TECHNO ECONOMIC ANALYSIS ON INTEGRATION OF GRID CONNECTED STORABLE SOLAR POWER GENERATION

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Degree Master of Science in Electrical Installations

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DECLARATION

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ABSTRACT

Sri Lanka is having renewable energy target of 20% at year 2020. According to “Long Term Generation Expansion Plan (LTGEP) 2015 - 2034” published by Transmission & Generation Planning Division of Ceylon Electricity Board (CEB), it is planned to add more and more renewable power plants to the National Grid. As the solar resource availability in Sri Lanka, it is planned to add also more and more solar power plants to the National Grid.

Prevailing load curve consists of a peak at night from 6.30 pm to 9.30 pm in Sri Lanka. So, additive solar power plants is useful if it has energy storable nature. But, the storable solar power plants are new to Sri Lanka and the plant technologies are advanced. So, Techno economic analysis on grid connected, storable solar power plants is required.

In the research work, three types of grid connected storable solar power plant technology options have been modeled to replace existing PV plant without storage in Hambantota hypothetically. Case study is done on existing grid connected, photovoltaic (PV) plant in Hambantota owned by Sustainable energy Authority (SEA). Discounted cash flow analysis using avoided cost scenario have been used. Analysis is done for 25 year operating period of plant.

Keywords: LTGEP, avoided cost, PV, Parabolic trough, Heliostat field, BESS, TESS

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I would be thankful to Dr. Athula Senaratne, Former Director of Sustainable Energy Authority and their kind staff to help me to gather the required data of PV plant in Hambantota.

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LIST OF ABBREVIATIONS

Acronym	**Definition**
BESS	Battery Energy Storage System
CBSL	Central Bank of Sri Lanka
CCPP	Combined Cycle Power Plant
CEB	Ceylon Electricity Board
CNPV	Cumulative Net Present Value
DCF	Discounted Cash Flow
DNI	Direct Normal Irradiance
DOD	Depth of Discharge
GoSL	Government of Sri Lanka
GPS	Global Positioning System
GT	Gas Turbine
HCE	Heat Collector Element
HFO	Heavy Fuel Oil
HTF	Heat Transfer Fluid
IPP	Independent Power Producer
KPP	Kelanitissa Power Plant
LCOE	Levelized Cost of Energy
LTGEP	Long Term Generation Expansion Plan
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
PV	Photovoltaic
SCA	Solar Collector Assembly
SEA	Sustainable Energy Authority
SOC	State of Charge
SPP	Small Power Producer
ST	Steam Turbine
TESS	Thermal Energy Storage system
VRLA	Valve Regulated Lead Acid

CHAPTER 1

INTRODUCTION

1.1 Background

Sri Lanka is a developing country located at South Asian continent which is a small island with the total land area of 65,545 km^2. It has sunshine all over the year with average irradiance of 5.5 kWh/m2/day according to the solar irradiance data of Solargis website as shown in figure 1.1 [1].

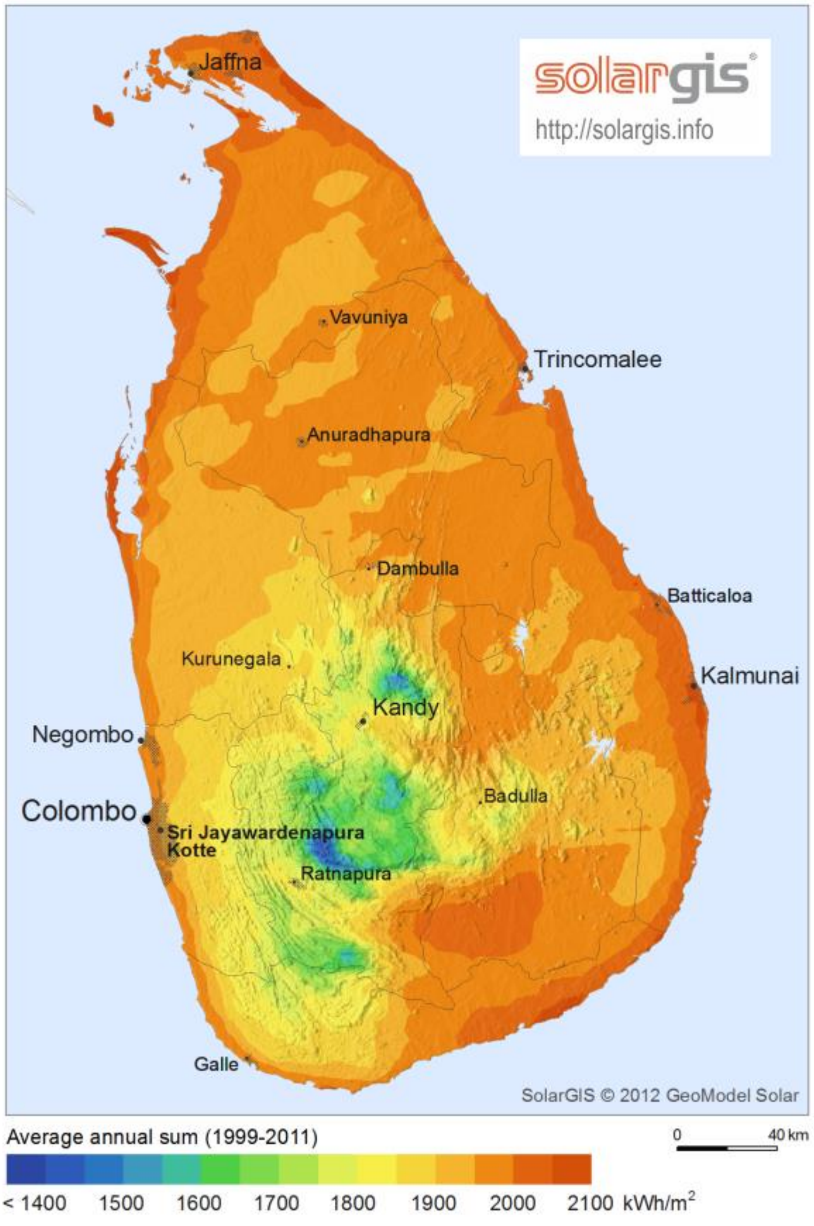

Figure 1.1: Average Solar Radiation in Sri Lanka in 2015

Though Sri Lanka is have a rich solar resource, electricity generation through solar energy has not encouraged a lot. High capital investment and friction for the start of new technology seems to be the problems [2]. As, solar is a renewable resource the technology for power generation have been encouraged.

It is promised by the Government of Sri Lanka (GoSL) that to achieve 20% renewable energy target at year 2020. Accordingly, solar, mini hydro, wind and geo thermal power generation is going to be increased in near future. The existing power generation mix is as figure 1.2. Major hydro power generation is 35%, coal power generation is 22%, Gas Turbine (GT) or Steam Turbine (ST) power generation is 9%, Diesel power generation is 20% and renewable power generation is 14%. When considering the power generation mix of renewable energy, solar power generation is 8%, mini hydro power generation is 65%, wind power generation is 7% and geo thermal power generation is 20% [3].

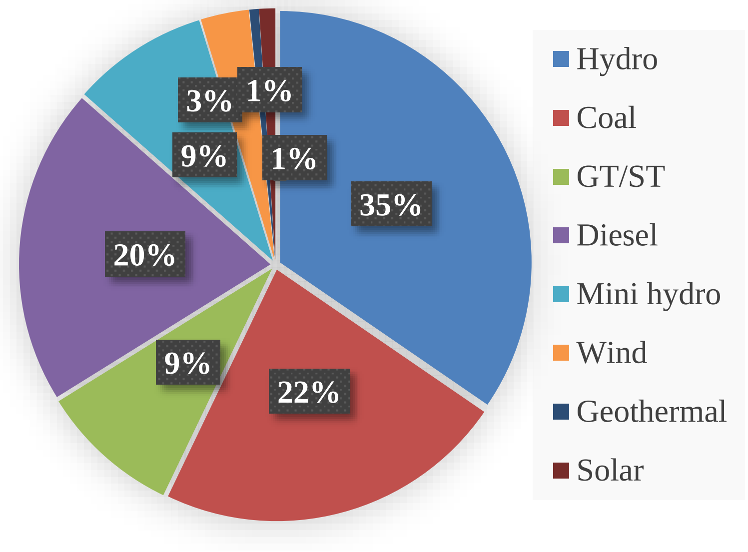

Figure 1.2: Electricity Generation Mix in Sri Lanka in 2015

1.2 Motivation

Ceylon Electricity Board is the GoSL owned utility provider of electricity generation. It consists of hydropower plants, thermal power plants, Independent Power Plants (IPPs) and Small Power Plants (SPPs). Thermal power plants consists of coal, GT/ST or diesel engine. IPPs are mainly GT/ST thermal power plants. The power generation mix of Sri Lanka from year 2011 to 2015 is shown in figure 1.3.

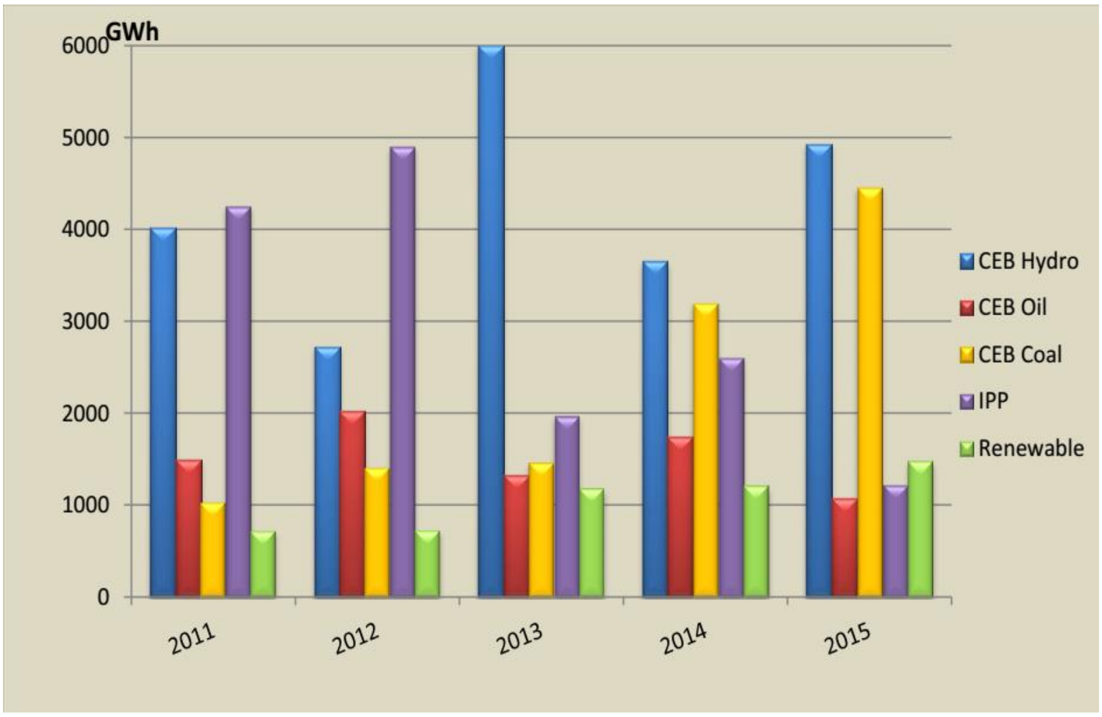

Figure 1.3: Electricity Generation Mix Sri Lanka in GWh from year 2011 to 2015

Sri Lanka is having a load curve as shown in figure 1.4 [4]. Base load runs by hydro power plants and coal power plants which have low per unit generation costs. Peak load runs by thermal power plants which have high per unit generation costs.

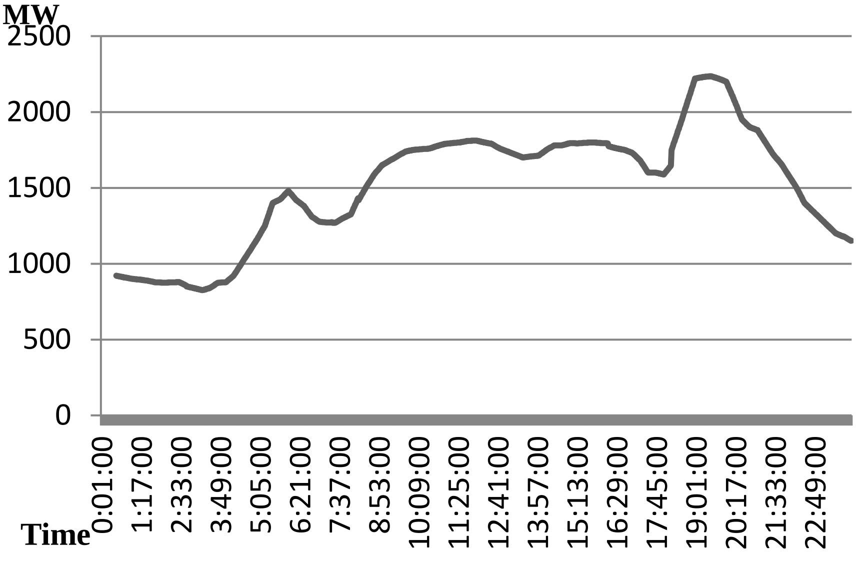

Figure 1.4: Load Curve in Sri Lanka in year 2015

While encouraging renewable energy power generation in Sri Lanka by renewable energy target solar power generation would have a significant increment as the high solar potential all over the country. Also, peak load power plants have to be replaced by high spinning reserved solar power plants. But, the avoided costs of peak load power plants are gain profits if discounted cash flow analyses are done considering system costs also. So, the discounted cash flow analysis is an important task in present situation.

“Avoided cost” is essentially the marginal cost for a public utility to produce one more unit of power according to the definition compiled by Independent Energy Producers’ Association (IEPA) in California which is a high amount of solar electricity producer. According to the power generation in Sri Lanka, thermal power plants could be called as marginal power plants. Actual capacity in MW, scheduled dispatch in GWh, actual dispatch in GWh and variation GWh are shown in table 1.1 [5].

Table 1.1: Scheduled and Actual Dispatches of first half of year 2015

	Capacity MW	**Scheduled GWh**	**Actual GWh**	**Variation GWh**
Puttalam Coal	900	4,683	4,457	(226)
Sapugaskanda B	72	264	166	(97)
New Chunnakam	24	176	85	(91)
Colombo Power Barge	60	253	122	(131)
ACE Embilipitiya	100	65	95	30
Sapugaskanda A	72	198	128	(71)
AES Kelanithissa	163	166	259	93
KPS CCY	165	745	645	(100)
ASIA Power	51	220	99	(120)
Northern Power	27	70	0	(70)
Westcoast	270	1,137	652	(485)
KPS GT 7	115	38	24	(14)
KPS Small GTs	85	5	1	(4)
CEB Barge	60	-	17	17
Total Grid Con. Thermal	2164	8,020	6,752	(1,269)
Renewable Energy	438	1,263	1,462	199
CEB Hydro	1,375	3,568	4,925	1,357
Total Generation	3,977	12,851	13,138	287

Small GTs of Kelanitissa Power Plant (KPP) has actual dispatch of 1 GWh , GT 7 has actual dispatch of 38 GWh, New Chunnakkam plant has 85 GWh, ACE Embilipitya has 95 GWh and ASIA Power plant has 99 GWh of actual dispatches of year 2015 according to the advanced order of dispatch respectively. All of the power plants are GT/ST power plants with high generation unit cost. The generation unit costs are shown in table 1.2 [5].

Table 1.2: Average Generation Unit Costs of Power Plants in Sri Lanka in 2015

Power Station	**Annual Generation (GWh)**	**Total Cost to CEB (Mn.LKR)**	**Average Unit Cost (Rs/kWh)**
Asia Power	99	4,219	42.42
AES Kelanitissa	259	5,873	22.67
Colombo Power	122	2,833	23.18
ACE Embilipitiya	95	2,211	23.39
West coast	652	23,706	36.35
Northern Power	0.38	709	1858.78
Sapugaskanda A	128	5,078	86.10
Sapugaskanda B	166	6,107	389.76
Kelanitissa Small GTs	1.06	1,053	1900.49
Kelanitissa PS GT 7	24	2,366	262.72
Kelanitissa CCY	645	18,563	29.75
Puttalam Coal	4,457	2,957	7.63
Uthura Janani	85	319	30.35
Barge-CEB	17	2,492	30.35
Victoria	795	679	3.17
Ukuwela	155	2,148	4.30
Kotmale	480	1,780	6.20
Upper Kotmale	495	1,839	5.05
Randenigala/Rantabe	648	506	2.58
Bowetenna	64	121	8.23
Nilambe	13	1,506	9.42
Old Laxapana/New Laxapana	791	558	1.86
Polpitiya	389	406	1.45
Wimalasurendra	131	812	3.03
Canyon	137	1,957	5.23
Samanalawewa	425	807	4.10
Kukule	336	156	3.22
Inginiyagala	45	136	2.90
Udawalawe	21	24,591	4.90
Renewable	1,474	15,905	16.97
All Hydro	4,925	73,139	3.23
All CEB Thermal	5,524	39,551	13.24
All IPP Thermal	1,228	153,186	32.21
All Plants	13,151	153,186	11.65

1.3 Objective

- To do techno economic analysis on integration of grid-connected, storable solar power generation.
    - To analyze technical parameters on the grid-connected, storable technologies suitable for Sri Lanka.
    - To analyze Spinning reserve technologies relevant to each solar energy concentrating or non-concentrating technology.
    - To do discounted cash flow analysis on Net Present Value (NPV) method considering avoided cost scenario.
    - To do sensitivity analyses by varying technical parameters of spinning reserve systems. Most cost optimum solution is the result.

CHAPTER 2

METHODOLOGY

As the first step, literature review on different type of grid connected storable solar power technologies used in the world are find out. The countries have the similar solar irradiance like Sri Lanka have been considered. The power demand curves in the considered countries and the renewable generation percentage are find out. The renewable generation mix and the portion of grid connected storable solar power generation have been compared with relevant demand. Technical parameters such as storage efficiency and concentrating or non-concentrating solar energy collector or reflector efficiency, overall plant efficiency, economical parameters such that Levelized Cost of Energy (LCOE) of each technology within each country have been compared. Energy-efficient and cost effective grid connected, storable solar power plant technologies match for Sri Lanka have been selected for further analysis.

As grid connected, storable pant technology is not existing in Sri Lanka, Photovoltaic (PV) plant without storage have been considered as a case study. Optical solar energy collector module technology have been searched by collecting technical data of the power plant. Other technical parameters which are related to the process of producing electricity from solar energy are find out. Discounted cash flow analysis have been done by considering avoided costs of that day time operating power plant. Cost parameters such that capital costs, Operation & Maintenance (O & M) costs have been collected from the existing site. The minimum avoided generation unit costs to make profits have been calculated.

As the next step, hypothetical models on each selected technology have been developed with the aid of software. For that site characteristics including location and land area have been fixed as the existing PV plant. Assumptions have been made for the design. Discounted cash flow analysis has been done by considering avoided costs of the night time and day time operating hypothetical power plants. Unit generation costs of peak load power plants have been considered for avoided cost calculation. Cost parameters such that capital costs, Operation & Maintenance (O & M) costs have been collected from manufacturers. The minimum avoided generation unit costs to make profits have been calculated. Finally, the recommendation have been made on calculated minimum unit generation costs of power plants. Sensitivity analysis have been done on technical parameters such that spinning reserve parameters.

2.1 Methodology of Information Collection

Literature Review is shown in the flow chart 2.1.

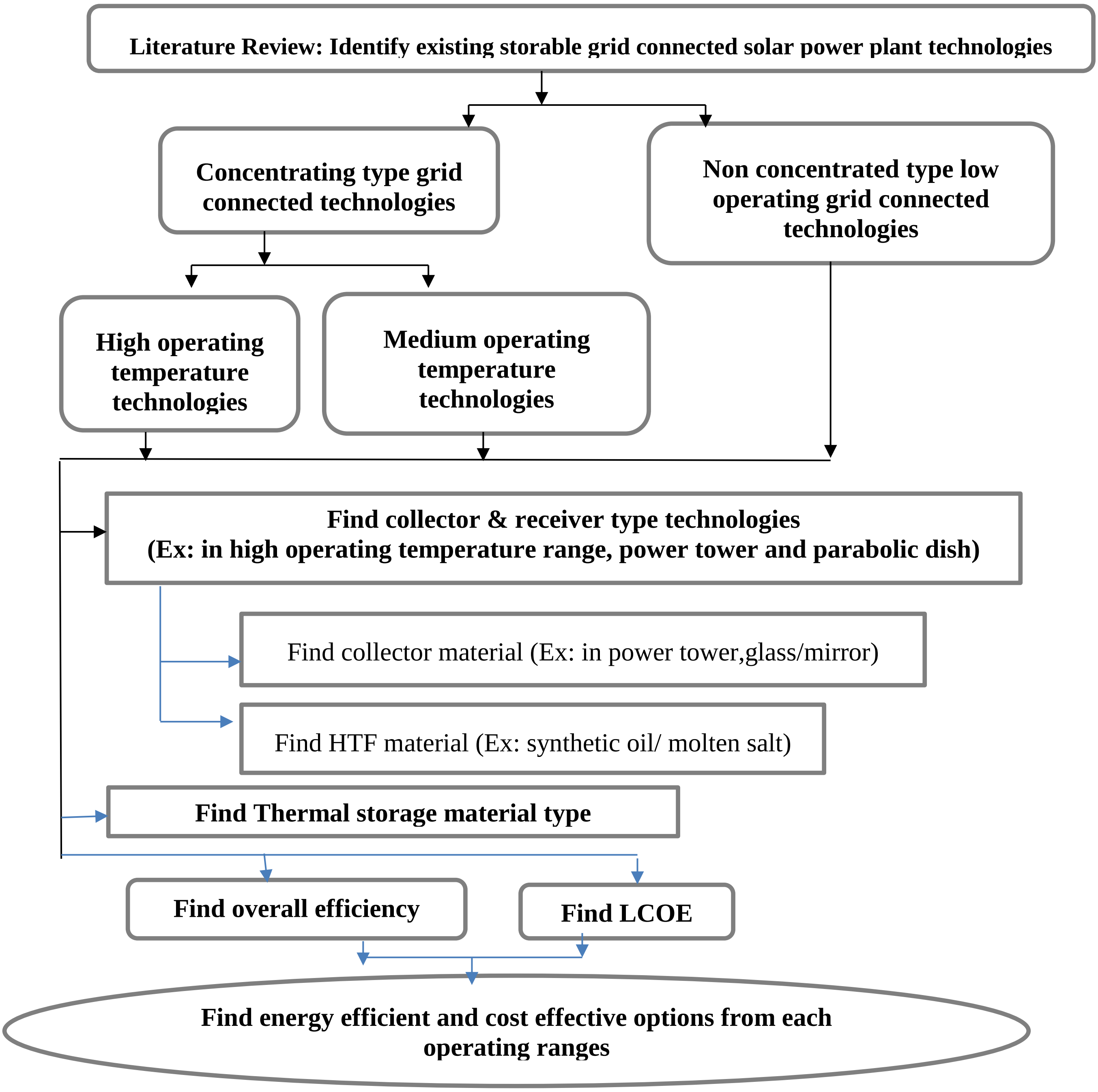

Figure 2.1: Flow Chart for Information Collection

2.2 Data Collection

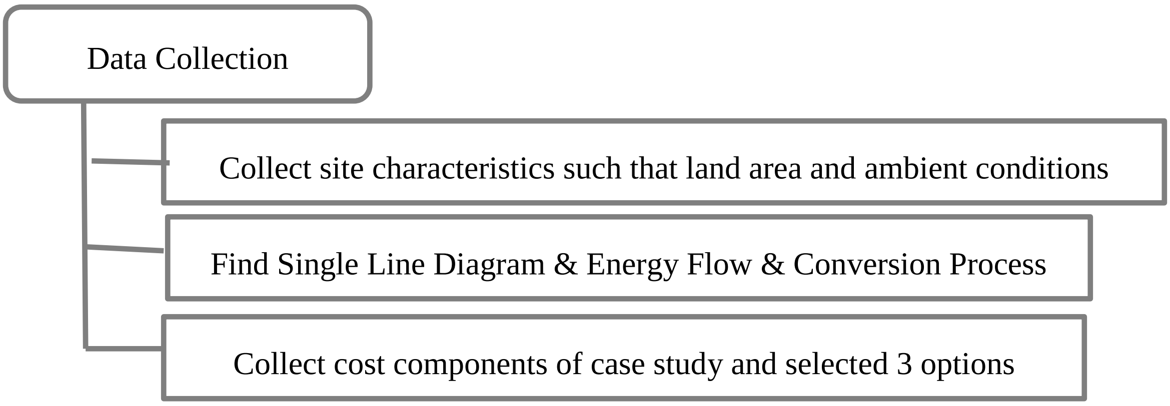

Figure 2.2: Flow chart – Data Collection

2.3 Design

Flow chart for the design is shown in figure 2.3.

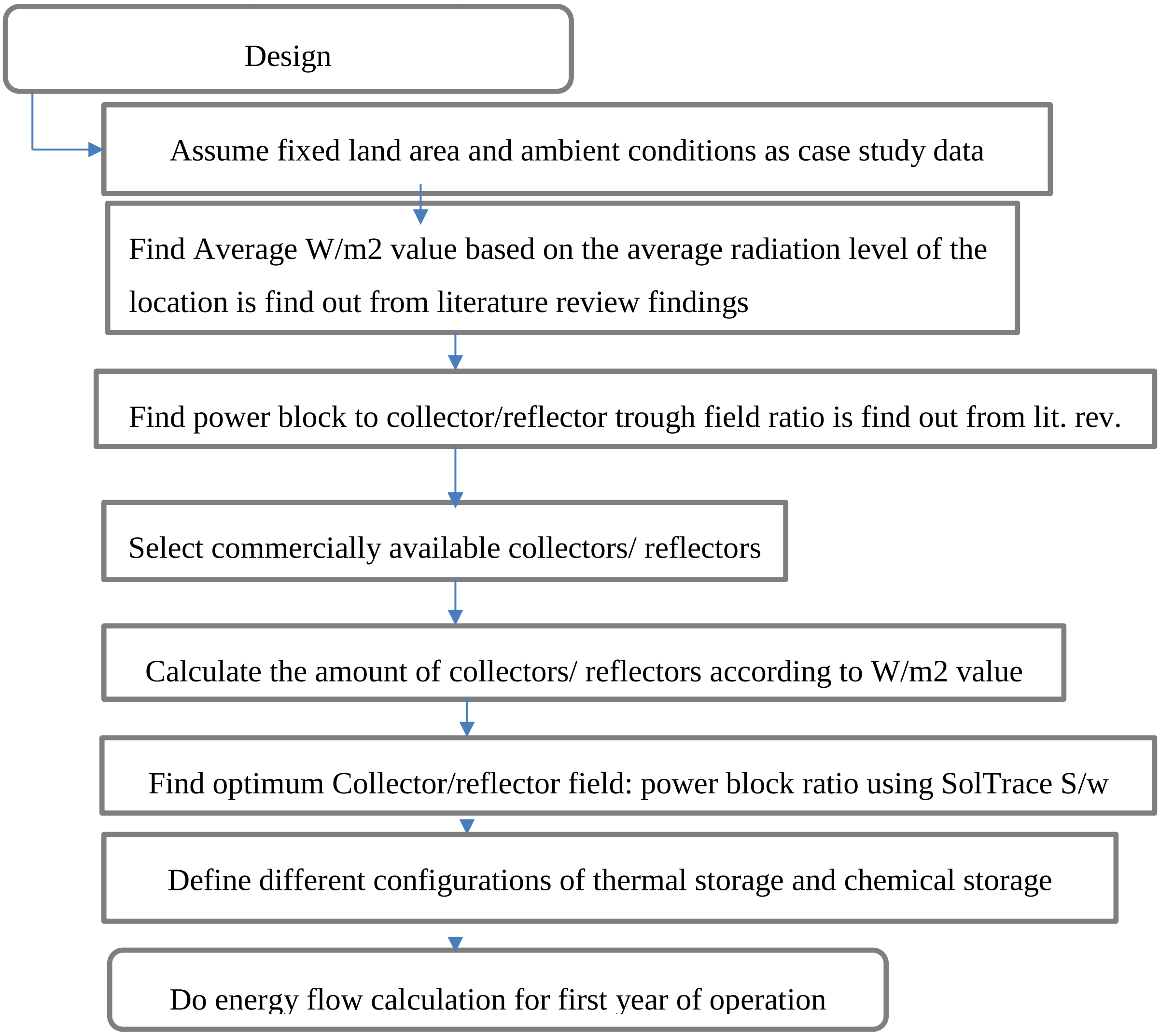

Figure 2.3: Flow Chart - Design

2.4 Summary of Analysis

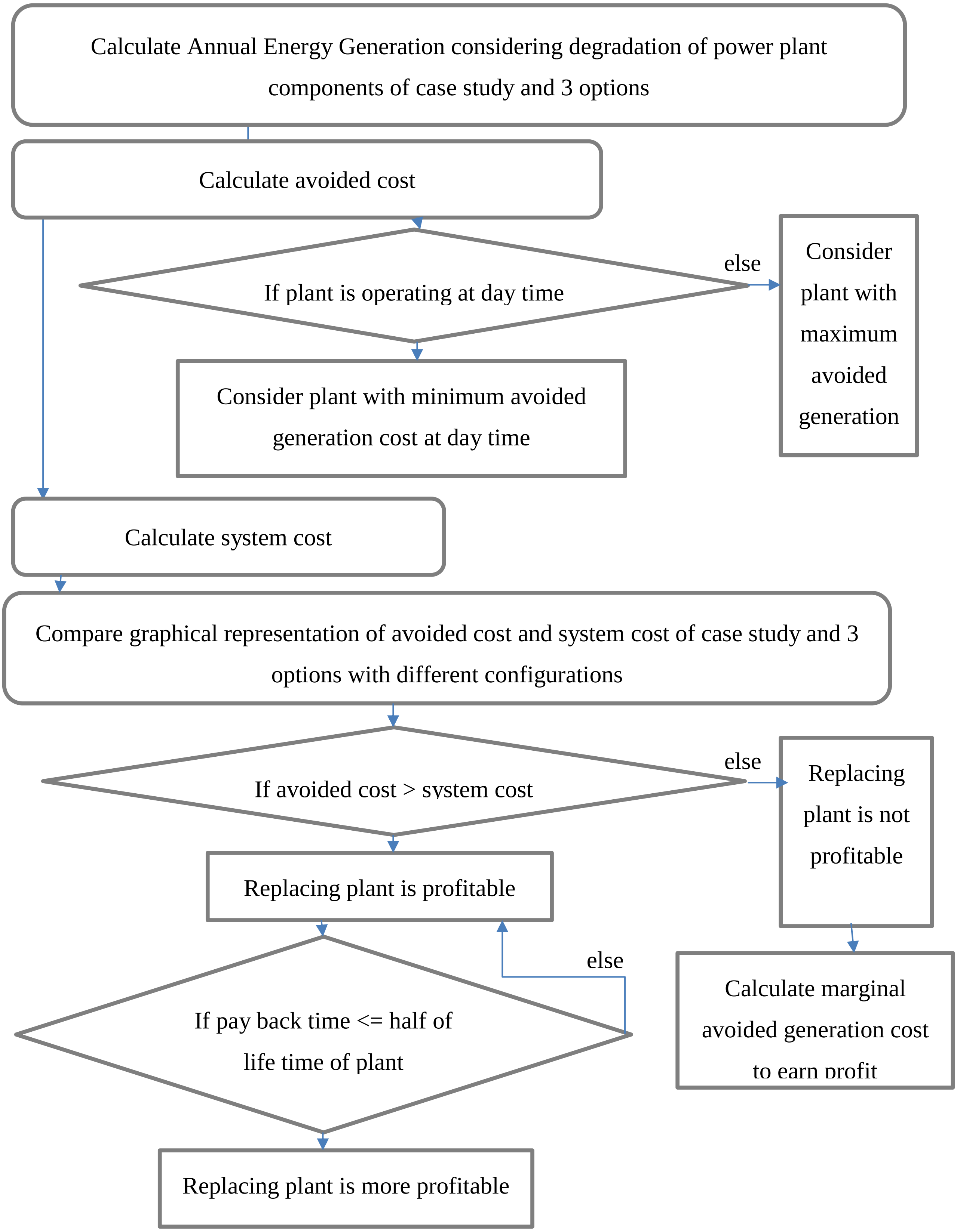

Figure 2.4: Flow Chart - Analysis

CHAPTER 3

LITERATURE REVIEW

Since the cross sectional area of the Earth is 127,400,000 km², the total power of the sun is intercepted by the Earth is 1.740×10^{17} W but as it rotates, no energy is received during the night and the energy of the sun is distributed across the entire surface area of the Earth, most of which is not normal to the Sun's rays for most of the day, so that the average insolation is only one quarter of the solar constant or about 342 W/m^2. Taking into account the seasonal and climatic conditions the actual power reaching the ground generally averages less than 200 W/m^2. The actual solar energy or insolation reaching a solar collector or array depends on its position on the Earth, its orientation and it also varies continuously with time as well as weather conditions. [6]

Because of the variation in the intensity of the Sun's radiation during the day and also the variations in the length of the day it is difficult to make comparisons of the Sun's energy falling upon the Earth at different locations. The graph opposite shows an example in which the insolation reaches 1000 W/m^2 at noon when the sun is at its highest point in the sky. An insolation of 1000 W/m^2 is known as the "Full Sun". Most of the time the incident energy is below this value because it depends on the angle of incidence of the rays of the sun with the ground, increasing during the day from a very low value at dawn as the Sun rises to a peak at noon and falling again as the Sun sets. Similarly the insolation will be reduced as higher latitudes due to the effect of air mass. [6]

Solar energy can be captured in two forms, either as heat or as electrical energy. One form is captured by **Thermal Systems**. Thermal systems capture the Sun's heat energy (infra red radiation) in some form of solar collector and use it to mostly to provide hot water or for space heating, but the heat can also used to generate electricity by heating the working fluid in heat engine which in turn drives a generator. Other form is **Photovoltaic Systems.** Photovoltaic systems capture the sun's higher frequency radiation (visible and ultra violet) in an array of semiconductors. The amount of energy captured is directly proportional to the area of the Sun's energy front intercepted by the collector. [6]

A solar collector is simply a heat collecting surface which intercepts the Sun's radiated energy and heats up a thermal working fluid. In practical thermal systems it is usually more convenient to focus the Suns heat energy on to a small receiver in order to obtain a higher temperature rise of the working fluid. Such collectors are called concentrators. [6]

3.1 Concentrating Type Solar Collectors

3.1.1 Parabolic Dish Collectors

A parabolic dish will capture the energy intercepted by the dish and concentrate it on a suitable heat absorber located at the focus. The amount of energy captured and hence the temperature rise of the absorber will be proportional to the area of the dish. [6]

Figure 3.1: Parabolic Dish Collector

3.1.2 Parabolic Trough Collectors

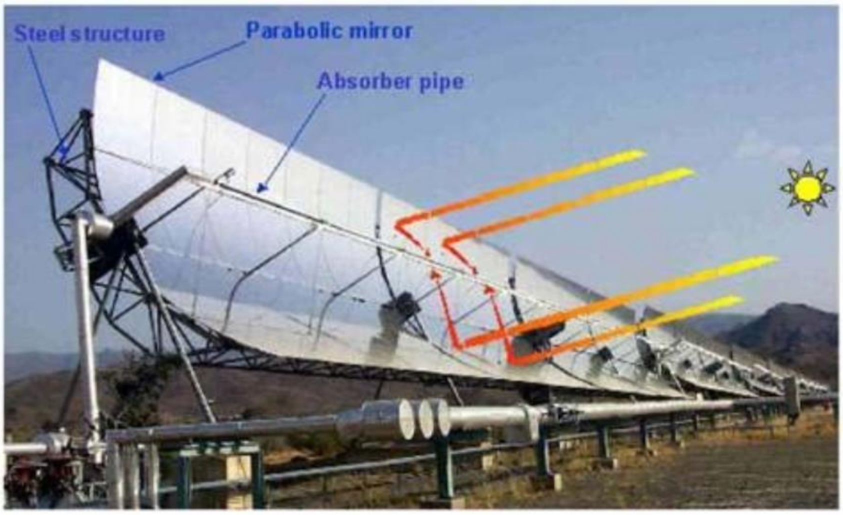

Figure 3.2: Parabolic Trough Reflector

Parabolic trough technology concentrates DNI, using single-axis sun tracking, onto a heat collection element (HCE) located at the focal line of the parabolic surface. A high temperature heat transfer fluid (HTF) such as synthetic oil with a relatively low freezing point, low vapor pressure, and the capability to retain heat absorbs the thermal energy in the HCE as it flows through the receiver tubes. Collected heat in the HCE is transported to the solar power block where a series of shell-and-tube heat exchangers, collectively the solar steam generator (SSG) boils and superheats incoming feed water [6].

3.1.3 Heliostat Field Collectors

A **heliostat** (from *helios*, the Greek word for *sun*, and *stat*, as in stationary) is a device that includes a reflective surface, which turns so as to keep reflecting sunlight towards central tower receiver, compensating for the sun's apparent motions in the sky.

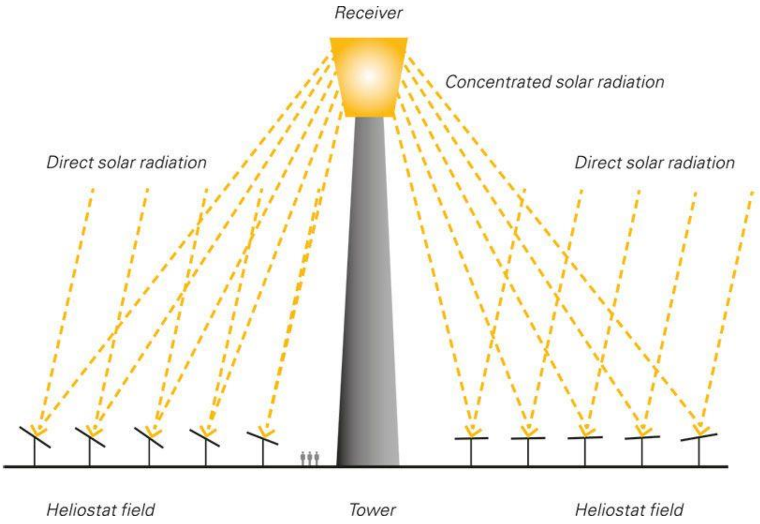

Figure 3.3: Path of Solar Rays in Heliostat Field

Central tower consists of compact tube system which acts as a receiver for reflective heat energy from sun by the ground located heliostat reflectors. A high temperature heat transfer fluid (HTF) such as synthetic oil with a relatively low freezing point, low vapor pressure, and the capability to retain heat absorbs the thermal energy in the central tower receiver as it flows through the receiver tubes. Collected heat in the central tower receiver is transported to the solar power block where a series of shell-and-tube heat exchangers, collectively the solar steam generator (SSG) boils and superheats incoming feed water [7].

3.1.4 Fresnel Collectors

Linear concentrating collector fields consist of a large number of collectors in parallel rows that are typically aligned in a north-south orientation to maximize annual and summer energy collection. With a single-axis sun-tracking system, this configuration enables the mirrors to track the sun from east to west during the day, which ensures that the sun reflects continuously onto the receiver tubes.

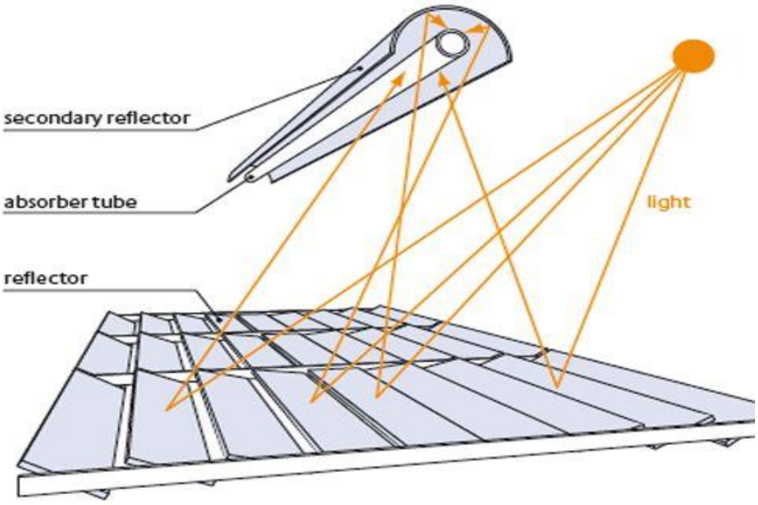

Figure 3.4: Fresnel reflector

3.2 Solar Tracker

Figure 3.5: Solar Tracker

Each SCA will track the sun via a logic controller located in the collector drive housing. The logic is preprogrammed using a GPS system to orient the SCA at the calculated sun position. Additionally included in this reference plant design is an empirical sun tracker that directly watches the sun’s path by measuring a voltage differential created by a shadow casted on a flat plate photovoltaic cell which sits centrally behind the HCE just in front of the reflector. [7]

3.3 Thermal Energy Storage Systems

Thermal energy storage involves the storage of heat in one of three forms; Sensible heat, Latent heat and thermo-chemical heat storage.

Sensible Heat Storage – Molten Salt (60% NaNo3, 40% KNO3)

Sensible heat storage is stored the heat by rising (increasing) the temperature of material and release it after the temperature of material is low. Also no change of phase is happen during the stored process. The amount of sensible heat storage depends on the ability of a material to store heat (heat capacity) and the mass of material [8].

$$\boldsymbol{\dot{Q} = \dot{m}.Cp.\ (T1 - T2)}$$

$\dot{m}$ - Flow rate of molten salt (m^3/s) - 0.002 m^3/s

ɳ - Density at 400^0C: 1900 kg/m^3

Cp - Specific heat of the material (kJ/kg K) at 400^0C – 1.5 kJ/kg K

T1 - Initial temperature (^oC) -250^0C

T2 - Final temperature (^oC) - 550^0C

3.4 Technology and Relevant Efficiency Comparison of Concentrating Plants

Parabolic trough technology with Thermal Energy Storage System (TESS), Heliostat field with TESS and parabolic dish technology are concentrating solar technologies are used in Regarding parabolic trough technology, there are two types of heat collector materials, mirror and polished metal, efficiencies of the collectors are 72% and 75% respectively. Latter is most efficient. Also, there are two types of heat transfer fluids are used. One is synthetic oil and other one is molten salt. The relevant efficiencies of heat transfer fluids are 90% and 95% respectively. Molten salt is the storage material and the efficiency is 85%. Power block is Combined Cycle Power plant (CCPP). Parabolic trough plant with mirrors as heat collectors, synthetic oil as heat transfer fluids and molten salt as storage material, the net plant efficiency is 21%. Other type of parabolic trough plants is consisted of polished metal as heat collector material and molten salt as both heat transfer fluid and storage material. Relevant net plant efficiency is 25%. Latter is the most energy efficient [9].

Regarding heliostat field technology with TESS, there are two types of heat collector materials, mirror and polished metal, efficiencies of the collectors are 83% and 88% respectively. Latter is most efficient. Also, there are two types of heat transfer fluids are used. One is synthetic oil and other one is molten salt. The relevant efficiencies of heat transfer fluids are 90% and 95% respectively. Molten salt is the storage material and the efficiency is 85%. Power block is Combined Cycle Power plant (CCPP). Parabolic trough plant with mirrors as heat collectors, synthetic oil as heat transfer fluids and molten salt as storage material, the net plant efficiency is 22%. Other type of parabolic trough plants is consisted of polished metal as heat collector material and molten salt as both heat transfer fluid and storage material. Net plant efficiency is 26%. Latter plant is the most energy efficient [9].

Parabolic dish plant consists of polished metal as heat collectors and collector efficiency is 90%. Power block technology is diesel engine. Overall plant efficiency is 30%. Parabolic dish technology is the most energy efficient technology and the summary is shown in table 2.2 [9]. Fresnel reflector plant consists of mirrors as heat collectors and collector efficiency is 65%. Heat transfer fluid is sintheic oil and efficiency is 90% and storage material is molten salt with 85% efficiency. Power block is CCCP and overall plant efficiency is 16%. Fresnel reflector technology is the least energy efficient technology.

Table 3.1: Technology and Relevant Efficiency Comparison of Concentrating Power Plants

PP Technology	Heat Collector technology	Heat Transfer fluid (HTF)	Storage technology	Heat collector efficiency	HTF efficiency	Storage efficiency	Power block	Net Plant efficiency
Parabolic trough with TESS	Mirror	Synthetic oil	Molten salt	72%	90%	85%	CCPP	21%
	Polished metal	Molten Salt	Molten salt	75%	95%	85%	CCPP	25%
Heliostat field with TESS	Mirror	Synthetic oil	Molten salt	83%	90%	85%	CCPP	22%
	Polished metal	Molten Salt	Molten salt	88%	95%	85%	CCPP	26%
Fresnel Reflector	Mirror	Synthetic oil	Molten salt	65%	90%	85%	CCPP	16%
Parabolic Dish	Polished metal	N/A	N/A	90%	-	-	Diesel Engine	30%

LCOEs of existing grid connected, storable power plants is compared. Parabolic trough plant with mirrors as heat collectors, synthetic oil as heat transfer fluids and molten salt as storage material, LCOE is 0.25 USD/kWh. Other type of parabolic trough plants is consisted of polished metal as heat collector material and molten salt as both heat transfer fluid and storage material. Relevant LCOE is 0.28 USD/KWh. First one is the most cost effective [9].

Heliostat field plant with mirrors as heat collectors, synthetic oil as heat transfer fluids and molten salt as storage material, LCOE is 0.3 USD/kWh. Other type of parabolic trough plants is consisted of polished metal as heat collector material and molten salt as both heat transfer fluid and storage material. Relevant LCOE is 0.33 USD/KWh. First one is the most cost effective [9].

LCOE of parabolic dish plant is 0.38 USD/kWh. Parabolic dish technology is the most expensive technology and the summary is shown in table 2.3 [9]. LCOE of Fresnel reflector plant is 0.29 USD/kWh.

Table 3.2: LCOE Comparison of storable Solar Technologies

PP Technology	Heat Collector technology	Heat Transfer fluid (HTF)	Storage technology	Heat collector cost (USD/ kWh)	HTF cost (USD/ kWh)	Storage cost (USD/ kWh)	Power block	LCOE (USD/ kWh)
Parabolic trough with TES	Mirror	Synthetic oil	Molten salt	0.2	0.03	0.02	CCCP	0.25
	Polished metal	Molten Salt	Molten salt	0.18	0.02	0.02	CCCP	0.28
Heliostat field with TES	Mirror	Synthetic oil	Molten salt	0.21	0.03	0.02	CCCP	0.3
	Polished metal	Molten Salt	Molten salt	0.2	0.02	0.02	CCCP	0.33
Fresnel Reflector	Polished metal	Synthetic oil	Molten salt	0.21	0.03	0.02	CCPP	0.29
Parabolic Dish	Polished metal	N/A	N/A	0.3	-	-	Diesel Engine	0.38

3.5 Non concentrating type

Photovoltaic modules are non-concentrating type optical solar energy consuming elements. Mostly, they are flat plate. Photovoltaic modules are absorbing optical solar energy by the material it made up of. The energy is then converted into electricity by photovoltaic process. Photo is another word for light. Cell material mainly affect the efficiency of the process.

NREL has done a research on cell technology comparison using different type of commercially available cell materials which are used to compose modules. The efficiency results of different cell material is as shown in figure 3.6 [10].

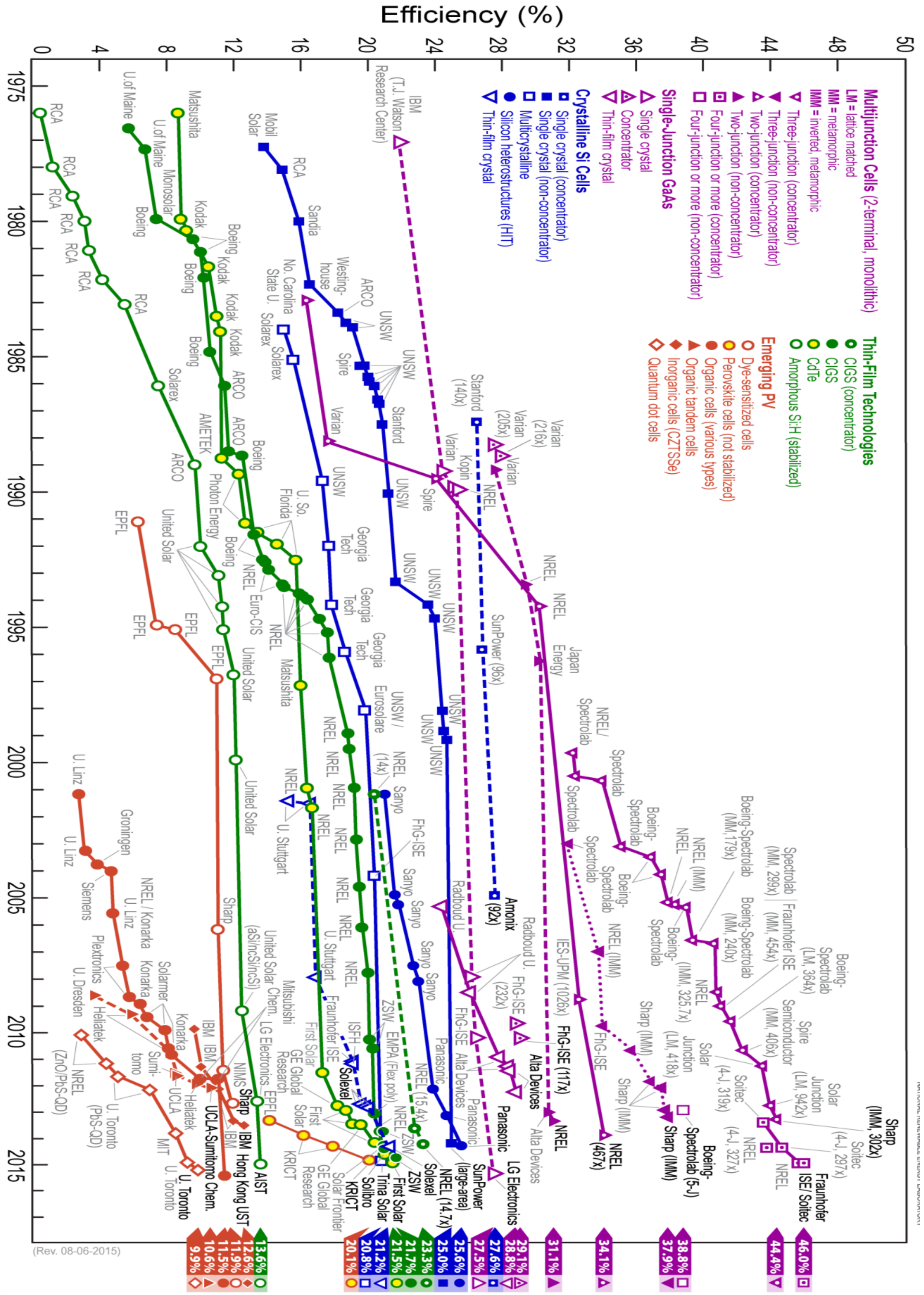

Figure 3.6: PV Cell Technology Comparison by NREL

CHAPTER 4

TECHNICAL ANALYSIS ON AVAILABLE SSPP OPTIONS

4.1 Comparison of PV Cell Technologies

Monocrystalline Si cells are considered to be most energy efficient and with module efficiency Monocrystalline Si cells are considered to be most energy efficient and with module efficiency range of 15% to 18%. And also, it is easily available in the market. But, it is expensive than other cell materials or PV modules due to the high costly production process. Polycrystalline Si cell material is 13% to 16% energy efficient and less expensive than monocrystalline Si cell material as the less expensive material production process. Thin film: Copper Indium Deselenide (CIS), Thin film: Cadmium Telluride (CDTe) and Thin film: Amorphous Si (a-Si) are 10% to 12%, 9% to 11% and 6% to8% energy efficient respectively. And they are less expensive than former two cell materials due to lower material production costs. The disadvantage of thin film cell materials is the need of more space for the same output of former two cell materials needed. Summarized results are as in table 4.1 [10].

Table 4.1: Summary of PV Cell Technology Comparison

Cell material	Module efficiency	Surface area (m^2)/kWp	Advantages	Disadvantages
Monocrystalline silicon	15 - 18%	7-9	- most efficient - easily available on the market -highly standardized	- most expensive - waste of silicon in the production process
Polycrystalline silicon	13 - 16 %	8-9	-Lower production costs than for monocrystalline cells - easily available on the market -highly standardized	- slightly less efficient than monocrystalline silicon modules
Thin film: Copper indium diselenide (CIS)	10 - 12%	9-11	-higher temperatures and shading have lower impact on performance -lower production cost	- more space for the same output needed

Thin film: Cadmium telluride (CdTe)	9 - 11%	11-13	-higher temperatures and shading have lower impact on performance -highest cost-cutting potential	- more space for the same output needed
Thin film: Amorphus silicon (a-Si)	6 - 8%	13-20	-higher temperatures and shading have lower impact on performance -less silicon needed for production	- more space for the same output needed

4.2 Comparison of Large Scale Battery Technologies

For electrical storage in large scale grid connected storable power plants, various types of technologies are used. Mainly flooded lead acid, Valve Regulated Lead Acid (VRLA) and Lithium ion technologies are used around the world. Former two type of lead acid batteries are less expensive regarding initial investment and their maintenance cost is higher with lower system cycle life. Lithium ion batteries have superior life cycle time but initial investment is high. Advantages and disadvantages of each type of battery are as shown in table 4.2 [11].

Table 4.2: Large Scale Battery Technology Comparison

Battery Type	Optimal Application	General Maintenance	Best Practices for Safety	Cycling Ability	Costs
Flooded Lead Acid	Off - grid, medium to high capacity	Electrolyte refreshing required by automatic or manual watering systems Equalization cycle can be periodically required	Hazardous Installed vertically only with basic racking solution Must be in well ventilated space	High Cycle life	Low initial cost of ownership Higher maintenance and accessory cost

VRLA Lead Acid	Grid - interactive, off grid, UPS and backup power, emergency vehicles	Maintenance - Free Superior shelf life Electrolyte does not need to be replaced Does not require equalization	Sealed VRLA requires very minor ventilation with 99% recombination efficiency	High to moderate cycle life	Low initial cost of ownership with reduced maintenance and accessory costs
Lithium - ion	Hybrid EV's or high ambient temperature with high cycle required	Maintenance - Free Superior shelf life Electrolyte does not need to be replaced Does not require equalization	Must be used with an onboard battery management system to prevent over - charge/ over-discharge/ thermal runaway	Superior cycling ability	Very high initial cost of ownership. Dependent on application

4.3 Efficiency of Thermal Collector & Receiver Arrangements

There are three types of collector & receiver arrangements are used.

$$\eta_{col} = \dot{Q}use / A_aI_a \quad \text{———— ①}$$

$\dot{Q}use$ - Rate of (useful) energy output (W)

A_a - Aperture area of the collector (m^2)

I_a - Solar irradiance falling on collector aperture (W/m^2)

To perform an energy balance on a solar thermal collector, one usually isolates the surface that absorbs the incoming radiation, and balances energy inflow and outflow to and from it. In a flat-plate collector, this is called the ‘absorber plate’ and for a concentrating collector, it is often called the ‘receiver’.

$$\dot{Q}use = \dot{E}opt - \dot{Q}loss \quad (W) \quad \text{———— ②}$$

$\dot{Q}use$ - Rate of useful energy leaving the absorber (W)

$\dot{E}opt$ - Rate of optical (short wavelength) radiation (W)

$\dot{Q}loss$ - Rate of thermal energy loss from the absorber (W)

Solar resource is reduced by a number of losses as it passes from the aperture of the collector to the absorber. These processes depend on the type and design of the specific collector. The rate of optical (short wavelength) energy reaching the absorber or receiver,

$$\dot{E}_{opt} = \Gamma\ \rho\ \tau\ \alpha\ I_a\ A_a \qquad (W) \tag{3}$$

Γ - Capture fraction (fraction of reflected energy entering or impinging on receiver)

ρ - Reflectance of any intermediate reflecting surfaces

τ - Transmittance of any glass or plastic cover sheets or windows

α - Absorptance of absorber or receiver surface

Once the solar energy resource (short wavelength radiation) has made its way down to the surface of the absorber or receiver of a collector, it raises the temperature of the absorber above ambient temperature. This in turn starts a process of heat loss from the absorber as with any surface heated above the temperature of the surroundings. These loss mechanisms are convection, radiation and conduction, and all are dependent on, among other things, the difference in temperature between the absorber and the surroundings.

$$\dot{Q}_{loss} = \dot{Q}_{convection} + \dot{Q}_{radiation} + \dot{Q}_{conduction} \tag{4}$$

Convection Loss - Convective heat loss of a solar collector receiver is proportional to the surface area of the absorber or receiver, and the difference in temperature between the absorber surface and the surrounding air. It can be written in general terms as:

$$\dot{Q}_{convection} = \bar{h}\ A\ (T_r - T_a) \tag{5}$$

$\bar{h}$ - Average overall convective heat transfer coefficient (W/m2.K)

A - Surface area of receiver or absorber (m2)

T_r - Average temperature of receiver (K)

T_a - Ambient air temperature (K)

Radiation Loss - Radiation heat loss is important for collectors operating at temperatures only slightly above ambient, and becomes dominant for collectors operating at higher temperatures. Figure below illustrates this transition for a black vertical surface in still air. The rate of radiation heat loss is proportional to the emittance of the surface and the difference in temperature to the fourth power. Described in equation form,

$$\mathbf{\dot{Q}radiation} = \boldsymbol{\varepsilon\sigma} \mathbf{A_r} \, (\mathbf{T^4_r} - \mathbf{T^4_{sky}}) \qquad \mathbf{(W)} \tag{6}$$

ε - Emittance of the absorber surface (or cavity in the case of a cavity receiver)

σ - Stefan-Boltzmann constant (5.670 × 10-8 W/m2 K4)

T_{sky} - Equivalent black body temperature of the sky (K)

Conduction Loss - The final mode of heat loss to consider in collector design is heat conduction. This is generally described in terms of a material constant, the thickness of the material and its cross-section area

$$\mathbf{\dot{Q}conduction} = \boldsymbol{\bar{k}} \, \boldsymbol{\Delta\bar{x}} \mathbf{A_r} \, (\mathbf{T_r} - \mathbf{T_a}) \qquad \mathbf{(K)} \tag{7}$$

$\boldsymbol{\bar{k}}$ - Equivalent average conductance (W/m.K)

$\boldsymbol{\Delta\bar{x}}$ - Average thickness of insulating material

Concentration ratio:

$$\mathbf{C_R} = \mathbf{A_r} / \mathbf{A_a} \tag{8}$$

Substituting Equation ② to ⑧ in ①

$$\eta_{col} = \Gamma\ \rho\ \tau\ \alpha - 1/\ C_R\ [h'(Tr - Ti) + \varepsilon\sigma\ (T^4_r - T^4_{sky})]$$

h' - combined convection and conduction coefficient (W/m^{2}K)

To increase solar collector & receiver system efficiency Γ, ρ, τ, α, CR should be increased. h' , ε should be decreased. Each parameter is considered for analysis.

4.3.1 $\boldsymbol{\Gamma}$- Capture Fraction

The term described fraction of reflected energy entering or impinging on receiver. And measure of Quality of shape of reflector and Size of receiver

$$\boldsymbol{\Gamma}=\frac{Reflected\ Energy\ Entering\ the\ Receiver}{Total\ Reflected\ Energy\ Reflected\ from\ the\ Collector}$$

$\boldsymbol{\Gamma}$ α Size of receiver (Ar)

According to the literature review data, ranges for capture fractions are decided.

Table 4.3: Ranges for Capture Fraction

Collector & Receiver Technology	A_r (m^2)
PD	0.4 - 0.6
PT	0.1 - 0.2
HF	50 - 70

4.3.2 ρ - Reflectance

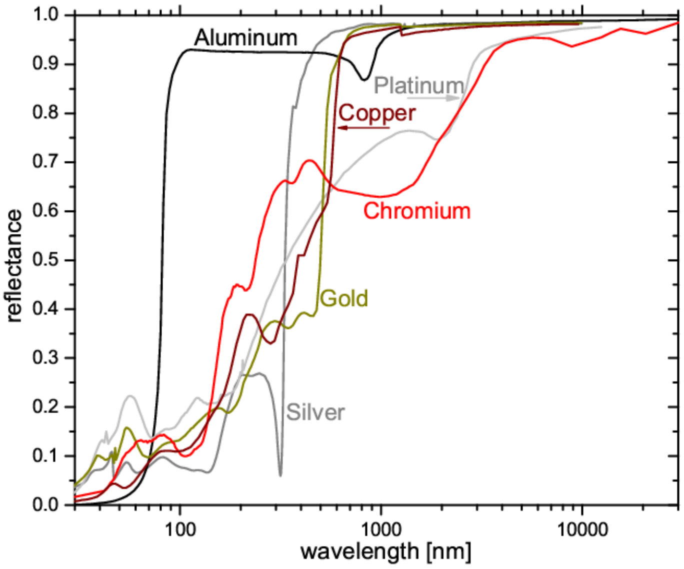

Figure 4.1: Reflectance of Material Comparison

Reflectance is a property of any reflecting surface associated with the collector. Properly designed concentrators will have capture fractions of 0.95 or higher, and silver/glass mirrors can have a reflectance of 0.94 and new aluminum reflecting surfaces have a reflectance of about 0.86.

4.3.3 τ- Transmittance

The term described for receiver. The transmittance is the fraction of solar radiation passing through all transparent cover material that sunlight passes through on its way to the absorber. Cover sheets of glass or plastic are used on flat-plate collectors, above the absorber to reduce convective heat loss.

For parabolic trough collectors a glass tube surrounds the absorber tube for the same reason. High-temperature cavity receivers may incorporate a quartz glass cover to keep the gas in the receiver separate from outside air or to permit pressurization of the gas within the cavity.

In all cases, the use of a cover sheet reduces the solar radiation passing to the receiver/absorber. Their benefit for reducing heat losses from the absorber must at least balance this reduction. The transmittance in Equation is the average overall transmittance and represents the total reduction in transmitted energy in the solar spectrum by all covers. For example, flat-plate collectors may have two or more cover sheets, sometimes of different materials, with the transmittance, τ being the product of each individual cover transmittance.

$$\tau = \tau_1 \tau_2 \tau_3$$

Transmittance of the cover also depends on the wavelength of light passing through it. Glass for example transmits most radiation in the visible spectrum, but does not transmit much in the infrared region.

Therefore, an absorber covered with glass will receive most of the incoming, short wavelength radiation, but will not transmit much of the long wavelength radiation loss coming from the absorber.

This characteristic of glass is the reason that glass greenhouses loose very little energy at nighttime. Carbon dioxide buildup gives our atmosphere a similar property and therefore the name ‘greenhouse effect’. According to the literature review data, ranges for transmittance are decided.

Table 4.4: Ranges of Transmittances

Collector & Receiver Technology	τ
PD	0.8 – 0.9
PT	0.85 - 0.94
HF	0.8-0.9

4.3.4 α- Absorptance

The absorption term represents the fraction of solar energy incident upon the surface, that is absorbed (the remainder being reflected). A good black surface can have an absorption of greater than 0.98, however, as surfaces degrade, this value can decrease. It is important to point out that this property is for radiation in the solar or ‘visible’ spectrum. For most real surfaces, the absorption varies as a function of the wavelength of the incident energy.

There is a class of surfaces used in solar collectors, called ‘selective surfaces’ that have a higher absorptance in the visible spectrum than at longer wavelengths, thereby reducing thermal radiation loss.

4.3.5 C_R - Concentration Ratio

The term "concentration ratio" is used to describe the amount of light energy concentration achieved by a given collector. Two different definitions of concentration ratio are in general use. They are defined briefly here so that the terms may be used.

Optical concentration ratio relates directly to lens or reflector quality; however, in many collectors the surface area of the receiver is larger than the concentrated solar image.

Thermal losses in such situations are larger than might be inferred from examination of the optical concentration ratio. Since geometric concentration ratio refers to receiver area, it is most commonly used because it can be related to collector heat loss.

Note that if the aperture insolation and receiver irradiance are both uniform over the entire area, the optical and geometric concentration ratios are equal.

Table 4.5: Ranges of Concentration Ratios

Collector & Receiver Technology	C_R
PD	500 - 1000
PT	100 - 500
HF	1000 - 2000

4.3.6 h' – Conduction & Convection Coefficient

Conduction loss is usually small compared to convection and radiation losses and therefore is combined with the convection loss term in most analyses. However, it is displayed here for completeness, and to emphasize the importance of ensuring that this mode of heat loss is minimum in any collector design.

Another important mode of conduction loss is the way the high-temperature absorber is attached to the frame and support structure. Use of low conductance materials such as stainless steel can reduce conduction loss into the frame or support casing. However, since most design issues around conduction can be handled without reducing the solar input, the term is generally combined with the convective heat loss term.

For parabolic dish concentrators, the absorbing surface is typically placed inside of a cavity. This protects it from wind, and naturally driven air currents. Little is known about convective heat loss from an open cavity, but it is clear that the position of the cavity and its internal temperature, along with wind speed and direction all affect the rate of heat loss from a cavity.

4.3.7 ε – Emittance

Surfaces that have a low emittance often have a low absorptance as well, reducing the absorbed solar energy. However there is a class of surface coatings called ‘selective coatings, that have low values of emittance when the surface is at relatively low temperatures, but high values of absorptance for solar energy.

The other term, which may be minimized, is the receiver surface area. As with convection loss, concentration of solar energy is the main design tool for reducing radiation heat loss by reducing receiver surface area. In addition, cavity receivers can be used since they have small openings through which concentrated solar energy passes, onto larger absorbing surfaces.

Since solar collectors operate out of doors, and generally face the open sky, they exchange radiation with the sky. The equivalent radiation temperature of the sky depends on the air density and its moisture content. When the relative humidity is high and at sea level, the sky temperature can be assumed to be the same as ambient air temperature. However, for low relative humidity or at high altitudes, the sky radiation temperature can be 6 to 8^{o}C less than ambient temperature. Of course if there is no atmosphere as with space applications, the equivalent sky temperature approaches 0 K.

4.4 Efficiencies of HTF and TESS Materials

The ‘useful’ energy for a solar thermal collector is the rate of thermal energy leaving the collector, usually described in terms of the rate of energy being added to a heat transfer fluid passing through the receiver or absorber.

$$\dot{Q}_{use} = \dot{m}\, C_p\, (T_{out} - T_{in}) \quad (W)$$

$\dot{m}$	- mass flow rate of heat transfer fluid (kg/s)
C_p	- specific heat of heat transfer fluid (J/kg.K)
T_{out}	- temperature of heat transfer fluid leaving the absorber (K)
T_{in}	- temperature of heat transfer fluid entering the absorber (K)

Table 4.6: Thermal Storage Material Comparison

Battery Type	Specific Energy (Wh/kg)	Energy Density (Wh/l)	No. of Life Cycles	Life Cycle Cost (USD/kWh)	Operating Temperature	Environmental Friendliness
Flooded Lead Acid	30	80	1200	0.17	Low and degrade at high	Hazardous because Pb
VRLA	40	100	1000	0.71	Low and degrade at high	Hazardous because Pb
Lithium - ion	150	250	1900	0.19	Good at high	Friendly

4.5 Efficiency of PVT SSPP

PVT SSPP is capable of collect both thermal energy and PV energy. PV process is done in same surface which energy is absorbed and thermal energy is reflected by collector surface. Therefore different portions of same surface are used for different collection mechanisms. Thermal portion efficiency is shown below.

$$\eta col = \Gamma \rho \tau \alpha - 1/ rCR [h'(Tr - Ti) + \varepsilon\sigma (T^4_r - T^4_{sky})]$$

r- Fraction of thermal collector area

As quality of shape of the receiver becomes low, Γ is low. As $r < 1$, T only $C_R <$ PVT C_R. Therefore, thermal efficiency of PVT collector is lower than T only collector efficiency. Therefore use of PVT collector is not with overall efficiency.

Technically efficient options are as below.

1. **Option 1: Flat Plate PV Plant with BESS**
2. **Option 2: Parabolic Trough (PT) Plant with TESS**
3. **Option 3: Heliostat Field (HF) Plant with TESS**
4. **Option 4: Parabolic Dish (PD) Plant with TESS**

CHAPTER 5

DATA COLLECTION FOR CASE STUDY

Data is collected from existing PV plant located at Hambantota. The plant is without storage. This is selected as the best case study for the research as storable technologies are not available for study in Sri Lanka.

5.1 Plant: Basic Data

PV plant which is owned by Sustainable Energy Authority (SEA) located at Buruthakanda in Hambantota district of Sri Lanka as 6.1429° N, 81.1212° E. It is without battery storages and operating at day time. Land area of the site is 40,000 m^2. Average irradiance level of the plant location is 5.55 kWh/m2/day according to DNI data published by NREL.

Plant consist of two stages such that first stage is funded by Korea International Cooperation Agency (KOICA) and second stage is funded by Japan International Corporation Agency (JICA). Each stage is using the same technology of converting solar power directly into electricity using semiconductor flowing process/ photovoltaic process. As the semiconductor materials used in two stages are different, the efficiencies of each stage of plant is different [12].

First stage is using Monocrystalline Si cells as cell material in PV module of solar field. Second stage is using Polycrystalline Si cell s for the same use. Appearance difference of two cell materials is shown in figure 5.1.

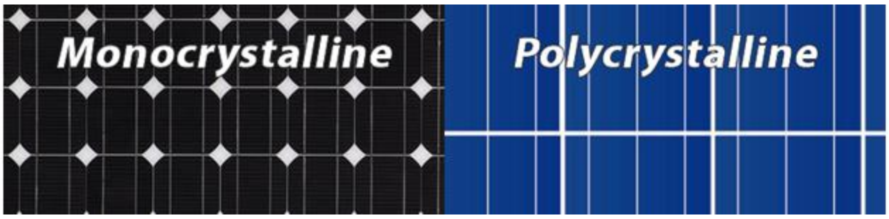

Figure 5.1: Appearance of two Cell Materials used in Two Stages

Solar Field Stage 1 (Funded by KOICA) [11].
Rated output = 500kW
PV Module Type = Poly-crystalline Si
PV Module Ratings = 250W
PV Module Manufacturer = Trina Solar
No. of Modules = 1980
No. of Strings/Array = 18
No. of Arrays = 5
Inverter Ratings = 200 kW
Inverter Manufacturer = LG CNS
No. of Inverters = 5

Solar Field Stage 2 (Funded by JICA) [11].
Rated output = 750kW
PV Module Type = Mono-crystalline Si
PV Module Ratings = 250W
PV Module Manufacturer = Kyocera
No. of Modules = 2130
No. of Strings/Array = 19
No. of Arrays = 7
Inverter Ratings = 200 kW
Inverter Manufacturer = LG CNS
No. of Inverters = 7

5.2 Single Line Diagram: Stage 1

First stage consists of Monocrystalline PV modules which one panel is made up of four number of modules. Nineteen panels have made one string and twenty one strings have made one array. Each array is connected to each distribution board and then to the inverter and next to the main distribution board and to 0.4/33 kV step-up transformer and finally to the Medium Voltage (MV) network of CEB to be distributed over the network area [12].

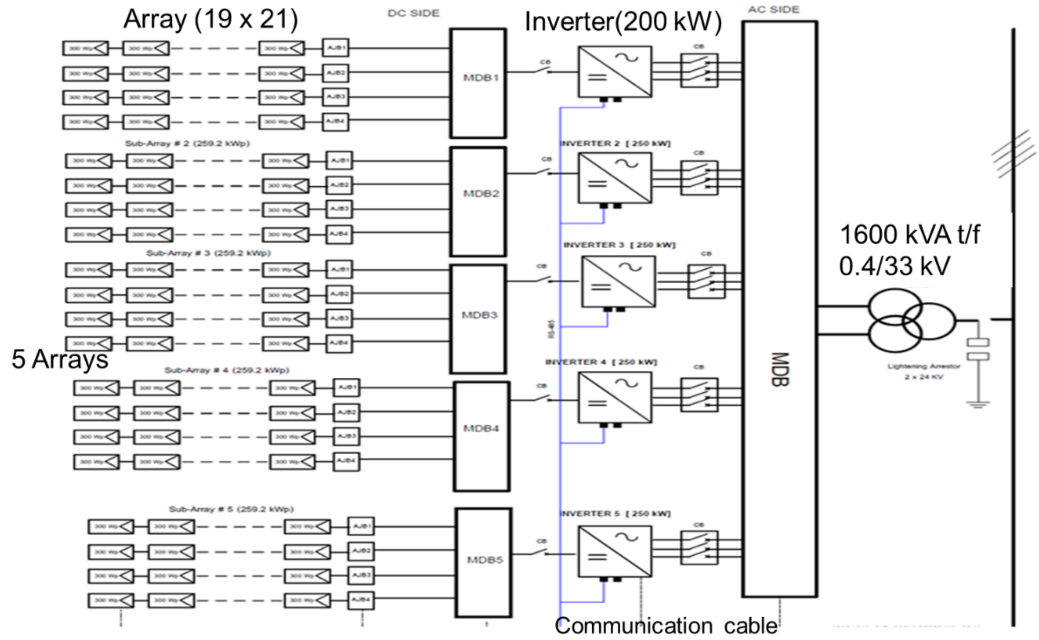

Figure 5.2: PV Plant Arrangement of Stage 1 of Hambantota PV Plant

CHAPTER 6

EVALUATION OF SOLAR POWER TECHNOLOGIES

6.1 Design Criteria and Assumptions

Site characteristics of the hypothetical plant is assumed same as the existing PV plant in Hambantota. Location is 6.1429° N, 81.1212° E. Land area of the site is 40,000 m^2. Average irradiance level of the plant location is 5.55 kWh/m2/day. Ambient conditions of the site are described in standard. Temperature is 25^0C, wind speed is 2.5 ms^{-1} and atmospheric pressure is 1.013 bar.

Design methodology is described as follows. Firstly, average W/m2 value based on the average radiation level of the location is find out from literature review findings [13]. Also, the power block to collector/reflector field ratio is find out from literature review [13]. Then, commercially available collector/reflector type is selected considering efficiency and cost. After that, number of collector/reflector is calculated to fulfill former found out W/m2 value. Then, collector/reflector field is layout with the aid of SolTrace software developed by NREL [14].

6.2 List of Equipment

All the equipment used for PV plant with BESS are complied with relevant IEC standards such that inverter is complied with IEC 62109-2: 2011.

Table 6.1: List of Equipment for Hypothetical PV Plant with BESS

EQUIPMENT NAME	QTY	EQUIPMENT NAME	QTY
PV MODULE ASSEMBLIES		Charge Controller	Lot
PV Modules	4712	INVERTER SYSTEM	
Junction Boxes	Lot	Inverters	8
PV Module Trackers	Lot	Inverter Panels	Lot
Module Fuses	Lot	Cables	Lot
BATTERY ENERGY		Charge Controller	Lot
Li-ion Batteries	178	TRANSFORMERS	
Battery Racks	Lot	Step-Up Transformer	1
Battery Jumpers	Lot	Unit Auxiliary Transformer	1

Solar Field Transformer	1	Automatic Transfer Switch (for back-up battery power) 1	1
Emergency transformer	1	OTHER EQUIPMENT	
Junction Boxes	Lot	Isolated Phase Bus Duct (IPBD)	Lot
CIRCUIT BREAKERS		Metering Current Transformers (CTs)	1
Main Circuit Breaker	1	Metering Potential Transformers (PTs)	1
Circuit Breakers	Lot	Control Relays	Lot
SWITCHES		Ground Grid	Lot
Circuit Switcher (switchyard)	1	Distributed Control System	1
Main Disconnect Switch	1	Uninterrupted Power Supply (UPS)	1
Transmission Line Disconnect Switch	1		

All the equipment used for Parabolic Trough plant are complied with relevant IEC standards as shown in table 6.2.

Table 6.2: List of Equipment for Hypothetical Parabolic Trough Plant with BESS

EQUIPMENT NAME	QTY	EQUIPMENT NAME	QTY
SOLAR COLLECTOR ASSEMBLIES		Hot Salt Tanks (inc. foundations)	1
Solar Collector Mirrors	4058	Hot Tank Immersion Heater	2
Solar Collector Receiver Tubes	Lot	Hot Salt Pumps	3 x 50%
Solar Collector Assemblies/	12	Cold Salt Pumps	3 x 50%
THERMAL ENERGY STORAGE		Salt to HTF Heat Exchangers	3
Cold Salt Tanks (inc. foundations)	1	Bulk salt Storage	30 MT
Cold Tank Immersion Heater	2	STEAM TURBINE & AUXILIARIES	
Hot Salt Tanks (inc. foundations)	1	Steam Turbine	1
Hot Tank Immersion Heater	2	Gland Steam Condenser	1
Lube Oil & Hydraulic Oil Skids	1	TRANSFORMERS	
Cooling Tower	1	Generator Step-Up Transformer	1
Steam Surface Condenser	1	Unit Auxiliary Transformer	1
Steam Jet Air Ejector (Holding & Hogging Ejectors)	1	Station Service Transformers	3
Deaerator/ Storage Tank	1	Excitation Transformer	1
Closed Feed water Heaters	2	Solar Field Transformers	3

HEAT EXCHANGERS		Solar Collector Drive Power Converters	12
Economizer (Preheater)	1x100%	Emergency Transformer	1
Evaporator (Steam Generator)	1x50%	CIRCUIT BREAKERS	
Preheater	1x50%	Generator Circuit Breaker	1
Super heater	1x100%	Main Circuit Breaker	1
Closed Cooling Water Heat	1x100%	SWITCHES	
HTF Heat Protection Condenser	1	Circuit Switcher (switchyard)	1
TANKS		Main Disconnect Switch	2
Demineralized Water Storage	1x100%	Transmission Line	2
Raw/Fire/CT Makeup Water Storage (Field erected)	1x100%	Generator Disconnect Switch	1
Potable Water Storage	1x100%	Automatic Transfer Switch	1
Blow down/ Flash tank	1x100%	OTHER EQUIPMENT	
Turbine Area Flash Tank	1x100%	Isolated Phase Bus Duct (IPBD)	Lot
Closed Cooling Water Expansion Tank	1x100%	Metering Current Transformers (CTs)	1
HTF Expansion & Overflow Tanks	1-Exp,3-O/f	Metering Potential Transformers (PTs)	1
PUMPS	Lot	Control Relays	Lot
HTF ULLAGE SYSTEM	Lot	Ground Grid	lot
EMMISSION GENERATING	Lot	Distributed Control System	1
GENERATOR	1	Uninterrupted Power Supply (UPS)	1
Power Distribution Center with Switchgear & Motor Control Centers (MCC) – STG & HTF Areas	1	Power Distribution Center with Switchgear & Motor Control Centers (MCC) – Cooling Tower & TES Areas	1

All the equipment used for Heliostat Field Plant are complied with relevant IEC standards.

Table 6.3: List of Equipment for Hypothetical Heliostat Field Plant with BESS

EQUIPMENT NAME	QTY	EQUIPMENT NAME	QTY
HELIOSTAT FIELD ASSEMBLIES		Closed Feed water Heaters High Pressure)	2
Heliostat Field Collectors	405	HEAT EXCHANGERS	
Solar Tower	1	Economizer (Preheater)	1x100%
Solar Collector Assemblies/ Drives	12	Evaporator (Steam	1x50%
THERMAL ENERGY STORAGE		Preheater	1x50%
Cold Salt Tanks (inc. foundations)	1	Closed Feed water Heaters High Pressure)	2
Cold Tank Immersion Heater	2	HEAT EXCHANGERS	
Hot Salt Tanks (inc. foundations)	1	Economizer (Preheater)	1x100%
Hot Tank Immersion Heater	2	Evaporator (Steam Generator)	1x50%
Hot Salt Pumps	3 x 50%	Super heater	1x100%
Cold Salt Pumps	3 x 50% /tank	Closed Cooling Water Heat Exchangers	1x100
Salt to HTF Heat Exchangers	3	HTF Heat Protection Condenser	1
Bulk salt Storage	30 MT	TANKS	
STEAM TURBINE & AUXILIARIES		Excitation Transformer	1
Steam Turbine	1	Raw/Fire/CT Makeup Wter Storage (Field erected)	1x100%
Gland Steam Condenser	1	Potable Water Storage	1x100%
Lube Oil & Hydraulic Oil Skids	1	Blow down/ Flash tank	1x100%
Cooling Tower	1	Turbine Area Flash Tank	1x100%
Steam Surface Condenser	1	Closed Cooling Water Expansion Tank	1x100%
Steam Jet Air Ejector (Holding & Hogging Ejectors)	1	HTF Expansion & Overflow Tanks	1-Exp,3-O/f
Deaerator/ Storage Tank (Open Feed water Heater)	1	PUMPS	Lot
HTF ULLAGE SYSTEM	Lot	Circuit Switcher (switchyard)	1

EMMISSION GENERATING	Lot	Main Disconnect Switch	2
Raw/Fire/CT Makeup Wter	1x100%	Transmission Line	2
GENERATOR	1	Generator Disconnect Switch	1
TRANSFORMERS		Automatic Transfer Switch (for back-up battery power)	1
Generator Step-Up Transformer	1	OTHER EQUIPMENT	
Unit Auxiliary Transformer	1	Isolated Phase Bus Duct (IPBD)	Lot
Station Service Transformers	3	Metering Current Transformers (CTs)	1
Excitation Transformer	1	Metering Potential Transformers (PTs)	1
Solar Field Transformers	3	Control Relays	Lot
Solar Collector Drive Power	12	Ground Grid	lot
Emergency Transformer	1	Distributed Control System	1
CIRCUIT BREAKERS		Uninterrupted Power Supply (UPS)	1
Generator Circuit Breaker	1	Power Distribution Center with Switchgear & Motor Control Centers (MCC) – Cooling Tower & TES	1
Main Circuit Breaker	1	Power Distribution Center with Switchgear & Motor Control Centers (MCC) – Cooling Tower &	1

6.3 Design Configuration Data

Hypothetical Model consists of PV field and BESS. Four configurations are BESS are shown for further analysis.

Case 1: 30% DOD

Case 2: 50% DOD

Case 3: 80% DOD

Case 4: 100% DOD

Selected battery type is li-ion according to the literature review findings and 48V, 2000Ah Li-ion battery manufactured by LG is considered. Life cycle time vs. Depth of Discharge (DOD) of battery is shown in figure 6.1 according to the manufacturer datasheet [15].

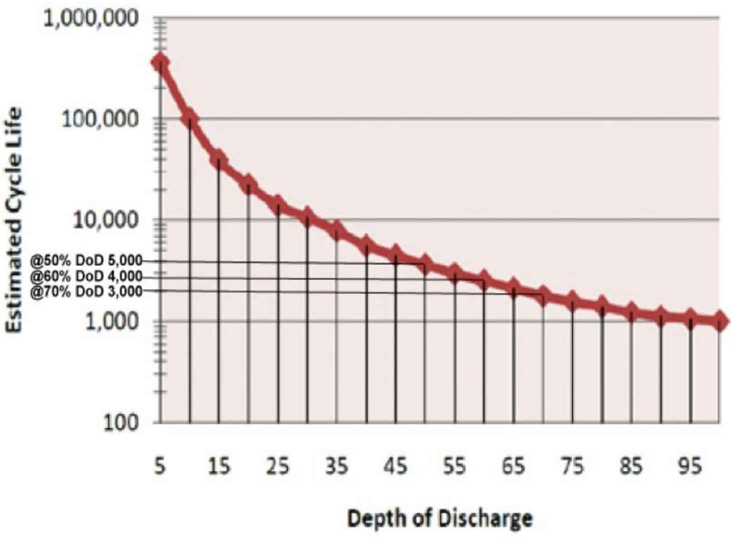

Figure 6.1: Estimated Cycle Life vs. DOD of 2000 Ah Li-ion Battery

Energy flow process of the plant is described as follows. PV modules absorbed optical solar energy and one portion of energy is lost. Other portion is used to produce electricity to supply to the grid or stored in battery to be used at night. Energy flow is shown in figure 6.2.

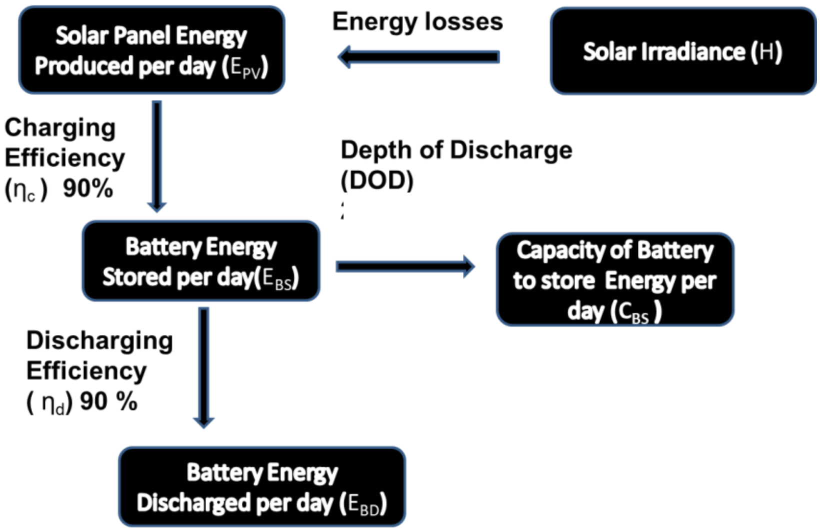

Figure 6.2: Energy Flow Diagram

Energy equations use for output energy calculation is shown below.

$$E_{BS}= E_{pv} . \eta_c$$

$$C_{BS} = E_{pv} . \eta_c . DOD$$

$$E_{BD} = E_{pv} . \eta_c . \eta_d$$

Charge controller is controlled the portion of energy stored in battery to be used at night and portion of energy transmitted to grid as following algorithm.

During Daytime within off-peak hours (Epv> 0 & 06.30 h< T< 18.30 h)

```
 If SOC >= SOC(max)
Stop charging the battery and supply the energy to the grid
 Else if SOC(max) >SOC> SOC(max DOD)
            Charge the battery
 Else if SOC< SOC(max DOD)
 Charge the battery
```

During peak hours (18.30 h< T< 21.30 h)

```
If SOC> SOC(max DOD)
Discharge the battery
If SOC< SOC(max DOD)
Stop discharging the battery
```

Hypothetical Model consists of Parabolic trough field and TESS.

Solar Field

Solar-Field Aperture Area:	16,540 m²
No. of Loops:	52
No. of SCAs per Loop:	4
SCA Aperture Area:	81 m²
SCA Length:	150 m
No. of Heat Collector Elements (HCEs):	120

HCE Manufacturer: Aalborg CSP
Parabolic Trough Type: Polished Metal

Heat-Transfer Fluid

Type: Molten Salt
Solar-Field Inlet Temp: 252°C
Solar-Field Outlet Temp: 312°C

TESS

Storage Type: 2-tank direct
Storage Capacity: 8 hours
Thermal Storage Description: Molten Salt

Power Block

Turbine Capacity (Gross): 2 MW
Turbine Capacity (Net): 2 MW
Turbine Manufacturer: MaxWatt
Output Type: Steam Rankine
Power Cycle Pressure: 60.0 bar
Cooling Method: Wet cooling

Selected parabolic trough collectors has 0.25 m focal distance, 120^0 rim angle, 2.1m trough length, 1.4 m aperture width and 0.05 m sandwich thickness. The efficiency change with temperature is shown in figure 6.3. It is assumed that temperature is 25^0C at site location [16].

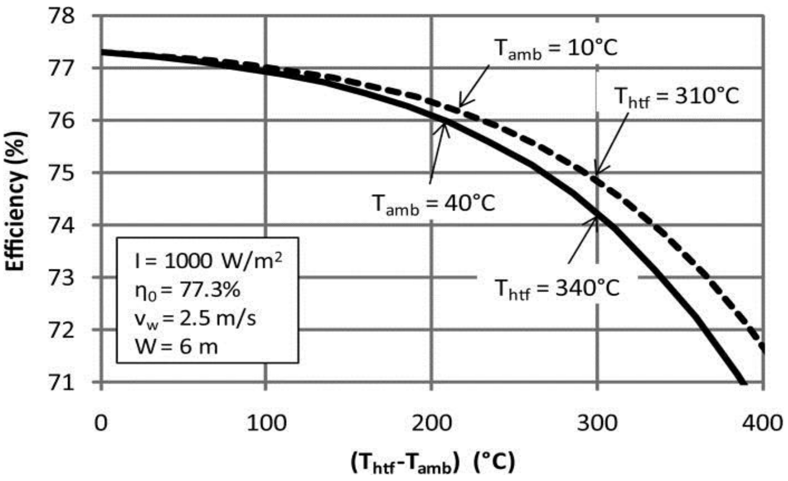

Figure 6.3: Parabolic Trough Reflector Characteristics

Energy flow process of the plant is described as follows. Receiver tubes and Central tower receiver system absorbed solar energy and one portion of energy is lost. Other portion is used to produce electricity to supply to the grid or stored in thermal storage to be used at night. Energy flow is shown in figure 6.4

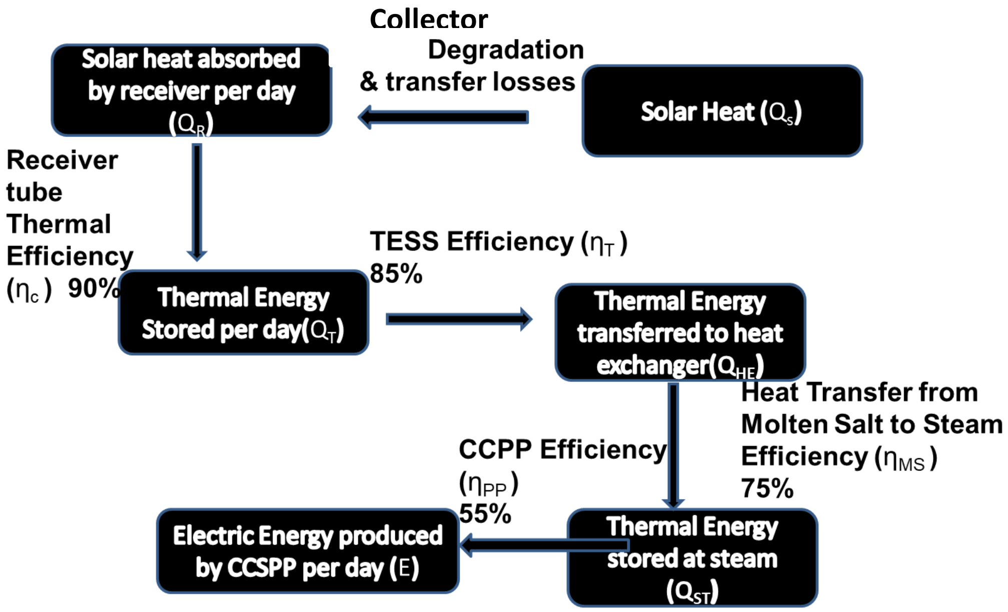

Figure 6.4: Energy Flow Diagram

6.4 Design Layout

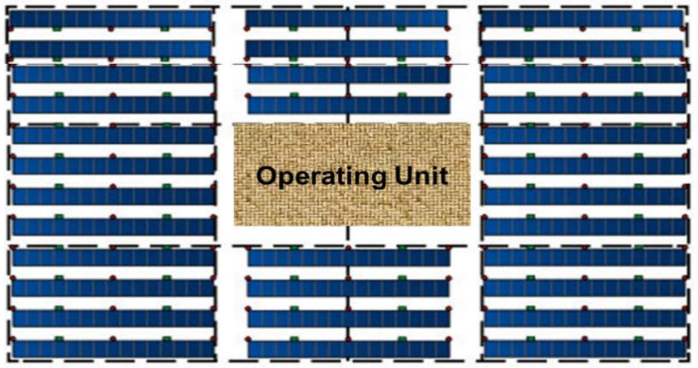

Figure 6.5: Layout of Land Area of Plant

Hypothetical plant is laid with the aid of SolTrace software developed by NREL. Land area of the site is considered as 40,000 m^2. Average W/m^2 value based on the average radiation level of the location is find out from literature review findings [13]. The power block to PV field ratio is find out from literature review [13]. Mono crystalline Si PV modules are used for the design. Eight number of PV arrays are developed.

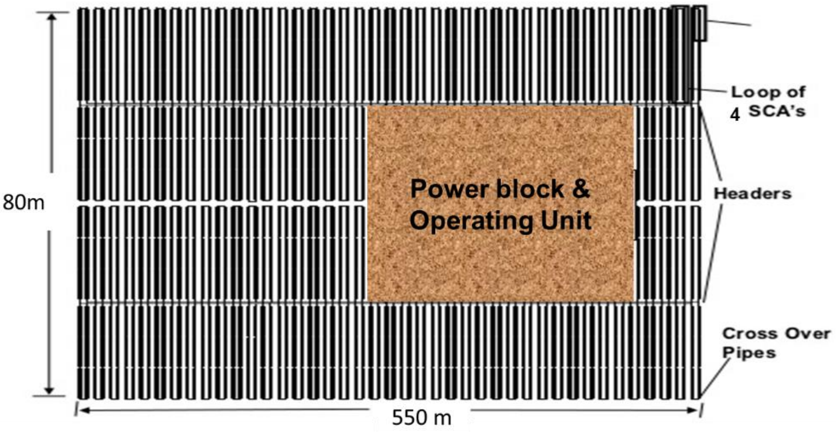

Figure 6.6: Land Area Layout of Parabolic Trough Plant

Hypothetical plant is laid with the aid of SolTrace software developed by NREL. Land area of the site is considered as 40,000 m^2. Average W/m^2 value based on the average radiation level of the location is find out from literature review findings [6]. The power block to Parabolic trough field ratio is find out from literature review [6]. Fifty two number of Parabolic trough loops are developed.

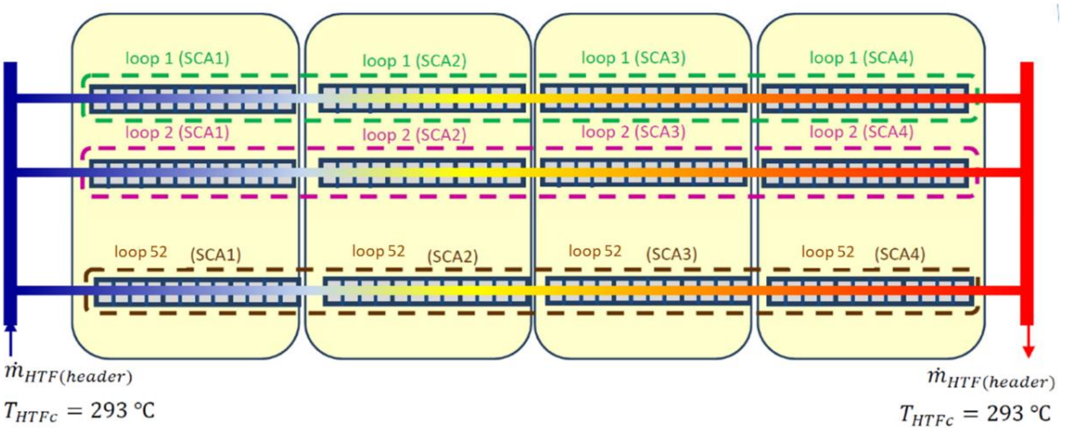

Figure 6.7: Loop Configuration

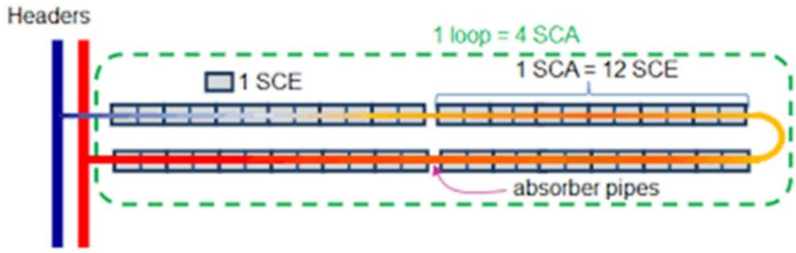

Figure 6.8: SCA Configuration

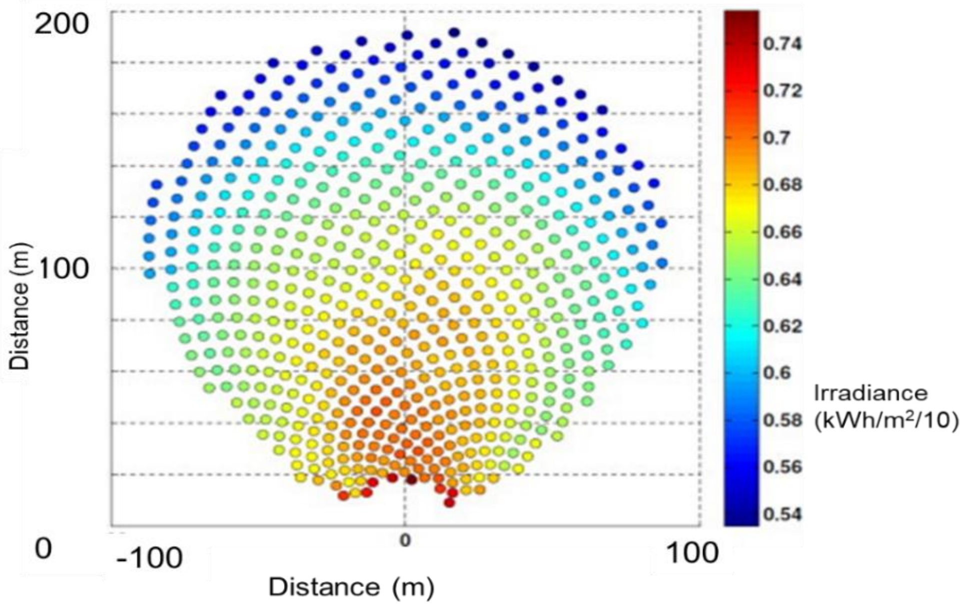

Figure 6.9: Heliostat Field layout

Hypothetical plant is laid with the aid of SolTrace software developed by NREL. Land area of the site is considered as 40,000 m^2. Average W/m^2 value based on the average radiation level of the location is find out from literature review findings [7]. The power block to Heliostat field ratio is find out from literature review [7].

Solar Field

Aperture Area:	16,222 m²
No of Heliostats:	14,280
Heliostat Manufacturer:	eSolar
Tower Height:	46 m

Receiver Manufacturer:	Victory Energy
Receiver Type:	Cavity

Heat-Transfer Fluid

Type:	Molten Salt
Receiver Inlet Temp:	270^0C
Receiver Outlet Temp:	560^0C

Power Block

Turbine Capacity (Gross):	2.5 MW
Turbine Capacity (Net):	2.5 MW
Turbine Manufacturer:	MaxWatt
Output Type:	Steam Rankine
Power Cycle Pressure:	60.0 bar
Cooling Method:	Wet cooling

TESS

Storage Type:	2-tank direct
Storage Capacity:	8 hours
Thermal Storage Description:	Molten Salt

Selected metal reflectors are cost effective and efficient than glass mirrors. The reflection property of reflectors are slightly degraded with time. And also, it is assumed that temperature is 250^0C at site location [17].

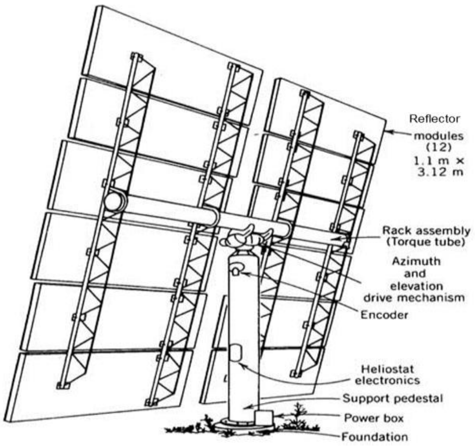

Figure 6.10: Heliostat Reflector Configuration

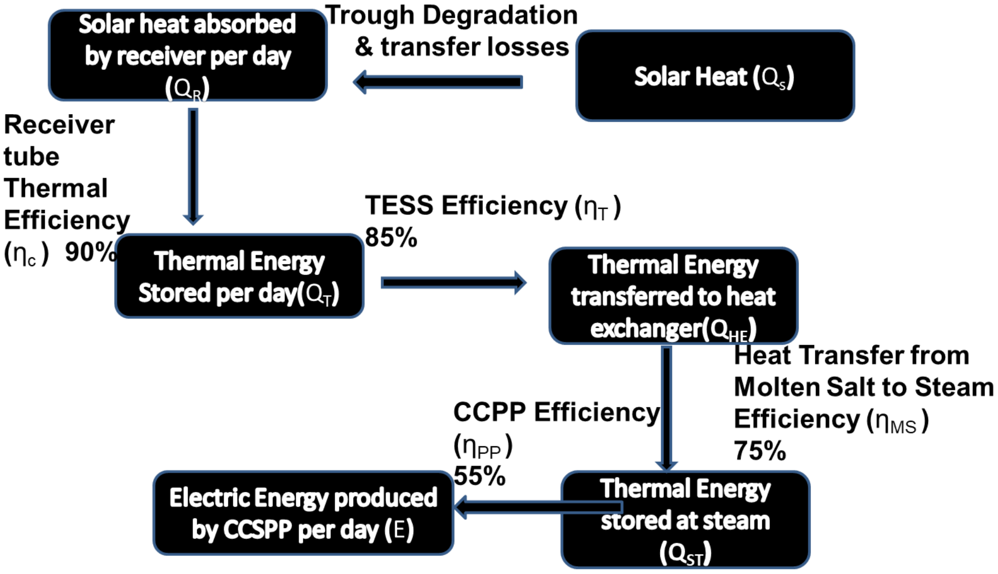

Figure 6.11: Energy Flow Diagram

6.5 Plant Arrangement of PV with BESS Plant

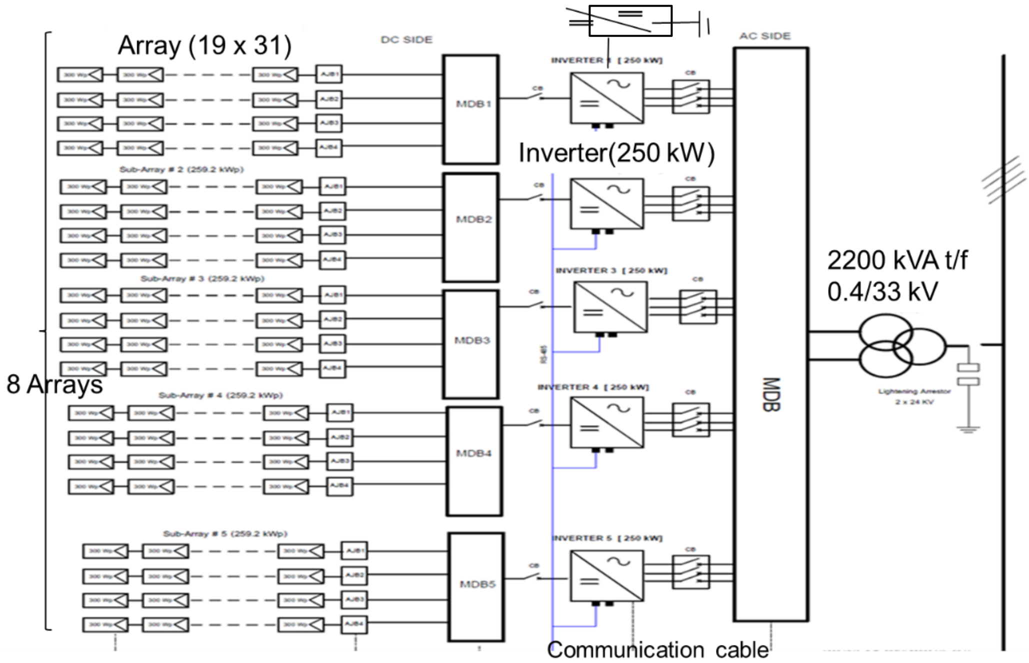

Figure 6.12: Single Line Diagram of PV with BESS

Arrays consists of Monocrystalline PV modules which one panel is made up of four number of modules. Nineteen panels have made one string and thirty one strings have made one array. Each array is connected to each distribution board and then to the inverter and next to the main distribution board and to 0.4/33 kV step-up transformer and finally to the Medium Voltage (MV) network of CEB to be distributed over the network area.

6.6 Process Flow Diagrams of Thermal Power Plants

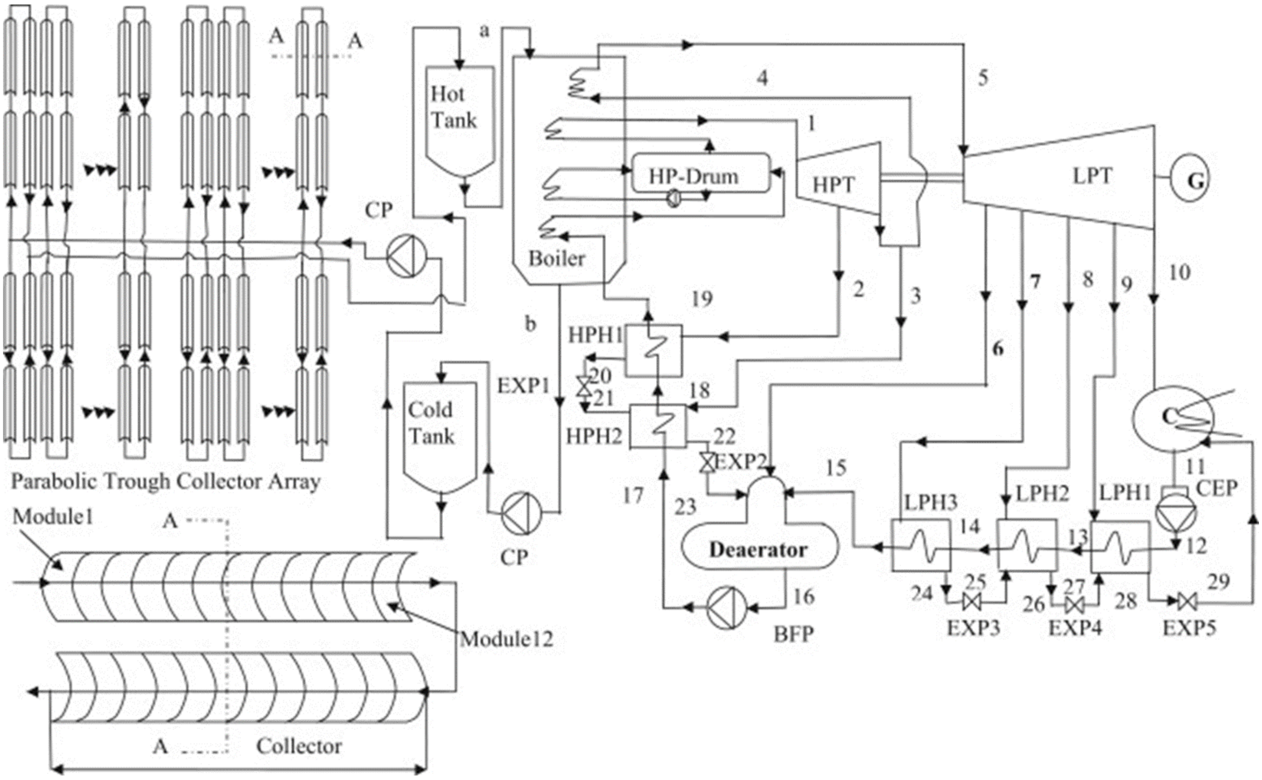

Figure 6.13: Process Flow Diagram of Parabolic Trough Plant with TESS

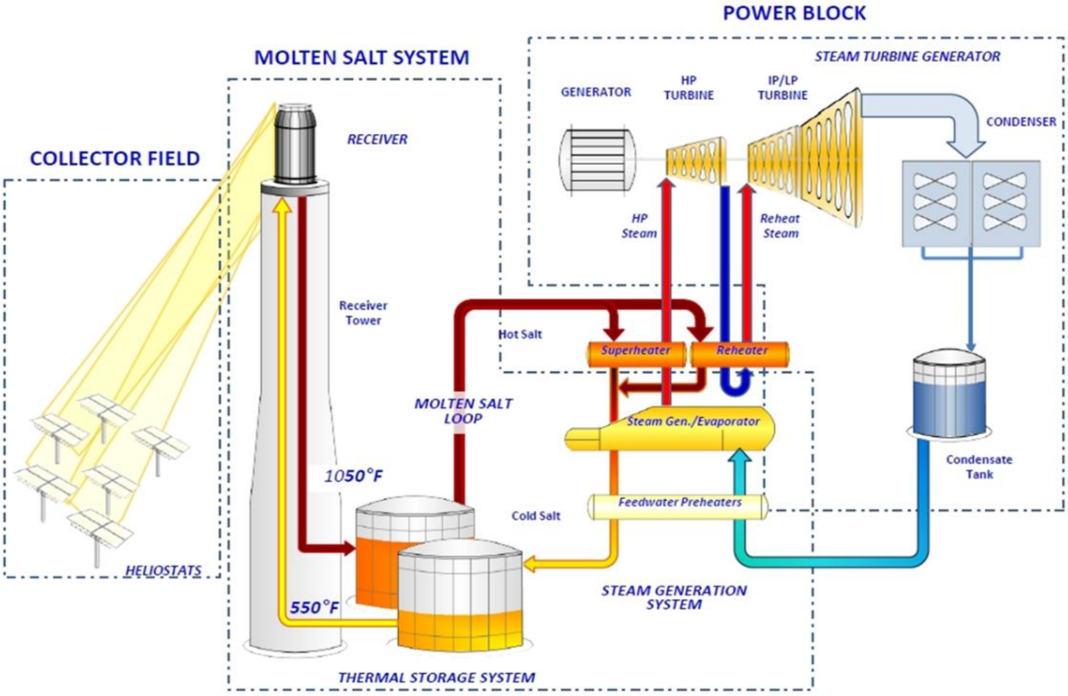

Figure 6.14: Process flow Diagram

Central tower consists of compact tube system which acts as a receiver for reflective heat energy from sun by the ground located heliostat reflectors. A high temperature HTF which is molten salt absorbs the thermal energy in the central tower receiver as it flows through the receiver tubes. Collected heat in the central tower receiver is transported to the solar power block where a series of shell-and-tube heat exchangers, collectively the SSG boils and superheats incoming feed water.

CHAPTER 7

CASH FLOW ANALYSIS OF SELECTED OPTIONS

Discounted cash flow analysis is done for case study and the designed models.

7.1 Step 1: Analysis Criteria and Assumptions

Hambantota PV plant is started its operation at 2014 and hoping a continuous operation near 25 years. So, the discounted cash flow analysis is done for a period of 25 years from year 2015 to year 2039. CEB is the major utility of electricity in Sri Lanka. The analysis is not utility point of view calculation but a justice calculation for all parties considering actual generation costs and O & M costs without making profits to one party.

It is assumed the inflation rate is 10% according to statistics of Central Bank of Sri Lanka (CBSL). According to a NREL report [18], it is assumed that O & M cost percentage of total installed capital cost is 1.12% for solar PV technologies and 1.16% for thermal storage technologies. It is also assumed that only PV modules are degraded through analysis period and other equipment such that inverter, power cables remains same efficiency.

Cost breakdown data of equipment and labour are collected from SEA for case study. Specimen calculation is done for first stage. For hypothetical models, Cost breakdown data of equipment are calculated from reviewed power plants of other countries and multiplying from correction factor according to Sri Lanka such that adding relevant taxes and considering conversion rates from USD 2015 and get average value comparing that price to the price of online available equipment. Cost breakdown data for labour are calculated from reviewed power plants of California, China and India, multiplying from correction factor according to Sri Lanka as described above.

7.2 Step 2: Annual Energy Generation Calculation

Annual energy generation is calculated throughout the analysis period following the equation below.

$$\mathbf{E^{1}_{2015} = A * r * H * PR = 1.721\ GWh}$$

E^{1}_{2015} = Energy generated in year 2015 (kWh)

A = Total solar panel Area (m^2); Area for 1 Panel: 1.61 m^2

r = solar panel efficiency (%); For monocrystalline panels: 15.1% (datasheet [19])

H = Annual average solar radiation on tilted panels (shadings not included);

Tilted Angle: (-15^0) – ($+15^0$), Azimuth Angle: 175^0 - 195^0

PR = Performance coefficient for losses (default value for 1MW system= 75%)

- Inverter losses (8 %)
- Temperature losses (15%)
- DC cables losses (2 %)
- AC cables losses (2 %)
- Shadings (40%)
- Losses at weak radiation (4%)
- Losses due to dust and mist (2%)

Note: PR=1-Plant Factor

Table 7.1: Design Calculation Summary

Plant	Power Plant Capacity (MW)	Annual Energy Generation of first year of operation (GWh)
Existing PV Plant - Hambantota	1237	1.76
Option 1: PV SSPP	1250	1.78
Option 2: PD SSPP	2775	3.85
Option 3: PT SSPP	2105	2.92
Option 4: HF SSPP	2523	3.50

First stage is using Monocrystalline Si panels following the degradation levels as shown in table 6.2. Peak wattage of the panel is 250 W, nominal current is 8 A, nominal voltage is 28 V. It is maintained 250^0C temperature to get maximum efficiency as the manufacturer data sheet. Panels are complied with IEC 61215 [19].

Table 7.2: Degradation Levels of PV modules used in Stage 1

Year	Degradation Level	Year	Degradation Level
1	1.0000	14	0.8827
2	0.9720	15	0.8756
3	0.9642	16	0.8686
4	0.9565	17	0.8617
5	0.9489	18	0.8548
6	0.9413	19	0.8479
7	0.9337	20	0.8412
8	0.9263	21	0.8344
9	0.9189	22	0.8278
10	0.9115	23	0.8211
11	0.9042	24	0.8146
12	0.8970	25	0.8080
13	0.8898		

Inverter used in first stage is with peak wattage of 200 kW and the efficiency is about 91% according to its operating input voltage and output current [20]. as shown in figure 6.1. It is noted that no degradation of inverter through its period of analysis.

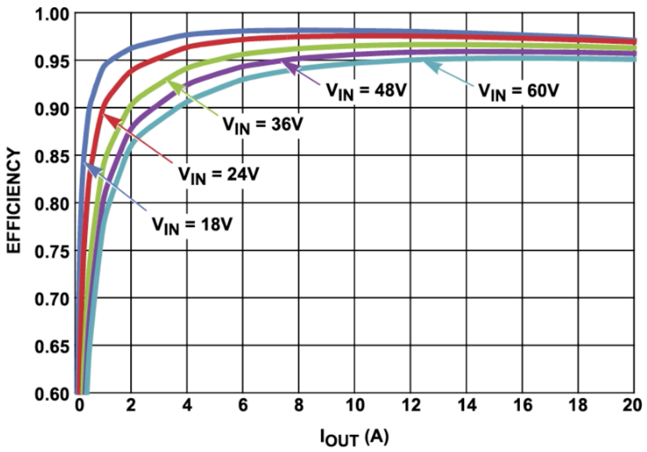

Figure 7.1: Inverter Characteristics of First Stage Inverter

7.3 Step 3: Per Unit Avoided Cost Calculation

Avoided cost is essentially the marginal cost for a public utility to produce one more unit of power as findings from literature review [21]. The replacement cost is called as "Avoided Cost, A_E" and it is calculated according to the equation below.

$$A_E = A_G + A_{T\&D}$$

Avoided Per Unit Generation Cost = A_G

Avoided Per Unit Transmission & Distribution Cost = $A_{T\&D}$

Annualized Equivalent Per Unit Total Avoided Cost = A_E

Annualized equivalent per unit generation cost is the addition of avoided per unit generation cost and avoided per unit transmission and distribution cost. Latter is also called as network loss cost. According to Statistical Digests published by CEB in year 2015, network losses are 10.17% of total generated energy of the year. Network losses are forecasted in LTGEP published in CEB in 2014 [22] as shown in figure 7.2.

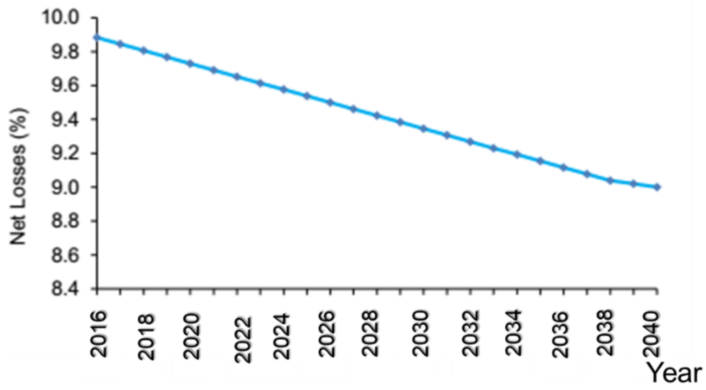

Figure 7.2: Net Transmission & Distribution Loss Forecast for year 2016- 2040

Degradation of network loss is considered for annual per unit avoided cost calculation.

7.4 Step 4: Avoided Cost Calculation

Kelanitissa old GT power plant which is operating at full time is considered for calculation. The considered data is as shown in table 7.7 [22].

Table 7.3: Per Unit Generation Cost of Peak Power Plants

	Kelanitissa			**Sapugaskanda**	
Name of Plant	GT (Old)	GT (New)	Comb. Cycle	Diesel (Station A)	Diesel (Station B)
Engine Type	GE FRAME 5	FIAT (TG 50 D5)	VEGA 109E ALSTHOM	PIELSTIC PC-42	MAN B&W L58/64
Fuel Type	Auto Diesel	Auto Diesel	Naphtha	Heavy Fuel Oil (HFO)	Heavy Fuel Oil (HFO)
Number of sets	4	1	1	4	8
Unit Capacity (MW)	16.3	113	161	17.4	8.7
Calorific Value of the fuel (kCal/kg)	10500	10500	10880	10300	10300
Heat Rate at Full Load (kCal/kWh)	4022	2860	1897	2245	2015
Full Load Efficiency (%)	21	30	45	38	43
Fuel rate considering full load (LKR/kWh)	48.096	34.200	21.210	18.751	16.830
Fixed O&M Cost (LKR/kWh)	0.6675	0.0393	0.4162	1.8844	1.7269
Variable O&M Cost (LKR/kWh)	0.10395	0.8073	0.43605	0.9207	0.27405
Total Generation Cost (LKR/kWh)	**48.868**	**35.047**	**22.062**	**21.556**	**18.831**

Total avoided cost is calculated by multiplying annualized equivalent total per unit avoided cost by annual generation units as the equation.

Total Avoided Cost = Annualized Equivalent Total Per Unit Avoided Cost x Annual Energy Generation Units

7.5 Step 5: Summarized Capital Cost Breakdown

Both first stage and second stage of Hambantota PV plant is having motor tracking system to track the path of the sun to get the maximum energy to the panel. PV field cost together with motor tracking system is summarized. PV module prices of two stages are different because of the technology difference, thus efficiency difference of the cell material which the module made up of. Cost breakdown data are summarized in table 7.8 by adding other expenses of the project such as administrative costs [12].

Table 7.4: Capital Cost Breakdown of Existing Plant

No	Description	Installed capacity (kW)	Qty	Unit	Rate/ MLKR	Amount/ MLKR
1	PV panel (Stage I) including assembly (mono-crystalline), motor tracking system	0.25	3012	No.	0.028	82.83
2	Inverter (Stage I)including panels and cables	200	5	No.	2	10.00
3	System Installaion cost including transformer(33kV/132kV)	1350	1	No.	126	126.00
4	PV module(Stage II) including assembly (Poly-crystalline), motor tracking system	0.25	2044	No.	0.03	61.32
5	Inverter(Stage II) including panels and cables	200	3		2	6.00
6	Other costs					150.00
	Total cost					**436.15**

For the fore cases of different battery configurations based on DOD, unit costs of battery are different. Life cycle is different. So, battery replacement is done according to the energy usage. So, capital cost of each case is different and costs of 30% DOD case is summarized as shown in table 7.9.

Table 7.5: Summarized Cost breakdown of 30% DOD BESS

Item Description	Unit Cost (MLKR)	Quantity	Total Cost (MLKR)
PV Module (250W)	0.03	4960	148.8
Invert system cost (200kW)	2	8	16
Battery (48V, 2000Ah)	3	177	531
Charge controller cost	1.1	8	8.8
Transformer system cost (1500kVA, 0.4/33kV)	126	1	126
Contingencies & Other			270
Total cost			**1100.6**

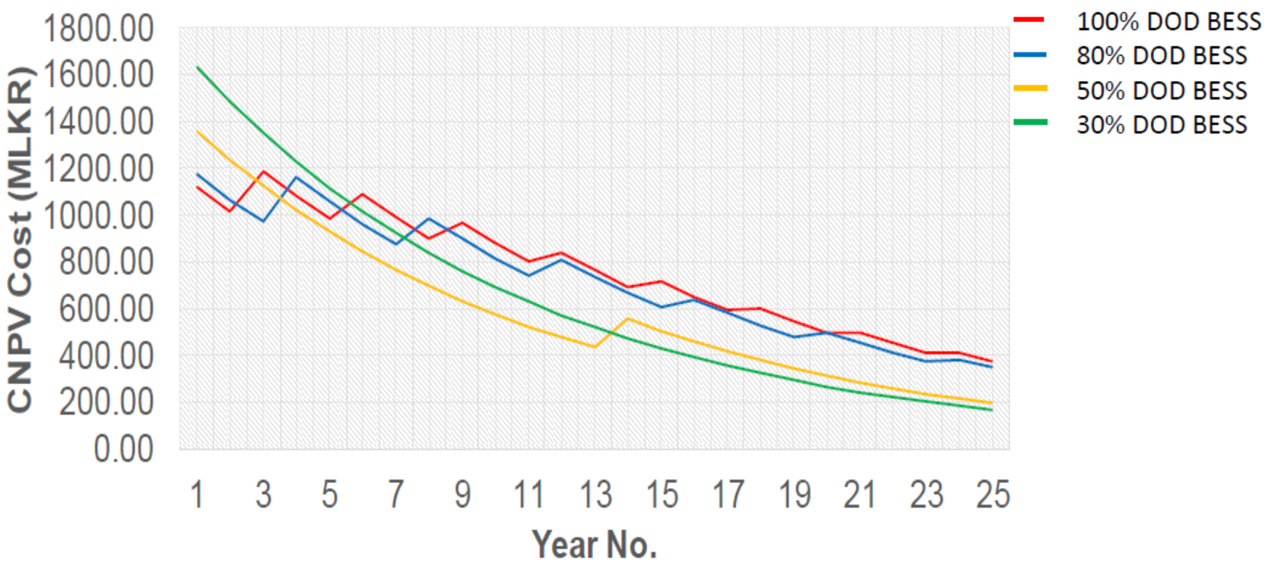

Figure 7.3: PV with BESS Comparison of Different DOD Configurations

For PT SSPP option cost breakdown is below.

Table 7.6: Summarized Cost breakdown of PT SSPP

Item	Qty	Unit	Material costs (MLKR)	Labour costs (MLKR)	Total costs(MLKR)
Site Improvements	1	LS	30.476	41.908	72.384
Solar Field	1	LS	443.706	587.247	1194.954
HTF System	1	LS	113.184	119.587	232.771
Thermal Energy storage	1	LS	431.518	12.262	443.781
Power Block	1	LS	178.528	93.532	472.061
Subtotal			1197.414	854.538	2415.952
Contingency					241.595
Total Estimate					**2657.548**

For HF SSPP, capital costs are summarized as table 7.11.

Table 7.7: Summarized Cost breakdown of HF SSPP

Item	Qty	Unit	Material costs (MLKR)	Labour costs (MLKR)	Total costs(MLKR)
Site Improvements	1	LS	30.476	41.908	72.384
Solar Field	1	LS	443.706	587.247	1930.955
HTF System	1	LS	113.184	119.587	232.771
Thermal Energy storage	1	LS	431.518	12.262	443.781
Power Block	1	LS	178.528	93.532	472.061
Subtotal			1197.414	854.538	3151.953
Contingency					315.195
Total Estimate					**3467.148**

7.6 Step 6: LCOE Calculation

LCOE is the division of NPV costs by NPV of energy as shown in the equation below [23].

$$\text{LCOE} = \frac{\text{Capital Cost} + \text{ Net Present Value of Total Cost incured during lifetime}}{\text{Net Present Value of Total Energy Produced during lifetime}}$$

$$\text{NPV of Costs} = \sum_{t=1}^{25} \frac{C_{OMF}^{t} + C_{OMV}^{t}}{(1+d)^{t}}$$

$$\text{NPV of Energy} = \sum_{t=1}^{25} \frac{E_{2015}^{1} + E_{2016}^{2} + \cdots + E_{2038}^{24} + E_{2039}^{25}}{(1+d)^{t}}$$

Fixed O & M cost = C_{OM}

Variable O & M cost = C_{OM}

Discount factor = d

Table 7.8: LCOE Comparison

Plant Option	LCOE (LKR/kWh)		
	For Plant without Storage	For Storage	For Combined Plant with Storage
PV with BESS (100% DOD)	18.2	14.9	33.1
PV with BESS (80% DOD)		13.6	31.8
PV with BESS (50% DOD)		10.4	28.6
PV with BESS (30% DOD)		12.0	30.2
PT with TESS	33.3	2	35.3
HF with TESS	35.4	2	37.4
PD with TESS	38.1	2	40.1

CHAPTER 8

RESULTS & DISCUSSION

Discounted cash flow analysis which is also called Net Present Value (NPV) method to analysis revenues and profits getting NPV of cost values. System cost is the addition of capital costs and total costs incurred throughout the life time of the plant.

8.1 Summary of Discounted Cash Flow Analysis of Existing PV Plant

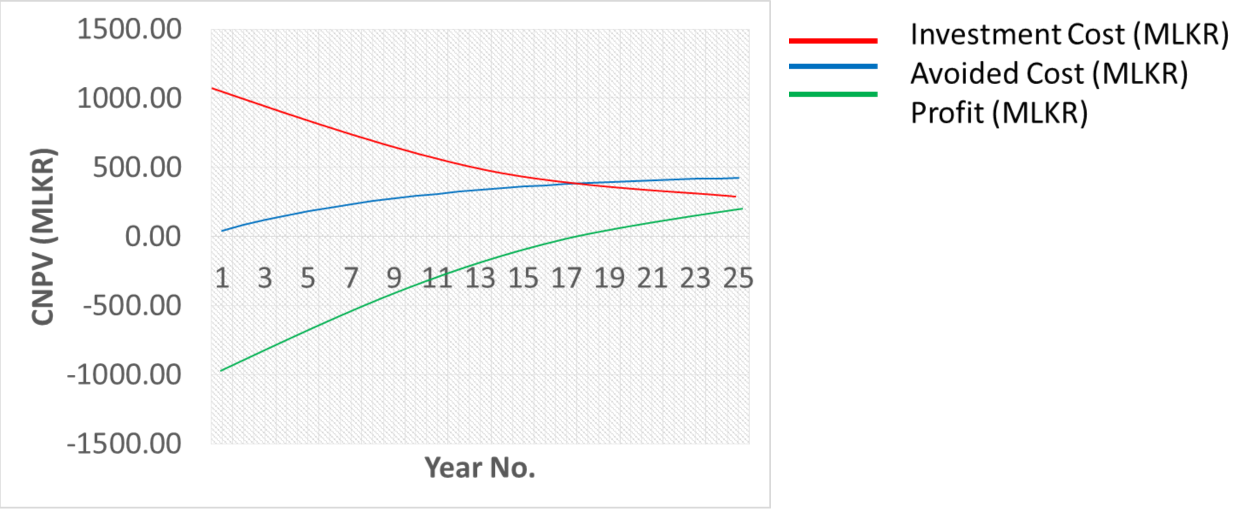

Figure 8.1: CNPV Comparison of Case Study

Hambantota PV Plant has the capital cost of 436.15 MLKR. For revenue calculation, considered flat tarrif is 25.09 LKR/kWh. The comparison shows that, for system cost NPV in 25th year is 564.41 MLKR and for avoided cost is 225.76 MLKR.

Sensitivity analysis is done by varying avoided generation cost by 10% and the depicted CNPV of avoided cost is 248.34 MLKR. The results are shown in table 8.1.

8.2 Summary of Discounted Cash Flow Analysis of PV with BESS Plant

Avoided generation cost of Kelanitissa power plant is 48.87 LKR/kWh. Comparing avoidedcost with system cost, the results are graphically represented in figure 8.2. Different BESS configurations have different system costs as the difference of unit cost prices and also with replacement costs due to the difference of life cycle times.

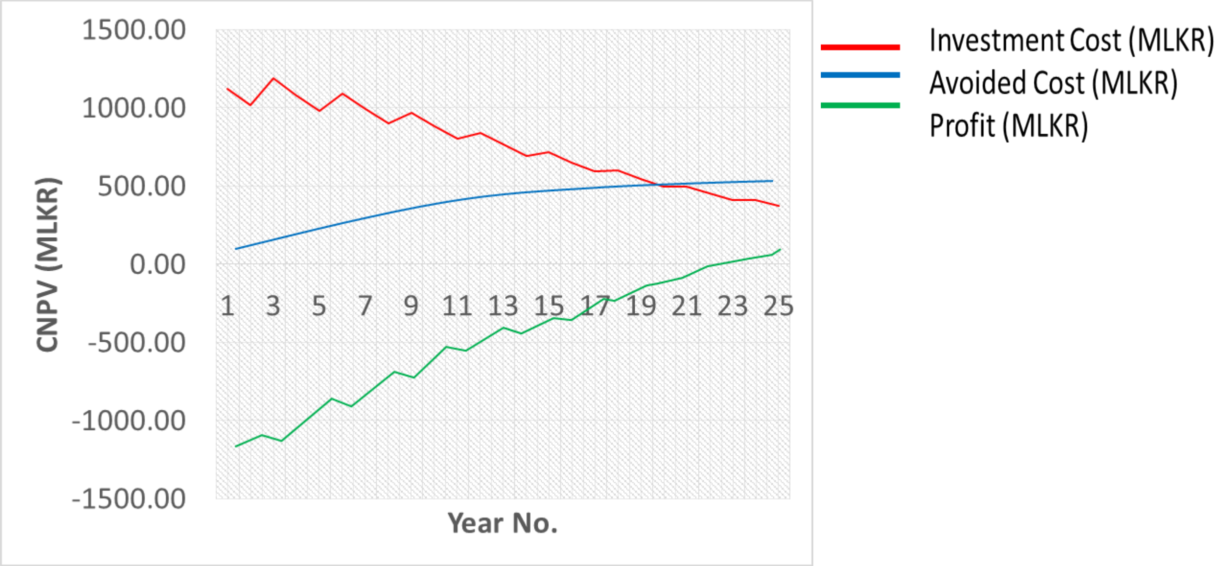

Figure 8.2: CNPV Comparison of 30% BESS

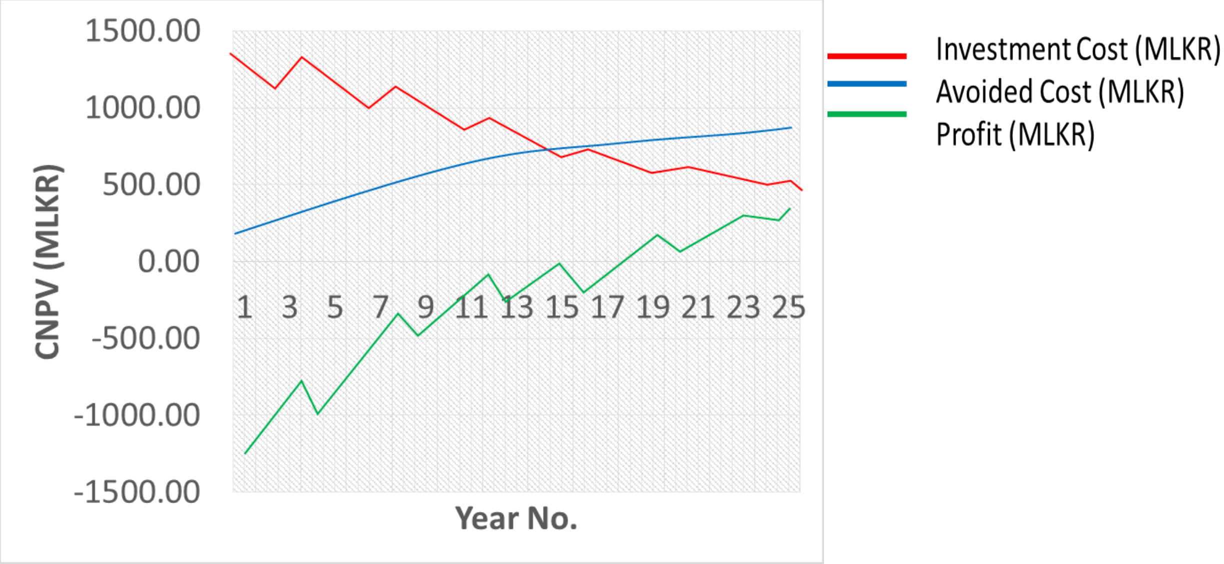

Figure 8.3: CNPV Comparison of 50% BESS

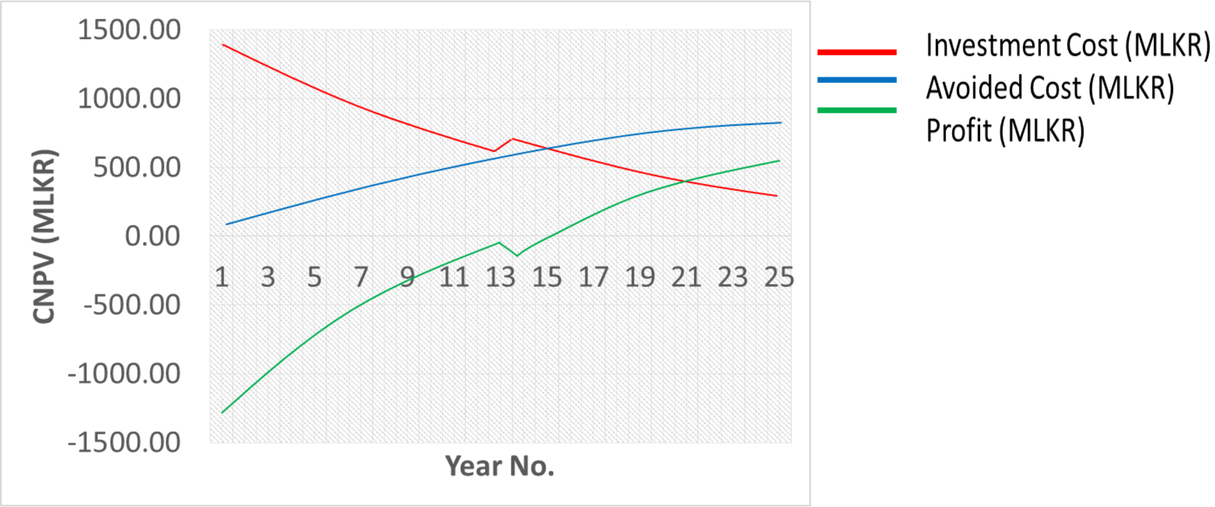

Figure 8.4: CNPV Comparison of 80% BESS

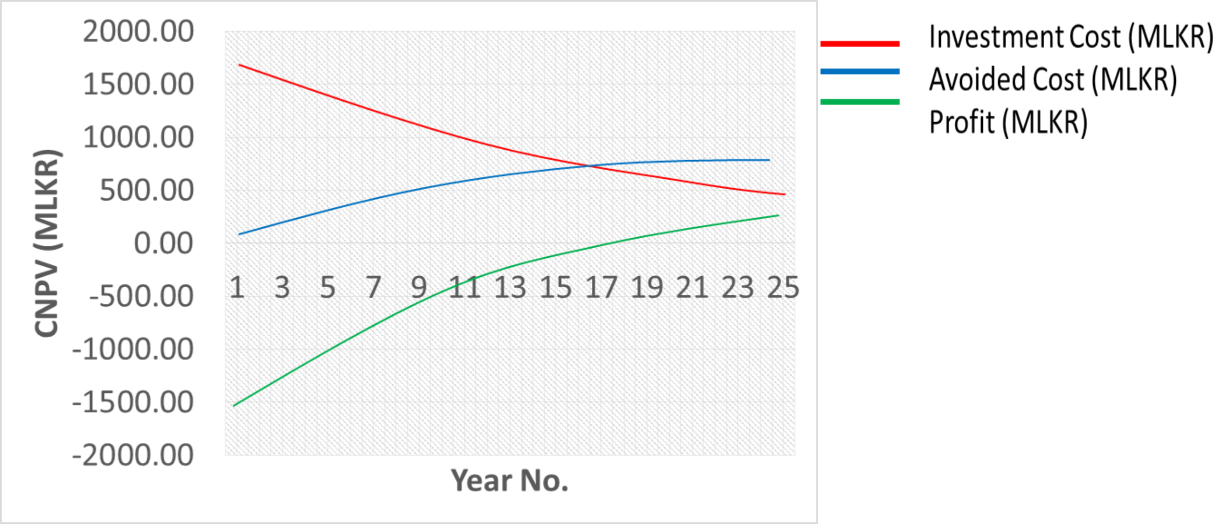

Figure 8.5: CNPV Comparison of 100% BESS

Avoided unit generation costs of each case have identified to know the profit margin.

8.3 Summary of Cash Flow Analysis of Parabolic Trough with TESS Plant

Comparison of avoided cost with system cost, the results are graphically represented in figure 8.6.

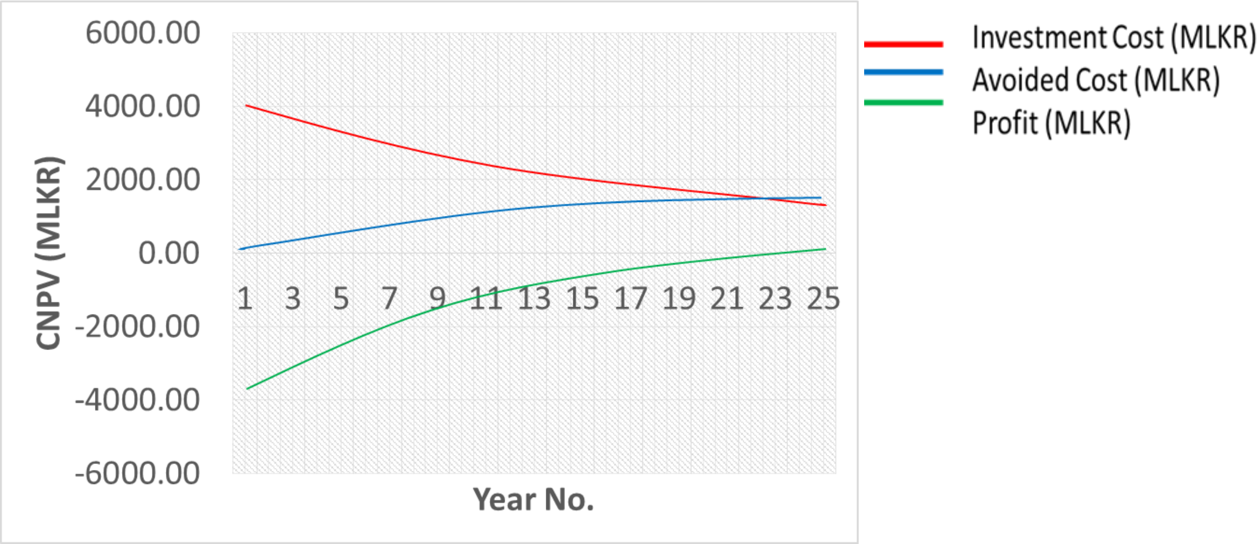

Figure 8.6: CNPV Comparison of Parabolic Trough Plant with TESS

8.4 Summary of Cash Flow Analysis of Heliostat Field with TESS Plant

Comparison of avoided cost with system cost, the results are graphically represented in figure 8.7.

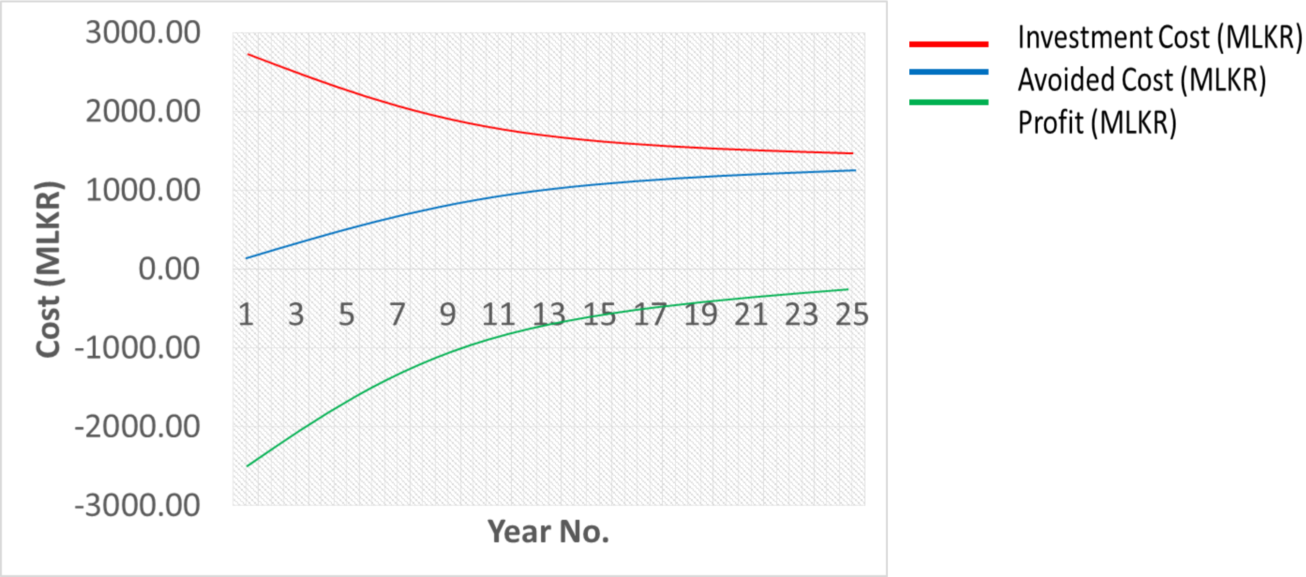

Figure 8.7: CNPV Comparison of Heliostat Field Plant with TESS

8.5 Summary of Cash Flow Analysis of Parabolic Dish with TESS Plant

Comparison of avoided cost with system cost, the results are graphically represented in figure 8.8.

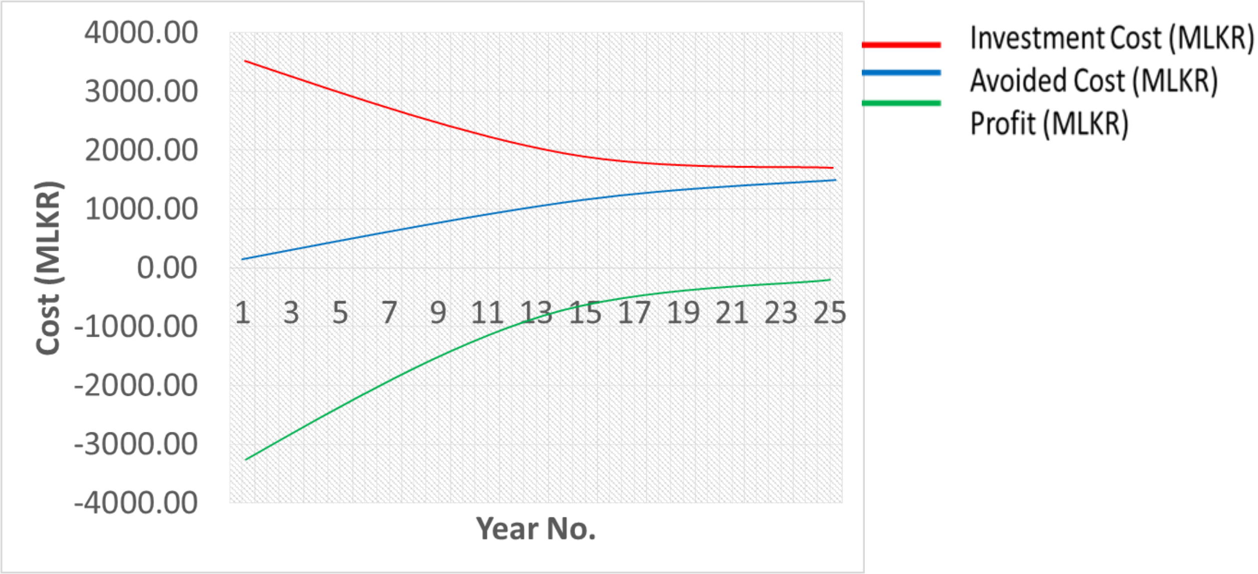

Figure 8.8: CNPV Comparison of Parabolic Dish Plant with TESS

8.5 Summary of Cash Flow Analysis of All Options

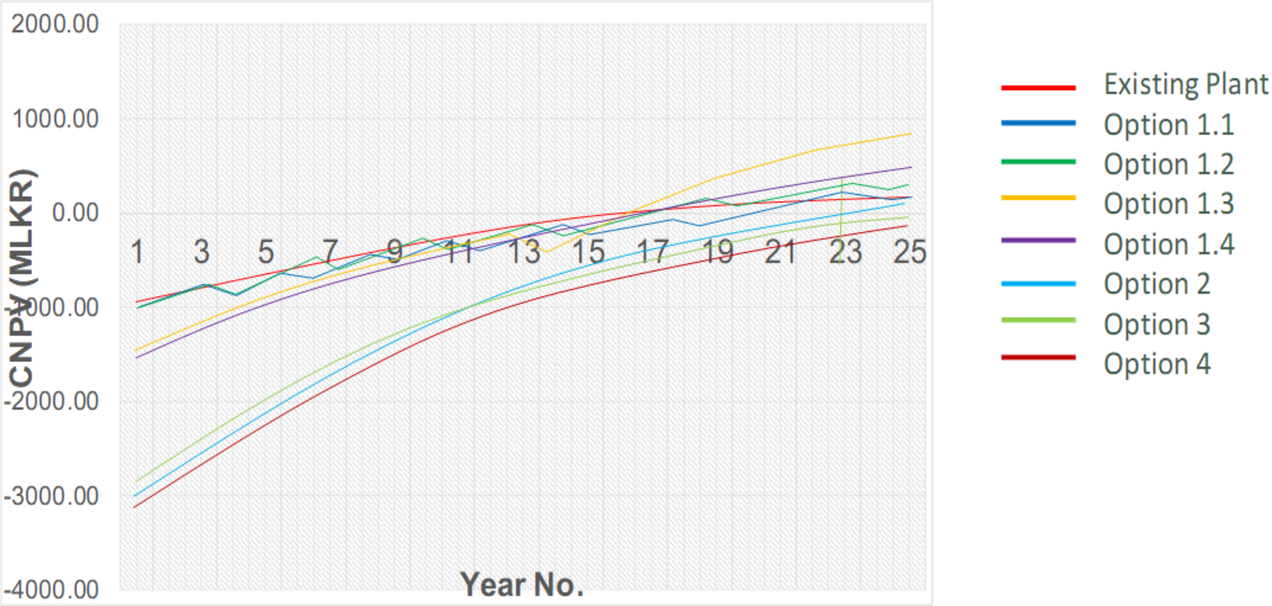

Figure 8.9: Summary Comparison of Options

Table 8.1: Summary of SSPP Options

Plant	NPV of Plant (MLKR)	Breakeven point (years)
Existing PV Plant	> 0	17.5
Option 1.1: PV SSPP with 100% DOD BESS	> 0	20.1
Option 1.2: PV SSPP with 80% DOD BESS	> 0	17.8
Option 1.3: PV SSPP with 50% DOD BESS	> 0	15.5
Option 1.4: PV SSPP with 30% DOD BESS	> 0	17.2
Option 2: PD SSPP	> 0	23.1
Option 3: PT SSPP	< 0	-
Option 4: HF SSPP	< 0	-

CHAPTER 9

CONCLUSION & RECOMMENDATION

In the research work, three types of grid connected storable solar power plant technology options have been modeled to replace existing PV plant without storage in Hambantota hypothetically. Discounted cash flow analysis using avoided cost scenario have been used. Analysis is done for 25 year operating period of plant. CNPVs of system costs which is the addition of capital cost and O & M costs and avoided cost is compared in the same graph. For base load plants and peak load plants, the considered avoided costs is different.

For all three options, avoided generation cost of marginal power plant is considered as 48.87 LKR/kWh. For, first option which is PV with BESS plant, four different type of battery configurations have been considered as 30% DOD case, 50% DOD case, 80% DOD case and 100% DOD case. Investment on SSPPs with 50% DOD BESS is more profitable than other three BESS configurations.

Investment on PD SSPP plant is less profitable than all configurations of PV SSPP.

Investment on PT SSPP plant and PD SSPP is not profitable.

REFERENCES

[1]. Solargis. (2015, November 25). *Irradiance Data of Sri Lanka* [Online]. Available: https://solargis.com/.

[2]. “Achievements of Renewable Energy Targets of Sri Lanka 2011”PUCSL, 2012

[3]. Asoka Abegunawardhana, “Renewable Energy Policies in Sri Lanka”, 2012

[4] “Statistical Digests”, CEB, 2014

[5]. *Load Duration Curve,* Statistical digests, CEB, 2014.

[6]. T. E. Boukelia; M. S. Mecibah; I. E. Meliche, “Design, optimization and feasibility study of parabolic trough solar thermal power plant with integrated thermal energy storage”, Algeria, 2015

[7]. Mohamed M. Abousaba; Hatem Abdelraouf; Fuad Abulfotuh; Marwa Zeitoun; Javier García-Barberena, “Modeling of central tower concentrated solar power plant”, Iran, 2013

[8]. Ankit Moldgy; R. Parameshwaran, “Solar thermal energy storage for heating applications — A review”, India, 2015

[9]. “Generation Performance in Sri Lanka 2014”, PUCSL, 2015.

[10]. NREL. (2015, January 20). *Concentrated Solar Power Technologies,* China [Online]. Available: https://www.nrel.gov/.

[11]. “PV Cell Technology Comprison”, NREL, 2015

[12]. Bansal NK, Sandeep G. Large scale Battery Storage Comparison for solar Technologies, New Delhi. 2014;

[13]. P Dimple Raja; Ketan P Detroja,”Optimal sizing of PV panels and battery for grid connected load under dynamic pricing”, California, 2015

[14]. SolTrace Software, NREL, 2013

[15]. LG CNS, 48V 2000Ah Li ion Battery, datasheet

[16]. Thermosolglass, 7 feet Parabolic trough reflector, data sheet

[17]. DiVA Portal, 10 feet central tower reflector, datasheet

[18]. “Parabolic Trugh Solar Power Plant Simulation Model”, NREL, USA, 2013.

[19]. LG CNS, Monocrystalline 250W PV module, datasheet

[20]. LG CNS, 200kW Solar Inverter, datasheet

[21]. “Avoided Cost Interim 2015”, IEPA, California, 2015

[22]. “LTGEP 2015-2034”, Transmission & Planning Brach, CEB, 2015

[23]. Ioan Luminosu; Aldo De Sabata; Dan Mărgineanu; Valentin Ciupe, “Solar thermal systems developed in the western part of Romania: An LCoE analysis”, Romania, 2015