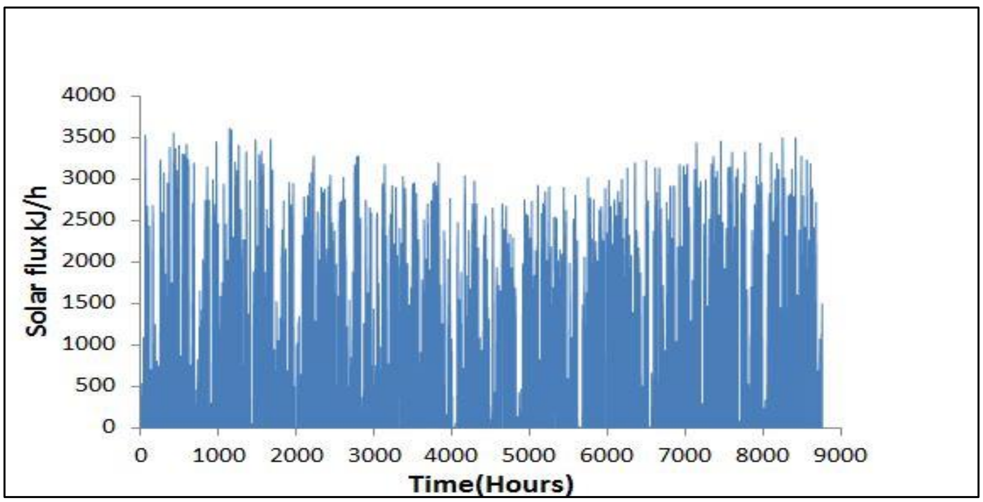

Figure 3: Solar radiation for Bahawalpur

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2.3 Thermal Power Plants basics

In thermal power plants heat energy is converted into electrical energy. Heat energy is extracted from high carbon containing fuels known as fossil fuels which include coal, oil and gas. This heat energy converts water into steam which runs the turbine. In other system, pressurized gas is heated and runs the turbine. Mechanical power of turbine is converted into electrical power through generators. Fossil fuels are called conventional fuels and release hazards gasses like Carbon into atmosphere.

2.4 Thermal Power Cycles

Thermal power plants working depends upon two cycles

- Rankine cycle
- Brayton cycle

2.4.1 Rankine Cycle

The Rankine cycle is an idealized thermodynamic cycle of a heat engine that converts heat into mechanical work while undergoing phase change.

The heat is supplied externally to a closed loop, which usually uses water as the working fluid. It is named after Willliam John Macquom Rankine, a Scottish polymath and Glasgow University professor

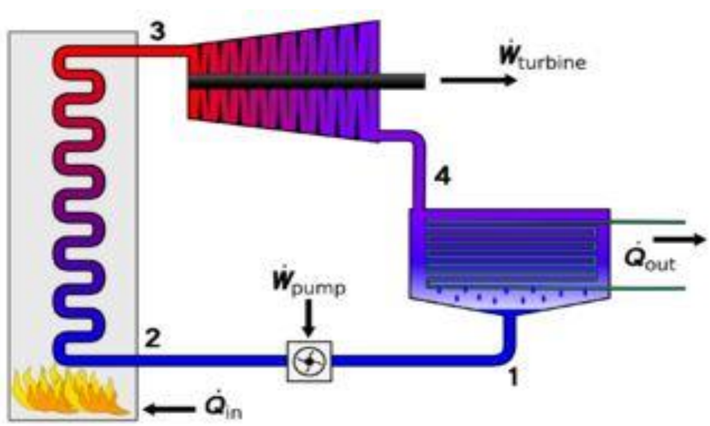

Figure 4: Rankine cycle flow diagram [13]

- Condensed water is pressurized through pump (W_{pump} is the pump work done) goes to heating system i.e. heating furnace where fossil fuels are burnt. Q_{in} is the heat supplied.

- Passing through the pipes of heating system, water gets heated and starts changing its phase
- Pressurized and heated steam is available at the end of the heating furnace and strikes the turbines blades to produce mechanical power
- Pressure and temperature is reduced at the turbine's outlet and it goes to condenser to continue the process in a loop. ($W_{turbine}$ is the turbine output work)

2.4.2 Brayton Cycle

The Brayton cycle is a thermodynamic cycle named after George Bailey Brayton. Although the cycle is usually run as an open system, it is conventionally assumed for the purposes of thermodynamic analysis that the exhaust gases are reused in the intake, enabling analysis as a closed system.

- Work (W_{in}) is done to pressurize air through adiabatic compression
- Heat (Q_{in}) released from the combustion process is used to heat up the pressurized air and air enthalpy is increased
- High temperature and pressurized air does work on turbine and transfer its energy into mechanical energy of turbine.
- In an open system exhaust gas is emitted into atmosphere. In a closed system it is fed back to the compressor

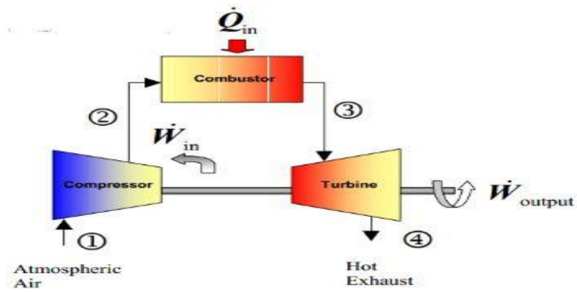

Figure 5: Brayton cycle flow diagram [14]

2.5 Solar Thermal Power

Energy conversion process of solar thermal power plants is same as conventional power plants have. Solar thermal power plants takes heat energy from sun and convert it into

electrical energy through Rankine or Brayton cycle. Solar thermal plants provide ease of a lifetime fuel and environmental protection from harmful gasses. Electric power production through sun energy demands high temperatures which are only achieved with concentrated power. Concentrators are reflecting mirrors used to focus light on a receiver to increase its temperature. Solar thermal power plants are differentiated on the basis of light concentrating technology.

2.6 Types of Solar Thermal Power Plants

Production of steam from solar radiation required a very high temperature which can't be achieved from normally falling solar insolation and there rise the concept of concentrating the rays to accomplish the desired temperature. So non concentrated form of solar energy is only used for the low temperature requirements such as room heating. Light in concentrated form is the input of concentrated solar power plant. Currently known solar concentrated technologies for utilizing solar potential to in terms of power production are

- Solar parabolic trough power plant (SPTPP)
- Parabolic dish power plant

- Solar dish power system
- Solar thermal tower power plant (STTPP)

2.6.1 Solar Parabolic Trough Power Plant

Light is being focused on an absorber tube by group of large curved reflectors having a parabola shape. The reflectors and the absorber tubes move in tandem with the sun as it daily crosses the sky, from sunrise to sunset. Parallel connected reflectors form the solar field. Heat is carried out by a heat transfer fluid through the absorber plate which is been heated by the sun. Simple parabolic trough system is shown in figure below

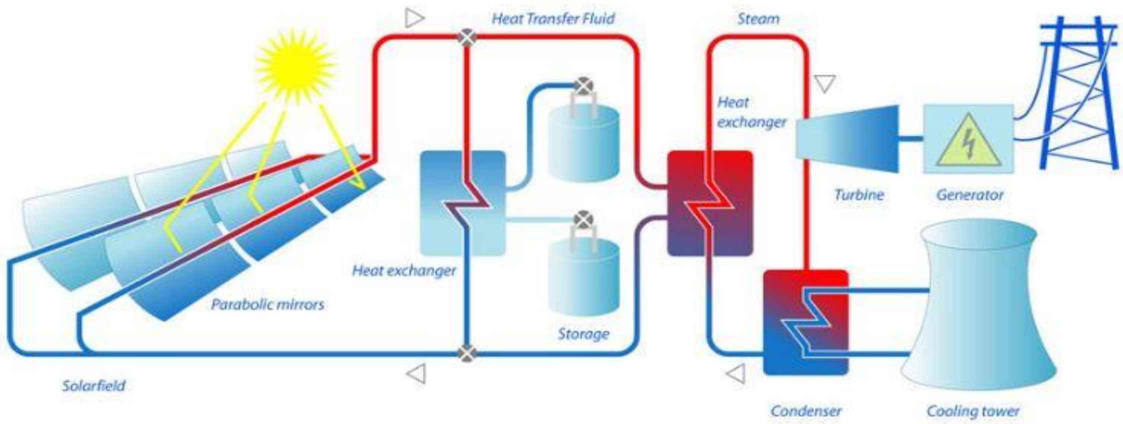

Figure 6: Parabolic trough power plant [15]

2.6.2 Parabolic Dish Power Plant

In a parabolic dish collector system sunrays are concentrated at a point which is supported above the center of dish. Tracking system is attached to track the sun for maximum utilization of sun energy. As this system involves the direct conversion of solar energy into electrical energy so no need of heat transfer fluid in it. PDCs offer the highest transformation efficiency of any CSP system. PDCs main disadvantage is their high cost and low compatibility with respect of thermal storage and hybridization. Promoters claim that mass production will allow dishes to compete with larger solar thermal systems. Each parabolic dish has a low power capacity (typically tens of kW or smaller), and each dish produces electricity independently, which means that hundreds or thousands of them are required to install a large scale plant like built with other CSP technologies

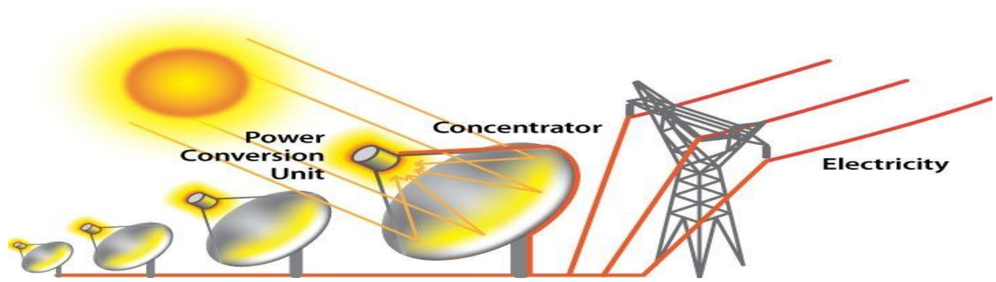

Figure 7: Solar dish power system [16]

2.6.3 Solar Fresnel Lens Power System

Linear Fresnel reflectors (LFR) approximate the parabolic shape of the trough systems by using long rows of flat or slightly curved mirrors to reflect the sunrays onto a downward facing linear receiver. Along the length of linear reflectors, solar receiver is fixed above the ground on a specific height. These reflectors are actually mirrors which can track the sun along single or dual axis. These Fresnel lens mirrors are advantageous due to their simple design of mirrors. This system requires low investment cost due to fix receiver. This system doesn't require any heat exchanger and heat transfer fluid as it directly produce steam. LFR plants have a disadvantage in form of less efficiency as compared to parabolic trough collector and solar power tower in converting solar energy to electricity. It is moreover more difficult to incorporate storage capacity into their design [17].

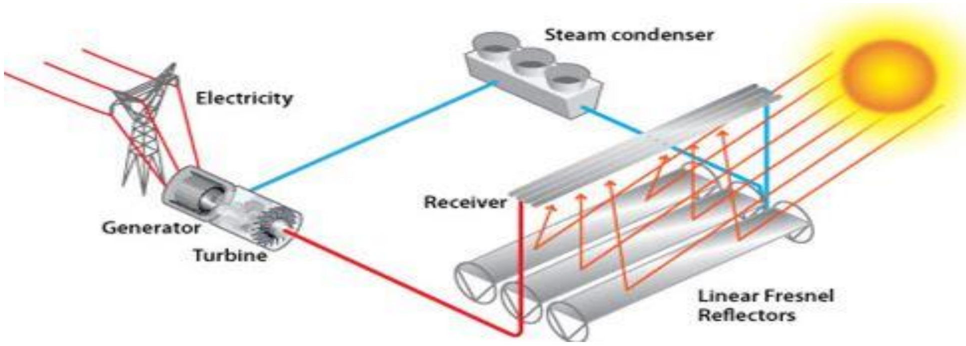

Figure 8: Fresnel lens power system [18]

2.6.4 Solar Thermal Tower Power Plant (STTPP)

Solar tower power plant is one form the renewable energy sources which makes environment free from CO_2 emission during the production of electricity. Solar tower power plant is cost effective technology to produce solar electricity on a large scale. In STPP the solar radiations from sun are first concentrated and reflected by heliostat field onto a receiver. Heat is transferred to the fluid moving inside the receiver. Some STPP directly use this fluid for steam generation while in some power plants HTF transfers heat to the water which turns into steam. Rankine or Bryton based turbine shaft is rotated by high temperature pressure steam. Generator rotor attached to the turbine shaft rotates at a fix speed to produce electricity. Solar tower concept is an emerging technology in world as only 22 thermal power plants are working based on tower technology out of 117 total solar thermal power plants. Especially in Pakistan this is taking birth as no tower power plants has been installed [11].

2.7 STTPP Advantages

Solar thermal tower technology is proving itself effective and better. Some advantages are discussed in this section [19]

- In solar parabolic system the mirrors can only track the sun in one direction, from east to west and making curved mirrors is brutally expensive. The modular nature of the mirrors makes construction easier.
- In solar dish system the heat transfer mechanism is all in the air. There is no inherent storage technology and operated at small scale.
- Solar thermal tower power plant can operate at higher temperatures.
- Heliostats can be air-cooled, or cooled by hybrid systems, which combine air and water cooling that eliminates a huge part of the water problem.
- Field mirrors can tilt in two directions rather than just one for heliostats

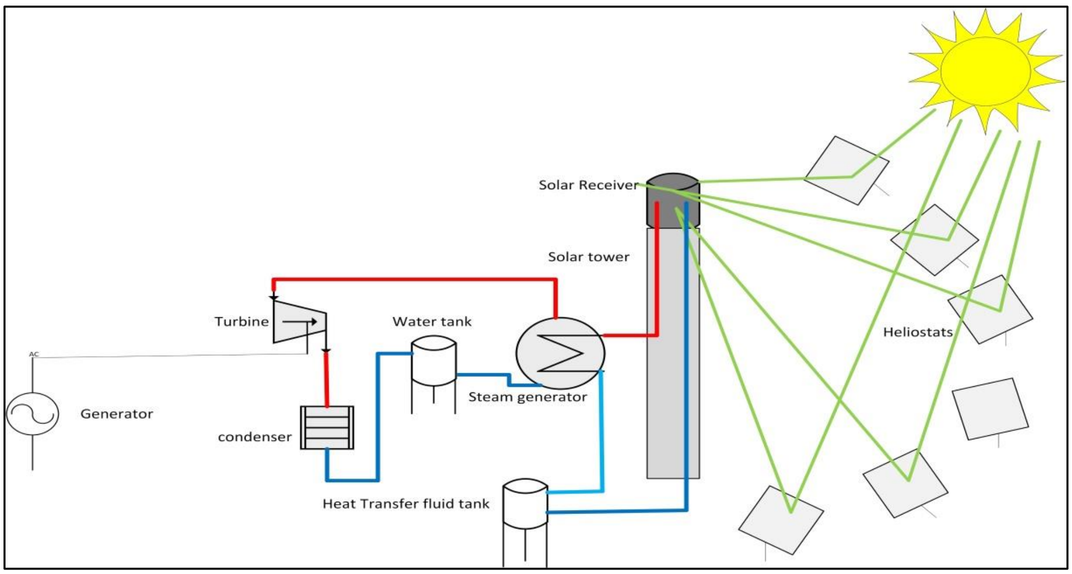

Figure 9: Solar thermal tower power plant [1]

2.8 STTPP Installed in World

Solar thermal technologies are proven since 1980s and replacing the conventional fuel power plants. Following table shows the thermal power plants installed in world.

Table 3: STTPP list [12]

No	Name	Location	Capacity (MW)

1	IVANPAH Solar Power Facility	USA	392
2	Crescent Dunes Solar Energy Project	USA	110
3	Coalinga central power tower	USA	29
4	Sierra Sun Tower	USA	5
5	Noor lll CSP project	Morocow	100
6	Delingha Solar Power Plant (Supcon)	China	10
7	Yanqing (DAHAN)Solar Power Station	China	1
8	Cerro Dominador Solar Thermal Plant	Chili	110
9	Ordos	China	2000
10	Gema Solar	Spain	19.9
11	Ps10 Solar tower	Spain	11
12	PS20 solar Power Tower	Spain	20
13	AZ 20	Spain	50
14	Alcazr Solar Thermal Power Project	Spain	50
15	Almaden Plant	Spain	20
16	Themis Solar Power Tower	France	1.4
17	Khi Solar One	South Africa	50
18	Redstone Solar Thermal Power	South Africa	100
19	Julich Solar Tower	Germany	1.5
20	Greenway CSP Mersin Solar power Tower	Turkey	5
21	Ashalim Power Station	Israel	121
22	Acme Solar Thermal Tower	India	2.5

2.9 STTPP Components

Solar thermal tower power plant uses reflected concentrated light and rest of the system works on the same principal as conventional fuel plants. This reflected light makes superheated steam which runs the turbine. Main components of STTPP are discussed in detail below

2.9.1 Heliostats Field

Although sun is the source of all energies having a great potential to be used in various forms but lower flux density on earth makes it un-useful in terms of generation electricity. So increasing the flux density radiation must be focus on a specific surface. large no of tracking mirrors used for focusing the light on a focal point to get the maximum radiation on a certain point for achieving high temperature are called heliostats. They consist of a flat or curving mirror, frame body, steel support and tracking mechanism. No of these mirrors in a field depends upon the power output of the system. For example IVANPAH solar power facility located in California, USA has 392 MW output with site area of 3500 acres and 1750 heliostats of 64 m^2 each while 11 MW PS10 tower power plant installed in Spain has only 624 Heliostats [17][18]. Heliostats cost and arrangement of the mirrors in a field takes 30-50% of the capital cost [8]. Due to large in number, shadowing effect of one heliostat to other minimize the reflectivity so distance between mirrors is kept large to block shadowing effect and hence land area for installation the plant increases. Mirrors should have good optical properties for high reflectivity. Heliostats optical efficiency depends upon Cosine effect, blocking effect, mirror reflectivity, atmospheric attenuation, and receiver spillage [21].

2.9.2 Solar Collectors

In power tower technology reflected sun rays from the mirrors are received on a central point which acts both as a receiver and a heat exchanger. In fact small circular pipes welded to each other form a circular shape at a specific height from the earth supported by the steel structure.

Heat is taken by heat transfer fluids flowing inside the receiver tubes. On the base of heat transfer fluid and receiver geometry receivers can be classified into following types; volumetric receivers, cavity receivers and particle receivers [22].

2.9.3 Heat Transfer Fluid

Heat transfer fluids act as the transporter by receiving heat energy and deliver it to the steam generation unit. Desired characteristics of a HTF include [23].

Table 4: Heat transfer fluid properties

No	Property	Value
1	Boiling point	High
2	Thermal stability	High
3	Vapor pressure	Low
4	Corrosion with metallic alloy	Low
5	Viscosity	Low
6	Thermal conductivity	High
7	Heat capacity	High

Power plants having Rankine cycle based turbine use water, Thermal oils, organics, molten-salts or liquid metals as a heat transfer fluid. Some Plants using Water as heat Transfer fluid are mentioned below [24].

Table 5: Water as HTF

No	Plant Name	Location
1	IVANPAH Solar Power Facility	USA
2	Sierra Sun Tower	USA
3	Coalinga solar power tower	USA
4	PS10	Spain

5	PS20	Spain
6	Yanqing (DAHAN) Solar Power Station	China
7	Greenway CSP Mersin Solar power Tower	Turkey
8	KHI solar one	South Africa
9	PS10	Spain
10	PS20	Spain

Requirement of large area for installation of tower power plant makes it undesirable to install it near cities or on agriculture land. So Desert or barrel land is the best option for it to be installed. Availability of water at deserts makes it unfeasible to use water directly as HTF there. Molten salt takes the heat first and then transfer to water for steam production in new power plants. Molten salt is a good candidate among thermal oil and liquid metals due to above mention properties meeting criteria [25]. The name of Some Solar tower power plants with molten salt as HTF mention in below table [26].

Table 6: Molten salt as HTF

Plant Name	**Location**
Crescent Dunes Solar Energy Project	USA
Gema solar	Spain
NOORlll	Morrocow
Ashalim	Israel
Redstone Solar Thermal Power Plant	South Africa

In Bryton cycle based turbines Air or gases with high pressure are used for rotation of shaft. As in Jullich solar tower Germany 2000 heliostats heat up the air to 700°C [27]

2.9.4 Steam Generators

Heat carried by the Heat transfer fluids used to change the phase of water into steam (Gaseous phase). Steam generator actually acts as a heat exchanger medium in which HTF flowing inside the tubes transfer its heat to the water flowing outside the tubes boundary. Main parts of the steam generators are

- Super heater
- Re-heater
- Evaporator
- Preheater
- Start-up feed water heater
- Liquid Circulation pumps

2.9.5 Turbine

Significant role of turbine is to rotate the generator's rotor with a fix rpm. Turbine shaft attached to the generator rotor plays a key role to achieve this goal. High pressure steam strikes with turbine blades result in the rotation of turbine's shaft and generator's rotor. On the basis of fuel state turbines are classified into two types.

- Rankine cycle based
- Bryton cycle based

Water in form of steam is used in Rankine cycle while air or other gases such as Helium used in Bryton cycle.

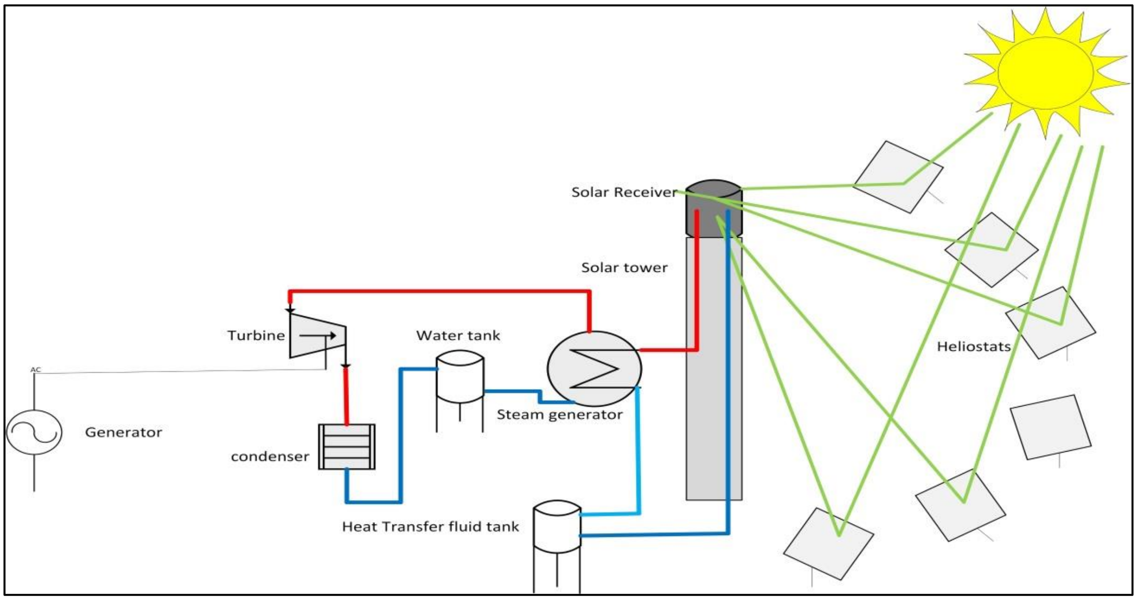

Figure 10: Working diagram of STTPP [1]

2.10 Previous Work Done for Improving Performance of STTPP

Heliostats are most expensive component of solar thermal tower power plant. Different approaches have been adopted to reduce their cost. Work has been done to make system cost effective i.e. by efficient heat transfer, improved reflectivity of material and purposing effective field of heliostats around the solar tower.

E Evert discussed the mathematical calculation of important parameters in solar tower power plant such as sun position, cosine effect, heliostats reflectivity, atmospheric attenuation and shading on heliostats [28]

Zhihao Yao simulated 1 MW DAHAN solar thermal tower power plant using TRNSYS based on energy balance for 22nd March for china. His findings were 3.22 GWh gross electrical energy with 2200 kWh/m^2 solar radiation and 14.6% solar to electric efficiency [29]

Rebbeca I. Dunn worked on molten salt storage system for 19.9 MW Torresol Gemasolar power tower to make it available after sunset as heated stored salt give advantage to use its energy for electricity production after sunset [30]

A. Yogev discussed solar reflector system for getting high temperature through mirrors to get better economics of STTPP plant [31].

J. Spelling worked on supercritical Rankine cycle to improve solar thermal heat transfer efficiency through dense particle suspension in heat transfer fluids from 39 to 45% [36].

Antonio L reviewed through international projects and found that volumetric receivers are better to get high efficiencies in STTP plants [32].

Scott A jones simulated 30 MW SEGS VI plant in TRNSYS and found software prediction error of 10% with actual experimental results [33].

H.L. Zhang reviewed different solar conversion technologies and proposed a method to convert monthly solar radiation data into hourly values [34].

Summary

Energy scenario of the world and Pakistan is discussed in this chapter. Disadvantages of conventional fossil fuels based power plants are discussed briefly. Solar thermal power plants are introduced and their types are shown with working mechanism. Solar thermal tower power plant is discussed with along with its components detail. It is concluded that

- Conventional fossils fuels plants have serious environmental hazards and their depletion is forcing world to shift on renewable energy technologies.
- Solar thermal power plants are good alternative of fossil fuels because they don’t emit harmful gasses. Sun energy is used as fuel input which makes them sustainable.
- Solar thermal tower power plants are efficient type of solar thermal power plants. Main components of solar thermal tower power plant are heliostats, tower, solar receiver, heat transfer fluid, heat exchanger, turbine and generator.

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CHAPTER 3

Modeling of Solar Thermal Tower Power Plant

3.1 Site Selection

Designing of a new system is essential before starting its construction. To evaluate the operating behavior of the system, software based simulation is a handy tool. Behavior of Transient system can be analyzed using a graphical based software name as TRNSYS. It can be used for heating and cooling design for buildings as well as to examine the thermal based production of electricity.

Pakistan has huge land in form of five major deserts which can be used for such type of system installation.

Table 7: List of deserts in Pakistan [1]

No	Desert	Location	Area km^2
1	Cholistan	Bahawalpur, Bhawalnagar and Rahimyar Khan	26300
2	Indus valley	Northern area of Pakistan	19500
3	Kharan desert	Northeast Balochistan	20000
4	Thal desert	Mianwali Region	305 km (length)
5	Thar desert	East Punjab and Sindh near Indian border	175000

These deserts are under Government ruling so if government of Pakistan takes any initiative to install a solar thermal power production unit in these areas initial land purchasing cost would be zero. Bahawalpur District is located in the south of Punjab Province. The

Meteorological Station in Bahawalpur district is located at 71.78 degree east longitude and 29.4 degrees north latitude (in terms of the geographical coordinates), and the observation field is 116 m above the sea level [2]. The basic available meteorological data and the sunshine hours from 1982 to 1991 and from 1996 to 2012 (27 years) of this Meteorological Station have been collected. According to the actual meteorological data, statistics have been worked out for major meteorological factors as shown in Table below

Table 8: Bahawalpur weather data

No	Parameters (Annual)	Value
1	Average temperature(°C)	25
2	Maximum temperature(°C)	50
3	Rainfall (mm)	201
4	Wind speed(m/s)	2.3

The total area of Bahawalpur district is 24830 km^2 and about 2/3 of its area is covered by Cholistan desert which is mostly barren. As such, during the development of large-scale thermal tower power plant, no significant problems like resettlement are expected to be faced.

As recently Quaid-e-Azam solar power plant has been installed in Bahawalpur Punjab Pakistan. It is 5.9 km wide from east to west and 8.1 km long from north to west covering area of 40.5 km^2. So it can be a good option to install solar thermal system at this location

3.2 Weather Data

Sun shines average 8-10 hours in Asian countries. In Pakistan solar radiation value is enough to generate power. These radiations are not uniform on all the year as variations occur day by day. Solar radiation data for a year is taken from TRNSYS as shown in figure below. Radiations peak is maximum in months of June and July which are between 5110 and 5840 hours in figure.

For this study solar radiations data of 26th July 2010 is used. Maximum 3400 kJ/h solar radiations are achieved which are not enough to generate electricity so heliostats are used. Daily normal incidence values are shown in graph below

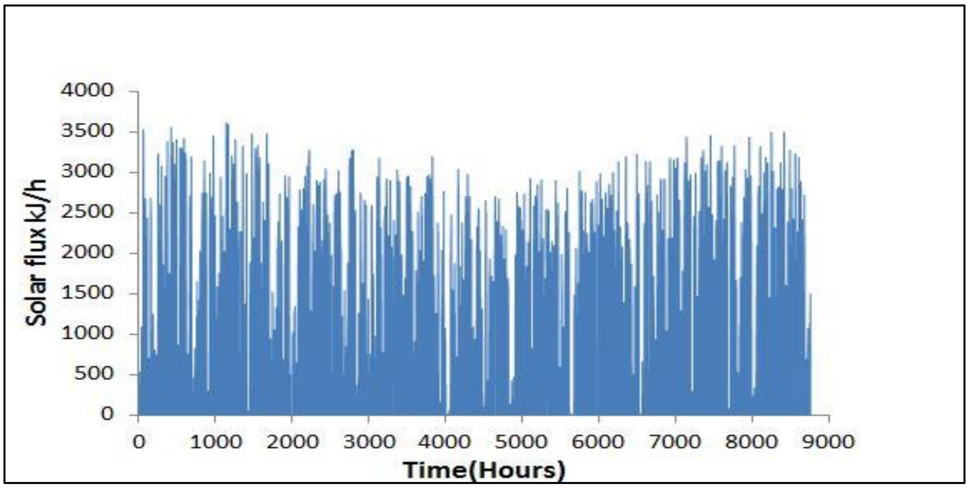

Figure 11: Radiation data

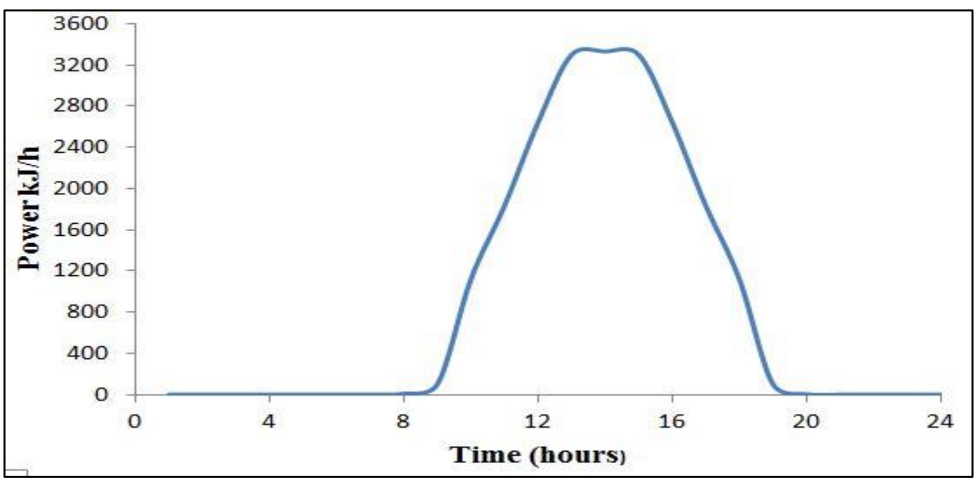

Figure 12: Daily normal incidence value

3.3 Heliostats

The heliostat field layout is an essential task for analyzing performance of solar tower plant. Accurate positioned heliostats provide better and economic system. Different Algorithms available in System advisory model are used to optimize the best configuration. Different combinations of heliostats rows and columns were analyzed. Maximum power was achieved through above mentioned distribution of heliostats around tower. Following figure shows the spreading of heliostats around solar tower. Tower is positioned at 0 axis and heliostats are shown by blue dots.

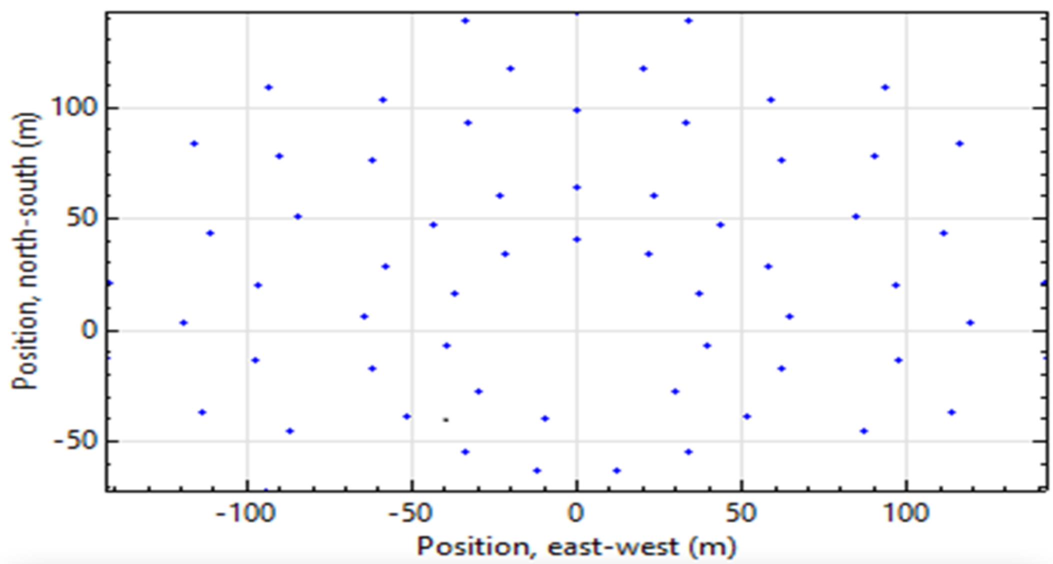

Figure 13: Heliostats positioning around solar tower

Heliostats do not reflect light hundred percent because of light is absorbed through the surface. Following table shows the input parameters of heliostats used in TRNSYS

Table 9: Heliostats parameters

Parameter	**Value**	**Unit**
Mirror surface area	64	m^2
Reflectivity	0.9	
Wind Speed	2	m/s
Solar zenith angle	90	°C

3.4 Tower and Receiver Dimension

Reflected light from heliostats is received by central receiver. For receiving maximum radiation, solar receiver's height and its distance from reflectors plays key role. Further increasing the receiver area or tower height will decrease efficiency in terms of cost. Increasing the tower height will tend to increase the distance of heliostat from the tower. It will increase the land area utilization. For efficient design Greenius software tool is used for calculating the optimized height and tower area. As shown in table below

Table 10: Solar tower and receiver dimensions

Parameter	**Rankine Cycle**	**Brayton Cycle**	**Combined Cycle**	**Unit**
Receiver height	2.17	5.98	4.03	m
Tower height	53.81	140	103.81	m

3.5 System Models

Electric power through thermal technology is produced through Rankine and Brayton cycles. In Rankine cycle steam is used to run the turbine which produces electric power while in Brayton cycle air/gas turbines are used. System efficiency is improved by using combined cycle system. Three systems are modeled in this work

- STTPP based on Rankine cycle
- STTPP based on Brayton cycle
- STTPP Combined cycle system

3.5.1 STTPP based on Rankine Cycle

In STTPP, the solar radiations from sun are first concentrated and then reflected by the heliostat field onto a receiver. Heat is transferred to the fluid moving inside the receiver. Some STPP directly use this fluid for steam generation while in some power plants HTF transfers heat to the water which is converted into steam. Turbine shaft is rotated by high temperature pressure steam. Generator rotor attached to the turbine shaft rotates at a fix speed to produce electricity. Modeling is shown in figure 14.

For production of 1 MW electric output five zenith angle data points and seven azimuth data points were used with 62 heliostats each of area 64 m^2. Components used in the TRNSYS are shown in table 11.

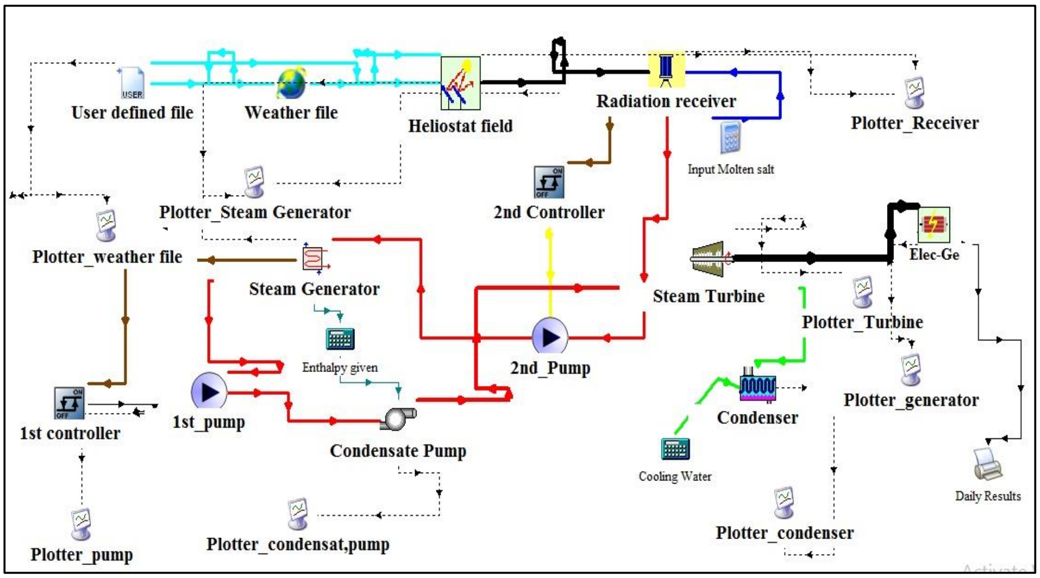

Figure 14: STTPP based on Rankine cycle

Table 11:TRNSYS components for Rankine cycle

Component	**Type in TRNSYS**
User defined file	Type 9-a2
Weather data file	Type 16-g2
Heliostats model	Type 394
Solar receiver	Type 495
1^{st} controller	Type 911

2nd controller	Type 911
Steam Generator	Type 5
1st pump	Type 114
2nd pump	Type 114
Steam turbine	Type 592
Generator	Type 375

3.5.1.1 Molten Salt Properties

Heat transfer fluids act as the transporter by receiving heat energy and deliver it to the steam generation unit. Power plants having Rankine cycle based turbine use water, Thermal oils, organics, molten-salts or liquid metals as a heat transfer fluid. Desired characteristics of a HTF include

Table 12: HTF properties

Constituents	**KNO_3-$NaNO_3$ (40-60 w_t%)**	**Units**
Density at 300°C	1725	kg/m^3
Kinematic viscosity	3.26	m^2/s
Heat capacity	1.495	kJ/kg.k
Thermal conductivity	0.52	W/m.k
Melting point	220	°C

As due to threat of freezing, It is necessary to keep this salt (KNO_3-$NaNO_3$ (40-60 w_t%)) above 280 ℃, so the initial temperature of solar salt is very high. For the first startup, it is required to heat the salt up to 280℃ by some other source like natural gas or oil. After sunrise, its temperature is further increased up to 570 °C. This heated salt is stored in a good insulator material tank so that we may not need to heat it again in the next morning.

3.5.1.2 Function of 1st Controller

When there's no sunshine after sunsets, steam generator passes liquid water to the turbine blades, which is undesired situation. To avoid this condition controller is used which stops the flow of water during sun set hours.

3.5.1.3 Function of 2nd Controller

Molten salt takes heat from solar receiver which is heated up by the sun. Molten salt transfers this heat to heat exchanger for steam production. After Sun sets, there's no solar radiation so solar receiver doesn't heat up and molten salt temperature does not go above 280℃. But when this 280 °C heated salt goes to heat exchanger it gives its heat to water and its temperature drops down which is not worthy for this system as molten salt would freeze below 280 ℃. To avoid this situation control function is used in TRNSYS. Below the lower dead band controller stops the flow of salt. As temperature increases above the dead band controller allows pump to transfer the salt to the steam generator.

Table 13: Controller parameters

Parameter	**Value**	**Unit**
Upper input temperature	20	°C
Lower input temperature	0	°C
Monitoring temperature	20	°C
High limit cutout	500	°C
Upper dead band	281	ΔC
Lower dead band	280	ΔC

The on/off differential controller generates a control function which can have a value of 1 or 0. The value of the control signal is chosen as a function of the difference between upper and lower temperatures, compared with two dead band temperature differences. The new value of the control function depends on the value of the input control function at the previous time step.

3.5.1.4 Enthalpy Calculator and Condensate Pump

Four important parameters of steam for running turbine's blades are; pressure, temperature, flowrate and enthalpy. Steam coming out from steam generator should have above four properties in it. But in TRNSYS steam generator output contains only flow rate and temperature. So other components are needed to provide enthalpy and pressure to turbine. Output of heat generator is shown below

Figure 15; Heat generator output

Parameter	**Value**	**Unit**
Source side inlet temperature	280	°C
Source side flow rate	19500	kg/h
load side inlet temperature	50	°C
Load side flow rate	13000	kg/h
Overall heat transfer coefficient transfer of exchanger	13000	

3.5.1.5 Steam Turbine

Input data taken from Siemens made 1 MW turbine used for this proposed system is shown in table below.

Table 14: Steam turbine data

Parameter	**Value**	**Unit**

Turbine type	SST-060 (AFA 4 G6a)	
Steam flow	13000-14000	kg/h
Inlet Pressure	15	bar
Inlet temperature	198	°C
Exhaust steam pressure	1	bar
Frequency	50	Hz
Outlet temperature	99	°C
Turbine speed	17526	rpm
Output power	1064	MW

3.5.2 STTPP based on Brayton Cycle

Four important properties of working fluid for power production in Brayton cycle are mass flow rate, temperature, pressure and enthalpy. Different combinations of these parameters are used in this modeling and results are produced. Siemens made gas turbine is taken as a model for this proposed system.

This diagram shows the basic loop of solar thermal tower power plant. For heating the air in the morning time natural gas can be used as to heat up the air. For rest of the time some part of the output heated air can be used heat the input air of compressor. Output of gas turbine can be used to run a steam turbine or for the heating purpose of the building which will increase the system efficiency. This model is not simulated for combined cycle facility

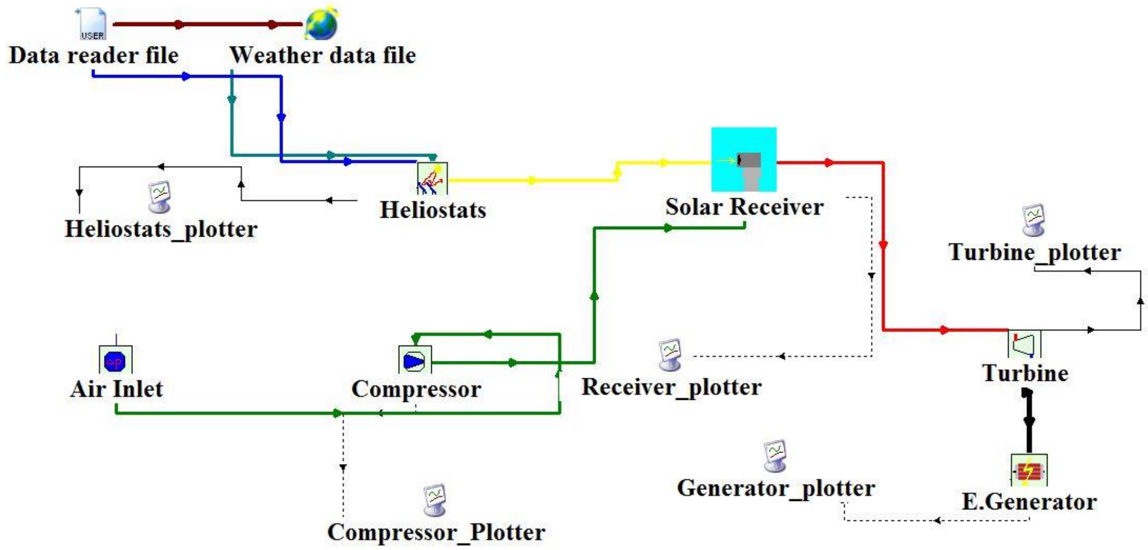

Figure 16: STTPP based on Brayton cycle

Following table shows the component used in TRNSYS to simulate the system

Table 15: TRNSYS component for Brayton cycle

Component	**Type in TRNSYS**
Data reader file	Type 9-a2
Weather data file	Type 16-g2
Heliostats model	Type 394
Solar Receiver	Type 422
Air source	Type 429
Compressor	Type 424
Turbine	Type 427
Generator	Type 428

3.5.2.1 Data Reader File

Data reader file provides the solar zenith and azimuth angle values to the weather file. These angles define the sun position which is important factor for getting maximum radiation. Heliostats position depends upon the sun position. Data reader file is uploaded in the TRNSYS component name as Type 9-a2.

3.5.2.2 Weather Data File

Bahawalpur solar radiation data is used in this system. Weather data file is imported into TRNSYS through the component name as Type 16-g2. It takes the global radiation data from user supplied file and sends it to the heliostats component.

3.5.2.3 Heat Transfer Fluid

Air is used as a heating fluid in this system. Air pressure and mass flow rate is provided to solar receiver through compressor. Temperature of air is increased in solar receiver. Air inlet component in TRNSYS is name as type -429. This model considers standard thermal properties of air at different points i.e. compressor inlet and outlet, solar receiver inlet and outlet and turbine inlet and outlet.

3.5.2.4 Solar Receiver

Air is used as a heating fluid in this system so air receiver component is selected from TRNSYS. Receiver area is kept constant for a particular model and then changed to analyze the behavior. Receiver output temperature is set according to the specification of turbine installed at its outlet. For getting the higher temperature solar flux value is kept high. Output efficiency is taken as 0.9 because some heat is lost through convection from outer body. Absorption fraction is taken as 0.9 which shows that all receiver area is not used for absorption of radiation. Solar receiver component Type-422 in TRNSYS is used in this system.

3.5.2.5 Air Compressor

This compressor model calculates the outlet conditions from the inlet state by using an isentropic efficiency which can be specified by the user as a function of the flow rate using a variable curve. In this way, the model calculates for a given compressor ratio the outlet- temperature t_{out}, is and enthalpy h_{out}, is for an isentropic compression by calling the Gas routine. The real outlet conditions are then calculated by using the isentropic efficiency and a new call of the Gas routine. Air is compressed through compressor which works on adiabatic compression. Air enters into the compressor at 1 bar pressure and 25 °C temperature. Compression ratio is set at 10.

3.5.2.6 Gas Turbine

This gas turbine model calculates the outlet conditions from the inlet state by using an isentropic efficiency which can be specified. For the inlet state the model considers the merge of the combustion- and cooling- air by computation new inlet conditions for the mixture. Siemens made gas turbine is proposed for this system. Mechanical efficiency of turbine is taken as 0.9.

3.5.3 STTPP Combined Cycle Model

. Combined cycle system gives maximum use of heat which is released from Brayton cycle. In this system, Brayton cycle's output gas is supplied to a Rankine power cycle. Exhaust air temperature at gas turbine outlet is fed to heat recovery steam generator which has two loops. Primary loop contains output air of Brayton cycle and secondary loop contains water. Water is converted into steam through hot air and runs the steam turbine. Brayton cycle based TRNSYS model which is explained in above section is used to get 1 MW electric output. Input of the secondary Rankine cycle based system comes through the primary Brayton cycle instead of sun.
Model of Combined cycle system is shown in figure below

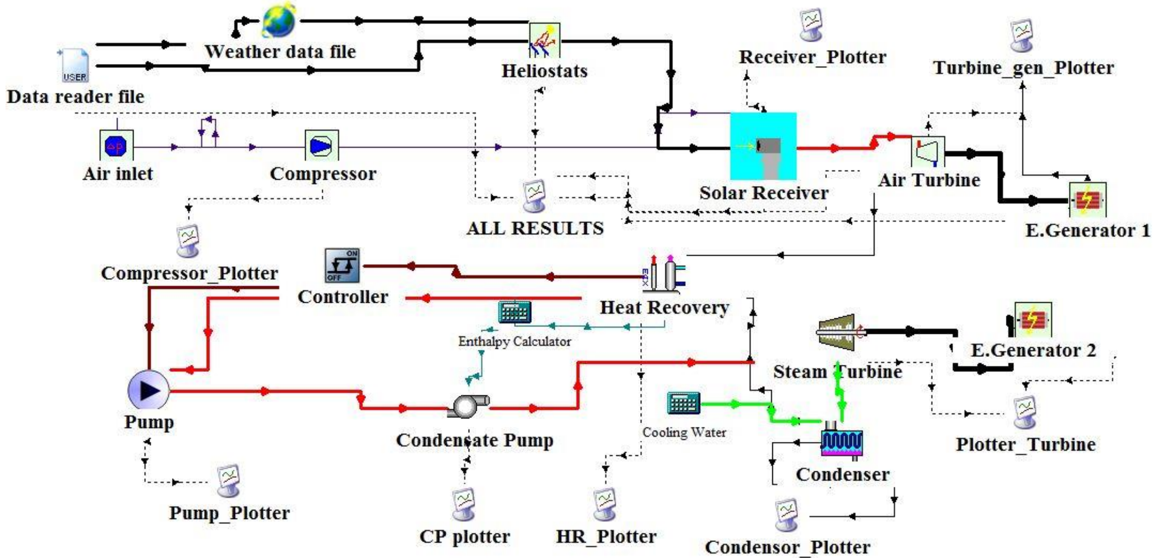

Figure 17: STTPP based on combined cycle

Type of the TRNSYS components are shown in table below

Table 16: TRNSYS Components for Combined cycle system

Brayton cycle Component	**Type in TRNSYS**
Data reader file	Type 9-a2
Weather data file	Type 16-g2
Heliostats model	Type 394
Solar Receiver	Type 422
Air source	Type 429
Compressor	Type 424
Turbine	Type 427
Generator	Type 428
Rankine cycle Component	**Type in TRNSYS**
1^{st} controller	Type 911
2^{nd} controller	Type 911

Steam Generator	Type 5
1st pump	Type 114
2nd pump	Type 114
Condensate pump	
Steam turbine	Type 592
Condenser	
Generator	Type 375

3.5.3.1 Primary and Secondary Loop

Combined cycle model has two loops i.e. Primary loop and Secondary loop.

Primary loop produce 1 MW electrical output which is used as an input of secondary loop and results are analyzed on the bases of input parameters i.e. mass flow rate, pressure, temperature and solar receiver area. Primary loop is based on Brayton cycle and it has the same modeling component with different input values used in above explained STTPP Brayton cycle system.

In the second loop Rankine cycle based system is used which do not get energy from sun. Heat recovery steam generator is used to extract heat of exhaust air from primary loop and transfer it to the water to make it steam. In this system 1 MW gas turbine output is fed to the steam turbine which also produces 1 MW electrical output. Siemens made turbine is taken as a model for Rankine cycle. Characteristics of steam turbine are the same as discussed in STTPP Rankine cycle based system.

3.5.3.2 Heat Recovery Steam Generator

This component models a heat recovery hot water generator; a device which uses the waste heat (usually from a gas turbine or a reciprocating engine) to make hot steam. This model relies on an effectiveness approach to calculate the heat exchange between the two fluids. If the device is running at its maximum load side flowrate and the outlet load-side temperature is still above the desired outlet temperature, the device provides internal control to bypass a portion of the hot-side fluid in order to keep the cold side at or below its set point. This model calculates the flowrate of load-side fluid that may be raised to its set point temperature based on the inlet source conditions.

3.5.3.3 Function of Controller

The on/off differential controller generates a control function which can have a value of 1 or 0. The value of the control signal is chosen as a function of the difference between upper and lower temperatures and, compared with two dead band temperature differences. The new value of the control function depends on the value of the input control function at the previous time step. For safety considerations, a high limit cut-out is included with this controller. Regardless of the dead band conditions, the control function will be set to zero if the high limit condition is exceeded. This controller is not restricted to sensing temperatures, even though temperature notation is used.

When there are no sun shine available and Brayton cycle output is zero this controller is used to stop the water striking to the turbine blades.

3.5.3.4 Gas Turbine

Kawasaki made gas turbine is taken as a model in the primary loop of this proposed system. Parameters of the considered turbine are mention in table below

Table 17: Kawasaki turbine characteristics

No	Parameter	Value
1	Turbine Model	KAWASAKI GPB 17/17D
2	Compression ratio	10
3	Temperature at turbine inlet	1040°C.
4	Pressure at turbine inlet	10 bar

5	Flow rate of air	24480 kg/h
6	Exhaust Temperature	560°C.

3.5.3.5 Steam Turbine

In the secondary loop steam turbine is used which produces 1 MW electrical power. Characteristics of Siemens made turbine are mentioned below in table

Table 18: Steam turbine characteristics

Parameter	**Value**	**Unit**
Turbine type	SST-060 (AFA 4 G6a)	
Steam flow	13000-14000	kg/h
Inlet Pressure	15	bar
Inlet temperature	198	°C
Exhaust steam pressure	1	bar
Frequency	50	Hz
Outlet temperature	99	°C
Turbine speed	17526	rpm
Output power	1064	MW

Summary

This chapter presents simulations of solar thermal tower power plant using TRNSYS software and explains its working. Systems performance is made better by adjusting the input parameters. System advisory model is used to find the layout of heliostats around solar tower. Greenius software is used to measure the dimension of towers. Three models of thermal power production are presented in this chapter. Solar thermal tower power plant based on Rankine cycle is modeled with different heat transfer fluids. Siemens made turbine input parameters are considered for this system.

STTPP Based on Brayton cycle is simulated with the input parameters of Kawasaki made gas turbine. Air is used as a heat transfer fluid and system modeling is based on different input mass flow rate, pressure, temperature and solar receiver area.

Third system is a Combine cycle model having two working cycles in which 1 MW Brayton cycle output is provided to a Rankine cycle to increase output. Siemens made gas turbine is taken as a model in primary loop.

Effects of changing input parameters in these models are discussed in next chapter.

References

[1] “Deserts in Pakistan” [Online]. Available: http://www.webchutney.pk/5-beautiful-deserts-of-pakistan-you-should-know-about/.” [Accessed: 25-July-2017]

[2] “Geographical data of bahawalpur [Online]. Available: http://dateandtime.info/citycoordinates.php?id=1183883.” [Accessed: 25-July-2017]

CHAPTER 4

Results and Discussions

4.1 STTPP based on Rankine Cycle

Solar concentrated power is necessary to achieve the desired temperature of solar receiver. Without concentrated power maximum 3400 kJ/h solar radiations are achieved which are not enough to generate electricity so heliostats are used. In the TRNSYS model input parameters i.e. mass flow rate, temperature and pressure of Siemens steam turbines are used to generate 1 MW electric power [1]. It is found that 107 heliostats are necessary to get the desired temperature.. Power from the heliostats is shown in table below. The maximum output from the heliostats is $1*10^7$ kJ/h. It shows the production of 632 Watts from a single heliostat in TRNSYS. It is assumed that sun is being tracked all the time by the mirrors. Power from the heliostats is shown in figure 18.

This concentrated power increases the solar receiver temperature up to 550 °C as shown in figure 19

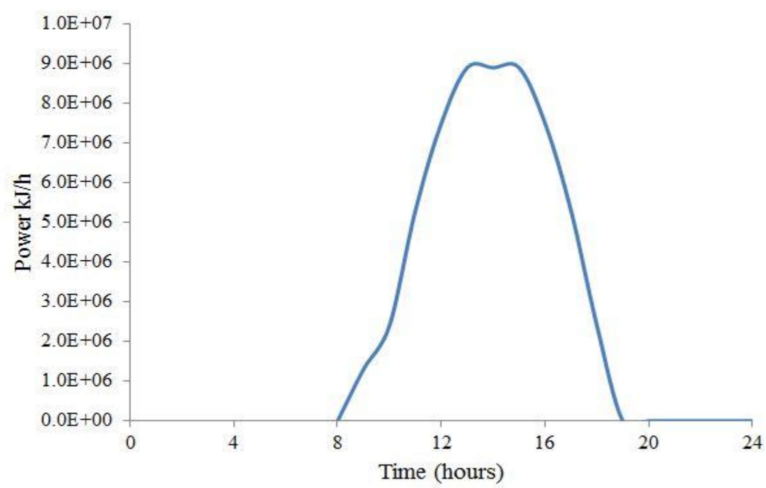

Figure 18: Heliostats Power

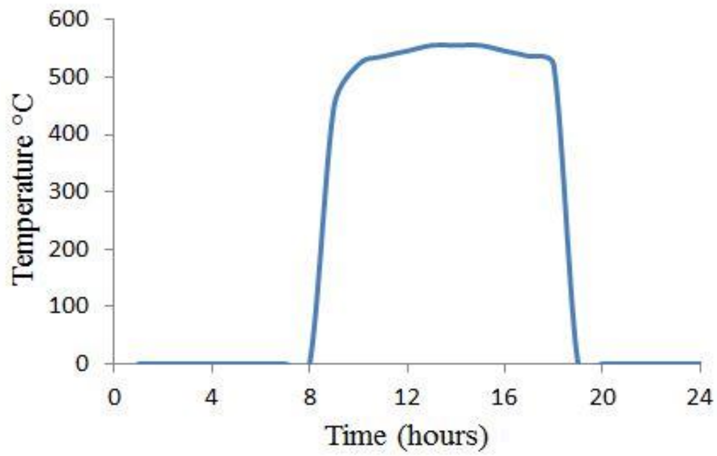

Figure 19: Solar receiver temperature

4.1.1 Effect of Solar Receiver Area on Molten Salt Temperature

Figure 20 shows the effect of changing receiver area for molten salt as heat transfer fluid. Solar receiver area of 25 m^2 is found to be good as minimum number of heliostat is required at this area. Temperature demand for molten salt is 580 °C which is achieved at 55400 kg/h for the solar receiver area of 25 m^2. Heat is transferred through convection process and increasing the flow rate increases the heat transfer.

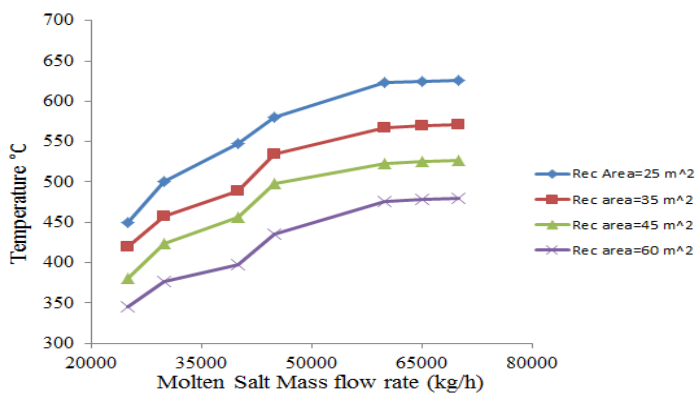

Figure 20: Temp curve against different receiver area

4.1.2 Effect of Water Flow Rate on Heliostats

Steam generator is used for steam production through the heat of molten salt. Rankine cycle turbine inlet mass flow rate is 14000 kg/h, increasing the rate of water, decreases the heat transfer as shown in the figure 21 below. Lowering the mass flow rate from 14000 kg/h decreases the temperature requirement because temperature rise increases. But at lower flow rate, pressure had to increase for producing required enthalpy to produce 1 MWe output. Increasing the flow rate is not recommended because it increases the heliostats requirement.

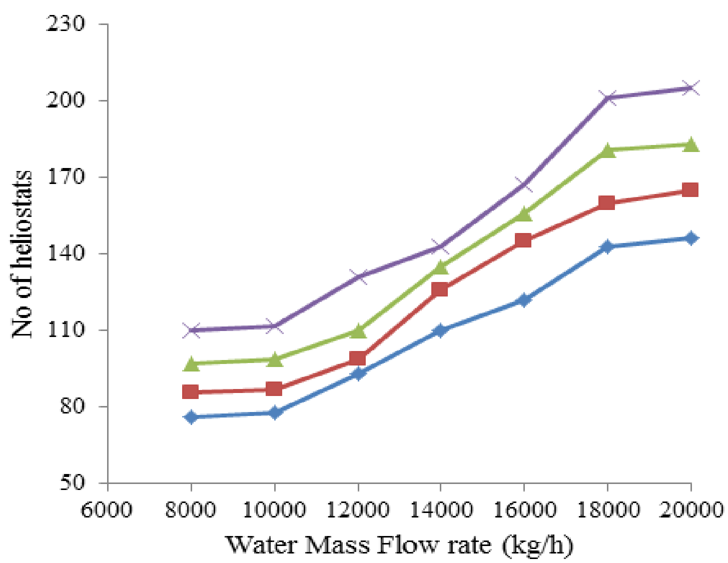

Figure 21: Effect of water flow rate on heliostats

4.1.3 Effect of Turbine Inlet Pressure

Effect of different pressure on turbine inlet is observed. First results were obtained at 15 bar and 107 heliostats were required for this system. First pressure is decreased to 10 bar at 25 m^2. At lower pressure boiling point of water decreases and steam is generated at lower temperature hence heliostats are decreased for this lower pressure shown in figure 22.

Effect of increasing the pressure is shown in figure 23. At high pressure boiling point of water is increased and steam is generated at high temperature. To get the high temperature from molten salt its temperature need to be increases through higher number of heliostats.

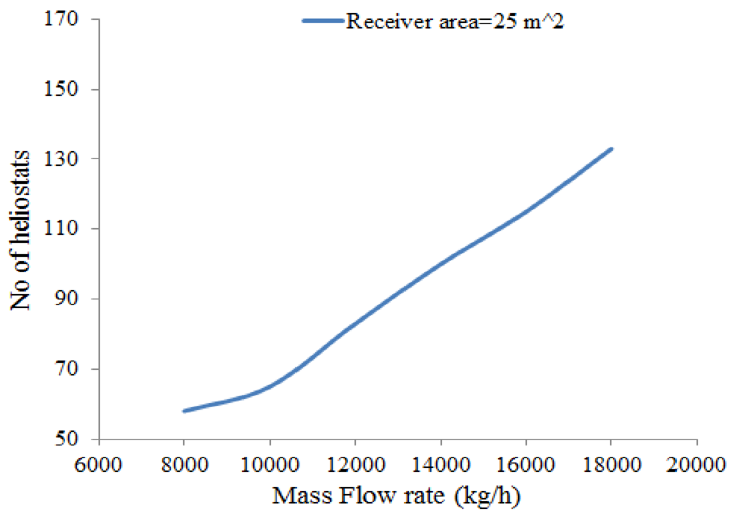

Figure 22: Pressure=10 bar

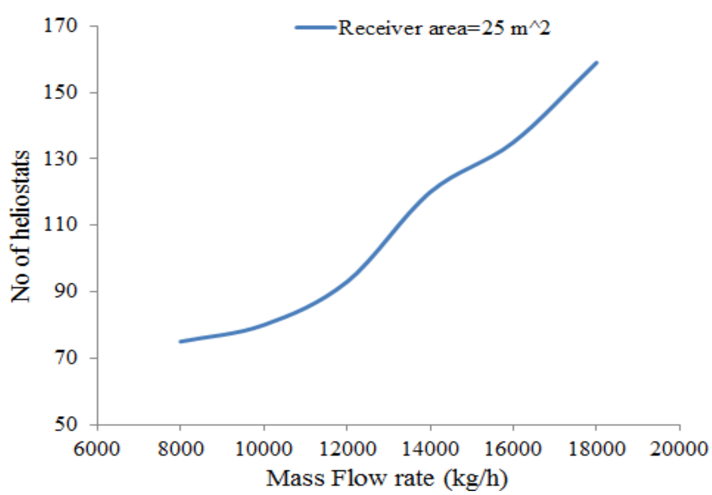

Figure 23: Pressure=20 bar

4.1.4 Power Output

Electrical power output from this proposed system is 4.83 kJ/h which equals to 1.250 MW. It shows that 1 MW of electricity is for supply purpose rest of 0.25 MW is for internal load. Power output can be changed by changing the flow rate of steam and molten salt, number of heliostats and pressure of steam striking the turbine. Between the time interval 0 h and 8 h there are no solar radiation falling on heliostats, so no output power is generated as it can be seen in graph. When radiation starts to increase after 5000 h, molten salt heats up and transfers its energy to water and steam is produced which generates electricity as shown by red line on graph.

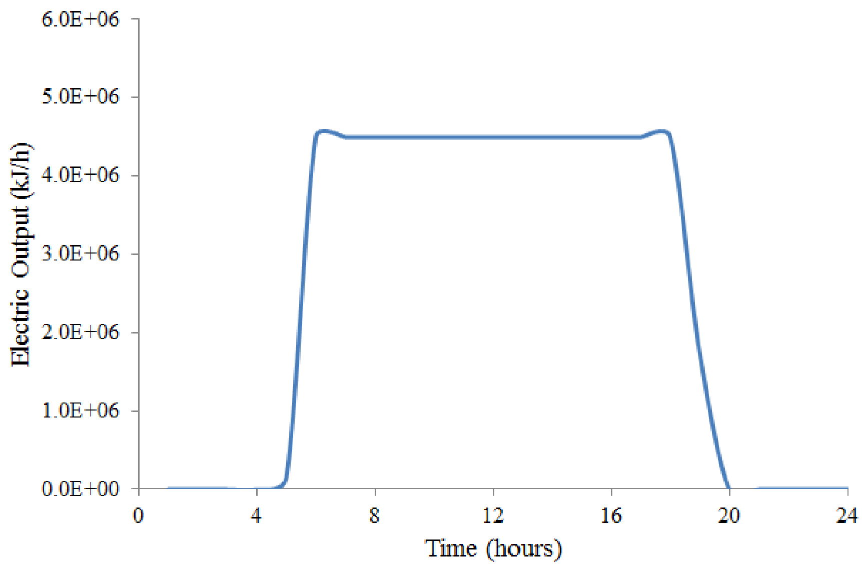

Figure 24: Electrical output of Rankine cycle

4.2 STTPP based on Bryton Cycle

Temperature, pressure and flow rate of working fluid are the key elements for any power generating turbine Simulation is performed on basis of these parameters. Compression ratio is set to 10 with input temperature of 25°C. Temperature of input air is increased with the aid of 945 solar reflectors each of area 49 m^2. Total output of the system is 9.44 MW by at this flow rate of

15.4 kg/s compressor takes 60 percent of this output as its input which is 5.44 MW so net output is 4 MW. Following graph shows the temperature of heated air at the solar receiver exit for the day of 22nd June along with the radiations values. Air started heating for hour 6 when sun starts shining and radiations increases. Peak of the temperature comes at the noon time when solar radiation value touches to 3000 kJ/h.

These radiations are just showing the increasing curve with the daily radiation pattern while these are not enough to raise the temperature up to 1600°C. Heliostats make this happen by reflecting light to central receiver. For getting highly accuracy and efficiency tracking mechanism is equipped with them. Tracking of the sun makes use of maximum available radiations at a particular time.

In this TRNSYS module it is featured that sun is tracked all the time. Heliostats power along with electrical output power is shown in the graph below

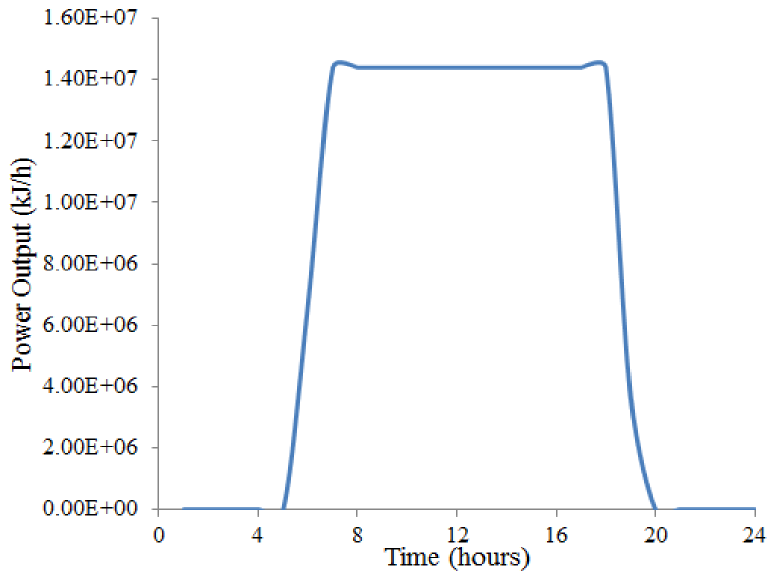

Figure 25: Heliostats and electrical power output of STTPP

This power is coming at the cost of solar energy. It is shown in above graph that solar efficiency can be calculated by differencing the heliostat power from electrical output. Solar output is $85*10^6$ kJ/h equals to 23.6 MW power and useful electrical output is 4 MW stating that solar efficiency is 16.9 percent. It is due to the high power consuming compressor.

To reduce the heliostats used in this system to generate 4 MW output power, different combinations of pressure and mass flow rate are used with changing the solar receiver area. Radiations falling on a smaller area tend to increase the temperature higher than the larger area but material degradation limits the use of smaller area. High receiver area increases the contact of air with the heated surface and temperature rises quickly.

4.2.1 Effect of Solar Receiver Area

Temperature rise of solar receiver depends upon its area which receives solar radiation. For a particular amount of solar radiation, increasing the receiver area produces less temperature from the required value. To heat larger area high solar radiations are required which means large number of heliostats would needed. In this system solar radiations are falling on a central receiver having an area of 25 m^2. Effect of changing solar receiver area on heliostats with different flow rate is shown in figure 26. At higher solar receiver area flux demand is increased to rise the temperature up to a specific value as shown in figure 24. Increasing the receiver area increased the demand of heliostats due to lower flux value.

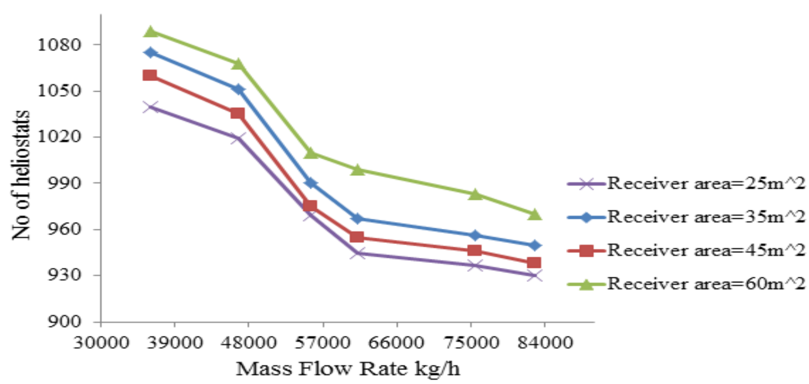

Figure 26: Effect of receiver area on Brayton cycle

4.2.2 Effect of Mass Flow Rate and Pressure

Different combinations of mass flow rate and turbine inlet pressure are observed. It is found that at flow rate of 75600 kg/h and 13 bar pressure heliostats are reduced to 930.further increasing the flow rate has not significant effect on heliostats.

Solar Receiver Area=25 m^2		
Mass flow rate (kg/h)	**Compression ratio**	**Heliostats**
36000	10	1020
	13	1004
55440	10	980
	13	955
75600	10	945
	13	930

4.2.3 Power Output

Electrical output of the system is shown in figure 27

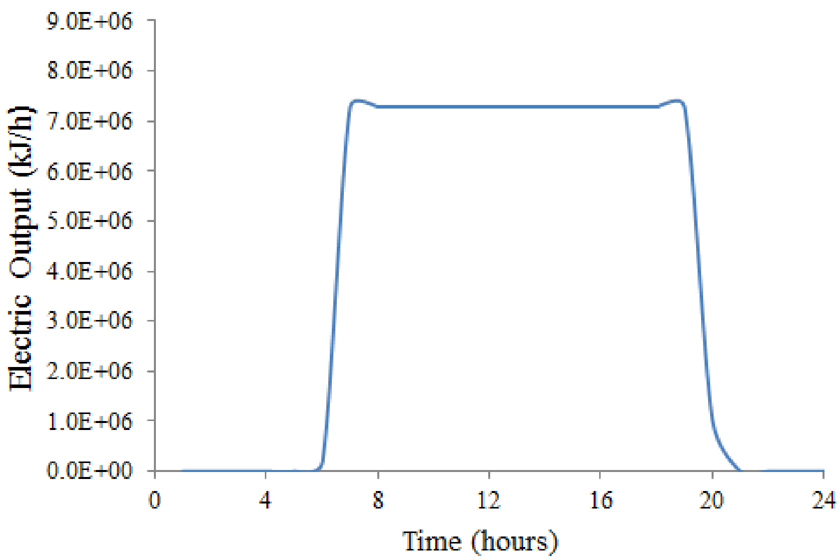

Figure 27: Electrical Output of Brayton Cycle

4.3 STTPP based on Combined Cycle

In this system heated air from the gas turbine (Brayton cycle) is used to generate steam through a heat recovery unit and runs a steam turbine (Rankine Cycle).

In this system power generated from the first Brayton cycle is 3.27 MW=11.8*10^7 kJ/h. Compressor is the high power consuming component in the system which takes almost 2.27 MW=8.2*10^6 kJ/h. Internal load for power generation is considered so total net useful power is 1.0 MW=3.60*10^6kJ/h. Solar mirrors are used to get this input power from sun energy.

All the energy collected is not used in the system some is wasted in the form of optical and system individual equipment losses. So it is observed that 185 heliostats, each of area 64 m^2 are first necessary to get 2.46*10^7kJ/h energy with solar reflectivity of 0.9. Radiation data of 22nd June is used.

Power output is increased by using the high temperature of exhausted air from the gas turbine, this heat is used to run a steam cycle for production of 1 MWe and total output of this cycle is 2 MWe as shown in the figure 27. Temperature at different points in Brayton cycle are shown in table 19

Table 19: Teperatures in Brayton cycle

No	Component	Temperature (°C)
1	Compressor inlet	25
2	Compressor outlet	338
3	Receiver inlet , (due to reflected radiations)	412
4	Receiver outlet	900-1100
5	Turbine inlet	900-1100
6	Turbine outlet	560

4.3.1 Effect of Solar Receiver Area

Solar receiver area had the same effect as in the Brayton cycle case. Optimum values are found at 24480 kg/h mass flow rate.

Air strikes the turbine blades with a specific mass flow rate. Increasing from that point will mechanically damage the turbine blades. If mass flow rate is decreased from particular value it will reduce the power output. To get required power at less mass flow rate, air temperature should get higher by increasing solar radiation through higher number of heliostats.

Graph below shows the effect of increased mass flow rate on number of heliostats with changing solar receiver area with power output fixed at $7.2*10^6$ kJ/h.

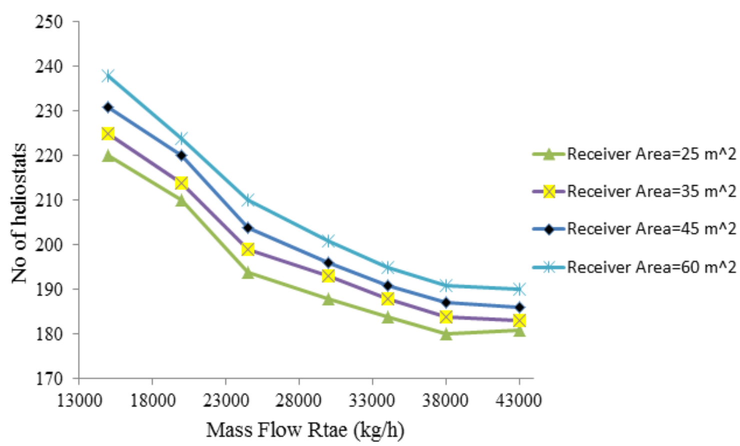

Figure 28: Mass flow rate vs heliostats

4.3.2 Effect of Mass Flow Rate and Pressure

Results were obtained by fixing the pressure 10 bar. Pressure is changed with different mass flow rates and effect on heliostats is observed. It is seen that at higher pressure, temperature requirement of turbine is decreased and required enthalpy is meet at higher pressure. Decreasing the pressure had an opposite effect. To get the rated power, number of mirrors used with different pressures is shown in graph below while fixing the mass flow rate of air at the required turbine input value.

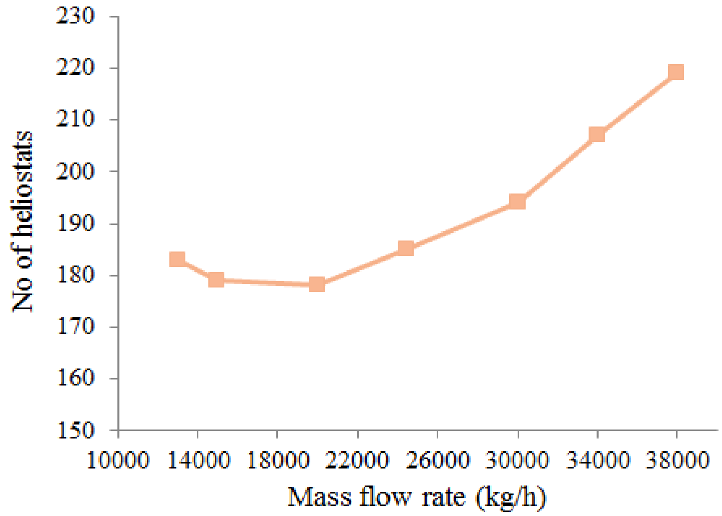

Figure 29: No of Heliostats at 15 bar pressure

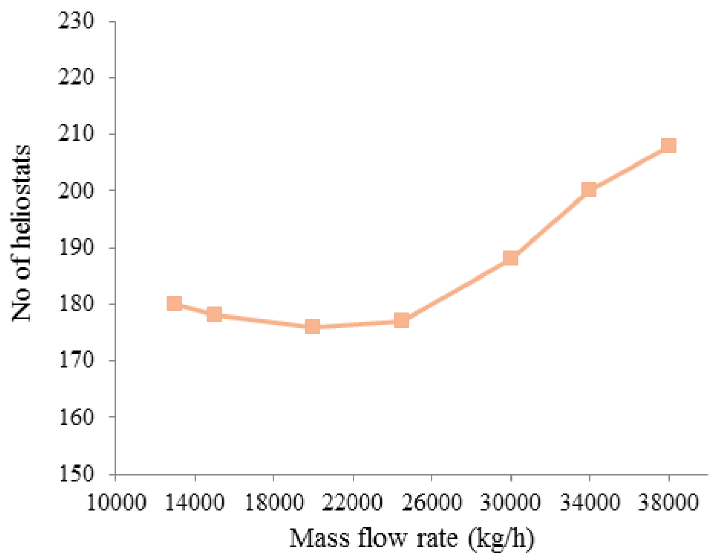

Figure 30: No of Heliostats at 8 bar pressure

4.3.3 Power Output

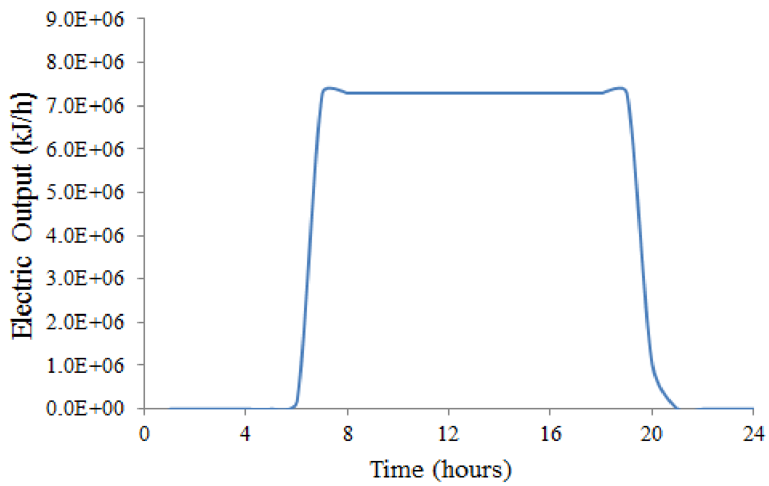

Figure 31: Electrical output of Combined Cycle

In this system heated air from turbine goes to Rankine cycle where its heat is recovered and system efficiency is improved. Air turbine output data is shown in table below

Table 20: Outlet air data

Parameters	Value
Enthalpy (kJ/h)	545
Temperature (°C)	560
Pressure (bar)	1.013

Heat recovery steam generator exchanges heat between two different fuels having different states. Hot side input is air and cold side input is water. Characteristics of HRSG are shown in table below

Table 21: HRSG parameters

No	Parameter	Values
1	Hot fluid input temperature (°C)	560
2	Cold side input temperature (°C)	70

3	Hot fluid outlet temperature (°C)	30
4	Cold fluid outlet temperature (°C)	200
5	Specific heat of hot fluid kJ/kg.K	1.0007
6	Specific heat of cold fluid kJ/kg.K	4.19

For the Rankine cycle Siemens made 1 MW turbine is considered as a model parameter for this system as shown in table below

Table 22: Siemens turbine parameters

No	Parameter	Value	Unit
1	Turbine type	SST-060 (AFA 4 G6a)	
2	Steam flow	13000-14000	kg/h
3	Inlet Pressure	15	bar
4	Inlet temperature	198	°C
5	Exhaust steam pressure	1	bar
6	Frequency	50	Hz
7	Outlet temperature	99	°C
8	Turbine speed	17526	rpm
9	Output power	1064	MW

Different input water flow rates were used to check the performance of the system. Maximum heat was exchange with flow rate of 14000 kg/h. Because of the phase difference of cold and hot fluid heat transfer was just enough to raise the temperature of steam up to 200 °C.

Summary

This chapter discusses the simulation results for three different models of solar thermal tower power plant. Amount of heliostats used in these models are reduced by changing the input parameters.

First model based on Rankine cycle shows an electrical output of 1 MW with 107 heliostats and molten salt as a working fluid. System behavior is observed with changing input parameters like mass flow rate and pressure of the HTF. Solar receiver area is changed from 25 to 60 m^2 and its effect on heliostats number is analyzed.

Second model of solar thermal tower power plant based on Brayton cycle, produced 4 MW electrical Output. Different values of pressure, mass flow rate and receiver area is applied and system behavior is observed. Heliostats are reduced from 945 to 930 by using different combinations of input parameters.

Combine cycle model produced 1 MW output through Brayton cycle and the output heated air at 560 °C is supplied to Rankine cycle which produced 1 MW electrical output and system efficiency is increased. This system used 185 heliostats each of 64 m^2 and it is optimized to 178 heliostats by varying the input parameters values to reduce initial cost.

References

[1] TRNSYS, “User Manual: TRNSYS 17 a TRaN sient SYstem Simulation program,” *TRNSYS Libr. Vol. 4 Math. Ref. Sol. Energy Lab. Univ. Wisconsin-Madison, USA*, vol. 3, pp. 1–486, 2009.

CHAPTER 5

Cost Analysis

Cost analysis for all models presented in chapter 3 is performed using RETScreen software to analyze the better system for Pakistan. Heliostats cost varies in Rankine and Brayton models while other initial costs are fixed. For the Combine cycle power system where Brayton cycle is primary cycle and cost of Rankine cycle is added with the Brayton cycle. Cost is optimized for each model and payback period is found to analyze the feasibility of system.

Some terms included in this chapter are taken from RETScreen user manual [1].

Simple payback period: represents the length of time that it takes for a proposed project to recoup its own initial cost, out of the income or savings it generates.

Equity payback period: It is the length of time that it takes for the owner of a project to recoup its own initial investment (equity) out of the project cash flows generated.

Inflation rate: is the projected annual average rate of inflation over the life of the project.

Discount rate: It is the rate used to discount future cash flows in order to obtain their present value. The rate generally viewed as being most appropriate is an organization's weighted average cost of capital.

Fuel escalation rate: It is the projected annual average rate of increase in base case and proposed case fuel costs over the life of the project.

5.1 Fixed Costs for each Model

For the cost analysis of each model of solar thermal tower power plant following costs are kept fix

- Infrastructure and Labor Cost
- Operating and Maintenance Cost

5.1.1 Infrastructure and Labor Cost

Data of Quaid E Azam Solar Photo Voltaic power plant installed in Bahawalpur having capacity of 100 MWe shows cost per kWp is $2131 [2]. Labor cost of this plant is used as basis of labor cost for solar thermal power plant. RETScreen is used for system's cost analysis. Different parameters considered for this cost include site maintenance cost, road and access network cost**,** equipment installation cost**,** public facilities cost in power plant**,** water supply and drainage works cost**,** and electrical system cost. .

5.1.2 Engineering Procurement and Construction

Continuous working of power plant without interruption requires continuous maintaining and operating expenses. For example in solar plant dust particle attenuates the reflectivity of solar mirrors. So continuous cleaning of heliostat through water is required. Continuous supply of water to the specific plant location demand cost. It takes cost to cool the generator which heats up due to current passing by continuous operating. 100 KVA transformer is used to fulfil the demand of internal load of plant oil is used which needs to be replaced after a specific time. For operating of power plant technical and non-technical staff is required. Technical staff includes engineers for generator and turbine operation as well as water purification system also demands for proper trained staff to continuous monitor its performance. Non-technical staff includes mechanics, guards and peon etc.

5.2 Variable Cost

Equipment cost for each model is varied due to different requirement of components in each model. For example steam turbine is used in Rankine cycle and gas turbine is used in Brayton cycle which both has different costs. Combine cycle system has a steam generator involve in its functioning which increases the price. Heliostats used in each model are different so cost is varied on this parameter. Variable cost includes following components.

- Turbine
- Solar Receivers
- Heat exchanger
- Heliostats

5.3 Cost Analysis of STTPP Based on Rankine Cycle

Most costly equipment of this STTPP is heliostats. Average cost per heliostats is taken as \$150/m2. Other equipment including compressor, receiver, turbine and generator costs are added in the analysis.

5.3.1 Total Cost

107 heliostats each of area 64 m^2 are used in this system for receiver area of 25 m^2.

Following table shows the equipment cost for this model.

Table 23: Equipment cost

Component	Cost
Heliostats	\$595200
Tower	\$200000
Solar Receiver	\$9773
Steam turbine and generator	\$600000
Total direct installation cost	\$1404973
	PKR 148927138

Following table shows the total cost of the system with indirect cost added to equipment (direct) cost

Table 24: Total cost

Parameter	Cost
Infrastructure and labor cost	\$234577

Equipment cost	$1404973
Total engineering and procurement cost/year	$115003
Total cost	$1754553
	PKR 185982618

5.3.2 Cumulative Cash Flow

Payback period time graph on RETScreen analysis is shown in figure 32.

The following Financial parameters used for the cost analysis are mentioned in table 26

Table 25: Financial parameters

Parameters	**Value**
Fuel cost escalation rate	5%
Inflation rate	3%
Discount rate	10%
Project life	50
Initial investment	PKR 186 Million
Payback period	10 years

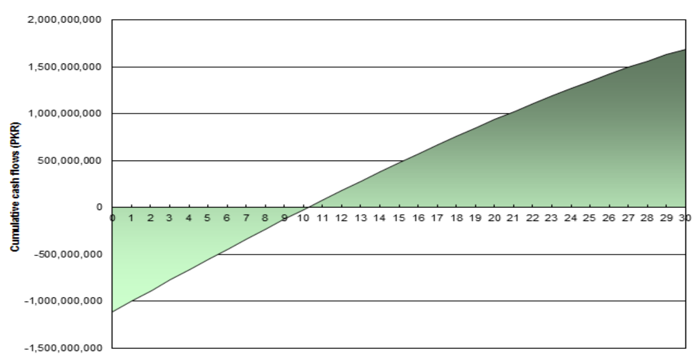

Figure 32: Cumulative cash flow graph

5.4 Cost Analysis of STTPP Based on Brayton Cycle

.STTPP based on Brayton cycle first produces 4 MW electric Output with 930 heliostats. Equipment cost is mentioned as direct cost and all other costs i.e. total engineering and procurement cost, infrastructure and labor cost are named as indirect cost.

5.4.1 Total Cost

In this model area of single heliostats is taken as 49 m^2. Total area of solar receiver is multiplied by per m^2 cost of receiver to find the total cost of heliostats. Equipment cost and indirect costs are added to find the system cost. Cost of the system with these heliostats is shown below

Table 26: Total cost of Brayton system

Type	**Cost**
Cost of heliostats	$6835500= 725 Million PKR
Other equipment cost	$577700= 200 Million PKR
Indirect cost	$2207547=400 Million PKR
Total cost	$9622641.5=1325 Million PKR
Per MW cost	331 Million PKR

5.4.2 Cumulative Cash Flow Graph

Cash flow graph is shown below which shows the payback period of Brayton Cycle based system.

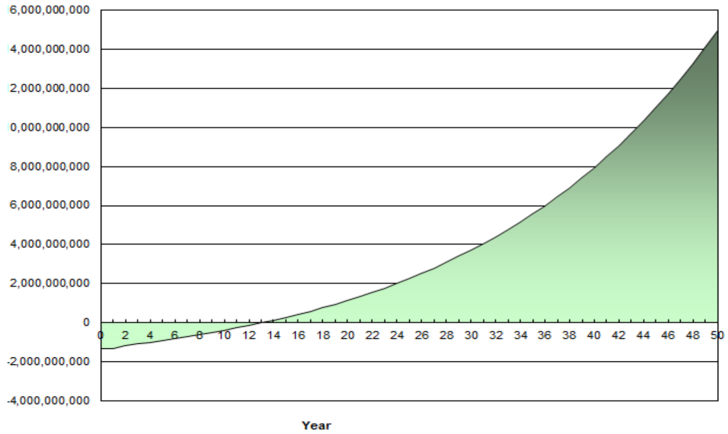

Figure 33: Cummulative cash flow graph

Parameters	**Value**
Total initial investment	PKR 1325 Million
Payback period	14 years
NPV ($)	12350013
Power generation	10512 MWh
Electricity export rate	32000 PKR/MWh
Capital Cost (/kW)	331000 PKR

5.5 Cost Analysis of STTPP Based on Combine Cycle

Most costly equipment of this STTPP is heliostats. Average cost per heliostats is taken as \$150/m^2. Other equipment including compressor, receiver, turbine and generator costs are added in the analysis. Initially, Brayton based cycle is used for cost analysis then combined cycle system is analyzed. Different combinations of mass flow rate, temperature, and compression ratio and receiver area are tried in this Combined cycle system and found that optimum number of heliostats is 185.

5.5.1 Heliostats Cost

185 heliostats each of area 64 m^2 are arranged in 14 rows and 14 column and spacing between them is 1m. 121*121 m^2 would be required to heliostats. Distance of first mirror from the tower is 50 m so area of 171*171 m^2 is needed to build the system while at most 470*470 m^2 is required for whole plant with other facilities such as offices, housing and road network.

Mass flow rate and pressure requirements are set according to turbine requirement. By changing the solar receiver area different heliostats number are taken. Cost of heliostats with changed receiver area is shown in table below

Table 27: Heliostats cost

Parameter	**Value**
Receiver area	25 m^2
Mass flow rate	24480 kg/h
Compression ratio	10
Heliostats required	185
Cost of a heliostat (size=64m^2/ heliostat)	$150
Total cost	$1776000=188 Million PKR

There is not a single solar thermal tower power plant in Pakistan so results are compared with the ACME solar tower in India which is neighboring country of Pakistan. It has $1.98 Million per Megawatt cost [3]

5.5.2 Cost Reduction

Per megawatt cost of system is decreased by adding the cost of combined cycle facility. Steam generator, Steam turbine, condenser, water pump and cooling tower are the main components which are added in the system. Piping structure, water storage tank and extra land are other factors which increased the cost. 1 MW power is added to the system through this facility. $0.75 Million is added to the initial cost. Total cost for this case is $1.8+$0.75=$2.55 Million equal to 225 Million PKR while total power is now increased to 2 MW which gives 112 Million PKR per megawatt cost. Payback time period of this investment is shown in the graph below. Life time of the project is taken 50 years. Within 11 years of working, initial investment is returned and plant makes profit

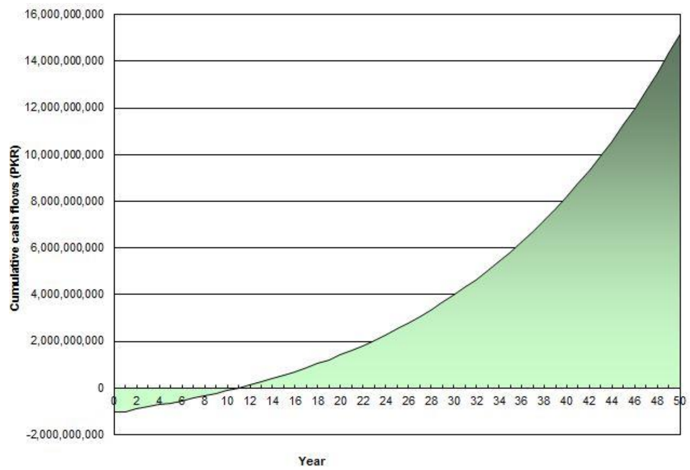

Figure 34: Annually cash flow

Financial parameters used for the cost analysis are mentioned in table below.

Table 28: Financial parameters

Parameters	**Value**
Total initial investment	PKR 332 Million
Payback period	11 years
NPV ($)	9764800
Power generation	5256 MWh
Electricity export rate	14000 PKR/MWh
Capital cost (/kW)	116000 PKR

5.6 Cost Comparison of Proposed Models

Economic evaluations are performed for solar thermal tower power plants models present in this work. Input parameters used to evaluate the three models are shown in table below

For the ease of understanding three models are named as shown in table below

Table 29: Model shown by new names

Model Name	
STTPP Rankine based model	Model 1
STTPP Brayton based model	Model 2
STTPP combined cycle model	Model 3

Table 30: Comparison of three models

Parameters for economic evaluations	**Model 1**	**Model 2**	**Model 3**
Analysis period (year)	50	50	50
Inflation rate (%)	3	3	3
Fuel cost inflation rate (%)	5	5	5
Discount rate (%)	10	10	10
Simple payback period	10	14	11
Capital cost (Millions PKR per MW)	186	331	112

It is concluded that on the basis of initial investment and payback period that combined cycle system is cost effective and proposed for installing in Pakistan.

Summary

Cost analysis of three models of solar thermal tower power plant are presented in this chapter by using RETScreen software

Infrastructure and labor cost, equipment cost and operation and maintenance costs are included in it. Three models are compared on the basis of initial investment and payback period. It is found that combined cycle model is cost effective with initial investment of 112 Million PKR with 185 heliostats used with the input parameters of Siemens made turbine.

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CHAPTER 6

Conclusion and Recommendations

6.1 Conclusion

Modeling of solar thermal tower power plant (STTPP) proposed for climate condition of Pakistan is presented in this work. STEC library in the TRNSYS software has all the components of STTPP i.e. heliostats, solar receiver, air compressor and turbo generator. South Punjab region is selected for this system and solar radiation data for Bahawalpur is used. Performance of the system depends upon input solar energy. Input flow rate, pressure and solar receiver area are optimized to get desired temperature of heat transfer fluid with using minimum number of heliostats. Three power generation systems are modeled based on two cycles: Rankine cycle and Brayton cycle. Different solar receivers are used for Rankine and Brayton cycle. Combined cycle system is used to increase the electrical output and reduce the cost of system. It is concluded that

- High reflectivity of heliostats reduces the system cost by minimizing the number of heliostats used.
- High solar flux is required for large solar receiver area to increase the temperature of heat transfer fluid up to a desired value.
- Heat transfer fluid's with good thermal properties i.e. specific heat and thermal conductivity increases the performance of STTPP.
- Mass flow rate and pressure of heating fluid affected the heat transfer between HTF and solar receiver.
- Output power from turbine depends upon the input mass flow rate, temperature and pressure of turbine. Temperature is achieved from heliostats. Reducing this temperature

requirement by increasing mass flow rate and pressure can reduce the initial cost of the STTPP because heliostats takes more than 50 percent initial cost of total cost.

6.2 Recommendations

- This wok can be extended to model the STTPP with different heat transfer fluids and storage capacity by finding the different sites having greater solar flux values in Pakistan
- Heliostats numbers can be reduced by enhancing the reflectivity of solar mirrors by using material with high emittance and low absorptivity values
- Pressurized CO_2 can be used as a heat transfer fluid to increase the thermal performance of the system.
- Design of solar receiver with high flux values can reduce the heliostats requirement of STTPP
- Storage of heated fluid can enable STTPP to operate in the dark periods.

CHAPTER 7

Hydro Power

7.1 Abstract

Run of river system is one of the valuable forms of generating electricity from hydropower. These systems are cheap compared to large scale dam structures because there is no need of large reservoirs for these systems. Hilly areas having natural slopes of water path are best sites for run of river system. Permanent magnet alternator PMA AC generator or turbo DC generator of (12-24 or 48 volt) is installed against the flow of water. Through electronics devices it is converted into 220 volt alternating current (AC). Inconsistent water flow of stream changes the rotation of generator shaft, due to which output voltage varies which damages the electrical and electronics equipment of load. To save the load from this water flow variation different solutions have been applied on lab scale Pico hydro power project in Oregon state university mechanical department. Two solutions were considered for load saving from voltage and frequency variations in case of an AC generating system. Electronic load controller (ELC) was proposed which manages output through dummy loads. Due to high cost of ELC using a battery inverter system was considered as a second solution.

Effect of changing water flow rate on turbine and electric efficiency of a Pico hydro system was analyzed. Rectifier, battery and inverter were installed to handle the load variation. The effect of flow rate on turbine and generator efficiency was investigated. The results obtained from experiments revealed that the PMA power and shaft power are first increased with increasing water flow rate but start decreasing after a certain value of flow rate. The maximum PMA efficiency of 71.32 % was achieved at a flow rate of 19.1 gallons per minute (gpm) and afterwards it started decreasing due to the stator and rotor losses inside the generator. The turbine efficiency related to net & jet head and water & jet velocity was maximum at 19.7 gpm.

7.2 Introduction

Hydro power production is a valuable source of electricity production in hilly areas where high elevated stored water in the form of large reservoirs is used for power production. Hydropower is a clean renewable source of energy. Earth contains 70% of water in different forms of storage system like river, sea and oceans [1]. High pressure water stream have great potential to generate electricity which is the most thrusted need of human survival on this planet. Some places offer naturally high pressure site where electric machinery is installed to generate power. Hydropower contributes 19% in world electricity production. In USA, Hydropower provides electricity on 0.85 cent per kilo watt hour [2]. These systems are called run of river systems where turbo generator system is installed against the high flow of water. DAM is the second form of extracting water potential to get electric power. DAM is a barrier or a wall which is made to store water at high elevation and create artificial pressure [3]. Hydro power is divided into large and small scale system depending upon the power output. . Small hydropower is mostly run of river having little or no storage. Diverted water from river goes to man-made weir and then to fore-bay to remove particles before hitting the turbine. Small hydropower refers to 2.5-25 MW. Mini, Micro and Pico are sub category of small hydropower production. Mini hydro power refers to schemes < 2 MW, Micro hydro refer to < 500 KW, Pico-hydro is below 10 kW [4]. Large scale hydropower system has a reservoir at high altitude from the ground. Stored water in this structure is released through gates to the turbine shaft. The channel through which water goes to turbine blades is called spillway.

Turbine selection depends upon head & flow rate and running speed of generator. High head hydro generates more cost effective projects. All turbines have power speed and efficiency speed characteristics. Turbines are classified according to high, low and medium head.

Large scale hydropower system is shown in figure 51

On base of operation turbine are classified into;

1. Impulse turbine

2. Reaction turbine

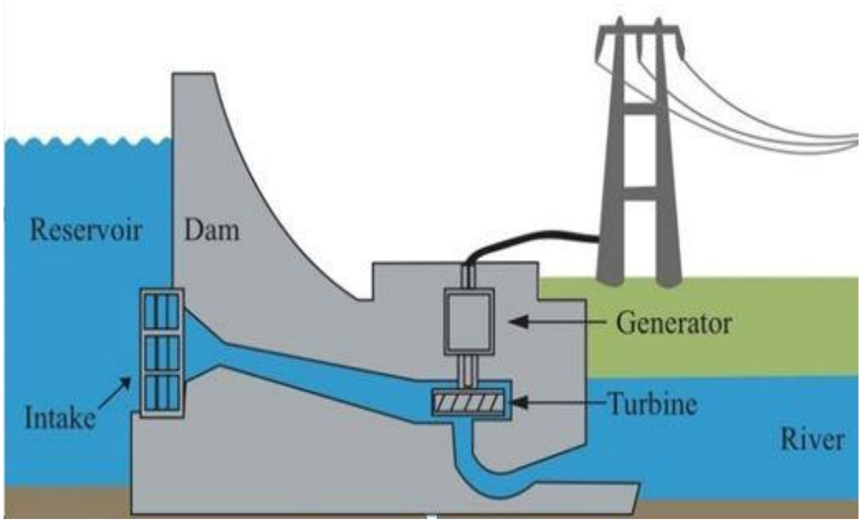

Figure 35: Hydro power system's working [5]

Impulse turbine rotor is fully immersed in water while impulse turbine runner works in air. Reaction turbines need more sophisticated fabrication. Impulse turbines are well suited for micro hydro applications but they are not suited for low head system [5].

Formula for hydro power output is $P = ή * ρ * g * Q * H$ where ρ is density of water, ή is hydraulic efficiency of turbine, g is acceleration due to gravity, Q is volume flow rate and H is effective pressure head of water [53]. Best hydraulic efficiency of turbine is 80-90%. Micro-hydro tends to be in range of 60-80% [6].

Small scale hydropower project do not need a huge reservoir. They are mostly run of river systems. Flowing water stream of a river produces AC or DC current through PMAs. These systems are less expensive than large scale systems but they have an issue of voltage and frequency fluctuation. Wen river flow increases or decreases output power is effected which in most cases damages the electric load attached with it. To overcome this situation different electronics circuitry is used.

7.2.1 Pakistan Hydro Power Production

Pakistan has total installed capacity of 23 GW out of which 7 GW comes from hydro while total hydro potential in country is 42 GW [7]. Province wise hydro production of Pakistan is shown in table below

Table 31: Province wise hydro production in Pakistan [8]

Location Name	**Production (MW)**
Punjab	1698
NWFP	3767
Azad Jammu Kashmir	1036
Northern areas	93

Pakistan had only 10 MW hydro potential before starting the MANGLA and TARBELA projects. Organization involved in hydro potential development on Pakistan

Table 32: Organization working on hydropower [9]

Abbreviation and Date established	**Name**
WAPDA (1958)	Water and power development authority
PPIB (1994)	Private water and infrastructure board
KESC (1913)	Karachi electric supply corporation
SHYDO (1986)	Sarhad hydel development organization
PPDB (1995)	Punjab power development board
IPDS	Irrigation power department Sindh
AJK HEB (1989)	Azad Jammu Kashmir hydroelectric board
AJK PPC (1989)	Azad Jammu Kashmir private power cell
NAPWD	Northern area public works department
PCRET (2001)	Pakistan council for renewable energy

	technologies

7.3 Research Question

I. To make the hydropower an efficient and feasible system by reducing the problems associated with Pico hydropower system on a lab scale project

7.4 Research Objectives

I. To learn the basics of hydropower production system and review the hydro power potential in Pakistan
II. Understand the effect of water flow rate on run of river Pico hydro power water system
III. Proposed the solution for electrical voltage and frequency variation problems
IV. Analyze the performance of lab scale Pico hydropower system at different input flow rates

7.5 Limitation of Study

I. Water flow rate couldn't exceed from 22 gpm due to available motor pump limitations.
II. Net head was fixed and couldn't increase due to limited space available
III. System was designed to maximum 126 Watt power

7.6 Methodology of Work

I. Literature review of hydropower and the experimental system available in hydro and climate lab in Oregon State University
II. Checking the equipment already available in lab
III. Procure the required product like generator, inverter, water tub and electric wires
IV. Install the new equipment with accuracy
V. Run the lab scale Pico hydro system

VI. Measuring the output voltage, current and power at different input flow rates

VII. Theoretical calculation of the flow loop

VIII. Analyze the behavior of the system from newly achieved data

Summary

This chapter discusses the basic working of hydro power systems and Pakistan hydropower potential is discussed. It focuses on hydropower production problems and defines the research objectives by highlighting the problem statement and provides a methodology to define the way for making hydropower system, a better and efficient one.

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CHAPTER 8

Hydropower Experimental Project

A lab scale project was available in hydro and climate lab Oregon State University. Brayan Cobb worked on impulse turbine performance characteristics and their impact on pico hydro installations. He didn't focus on the electrical efficiency of pico hydropower system. His experimented setup was available in lab and this work is mainly focus on improving the electrical efficiency of pico hydro system and resolve the electrical problems associated with it.

8.1 Electrical Problems

Equation of the hydro power production $P = ή * ρ * g * Q * H$ shows that output power directly depends upon the flow rate of water striking to the blades of turbine. Other parameters are

H= Hydraulic head

g= gravitational acceleration

$ρ =$ volumetric flow rate

In run of river systems turbine and generator shafts are connected to each other. Water strikes the turbine blades and it rotates the generator rotor which generates electric voltage according to the Faradays law of electromagnetic induction which states that "whenever an electric conductor moves (rotates) in an electric field voltage is induced on the conductor".

According to the Faradays law

Voltage generated = $\frac{N\Delta BA}{\Delta t}$

Where N= speed of the generator's rotor (revolution per minutes (rpm))

B= Magnetic field

ΔT= change in time

Rotor of generator is connected to shaft of turbine so high flow rate of river increases its speed and high voltage is produced. If electric load is directly connected to generator it will be damaged by over voltage. Vice versa will happen if flow rate is decreased and less voltage is produced. Low voltage also causes electric appliances to damage. Electronic devices like voltage regulators are used instead of directly connecting the electric load to generator but each electronic device has a limited up and down values so besides using them it is also recommended to use mechanical things to adjust the flow of water but it makes the Pico scale project costly.

8.2 Proposed Solutions

Two solutions were proposed to overcome this situation. First system was based on Electric load controller and second solution consists of a battery bank system.

8.2.1 ELC Based Circuitry

To overcome the water flow problems electronic load controller (ELC) is a good choice for Pico hydro system [1]. ELC works on sensing the variations in electric frequency caused by the changing in speed of turbine's shaft. It takes a set in value of frequency which is monitored by relay circuit. If frequency limit is set to 60-65 Hz relay will trigger the circuit when it goes beyond set value and dummy load is operated. Dummy load increases the load on generator's output. As the load increases over the limit, rotor speed slows down and electric current frequency comes down to its normal value. ELC based system configuration is shown in the figure 36

Limitation with this system is that it deals only increased flow rate of water. Whenever water flow rate decreases the electric frequency, ELC cut off the load from the system. So this system was not considered for lab project.

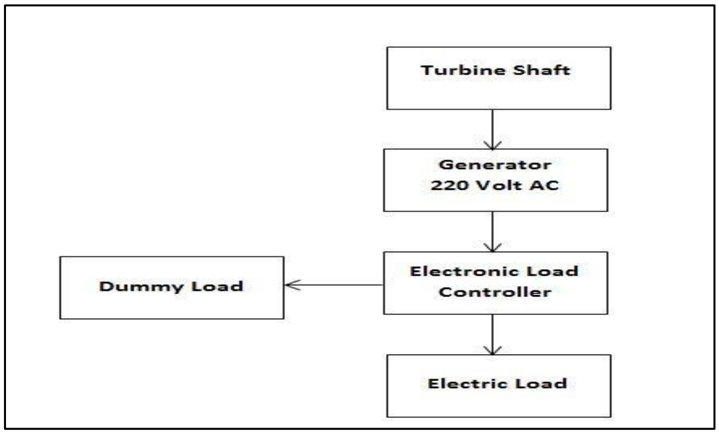

Figure 36: ELC based system

8.2.2 Battery Inverter System

In this system output of generator is not provided to the load directly. 220 volt AC output of alternator is stepped down by a step down transformer to 12 volts and used to charge a battery. Battery is selected depending upon the usage requirement. Inverter circuit is used to get the AC power at 60 HZ frequency. Step up transformer is used to step up the 12 volt to 220 volts. Basic diagram of this system is shown in figure 37

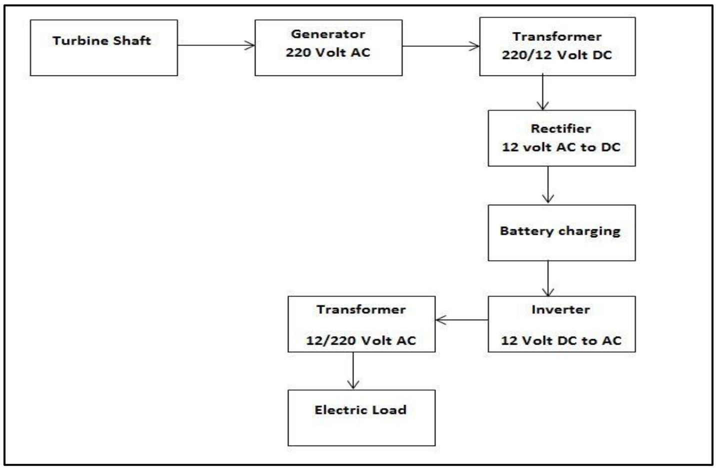

Figure 37: Battery based system

8.3 System Configuration

A lab scale project was modified for this configuration as shown in figure below. .

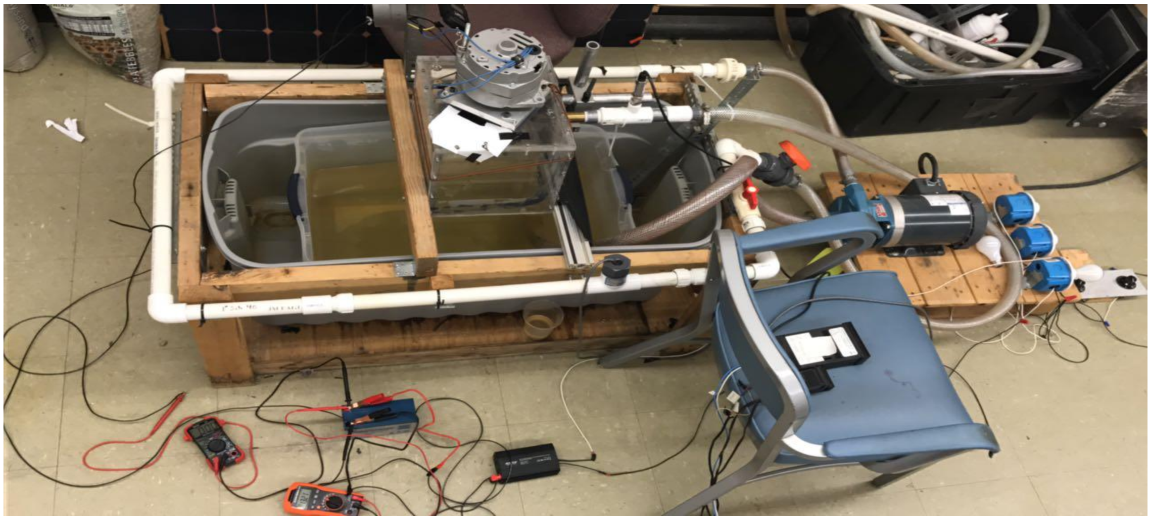

Figure 38: Lab scale project at Oregon State University

Following equipment was used in the system.

Table 33: Components of hydro power project

Equipment	Specifications	Manufacturer

Permanent magnet alternator	Max rpm = 2700 Max 3-phase AC voltage = 170 V	Wind blue power [2]
Pelton turbine	Material = brass, PCD = 100 mm	ABS Alaskan [3]
Centrifugal pump	Power = 2 HP	MP Pumps
Pressure transducer	0 – 50 psig	Omega Engineering
Flow rate sensor	0 – 50 gpm	Omega Engineering
Laser tachometer	2.5 - 99,999 rpm	Neiko
Hanging Scale	0 – 50 kg	Mango spot LCD Electronics
Battery (dry lead acid)	Voltage = 12 V, Current = 9 Ah	
Rectifier	Max current = 150 A	Wind blue [4]
Inverter	Power = 300 W, Input voltage = 12 V, Current = (> 0.6 A)	SNAN [5]
Loads	2 bulbs (60 W each)	

8.4 Analyzing the System Behavior

System behavior was observed using different mass flow rates. Following results were obtained with mass flow rate starting from 9.4 gallons per minutes (gpm) and goes up to 22 gpm. Results were compared with experimented values of Bryan Cobb's paper who worked on this system without using the battery. He used a DC generator and directly connected the generator's output to the DC bulbs. His system efficiency was up to 74% but the load was not protected by the changing input.

Table 34: Different flow rates and efficiency

Flow rate	**Pressure**	**PMA speed**	**Output Current**	**PMA Power**	**Turbine efficiency**	**Generator efficiency**	**System efficiency**
(gpm)	(Psi)	(rpm)	amps)	(Watt)	%	%	%
9.4	5.86	350	0.04	4.4	27.92	38.54	10.76
11.2	8.7	400	0.099	10.89	28.29	55.65	15.74
12.3	10.2	450	0.15	16.5	29.94	59.95	17.95
15.4	16.29	559	0.3	33	30.31	60.33	18.29
17.4	20.88	624	0.5	55	32.35	65.51	21.19
19.1	25.26	766	0.81	89.1	36.37	71.32	25.94
19.7	28.4	860	0.96	105.6	41.99	66.93	28.11
22	32.09	920	1.149	126.39	37.05	64.80	24.01

In this system we got a maximum system efficiency of 24 % and power output was 126 watts. Turbine efficiency was increased throughout with the increased flow rate but generator efficiency increased up to 19.1 gpm and start decreasing as flow rate increased further. It is mainly due to increased electric losses in alternator. System efficiency is calculated by multiplying turbine and generator efficiency. Maximum efficiency was achieved at 19.7 gpm flow rate.

8.5 Conclusion

AC generator in a Pico hydro system demands to attach a battery at its output before connecting the load. The generator frequency increases or decreases with variation in flow rate of water that fluctuation disturbs the load. Turbine and generator efficiencies were estimated and compared with Bryan Cobb's experimental results. He tested the efficiency of turbine with a direct load connection, taking into account different parameters like speed ratio, jet misalignment and nozzle angle. In this system, battery-inverter circuit is attached to control the frequency. That system was able to provide the safe frequency according to load requirement but the system efficiency was decreased

Summary

Electrical voltage and frequency variations problems and river flow rate effect on system performance are discussed in this chapter. Solutions for these problems are proposed based on a hydro power project in Oregon State University.

It is found that

- At 19.7 gpm flow rate of water, maximum system efficiency was achieved.
- It is found that Electronic load controller gives system protection when electrical frequency is increased. It disconnects the main supply from the load if frequency is decreased.
- Battery based system gives protection for high and low frequency values

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Modeling of 1 MW Solar thermal tower power plant using TRNSYS

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***Abstract*—This paper presents an economic, cost effective model of solar thermal tower power plant. In STTPP Heliostats are most expensive component and take 40 percent cost of overall power plant which is unenviable. In this work main focus was to find the minimum number of heliostats required to generate 1 MW of electricity by changing the flow rate, temperature and pressure of heat transfer fluid and steam. Effect of changing the flow rate on heliostats is discussed. For optimum placement of reflecting mirrors and solar receiver height, System Advisory Model (SAM) is used. It was found that minimum 62 heliostats are required for 13000 kg/h steam flow rate. Further reduction in heliostats resulted in decreased steam flow rate which is limited by turbine. Solar radiation data for 26 July was taken from the MHP station installed in NUST, Islamabad Pakistan**

Keywords—sustainable energy; solar thermal; heliostats; tower power plant; TRNSYS; SAM

ABBREVIATION

TRNSYS	Transient system simulation
MW	Mega watt
SAM	System Advisory Model
U.S	United States
TWh	Tera watt hour
GW	Gega Watt
GWh	Gega watt hour
DC	Direct current
PV	photovoltaic
STTPP	Solar thermal tower power plant
MHP	Meteorological high precision

NUST	National University of science and technology
HTF	Heat Transfer Fluid
STEC	Solar Thermal Electric Components

I. Introduction

Energy is the most vital and essential factor for the development, stability and economy of a progressive country. Culture evolves as the amount of energy harnessed per capita per year is increased. Human dependency on technology thus demands the continuous energy production. Developing the reliable, cheap, and trustworthy source of energy is the basic need of world growing economic nations. According to the United States monthly energy review April 2016, U.S energy production in 1990 was 3037 TWh while it has been raised up to 4013 TWh in 2013 [1]. Demand of energy is rapidly increasing with the growing rate of world population. World electricity production in 1995 was 13095 TWh for 574 million people [2]. The electricity increased up-to 20852 TWh in 2010 while world's population increased up-to 691 million [3] Pakistan has a strong strategic locality in south Asian countries and to make its impact on the global world, it has to become a robust economic power. Unfortunately, Pakistan is passing through stressful and devastating circumstances due to economic tumbling. One of the main reasons for economic rise and fall is the lack of energy/power production. Pakistan being the 6th largest country of the world according to population has only 43 Watt per capita energy availability, which is very low indeed and 1/7th of world average per energy capita due to various reasons in which most important one is its dependency on oil and gas for electricity production [4]. Pakistan's electricity sector consumed 15 million tons of oil equivalents in 2008 that amounted to 28% of fossil fuels supplied to the country. These fossil fuels not only increase the financial burden on economy but also having a serious impact on environment by emitting CO_2 [5]. As shown in the figure below.

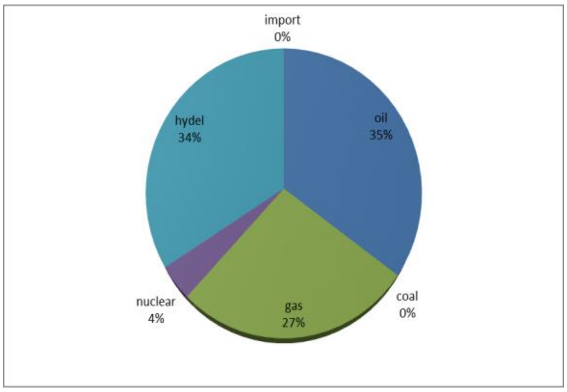

Figure 1: Energy Mix [6]

Pakistan is producing 60% of its electricity from oil and gas through the thermal power plants and facing a shortfall of 5-7 GW as it is producing 18-20 GW power while its installed capacity is approximate 25 GW [7] [8]. Along this, Pakistan has a great potential of renewable energy sources which are abundant and plentiful in nature. Pakistan has a 3000 MW electricity potential from biogas and 5000 MW can be generated from livestock. Its 42% electricity can be generated by producing 18 million cubic meter biogas from biomass resources [9]. There is a great potential of electricity generation through wind in southern areas of Pakistan especially in coastal areas of Sindh and Baluchistan. Twenty sites located at coastal belt in south reveal that 2441 km^2 of area is suitable for production of 11 GW power. Pakistan having a high solar potential ranging from 5-7 $KWh/m^2/day$ can use solar photovoltaic and solar thermal technologies to harness this energy giving sustainable and renewable source of electricity to the country [10] Pakistan has taken an initiative in solar PV power plant installation named as Quaid-e-Azam solar power plant with 1000 MW DC installed capacity [11].

II. Goal of this study

Solar energy for electricity production can be harnessed either by solar PV technology or by solar thermal power plants. Solar photovoltaic panels generate DC power by receiving the solar radiations. Converters are used to convert it in to AC current. Solar thermal power production is more advantageous due to its AC power production system instead of DC. Electric appliances which are called electric loads need pure sine wave of alternating voltage. If power source is pure AC it will produce the required sinewave. Converting a DC voltage into AC signal does not produce pure sinewave. Harmonics are produced during this conversion process which disturbs the load. Increasing the number of converters will increased the harmonics [12]. Power quality is affected by these harmonics [13]. Electronic converters which are used for this purpose are expensive too. Building a converter station makes system costly [12]. Government of Pakistan has not been focused on solar thermal power technologies yet. STTPP is one of the renewable energy sources which produces AC voltage and current and keeps environment free from CO_2 emission during the production of electricity. STTPP provides concentrated light which gives high temperature and make system cost effective to produce solar electricity on a large scale. Goal of this study arises from this point that there is not a single solar thermal tower power plant working or under construction in Pakistan and an efficient source is being neglected. This work will help for researchers to think and take initiative to install environment friendly solar thermal power plants.

III. Solar thermal power plants

Solar energy has been harnessed through photovoltaic technology since 1950 when first conventional photovoltaic cell was produced. Solar thermal power production started in late 1980s and boosted up by first two commercial plants in Spain name as PS10 and PS20. Thermal power plants take energy from coal or oil to convert water into steam for rotating turbine's shaft while in solar thermal plants this energy comes from sun. Yearly irradiation on total earth amounts to more than 1 billion terawatt hours which is more than 60,000 times the global power demand [3]. This huge potential is used through solar thermal power conversion by means of our types of solar plants [2].

1. Solar parabolic trough power plant(SPTPP)
2. Solar thermal tower power plant (STTPP)
3. Solar dish power plant
4. Solar Fresnel lenses reflector system
5. Solar updraft tower system

STTPP plant has better efficiency and cost compared to other thermal technologies [14]. Solar tower has high concentration ratio than parabolic trough. Solar tower has concentration ratio near 300 to 800 suns while parabolic trough has up to 80 [1]. Central receiver system gets high temperature than parabolic troughs and heat transfer fluid takes high temperature in this system and efficiency is improved in terms of heat transfer [15].

IV. WORKING OF STTPP

In STTPP, the solar radiations from sun are first concentrated and then reflected by the heliostat field onto a receiver. Heat is transferred to the fluid moving inside the receiver. Some STTPP directly use this fluid for steam generation while in some power plants HTF transfers heat to the water which is converted into steam. Rankine or Brayton based turbine shaft is rotated by high temperature pressure steam. Generator rotor attached to the turbine shaft rotates at a fix speed to produce electricity. Solar tower concept is an emerging technology in world as only 20 thermal power plants are based on tower technology out of 117 total solar thermal power plants in world. Especially in Pakistan this is taking birth as no tower power plants have been installed yet.

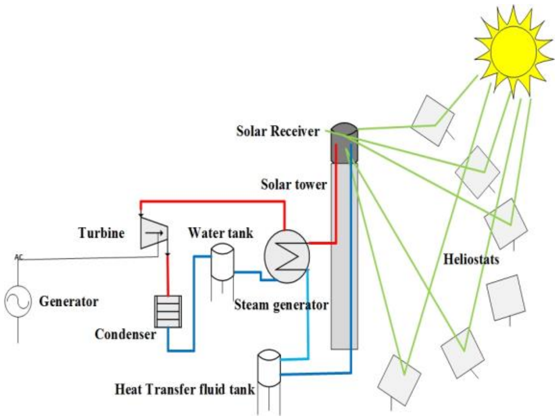

Figure 2: Schematic of STTPP

V. Literature review

Zhihao Yao simulated 1 MW DAHAN solar thermal tower power plant using TRNSYS based on energy balance for 22nd March for china. His finding were 3.22 GWh gross electrical energy with 2200 kWh/m^2 solar radiation and solar to electric efficiency was 14.6% [16].

Rebbeca I. Dunn worked on molten salt storage system for 19.9 MW Torresol Gemasolar power tower to make it available after sunset as heated stored salt give advantage to use its energy for electricity production after sunset [17].

A. Yogev discussed solar reflector system for getting high temperature through mirrors to get better economics of STTPP plant [18].

J. Spelling worked on supercritical Rankine cycle to improve solar thermal heat transfer efficiency through dense particle suspension in heat transfer fluids from 39 to 45% [19].

Antonio L reviewed through international projects and found that volumetric receivers are better to get high efficiencies in STTP plants [20].

Scott A jones simulated 30 MW SEGS VI plant in TRNSYS and found software prediction error of 10% with actual experimental results [21].

H.L. Zhang reviewed different solar conversion technologies and proposed a method to convert monthly solar radiation data into hourly values [2].

P Harper modeled a 5 MW combined cycle thermal power plant in TRNSYS using 200 heliostats of 100 m^2 each [22].

E Evert discussed the mathematical calculation of important parameters in solar tower power plant such as sun position, cosine effect, heliostats reflectivity, atmospheric attenuation and shading on heliostats [23].

VI. Methodology

Methodology adopted to model a cost effective STTPP was to reduce the number of heliostats as they are the most cost taking part of the plant.
Steam turbine needs high pressurized steam with a specific enthalpy and mass flow rate. System was optimized to get desired enthalpy which is enough to generate 1 MW output power. Optimizing parameters were mass flow rate, pressure and temperature of steam. Siemens made 1 MW turbine specifications were considered as input parameters as shown in table below

Table 1: Siemens made turbine

No	Parameter	Value	Unit
1	Turbine type	SST-060 (AFA 4 G6a)	
2	Steam flow	13000-14000	Kg/h
3	Inlet Pressure	15	bar
4	Inlet temperature	198	°C
5	Exhaust steam pressure	1	bar
6	Frequency	50	HZ
7	Outlet temperature	99	°C
8	Turbine speed	17526	rpm
9	Output power	1064	MW

To meet this system design specific number of heliostats were needed which is explained in results and discussion. Efforts were put on modeling a system which produces same output power with less number of heliostats by adjusting enthalpy at different temperatures and pressures.

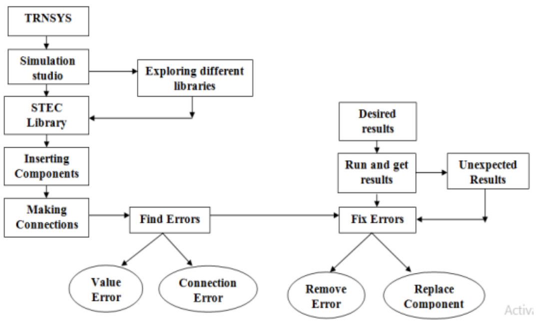

Figure 3: Methodology in TRNSYS

VII. Modeling

Designing of a new system is essential before starting its construction. To evaluate the operating behavior of the system, software based simulation is a handy tool. Behavior of Transient system can be analyzed using a graphical based software name as TRNSYS. It can be used for heating and cooling design for buildings as well as to examine the thermal based electricity production. In STTPP, the solar radiations from sun are first concentrated and then reflected by the heliostat field onto a receiver. Heat is transferred to the fluid moving inside the receiver. Some STTPP directly use this fluid for steam generation while in some power plants HTF transfers heat to water which is converted into steam. High temperature and pressurize steam rotates turbine shaft based on Rankine or Brayton cycle. Generator rotor attached to the turbine shaft rotates at a fix speed to produce electricity. Initially model was made by using parameters of Siemens steam turbine.

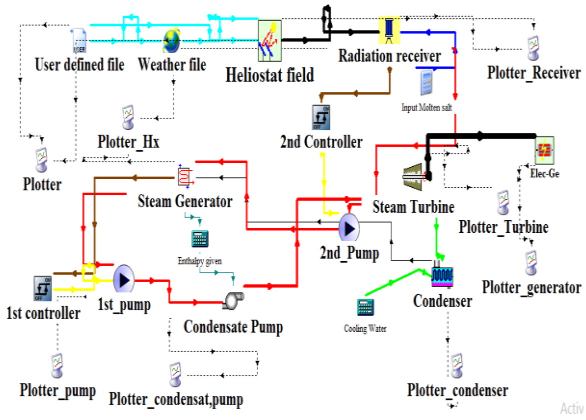

Figure 4: TRNSYS Modeling

A. Heliostats

Five zenith angle and seven azimuth data points are used with 62 heliostats each of area 64 meter. As the surface of the mirror does losses in form of convection so reflectivity is not 100%. Reflectivity is taken as 0.9 and average speed of wind is taken as 2 m/s as shown in table below

Table 2: Heliostat parameter

No	Parameter	Value	Unit
1	No of concentrator units	62	
2	Mirror Surface area	64	m^2
3	Reflectivity	0.9	
4	Direct Normal Insulation	1*10^7	kJ/h
5	Wind Speed	2	m/s
6	Solar zenith angle	90	degrees

So the maximum output from the heliostats is 1*10^7 kJ/h. It shows the production of 632 W from a single heliostat in TRNSYS. It is assumed that sun is being tracked all the time by the mirrors but tracking mechanism is not discussed in this paper in detail.

B. *Position of Heliostats*

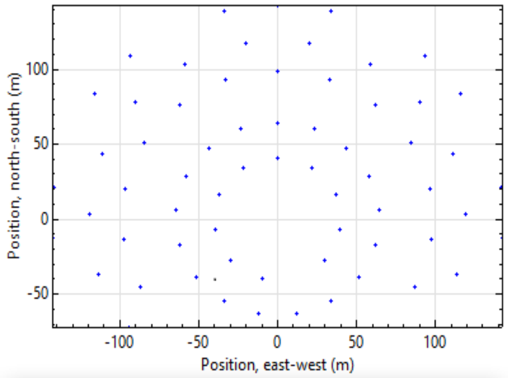

Figure 5: Heliostat positioning

The heliostat field layout is an essential task for any solar Tower plant optimization process. Different Algorithms available in System advisory model are used to optimize the best configuration.

C. *Tower and receiver dimension*

Reflected light from heliostats is received by central receiver. For receiving maximum radiation, solar receiver's height and its distance from reflectors plays key role. Further Increasing the receiver area or tower height will decrease efficiency in terms of cost. Increasing the tower height will tend to increase the distance of heliostat from the tower. It will increase the land area utilization. For efficient design system advisory model tool is used for calculating the optimized height and tower area. As shown in table below.

Table 3: Tower and Receiver parameters

No	Parameter	Value	Unit
1	Receiver height	2.17	m
2	Receiver diameter	2.35	m
3	Tower height	53.81	m
4	Heliostats number	62	

D. *Molten salt properties*

Heat transfer fluids act as the transporter by receiving heat energy and deliver it to the steam generation unit. Power plants having Rankine cycle based turbine use water, CO_2, thermal oils, organics, molten-salts or liquid metals as a heat transfer fluid. Desired characteristics of a HTF include.

Table 4: Molten salt properties

No	Constituents	KNO3-NaNO3 (40-60%)
1	Density at 300°C	1725
2	Kinematic viscosity at 300°C	3.26
3	Heat capacity	1.495
4	Thermal conductivity	0.52
5	Melting point	220

As due to threat of freezing, it is necessary to keep salt (KNO3-NaNO3 (40-60 %)) above, so the initial temperature of solar salt is very high. For the first startup, it is required to heat the salt up to by some other source like natural gas or oil. After sunrise, its temperature is further increased up to. This heated salt is stored in a good insulator material tank so that we may not need to heat it again in the next morning.

E. *Function of 1st controller*

When there's no sunshine after sunsets, steam generator passes liquid water to the turbine blades, which is undesired situation. To avoid this condition controller is used which stops the flow of water during sun set hours.

F. *Function of 2nd controller*

Molten salt takes heat from solar receiver which is heated up by the sun. Molten salt transfers this heat to heat exchanger for steam production. After Sun sets, there's no solar radiation so solar receiver doesn't heat up and molten salt temperature does not go above. But when this heated salt goes to heat exchanger it gives its heat to water and its temperature drops down which is not worthy for this system as molten salt would freeze below. To avoid this situation control function is used in TRNSYS. Below the lower dead band controller stops the flow of salt. As temperature increases above the dead band controller allows pump to transfer the salt to the steam generator.

Table 5: Controller parameters

No	Parameter	Value	Unit
1	Upper input temperature	20	°C
2	Lower input temperature	0	°C
3	Monitoring temperature	20	°C
4	High limit cutout	500	°C
5	Upper dead band	281	ΔC
6	Lower dead band	280	ΔC

The on/off differential controller generates a control function which can have a value of 1 or 0. The value of the control signal is chosen as a function of the difference between upper and lower temperatures compared with two dead band temperature differences. The new value of the control function depends on the value of the input control function at the previous time step.

G. *Enthalpy calculator and condensate pump*

Four important parameters of steam for running turbine's blades are; pressure, temperature, flowrate and enthalpy. Steam coming out from steam generator should have above four properties in it. But in TRNSYS steam generator output contains only flow rate and temperature. So other components are needed to provide enthalpy and pressure to turbine. Output of heat generator is shown below.

Table 6: Steam generator

No	Parameter	Value	Unit
1	Source side inlet temperature	280	°C
2	Source side flow rate	19500	Kg/h
3	load side inlet temperature	50	°C
4	Load side flow rate	13000	Kg/h
	Overall heat transfer coefficient transfer of exchanger	13000	

VIII. Results and discussion

A. *Solar radiation*

Sun shines average 8-10 hours in Asian countries. In Pakistan solar radiation value is maximum at Baluchistan. These radiations are not uniform on all the year as variations occur day by day. Solar radiation data for a year is taken from TRNSYS as shown in figure below. Radiations peak is maximum in months of June and July which are between 5110 and 5840 hours in figure.

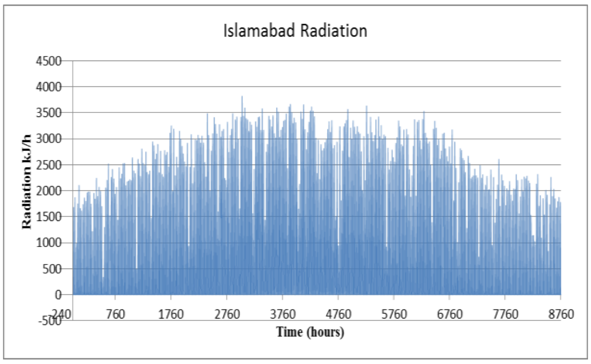

Figure 6: Solar incidence

For this study solar radiations data of 26 July is used. Maximum 3400 kJ/h solar radiations are achieved which are not enough to generate electricity so heliostats are used. Daily normal incidence values are shown in graph below.

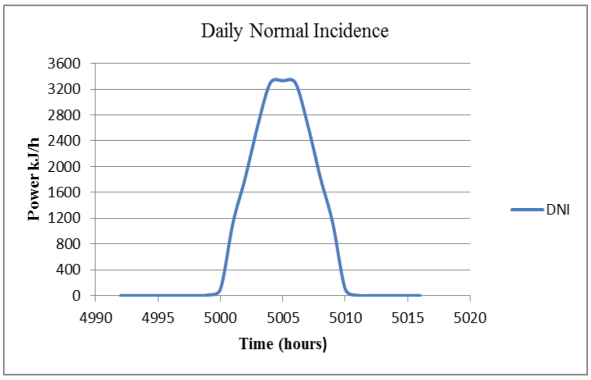

Figure 7: DNI for 26th July

62 heliostats each of area 64m^2 is been used to achieve desired 2796 kJ/kg enthalpy at a fixed pressure and mass flow rate. Input power of these mirrors is shown in below.

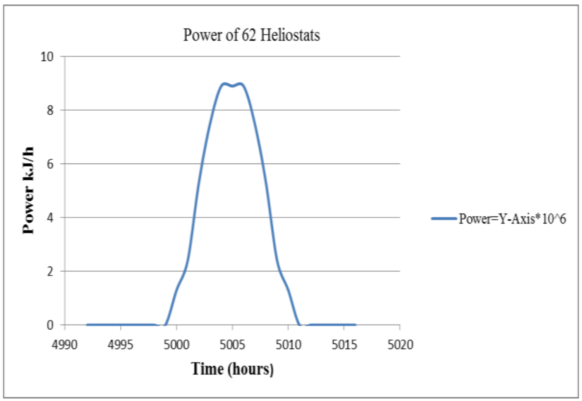

Figure 8: Heliostats Power

Solar receiver temperature goes up to 550°C as shown in graph below.

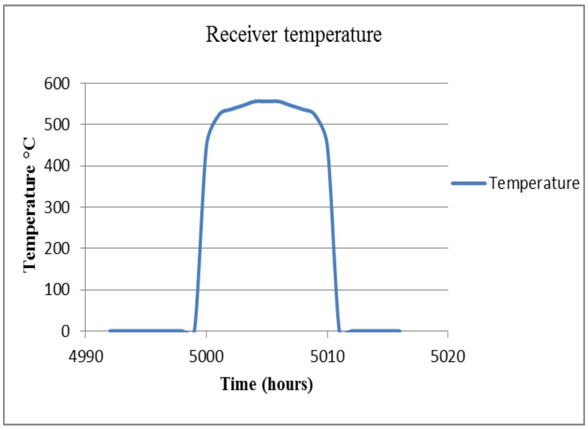

Figure 9: Solar Receiver Temperature

B. Effect of different heat transfer fluids on Heliostats

1. Water as a HTF

Two heat exchange process are involved in this system. First is when molten salt takes heat from solar receiver and second involves when it delivers its heat to water and makes steam. It was supposed that if water is used directly as a heat transfer fluid heliostats requirement may decreased because only one heat exchanger would include and heat loss will be decreased but results obtained were different. As shown in graph below heliostats are still required above 62 at 13000kg/h flow rate.

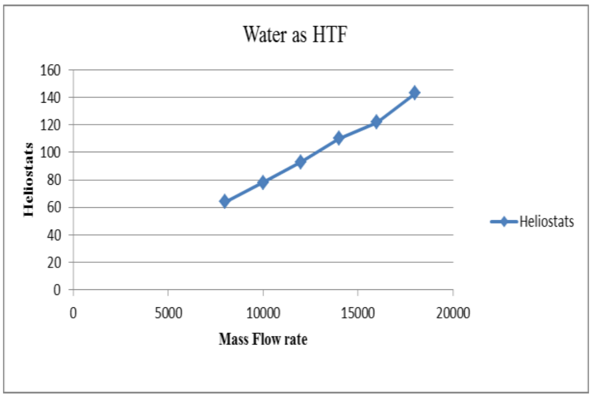

Figure 10: Water using as heat transfer fluid

It is due to high specific heat of water than molten salt. Water required 4.19 kJ/Kg heating value to raise the temperature up to one degree Celsius while molten salt has 1.2 kJ/kg specific heat. So this is not feasible to use water directly as a HTF if the goal is to reduce cost in terms of reducing heliostats number.

2. CO_2 as HTF

Effect of using CO_2 in primary loop is observed. Its specific heat is very low than water so heat transfer was efficient in primary loop. Less heliostat were required to heat the CO_2 up to a specific temperature where it can make steam of desired temperature in the secondary loop. CO_2 mass flow rate was varied and water flow rate was fixed because of requirement of steam turbine. Result is shown in graph below.

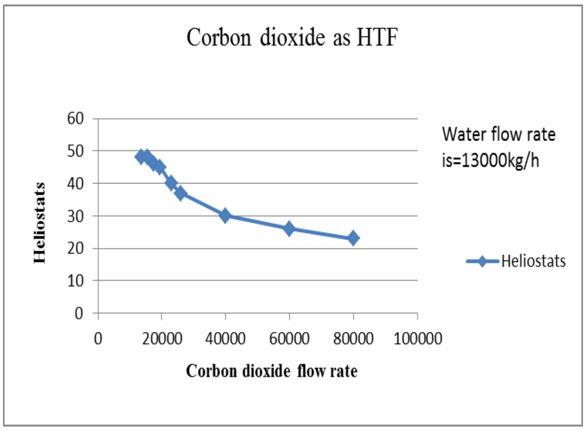

Figure 11: Carbon dioxide as a HTF

3. Molten salt as HTF

Molten salt provides the ease of storage. Keeping the flow rate constant in second loop, molten salt flow rate was changed in primary loop. It was observed that increasing the molten salt flow rate increased the heat transfer in the second loop but opposite effect was seen in primary loop. It is due to the fact that in primary loop heat transfer is between one solid body and liquid while in secondary loop heat is been transferred between two liquids.

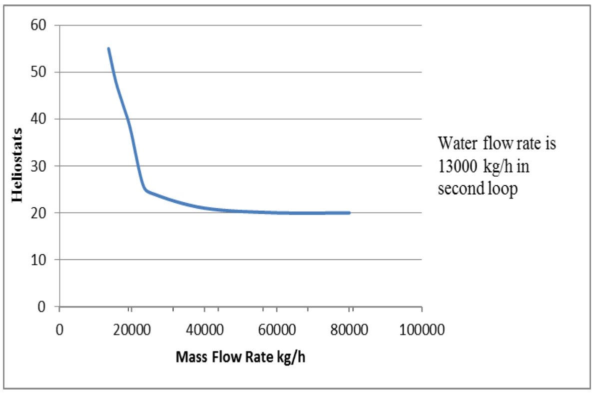

Figure 12: Molten Salt flow rate effect on heliostats

4. Effect of changing molten salt flow rate

It was observed that increasing the flow rate of molten salt will reduce the demand of heliostats but it should be compromised upon the cost of pump to increase flow rate. At 60000kg/h, 26 heliostats are required to produce 1 MW power output and further increasing the flow rate has minor effect on heliostats. 26 heliostats and 60000kg/h molten salt flow rate is considered in further discussion for this system. Effect of increasing the molten salt flow rate on heat transfer in primary and secondary loop is shown in graph below.

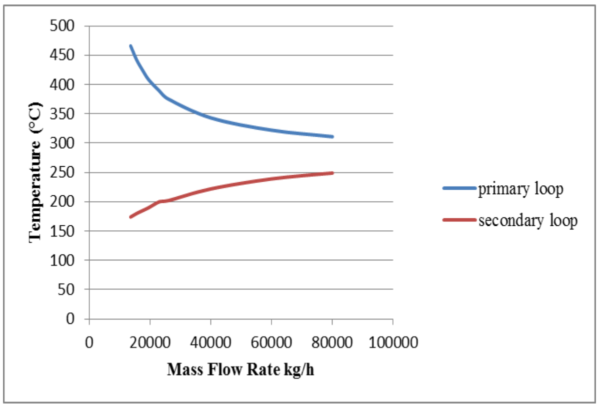

Figure 13: Temperature effect in two loops

It is shown that temperature of the molten salt is decreasing due to increase in its flow rate in primary loop. In the secondary loop steam temperature is increasing due to molten salt mass flow rate decreasing effect. 198 degree Celsius temperature is needed for turbine which is achieved at 60000kg/h so no need to increase floe rate further.

5. Effect of changing steam flow rate

Steam mass flow rate was fixed at 13000 kg/h in above results as it was required by Siemens made turbine. Mass flow rate changing effect is observed at fixed heliostats, molten salt flow rate and pressure. It is noticed that by decreasing the steam flow rate less number of heliostats are required to produce 1 MW because heat transfer process becomes efficient but steam pressure had to be increased. Initially it was 15 BAR with 13000kg/h flow rate and 26 heliostats. To decrease the flow rate at 11000kg/h heliostats required were 22 but pressure demand was 40 BAR. It will again increase cost to generate more pressure so compromise has to be made between pump and heliostats cost.

C. Power output

Electrical power output from this proposed system is 4.83 KJ/h which equals to 1.250 MW. It shows that 1 MW of electricity is for supply purpose rest of 0.25 MW is for internal load. Power output can be changed by changing the flow rate of steam and molten salt, number of heliostats and pressure of steam striking the turbine. Between the time interval 4992 h and 5000 h there are no solar radiation falling on heliostats, so no output power is generated as it can be seen in graph. When radiation starts to increase after 5000 h, molten salt heats up and transfers its energy to water and steam is produced which generates electricity as shown by red line on graph.

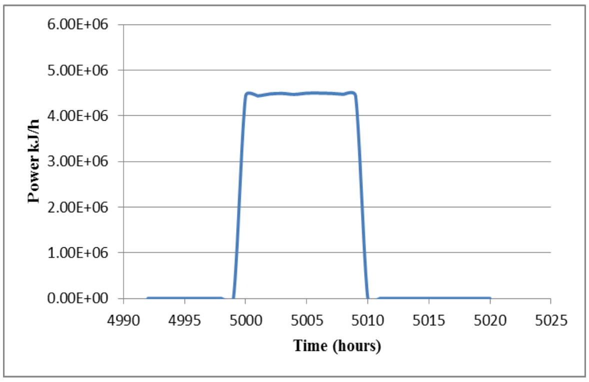

Figure 14: Electrical power

Conclusion

TRNSYS based Model of solar thermal tower power plant for Islamabad, Pakistan is presented. Solar thermal tower power plant's major cost taking factor is large number of light reflecting mirrors called heliostats. For a cost efficient tower system, use of minimum number of mirrors is important. In this study different heat transfer fluids effect is discussed. It is found that using water directly as a HTF makes system less efficient because it required 62 heliostats with water flow rate of 13000 kg/h. Using CO_2 as a HTF reduced the mirrors to 23 at a flow rate of 80000kg/h but it is difficult to store and handle this gas. Molten salt is also tested and its effect on mirrors is checked. It is found that at 60000kg/h flow rate of molten salt, and 13000 kg/h flow rate of water, used 26 heliostats and 15 BAR pressure to produce 1.25 MW output power. Further increasing the water flow rate heat transfer was becoming inefficient. Decreasing the flow rate of water reduced the number of heliostats from 26 to 20 but it increased the pressure demand up to 40 BAR. So it is not recommended to decrease water flow rate further.

Acknowledgment

This work is continuously supported by my supervisor Dr. Majid Ali, faculty member Dr. Adeel Waqas and research fellow Sara Sultan

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Modelling of a Solar Energy driven Water Desalination System using TRNSYS.

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***Abstract*—The overall broad purpose of this paper is to develop and evaluate a small scale solar humidification dehumidification water desalination system using a graphical tool TRNSYS and assess its thermal behavior. Considering the intense need for the development of alternate technologies for energy deficient and impoverished countries of the world like Pakistan, this model is in particular anticipated for underprivileged communities where pure and**

uncontaminated drinking water as well as modern technologies are not accessible. The system consists of isolated components for heating, evaporation and condensation, in order to lower the thermal losses. The weather file used was in standard TMY 2 format for Asian data. A flat plate solar collector, humidifier and dehumidifier are to be integrated in an open air open water configuration. The simulations for a water heated cycle revealed that the output water temperature be reliant strongly on the incident solar radiations and inlet water temperature. Collector area and inlet water flow rate also had a considerable impact on productivity. A significant increase in efficiency was observed by using a water storage tank and pre heating the feed water favorably influenced the output.

***Index Terms*—Solar thermal energy, solar water desalination, humidification-dehumidification, solar collector, water flow rate, water cycle.**

ABBREVIATIONS AND ACRONYMS

HDH	Humidification-dehumidification
CAOW	Closed Air Open Water
CWOA	Closed Water Open Air
OAOW	Open Air Open Water
CACW	Closed Air Closed Water
RH	Relative Humidity
TRNSYS	Transient System Simulation
HAP	Hourly Analysis Program

I. INTRODUCTION

Water scarcity and contamination are the swiftly growing global challenges that are increasingly posing a threat to mankind. This is especially problematic for underprivileged areas where people are not facilitated with modern purification technologies and still they can't even afford to imagine having it.

The best possible solution to meet the high safe water demands is harnessing the huge potential of sea water. All that needed to be done is using the efficient and cost effective technology for salt and impurities removal that is what we generally refer to as desalination. Lot of research is being done in this regard but the most common technologies being used now a days are mostly cost and energy intensive. In order to balance the economics and efficiency, the most promising technology so far is solar energy driven HDH water desalination which has the potential to provide clean water consuming the ecological, cheap and abundant natural energy.

A. Need of Desalination in Pakistan

Pakistan lies at number 80 among 122 countries regarding water quality [1]. About one third of 200 million people don't have access to clean drinking water. According to UNICEF, almost 40% of patients in Pakistan are being suffered from water-related problems [2].

Keeping in mind the current scenario of Pakistan's energy crisis, there is intense need to explore alternate cheap energy sources and water purification technologies.

B. Solar Energy Status in Pakistan

Solar energy is the most reliable, cleanest, cheapest and abundant source of energy that could be efficiently utilized in thermal processes. Pakistan has a strong potential for solar power, as we are lucky enough to enjoy radiations from sun throughout the year with 10 sun shine hours on average and average global insolation is almost 5-7 kWh/m^2/day [3].

II. SOLAR DESALINATION

The basic principle in the thermal energy driven HDH desalination process is to recuperate fresh water condensate from moist air coming from humidifier. The moisture absorbing capacity of air increases with the increase in air temperature [4].

The system consists of three main components; Solar collector for water or air heating, humidifier to humidify the dry air and dehumidifier or heat exchanger for condensation.

The process relies on the evaporation of the feed water in the humidifier and consecutive condensation of the humidified air inside the dehumidifier [5]. Pre-heated sea water is introduced into the condenser (dehumidifier) and is distributed through the solar collector to get higher temperature. From the other end, in the humidifier, dry air is pumped in which extracts water vapours from the incoming hot water stream when comes in contact with it and the remaining brine is collected at the bottom. Then the humid air carries the vapours to the condenser where fresh water vapours are recovered and air cools down by losing its heat to the incoming feed water [6].

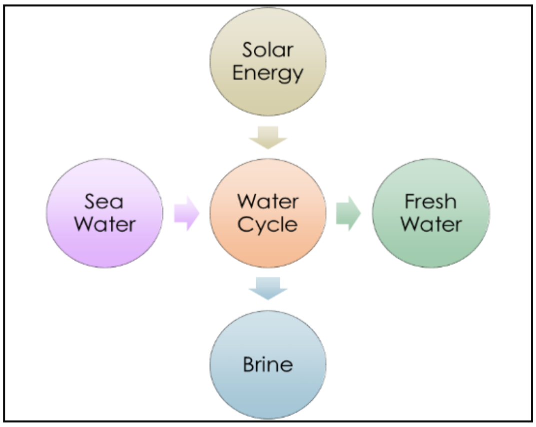

Figure 1: Basic HDH principle

A. Classification of Desalination Processes

Solar desalination systems are categorized into two systems [7];

Direct desalination systems in which solar energy is directly used to produce fresh water using solar water/air heaters or solar collectors.

Indirect desalination systems may involve transformation of solar energy into some other form of energy which is then used for desalination.

Solar stills, solar humidification dehumidification desalination systems and solar chimneys are included in the direct desalination systems [8].

Indirect systems are further divided into three categories; Thermal processes, membrane based processes and chemical processes [9].

These technologies have lot of drawbacks like high capital cost and power consumption. Instead, direct desalination systems are more feasible [10].

III. Classification of Solar HDH systems

Solar HDH systems can be classified under two broad categories on the basis of configuration and heating fluid [11].

On the basis of heating fluid, two types of solar HDH systems are water heated systems and air heated systems. The behaviour of the system is altered critically depending on the heated stream type. Either of them could be integrated in four different configurations [4] [12].

1. Closed air open water system (CAOW)
2. Closed water open air system (CWOA)
3. Closed air closed water system (CACW)
4. Open air open water system (OAOW)

In the CAOW systems, air is circulated between humidifier and dehumidifier in a closed loop, and sea water is extracted from humidifier as waste brine in each cycle. Such systems are mostly water heated systems but research has also been done on air heated closed air systems.

CWOA works with closed water loop and the dehumidified air is released back to atmosphere. But in such systems, the recovery rate is relatively low due to heat loss by humid air during dehumidification.

In OAOW-air heated systems, air stream makes a single pass through the system. Hence, the connection between humidifier and dehumidifier is not established. Same is the case with water heated systems.

Literature suggests that closed air open water system is the most suitable system [4].

IV. Literature review

Muller Holst et al. [5] optimized a decentralized small scale thermal desalination system using TRNSYS simulation tool, based on principle of multi-effect humidification (MEH) system inside a thermally shielded box at atmospheric pressure. The air was naturally circulated and condensate produced was 0.5-2m^3/day.

M.M. Farid et al. [13] also evaluated performance of an MEH unit and studied the influence of inlet water flow rate on the system's productivity. Mathematical modelling was done with forced air convection and assuming that air temperature was fluctuating linearly from bottom to top. They reported that the humidifier area's consequences were significant only for large values of collector area and for smaller collector area, the productivity slightly increases with increase in condenser area.

Nafey, Fath et al. [14] considered closed air and closed water loop configuration using flat plate solar heaters for water and air heating and found greater effects of solar water heater area than the air heater area. Strong effects of solar intensity and water and air temperature were observed at higher flow rate values of water.

E. Chafik [15] designed a new type of four-fold-web-plate collector to be used for MEH desalination system with optimally designed pad humidifier and tube-fin heat exchanger. A transient simulation program was developed in TRNSYS and predicted operating data was compared with experimental tests and a desalination plant with $10m^3/d$ productivity was constructed using these results.

Yamali and Solmus [16] numerically investigated the solar desalination system for Ankara, Turkey and observed the strong influence of water and air flow rates and temperatures on the system productivity. Solar air heater area also had a strong impact but effect of wind speed variations influenced slightly the system's performance.

Juma Yousuf Alaydi [17] modelled solar desalination system using parabolic solar collector for water heating. Different parameters for collector's performance like rim angle, collector's aperture and receiver's diameter were analysed and optimized for large scale water production.

A closed air water heated cycle with single effect was studied by Stefania Cherubini and Antonio Perdichizzi [18] in TRNSYS. Two different configurations were analysed, 1st was based on direct desalination system with solar collector to heat up the feed water, but the 2nd was an integrated cooling desalination system where the heat from solar collector was being absorbed by LiBr absorption chiller and the heat rejected by chiller was utilized to drive the process. The system performance in both cases was strongly affected by inlet feed water temperature. For case 1, the performance was improved but it was decreased in the 2nd case for higher water temperatures.

A solar liquid desiccant air conditioning (SLDAC) desalination system was evaluated by M. Elhelw [19] for Borg Al-Arab, Egypt. Simulations were carried out by TRNSYS and for hourly cooling loads determination, Hourly Analysis Program HAP 4.7 was used. In July and August, the vapour desorption in the regenerator was highest and was increased by increasing the solar collector area. But the collector area doesn't affected the amount of vapour absorbed in the conditioner.

V. PROPOSED MODEL

A Transient System Simulation Tool for solar systems called TRNSYS was used for modelling of a water heated single stage HDH desalination system. The components called types were dropped from TRNSYS 17 library in the simulation studio.

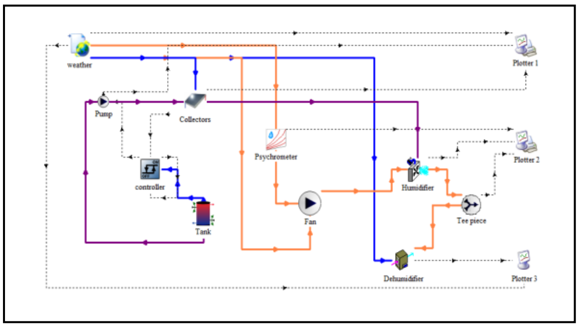

Figure 2: TRNSYS Model

A solar flat plate collector to heat the feed water is used with a water storage tank. The air circulation was forced convection type and a variable speed fan was used for this purpose. A type 641 humidifier is used with a psychrometer (mode 2) which takes dry bulb temperature and percent relative humidity from the weather file and calculates other properties of moist air to provide at the humidifier inlet. The outlet saturated moist air from the humidifier outlet is modelled by a tee piece (mode 6) and after being mixed it is sent to a type 688 unitary dehumidifier at ambient pressure.

The standard TMY 2 weather file for climate conditions of Pakistan was called and the data for wind and solar radiations was used in different components via connections between Types.

Different parameters for each component were analysed and optimized for required results. Major performance effecting constraints were; water inlet temperature, inlet water and air flow rate, solar collector area and percent relative humidity of air.

The final parameters for proposed model are given in the table below.

Table 1: Parameters used for modelling

Parameter	Value
Flat Plate Collector	
Collector area	1.5 m^2
Flow rate	10 kg/h.m^2
Collector slope	45°
Humidifier	
Inlet Air Temperature	20°C
Inlet Air % Relative Humidity	20
Inlet Water Temperature	100°C
Dehumidifier	
Rated Air Flowrate	50 kg/h
Water Storage Tank	
Tank volume	3 m^3

VI. Results & discussions

Daily and hourly simulations were performed by an online plotter in TRNSYS for the whole year and specifically for the month of June in Islamabad, Pakistan. Temperature values are specified on the left side of graph, while right hand side shows heat transfer rates.

The meteorological parameters such as ambient temperature, solar radiations and percent relative humidity are used as input. The solar radiation trend for a 45° tilted surface for the first week of June are given in fig. 3.

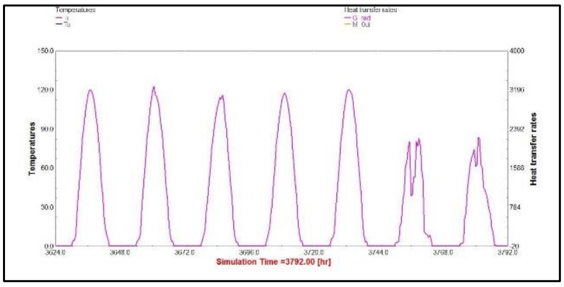

Figure 3: Global radiations for June

Fig. 4 is showing the trend of dry bulb temperature of air for June. Ambient air shows greater temperatures in June and July, i.e. up to 40°C.

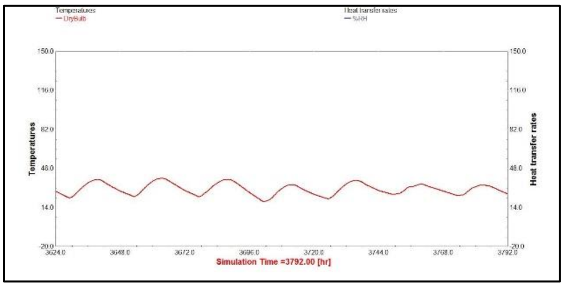

Figure 4: Dry Bulb temperature in June

Collector outlet temperature with optimized values for collector area and inlet mass flow rate is shown in fig. 5. The outlet temperature is greatly influenced by global radiations and dry bulb temperature of air and follows the same trend as both. In June and July, the ambient air temperature and solar radiations are maximum, so the collector output temperature goes higher.

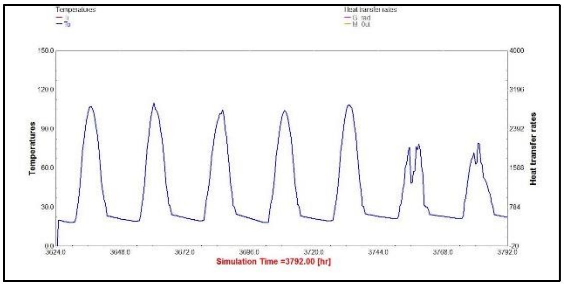

Figure 5: Collector outlet temperature

Similar trend has been observed for daily results, i.e. for peak radiations during mid-day, the output temperature is maximum and then goes on decreasing as sun sets in the evening.

Water inlet temperature, inlet mass flow rate and solar collector area also have strong impact on the outlet temperature of water. The effects are being discussed in fig. 6, where the outlet temperature is shown as a function of inlet temperature. The results are good enough for 20°C inlet water temperature.

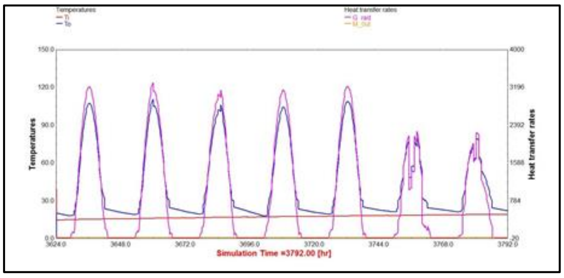

Figure 6: T outlet Vs T inlet

Collector area was also a very important parameter. For 1m^2 area, the output was between 50 to 70°C, as in fig. 9, which is too low for the system's requirement. But by increasing the area up to 2m^2, (see fig. 10) the maximum temperature at the collector outlet was exceeding 120°C, slightly higher than the required temperature. So, 1.5m^2 was found to be the optimum value for collector area.

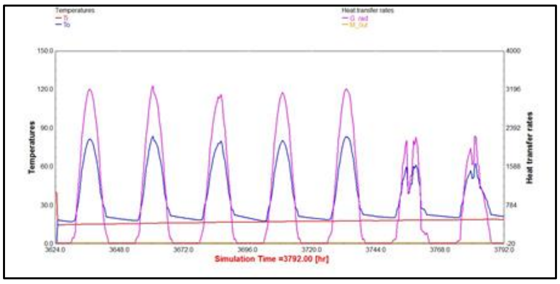

Figure 9: For 1m^2 collector area

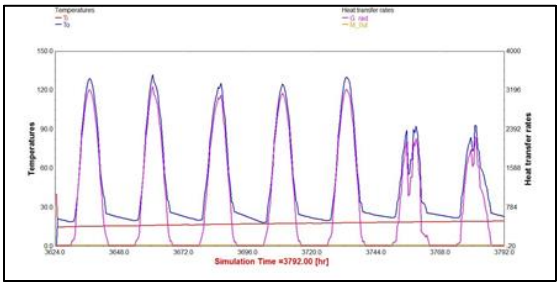

Figure 10: For 2m^2 collector area

Considerable results were witnessed by changing the inlet flow rate of feed water. Flow rate was adjusted according to collector area. For smaller areas, flow rates values should be small. For collector area 1.5m^2, flow rate 15kg/h, the output temperature was decreased up to 50, as in fig. 11.

Similarly for smaller flow rate values up to 5kg/h, as depicted in fig. 12, the result was again abnormal, i.e. the outlet temperature became too high, beyond our system requirements. For this value of inlet mass flow rate, 1m^2 collector may be significant, but to have more output production, 10kg/h mass flow rate with 1.5 m^2 area is more attractive option.

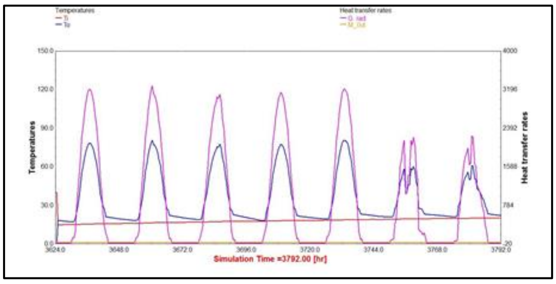

Figure 11: At 15kg/h flow rate

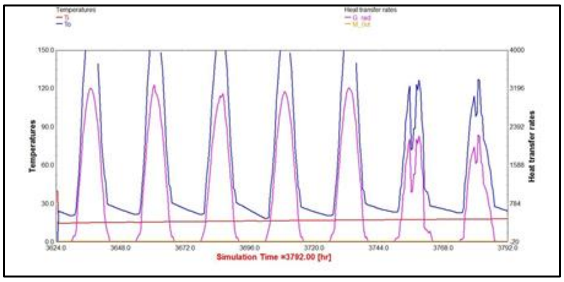

Figure 12: At 5kg/h mass flow rate

Fig. 13 shows the temperature of air leaving the dehumidifier. This parameter is helpful in estimating the recovery rate of condensate in the dehumidifier. Smaller values of outlet air temperature means that maximum heat has been released by air that is to be absorbed by feed water for a closed cycle case.

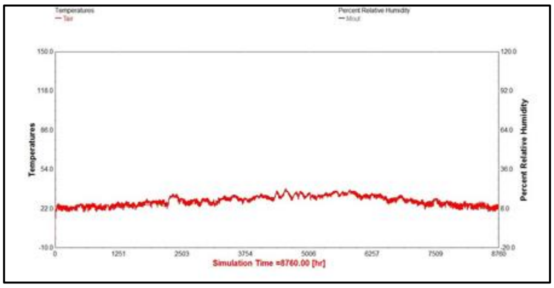

Figure 13: Outlet air temperature from dehumidifier

The figure shown below presents the output condensate mass flow rate from the dehumidifier, which is between 3 to 4 kg/h in this case. This parameter was greatly influenced by the temperature of water at inlet and condensate recovery rate. The output was surprisingly increased by introducing a water storage tank in the system that could pre heat the water before it enters the dehumidifier, hence increasing the overall efficiency.

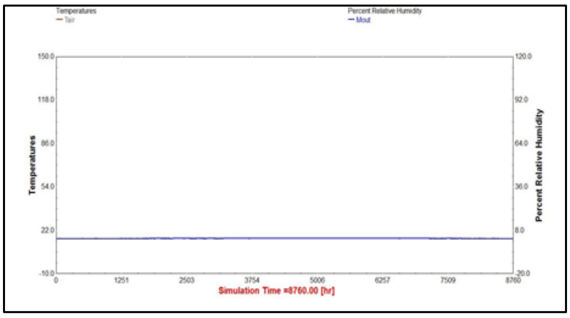

Figure 14: Mass flow rate of condensate

VII. CONCLUSION

A Transient Simulation Model for the single stage, water heated solar HDH desalination system has been presented for Islamabad, Pakistan. The air was circulated in forced convection in an open air open water configuration in which a flat plate solar collector, humidifier and a unitary mode dehumidifier were integrated along with other components like fan, pump and controller. A mode 2 Psychrometer was used for moist air properties calculations. Daily simulations were performed by an online plotter and following results were concluded:

- System's performance is greatly influenced by inlet water and air temperatures and for a good system, water storage tank must be used to enhance productivity.

- Solar collector area and inlet mass flow rate also had a strong impact on productivity and both parameters are optimized according to system's requirement.
- Both output temperatures from collector and dehumidifier are the function of ambient temperature and global solar radiations and follow the same trend.

ACKNOWLEDGMENT

This work couldn't have been done without the continuous support of my Supervisors Dr. Adeel Waqas and Dr. Majid Ali. The financial support of U.S. Pakistan Center for Advanced Studies in Energy, NUST is acknowledged.

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