An investigation to maximize efficient utilization of renewable energy capacity integrated in an existing industrial cogeneration plant

A

Thesis

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By

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PUNJAB
2024

DECLARATION

I hereby declare that this research work “An investigation to maximize efficient utilization of renewable energy capacity integrated in an existing industrial cogeneration plant” has been composed solely by myself and has not been submitted anywhere. It was carried out by me for the degree of Doctor of Philosophy in Electrical Engineering under the guidance and supervision of Dr. Amit Kumar Singh, Lovely Professional University, Phagwara Punjab, India.

The interpretations put forth are based on my reading and understanding of the original texts and they are not published anywhere in the form of books, monographs or articles. The other books, articles and websites, which I have made use of are acknowledged at the respective place in the text.

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CERTIFICATE

This is to certify that the thesis entitled “An investigation to maximize efficient utilization of renewable energy capacity integrated in an existing industrial cogeneration plant” being submitted by **ANKEM V R N B Manikyala Rao** for the degree of Doctor of Philosophy in Engineering from Lovely professional University, Jalandhar is a record of bonafide research work carried out by him under my supervision at the School of Electronics and Electrical Engineering. In our opinion, this is an authentic piece of work for submission for the degree of Doctor of Philosophy. To the best of our knowledge, the work has not been submitted to any other University or Institute for the award of any degree or diploma.

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ABSTRACT

With reforms in the electricity sector and as per the Electricity Act 2003, electricity generation is deregulated with a concept of electricity that can be produced by anybody and sold to any consumer. This permits utilizing the existing transmission network by paying open access charges. Accordingly, captive power generation is encouraged to meet enormous demand requirements that are increasing daily due to growth in all sectors.

An increase in installed generation capacity resulted in an adverse effect on environmental pollution levels and global warming effects. This is due to most of the generation is based on conventional fossil fuels. This is creating a vacuum on availability of the fuels like coal, oil, and natural gas. This has become a threat to the energy security and to future generations also.To obviate these problems government policies are aimed at encouraging renewable energy generation through incentives and regulations. As a part of these policies, most of the state regulatory commissions imposed regulations on the mandatory generation of renewable energy. A fixed percentage of renewable energy in total generation has become compulsory. In case of non- fulfillment of renewable energy plants addition, equivalent renewable energy certificates are (RECs) insisted. With this most of the captive/cogeneration plants have gone for renewable energy generation mainly either solar or wind. However, the integration of renewable energy with conventional energy generation posed many challenges to the co-generators especially on the efficiency and operating parameters of the process systems due to the variable nature of renewable energy.

In cogeneration power plants, sequential generation of heat and power takes place. Two approaches of either topping or bottoming cycle are adopted. Integration of renewable energy leads to variations in the cogeneration levels (both thermal as well as electrical) resulting in a lot of fluctuations in process parameters (steam, Pressure, and flow). The variable nature of renewable energy generation levels based on daily and seasonal atmospheric variations, lead to inefficiencies. Effects on plant operation are much more severe in the case of solar/ wind as solar generation depends mostly on the environmental conditions. With renewable generation power reduction from TGs takes place to maintain constant electrical load. The load reduction contributes HP and LP extraction flows. Due to reduction in extractions, balance steam supply is met through HP and LP PRDS (Pressure reducing and desuperheating) stations. Whenever a

boiler load reduction takes place below a minimum level of 60% load, additional oil support is essential as per the original design, to avoid furnace disturbances. All these introduced inefficiencies resulting in an increase in the cost of generation.

The objective of the research is to study the effects of the integration of renewable energy (RE) with cogeneration power plant operations. In this research, the study of a typical cogeneration plant with double extraction and condensing type turbines with an additional auxiliary steam turbine is taken up. The cogeneration plant supply steam at high, medium, and low pressures (HP, MP, and LP) and requisite electrical load to a chemical process industry. Renewable energy generation (solar) is added directly to plant electrical network to fulfill the statutory requirements. The study focused on the study of post-operational constraints that arose with the addition of photovoltaic solar power plant. The fluctuations of generation from turbo generator, import and export of power to the grid, flow and pressure variations of HP and LP steam, variations in HP and LP PRDS (Pressure reducing and Desuperheating) valves opening are the main factors for inefficiency. The reduction of boiler loading below a minimum level necessitating oil support, etc are the main post operational constraints. Suitable optimization techniques are suggested to mitigate the inefficiencies. Conducted the experiments practically and the data is obtained for various solar generation levels. The break-even point is arrived at by cost-benefit analysis to optimize the plant operation. The study revealed that it is economical to utilize renewable energy until overall system efficiencies are maintained and to store further renewable energy beyond the break-even point i.e., the point beyond which renewable energy utilization becomes inefficient in cogeneration plants. The stored energy can be utilized during periods when renewable energy generation is less than the break-even point. After establishing the break-even point through the practical experimentation method, a systematic methodology based on the heuristic forward chaining approach technique is developed to establish the break-even point. An algorithm/flow chart is developed based on the turbo-generator load and extraction pressure controller's behavior with renewable energy injection. Based on technical limitations associated with co-generation plants equations based on theoretical concepts are developed. Main limitations with extraction cum condensing type turbines are ensuring minimum flows through the low-pressure part of a turbine as well as to the condenser. These equations guided the high and low-pressure extractions from a turbine. Based on the mathematical model developed, optimality conditions based on pressure loss due to steam flow

through high-pressure and low-pressure desuperheating stations and steam generator flow are established. An iterative technique is used and algorithm is developed. The algorithm developed is executed using MATLAB. Data is obtained at different renewable energy generation levels with an increment of 1 MW in each iteration cycle. The iteration process is terminated when any one of the optimality conditions deviated. The accurate value of a break-even point is obtained using Newton Raphson's empirical formula. The Break-even point obtained is compared with the practical experimentation results. The model developed is system/case-based therefore, design as well as technical limitations may vary from system to system. To select a suitable storage device for the present application, a review of comparative studies between various energy storage techniques is carried out and presented. Based on the form of energy stored in the system total 5 categories of storage options viz. electrochemical, mechanical, chemical, thermal, and electrical storage systems are studied. The advantages and disadvantages of the various storage technologies are studied. The numeric values like Capacity, duration of storage, type of storage, lifetime, response time, duration of discharge at maximum power level, specific energy, energy density, efficiency, etc. are considered. Based on the data from the literature, the suitability of each technology is analyzed on technical parameters. Based on analysis concluded electrochemical and hydrogen storage technologies are suitable to present application. Based on further economic study, it is concluded lead acid batteries can be the best suitable storage option for the present case. Total capital and life cycle costs, and net energy analysis based on two energy ratios viz electrical energy stored on invested and the overall energy efficiency is the factors considered during economic analysis. The methodology presented for the determination of suitable storage technology can be a guiding principle for various cogeneration and grid-connected renewable energy systems.

Further, designed the battery energy storage system and estimated the capacity based on the practical solar irradiance data. A rule-based algorithm is developed to control the charge and discharge cycles of battery storage based on predefined conditions. The payback period is estimated based on the expected monetary benefits due to proposed energy storage and ensured the proposed system is economical. The post-operational issues are resolved by introducing energy storage. The methodology presented can be a guiding tool for various renewable energy-integrated cogeneration systems optimization.

The research helped to resolve societal issues, industrial issues, Government issues, business issues, and environmental issues, energy security threat. The research addressed these societal problems. The remedial solutions to the challenges being faced by cogeneration plants on integration with renewable energy are addressed. Finally, the research results in an increase in renewable energy share. Hence, minimizes fossil fuels utilization and minimizes the environmental degradation issues like global warming and increase in emission levels, etc. Research also focused on the age-old cogeneration plants design concepts optimization through renewable energy integration techniques through storage options.

However, depending on the requirement of heat and electrical loads, industries have adopted different conventional designs based on process requirements. The improvements to the existing conventional cogeneration designs are proposed. New design aspects to optimize the cogeneration plants further by integrating with renewable energy using suitable energy storage devices are suggested. An increase in the efficiency of renewable energy-integrated cogeneration plants results in drastic savings in fossil fuels. Hence, adopting new design aspects enhances energy security and at the same time protects the environment from degradation.

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Throughout the writing of this dissertation I have received a great deal of support and assistance. First and foremost, I would like to express my deep and sincere regards for my supervisor, Dr. Amit Kumar Singh for providing me the opportunity, support and freedom to carry on this research work. His passion, guidance, and discipline have been indispensable to my growth as a scientist and as a person over these past four years. I am especially grateful for his devotion to his students’ education and success.

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CONTENTS

LIST OF CONTENTS

CHAPTER-1

INTRODUCTION

CHAPTER-2

CASE STUDY OF AN IDENTIFIED RENEWABLE ENERGY (RE) INTEGRATED COGENERATION PLANT

CHAPTER-3

LITERATURE REVIEW

CHAPTER - 4

BEP (BREAK-EVEN POINT) ESTIMATION BY REAL–TIME / ONSITE DATA

CHAPTER - 5

BEP ESTIMATION BY HEURISTIC FORWARD CHAINING APPROACH

CHAPTER-8

INDUSTRIAL COGENERATION PLANTS DESIGN OPTIMIZATION BY INTEGRATING WITH RENEWABLE ENERGY

CHAPTER-9

CONCLUSION & FUTURE SCOPE OF RESEARCH

APPNDIX A

LIST OF FIGURES

LIST OF TABLES

ACRONYMS AND ABBREVIATIONS

Acronyms	Description
ALCC	Annualized Life Cycle Costs
AWS	Automatic Weather Station
BEP	Break-even Point
BESS	Battery Energy Storage Systems
BFWP	Boiler Feed Water Pump
BOP	Balance of Plant
CAES	Compressed Air Energy Storage
CEP	Condensate Extraction Pump
CHP	Combined Heat and Power
CT	Charging Timer
DC	Direct Current
DOD	Depth of Discharge
ECES	Electrochemical Storage
EES	Electrical Energy Storage
EHTC	Electro Hydraulic Turbine Controller
$ESOI_e$	Electrical Energy Stored on Invested
ESP	Electro Static Precipitator
ESTs	Energy Storage Technologies
FD	Forced Draft
GHI	Global Horizontal Incidence
GTI	Global Tilted Incidence
HP	High Pressure
HPS	High Pressure steam
HV	High Voltage
ID	Induced Draft

KCR	Kendriya Chemical Refinery
LCC	Life Cycle Cost
LCOE	Levelized Cost of Electricity
LCOS	Levelized Costs of Storage
LHS	Latent Heat Storage
LIB	Lithium-Ion Batteries
LP	Low Pressure
LPS	Low Pressure steam
MATLAB	Matrix Laboratory
MCR	Maximum Continuous Rating
MP	Main Plant
MPP	Maximum Power Point
NRV	Non-Return Valve
O&M	Operation and Maintenance
PCS	Power Conversion Systems
PCT	Phase Change Temperature
PCU	Power Conditioning Unit
PHES	Pumped Hydro Energy Storage
PRDS	Pressure Reducing and Desuperheating Station
PSCAD	Power System Computer-Aided Design
PV	Photovoltaic
R/P	Reserves to Production ratio
RE	Renewable Energy
RECs	Renewable Energy Certificates
REMC	Renewable Energy Management Centers
RES	Renewable Energy Sources
RFB	Redox Flow Batteries
RHFC	Regenerative Hydrogen Fuel Cell
RPPOs	Renewable Power Purchase Obligations
SG	Steam Generator

SGs	Steam Generators
SHS	Sensible Heat Storage
SLDC	State Load Dispatch Centre
SMES	Super conducting Magnetic Energy Storage
SOC	State of Charge
SSB	Sodium Sulphur Batteries
STC	Standard Test Conditions
T & D	Transmission and Distribution
TCC	Total Capital Cost
TCES	Thermo-Chemical Energy Storage
TG	Turbo Generator
TGs	Turbo Generators
TPH	Tonnes Per Hour
VAR	Volt Ampere Reactive

List of Symbols

Symbol	Description
€	EURO currency
λ	Life cycle
ε_e	Cradle- to- gate electrical embodied energy
G_{ref}	Solar radiation at STC amounting to1000W/m^2
K_t	Temperature coefficient of mono and poly crystalline Si cells amounting to $K_t = 3.7\ 10^{-3}$/°C
T_{ref}	reference temperature at STC amounting to 25 °C

CHAPTER-1

INTRODUCTION

1.0 INTRODUCTION

In this chapter the basic concepts of cogeneration including the advantages in industries that require both thermal and electrical energies are presented. The main advantages of efficiency improvement, reduction in cost of production, and reduction in transmission losses etc. are highlighted. The changes in energy industry over a period of time on account of increase in generation levels and demand are indicated. The regulation on renewable power purchase obligation enforced the industries to generate fixed percentage of renewable energy (RE). The cogeneration industries are gone for renewable energy generation like solar/wind to fulfil the renewable power purchase obligation. The estimation of RE capacity plant to be installed is illustrated by considering an identified industry. However, with integration of renewable energy, the challenges faced by the industry based on practical observations/experience are presented. Finally the main motivation to take up this industrial problem as a research thesis is expressed. The thesis outlines and the main objectives of the thesis to maximise RE utilization are expressed clearly. Finally the works carried out to achieve the objectives are brought out in a flow chart indicating the results achieved at various stages of the work.

1.1 COGENERATION

Cogeneration or Combined Heat and Power (CHP) can be termed as the sequential generation of two different forms of energy from a single primary energy source [1]. Co-generation is of topping or a bottoming cycle. In topping cycle primary fuel energy is first used to produce electrical energy in turbines (Gas/diesel engines/steam turbines). The exhaust/extraction from these turbines in the form of thermal energy is used mostly in process industries to meet the process heat or other thermal requirements. In a bottoming cycle, the primary energy produces high temperature thermal energy for utilization in process. The heat rejected from the process is used for generation of electricity through recovery boilers and steam turbines. Both topping and bottoming cycle co-generation systems are commonly used in process industries.

Advantages of using cogeneration technology can be many. Main advantage is the tremendous savings of primary energy when compared against the supply of electricity and heat from conventional power stations and boilers. The main savings of energy with topping cycle is due to utilising the latent heat of the exhaust / extraction steam from the turbines.

Otherwise same thing could have been wasted through cooling tower. Hence backpressure turbine systems are more efficient. Saving of fossil fuels helps in reduction of greenhouse gases. Cogeneration helps in reduction of transmission and distribution losses as the power required is being generated at the load point itself. .

Other advantage of cogeneration is reduction of the energy bills, hence cost of generation. The wheeling of power provision in electricity act 2003 benefitted the cogeneration systems [2] by earning more profits. As power produced through cogeneration is at a cheaper rate the profits are at higher rate than conventional power plants. It is not an astonishing that some of the industries are earning more profits than their main product. Another advantage of cogeneration is that it helps in higher production as the reliability of the plant improves due to non-dependence on external agencies for energy requirement.

The fossil fuels are depleting at a faster rate, hence forcing to adopt the energy efficient technologies to maintain sustainable development and energy security. Hence, government policies are revised to encourage the renewable energy generation. Cogeneration / CHP plants are instructed to generate fixed percentage of their total demand through RE route. Many industries have installed RE plants and integrated with the existing cogeneration/CHP plants. With RE addition, it is observed that the existing optimality conditions are deviated due to deviation of the operating parameters from the standard /designed values. This resulted in inefficient operation of the cogeneration plants. Many co generators are left with options of either to lose the efficiencies or switching off the part of the installed RE capacity. Hence, the main aim of the research is on study of the issues developed after integration and to maximise the efficient utilisation of the RE capacity installed.

1.2 NECESSITY OF THE INTEGRATION OF RENEWABLE ENERGY

With reforms in electricity sector and as per the electricity act 2003, electricity generation is deregulated with the concept of electricity can be produced by anybody and can be sold to any consumer by utilizing the existing transmission network by paying open access charges [2]. Accordingly captive power generation is encouraged.

With increase in installed generation capacity to meet the enhanced demand levels resulted in an adverse effects on environment pollution levels and global warming effects as the most of the generation is on conventional fossil fuels. This is also creating a vacuum on availability of the fuels like coal, oil and natural Gas, reducing the Reserves to Production (R/P) ratio at a faster rate. Hence, become a threat to the energy security and to the future Generations.

To obviate these problems government policies are aimed at encouraging RE generation through incentives and regulations. As a part of these policies most of the state regulatory commissions made mandatory that at least 5% of the total generation should be from RE resources out of which at least 0.25% should be from solar. Otherwise equivalent Renewable Energy Certificates (RECs) should be produced through purchase from power exchanges [3]. With this most of the captive/cogeneration plants have gone for RE generation mainly either solar or Wind. However the integration of the RE with the conventional energy posed many challenges to the co generators especially on the efficiency and operating parameters of the process systems due to variable nature of the RE.

1.3 CAPACITY ESTIMATION OF RENWABLE ENERGY PLANT

To meet the Renewable power purchase obligation, added solar plant based on the environmental conditions and the capacity of the plant is selected as follows

Evaluation of required energy generation to meet RPPO obligation

Daily electrical power consumption of HWP (M) = 35 MW* 24 hrs = **840MWh/day**

5% of whole consumption /day = **42000 kWh/day**

5% of whole consumption year = **15330MWh/year**

Considering the degradation of the PV cell performance with time and variation in the solar irradiation data, weather parameters etc., and an additional 10% capacity over and above the calculated value is considered for evaluating the plant capacity. Accordingly the plant energy generating capacity is worked out as:

1.1x 15330 = 16863 MWh / Year

Hence energy generating capacity in MW=16863/365*24=1.92 MW

Considering 16 % solar plant efficiency, capacity of the Solar plant =1.92/.16=11.7 MW (Peak). Accordingly 12 MW (peak) PV solar plant is set up.

1.4 STATEMENT OF THE PROBLEM

Integration of the RE with the conventional energy posed many challenges to the co generators especially on the efficiency and operating parameters. Reduction of steam flows from Steam Generator (SG) and turbine extractions introduced the inefficiencies. To maintain the optimality conditions co generators are forced to switch off the part of RE capacity. The main problem is the non-utilization of installed RE capacity fully. This resulted in to the violation of RPPOs obligations including losing the environmental friendly energy. This necessitated to design a system to utilise the installed RE capacity fully without deviating the optimality conditions.

1.5 MOTIVATION

In close association with industry, personally experienced the challenges/problems faced on integration of RE with the existing cogeneration plant. Associated with the experiments conducted and established the conditions responsible for deviations from the optimality conditions. Based on the experiments, it is concluded that the main factors attributed to inefficient operation are reduction of extraction steam flows through turbines resulting in an increase in the heat rate of a turbine, and reduction of SG outlet flows to below the threshold values, resulting in oil support and cost escalation. To optimize the cost at present, it was suggested to the management to restrict solar plant capacity up to the point optimality conditions are not deviated. It is found that only 50% of the installed solar plant has become operative. With the revised operation, the industry is keeping 50% of the solar plant idle and is not able to fully meet the RPPOs obligation. Hence, the main motivation of this research was initiated from a practical problem faced in the industry. Hence, it was decided to innovate a way of fully utilizing the installed solar capacity and to optimize the cogeneration plant's operation. Knowing that a potential outcome of this research could resolve major global issues of energy security and environmental degradation in addition to presenting a solution to the many cogeneration plants further boosted the motivation to take up the research.

1.6 THESIS OUTLINE

To present a solution to the many cogeneration plants taken up the research with the following objectives,

1. To investigate the challenges developed in achieving full capacity utilization of RE integrated with an existing industrial cogeneration and collecting data.
2. To establish a Break-even Point (BEP) beyond which RE utilization becomes inefficient by developing an algorithm using a suitable heuristic technique.
3. To establish a comparative analysis of RE storage options available and determine suitable technique to store RE beyond the BEP.
4. To estimate capacity of energy storage device based on the expected renewable energy generation and estimated BEP.
5. Devise a control mechanism to store RE beyond BEP and reutilize the same during non RE period.
6. To develop and Simulate Mathematical modeling using MATLAB to balance energy flows including energy storage and discharge devices to maximize RE capacity utilization.

1.7 DESCRIPTION OF THE WORK DONE IN THE THESIS

Objectives mentioned are achieved systematically. Fig 1.1 indicates works carried out in sequence to achieve the objectives including the results achieved.

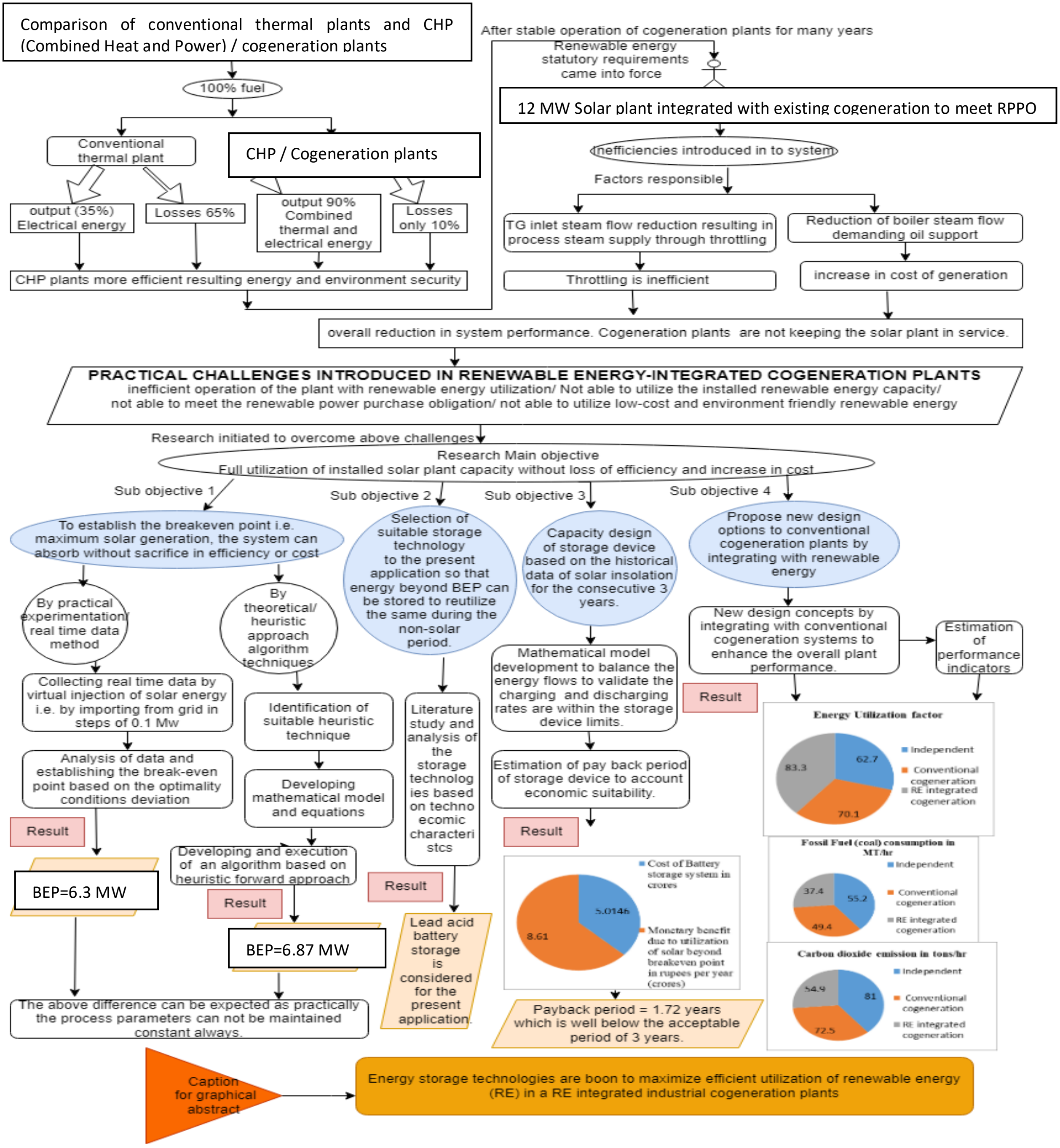

Figure1.1.Master flow chart describing the work done

1.8 SUMMARY

Finally, the research resolved the major problems developed in a CHP plant after integration. Estimation of BEP and design of suitable storage capacity to store the RE beyond BEP prevented deviation from optimality conditions. This made the system optimization at full solar capacity possible without affecting the efficiency of the cogeneration plant.

CHAPTER-2

CASE STUDY OF AN IDENTIFIED RENEWABLE ENERGY INTEGRATED COGENERATION PLANT

2.0 INTRODUCTION

Cogeneration plant is identified where renewable energy of 12 MW capacity is added to the existing system. In this chapter the identified plant systems and equipments are described in detail by developing the block diagram of the system. The turbine control systems of hydraulic and electro hydraulic turbine controller are explained. The high pressure and low pressure extraction controllers and the control philosophy including the speed and power controllers' significance are presented. The import / export controller behaviour on injection of renewable energy is illustrated to understand the post operational effects of renewable energy integration. The post effects of the RE integration are brought out in detail to present a clear picture of the challenges faced by the industry. The practical observations made during plant operation with RE plant are listed. The practical observations presented in this chapter can be a guiding factor for further study and to reach a feasible solution.

2.1 DESCRIPTION OF AN IDENTIFIED RENEWABLE ENERGY INTEGRATED COGENERATION PLANT

Figure 2.1 represents the block diagram of a cogeneration plant where RE is integrated. Here the solar plant indicated is integrated with the system later and connected to the existing plant electrical main 6.6 kV switchgear.

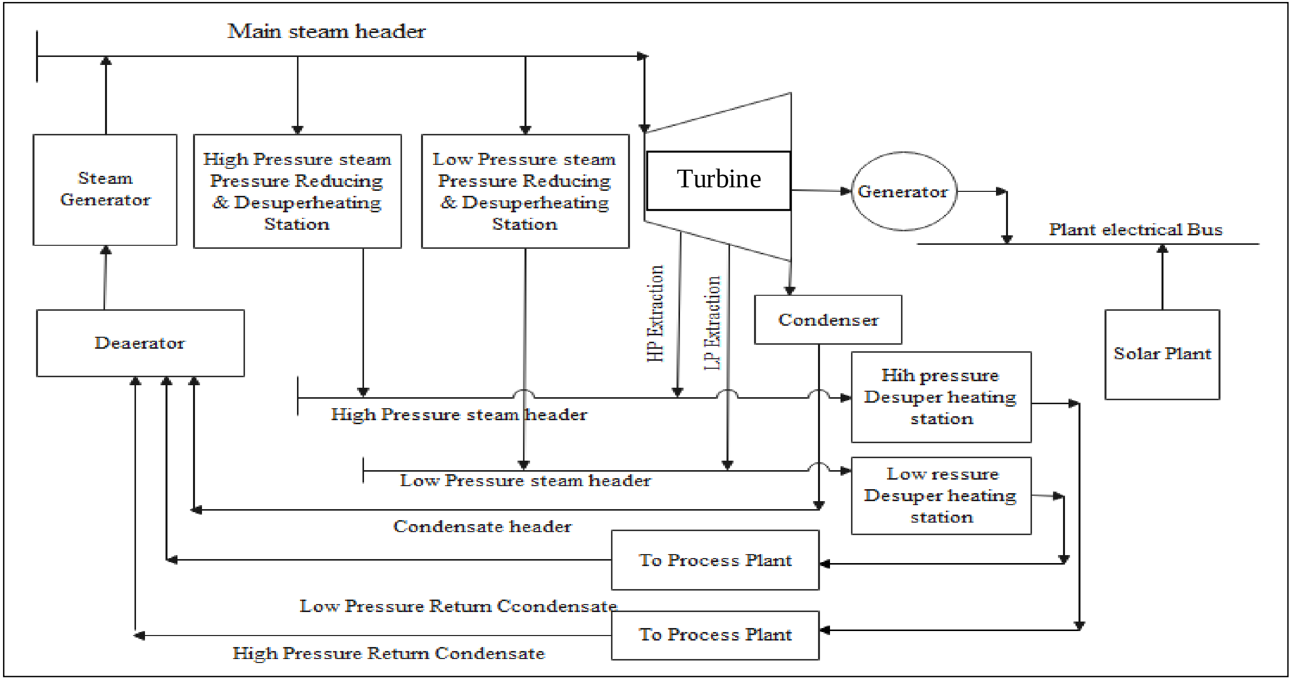

Figure 2.1 Block diagram of the cogeneration system

Cogeneration plant of KCR (Kendriya Chemical Refinery) in Telangana state of India is provided to meet the steam and power requirements of chemical process plant (generally termed as Main Plant). Main Plant (MP) requires around 240 Tonnes Per Hour (TPH) of HP steam at a pressure of 32 ata and 240^0C and 45 TPH of LP steam at a pressure of 8 ata and 180^0 C. Total power requirement of Main Plant is 35 MWe. Steam Generators (SGs) of 3 Nos, each capable of delivering superheated steam at the rate of 265 TPH at 106 ata & 485^oC. SG consists of radiant boiler with integral super heaters, forced flow section (Economizer) and tubular air heater with two Forced Draft (FD) and two Induced Draft (ID) fans and Electro Static Precipitator (ESP). The boiler Plant is equipped with ancillary equipment to fire pulverized coal, furnace oil and High Speed Diesel (HSD). The steam outlet header of each SG is connected to a common header with an isolating valve, which is known as main steam header. Inter-connecting valves between Unit-I & II and Unit- II & III are provided on Main Steam Header. In the block diagram all the 3 SGs are indicated as a single block.

Similarly, 3 Nos of Turbo Generator (TG) sets of double extraction are provided to supply process steam and power to process plant for production of chemicals. Each TG is capable of generating 30 MWe at 0.85 power factor. The steam throttling parameters at turbine inlet are 100 Kg/cm^2 and 480^0C. The TG is equipped with electro-hydraulic governing system with a backup of hydraulic. The turbines are of extraction condensing type having two extractions. First extraction, also called as HP extraction, is controlled at 33.5 ata with the help of turbine governing control system. Second extraction also called as LP extraction is un-controlled but controlled outside at 9.5 ata with the help of pressure control valve. In the block diagram all the 3 Turbo Generators (TGs) are indicated as a single block.

Main Steam Header (MSH) supplies steam to TGs, High Pressure Steam (32ata) Reducing and De- Superheating Station (HPPRDS) and Low Pressure Steam (8ata) Reducing and De - Superheating Station (LPPRDS). HP Steam can be supplied through HP PRDS station and Turbine HP extraction. HPPRDS steam supply is used during plant startup and in case where HP extraction steam from operating TG Units is not sufficient to cater the requirements of process main plant. There are two HPPRDS stations A and B. Each HPPRDS is provided with a pressure and a temperature control Valves. In the block diagram both HPPRDS stations are indicated as a single block. The temperature of HP steam going to process plant is controlled by the HP de-superheating station on HP Steam header. Spray water required for de-superheating is obtained from boiler feed pump discharge header.

LP Steam system is similar to HP steam system. LP steam header is maintained at 8 ata and 238^oC. During normal operation, TGs will meet the requirements of LP Steam. In case where extraction steam is not sufficient, PRDS will maintain the supply. The temperature of LP steam going to main plant is controlled by the LP de-superheating station provided on LP steam header. Spray water required for de-superheating is obtained from common header of CEP discharge. LP steam is also used for feed water heating in deaerator. Both HP and LP steam return condensates from process plant are fed back to cogeneration plant.

Extraction cum condensing type turbines are provided with additional controls than conventional type turbines. These are required to maintain the extraction pressures. Additional interlocks to maintain minimum steam flow to LP part of the turbine is provided to avoid starvation effects even though inlet flow is maintained [4]. Hence, the main controls provided in the TG system are power/speed control, HP, and LP extraction pressure controls. In addition to these cogeneration plants/ captive power plants are provided with master import and export controller to maintain the total import or export from or to the grid constant. HP and LP control valves provided for controlling get the signals from these controls. Speed /power controller maintains the TG generation constant at a predefined set value by operating both HP and LP control valves in the same direction. Hence, in case of reduction in TG generation both the HP and LP control valves get close so that the steam flow reduction in both the HP and LP part of the turbine remains constant [4], [5]. HP extraction pressure controller maintains the HP pressure constant by operating the HP and LP control valves in the opposite direction. Hence, in case of reduction in HP pressure, the HP control valve gets open more and LP control valve gets close .This ensures the increase in HP power gets lowered in LP part of the turbine. The ratio module provided determines the ratio of HP and LP control valves opening. Master import and export controller generates the signal to operate the power controller to maintain the import/export constant. Based on variations in HP pressure, the HP pressure controller maintains the pressure without impacting power generation. Normally the second extraction pressure control is uncontrolled i.e., controlled externally through a control valve. However, interlocks to the LP control valve ensure the minimum steam flow through the LP part of the turbine. Quick closing Non-Return Valve (NRV) in the LP extraction pressure ensures minimum flow to condenser beyond LP stage extraction by getting close fully. These control mechanisms ensure safe operation of turbine systems as well as maintains the constant parameters at pre-defined set values. While maintaining the parameters and ensuring safety, the system may shift towards inefficiency. For example, LPPRDS starts opening due to the reduction of LP steam in the process of maintaining constant HP stage pressure during the reduction of load on TG.

Over a period of time in order to meet the RPPO obligations the power generation through SPV (solar power plant) of the order of 12 MWp (DC) is installed. Figure 2.2 indicates the block diagram (Block A) of Grid Integrated 12 MWp solar power plant. Block B, C, D, E, and F are similar to block A.

The solar plant is connected to the grid connected process plant 6.6 kV switchgear. This switchgear is connected to the cogeneration plant also. The Installed solar system consists of total 47600 modules each of 255 watts, 21 modules are connected in a series to form the string and 24 strings are connected in parallel, and then connected to the inverter to meet the required power.

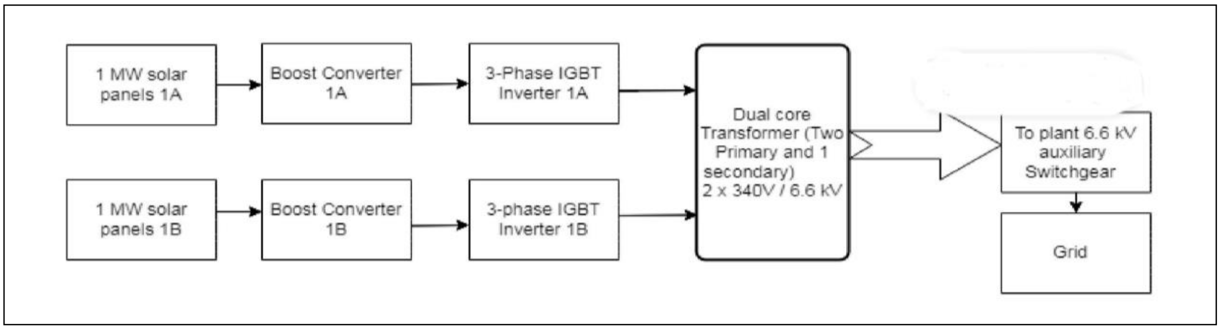

Figure 2.2 Block diagram (Block A) of Grid Integrated 12 MWp solar power plant

In solar power plant total 12 MWp is divided into 6 blocks, A to F each block connected to 2 inverters having the capacity of 1MW. Power evacuation shall comprise of transformer, circuit breaker, isolator, current and potential transformers, metering unit, protection relays etc. Power evacuation for 12 MWp solar power plant single line diagram is as shown in Fig.2.2.The AC power output obtained through the 12 MWp DC systems is divided into two inputs and connected to the process plant substation. The existing distribution voltage within the plant is 6.6 kV. So the transformers for the AC power evacuation of SPV are also designed for 6.6 kV. Main control room within the plant premises is established to receive the output power from the transformer and onward export to the substation. The output supply of 3 phase, 340V, 50 Hz of the inverters voltage is stepped up by using a 2.5MVA capacity dual primary-single secondary (340V/6.6 kV) transformers .This output of the transformer at 6.6 kV level is taken to the main 6.6 kV switch yard of the substation.

2.2 CONTROL PHILOSOPHY

The TG is equipped with two types of governors. One is hydraulic governor and the other one is Electro Hydraulic Turbine Controller (EHTC). Hydraulic governor is normally standby governor to the EHTC. The hydraulic governor has speed controller and extraction pressure controller. The governor works on hydrodynamic principles is simple and easy to operate and maintain. The EHTC governor has speed controller, extraction pressure controller, load controller, frequency controller, and power import/export controller. It utilizes the electronic methods of measuring and processing of signals, which offer the advantages such as flexibility, dynamic stability and integration of complicated functional relationship. The processed electronic signals are introduced in hydraulic circuit through Electro-Hydraulic converter.

2.2.1 SPEED CONTROL:

Turbine speed is sensed by governor impeller, which is driven by turbine main shaft. Governor impeller is supplied with a small quantity of oil. Depending upon the speed of turbine, impeller develops oil pressure from 1.5 to 2.5 kg/cm^2. This oil pressure is called as primary oil pressure. Primary oil pressure acts on bellow of speed governor. The force exerted on the bellow by primary oil pressure is transmitted to the lever through a pin. A compression spring (also called as speeder spring) is mounted on the top of the lever. Spring is pre-compressed by speeder gear motor or a hand wheel. The spring balances the primary oil pressure acting on the bellow. The travel of the bellow is transmitted to the lever, which is pivoted at one end. At its free end the pivoted lever is connected to control sleeves of hydraulic amplifier. Hydraulic amplifier consists mainly of two sets of control sleeves; follow up piston, tension spring and a set of lever system for extraction pressure control. Control sleeves and follow up pistons are provided with control ports. The follow up pistons are held in their respective control sleeves with the help of tension springs. The overlap of ports between control sleeve and follow up piston depends upon primary oil pressure, speeder gear position and tension in the tension springs. Oil from the trip oil circuit is admitted into the follow up piston through an orifice. The pressure inside follow up pistons depends on overlap of control ports. This pressure is called as secondary oil pressure. Variations in primary oil pressure due to speed change, or change in speeder gear position causes the overlap of port between control sleeves and follow up piston to re-adjust. This results in either increase or decrease of HP and LP secondary oil pressures. These pressures are transmitted to the HP and LP control valves actuators respectively.

2.2.2 EXTRACTION PRESSURE CONTROL:

Extraction pressure is sensed by a pressure transmitter and provides actual value to a pressure controller. Pressure controller, depending on the set pressure and actual pressure, produces 0.2 to 1.0 kg/cm^2 pneumatic signal. This signal is transmitted to a pneumatic actuator (Positioning device) which in turn positions the tension springs in follow up pistons through levers. Upon decrease in extraction pressure HP follow up piston spring is pulled up and LP follow up piston spring is released. This results in increase in HP secondary oil pressure and decrease in LP secondary oil pressure. Upon increase in extraction pressure, control action is reversed. These pressures are transmitted to the HP and LP control valves actuators respectively. These HP and LP secondary oil pressures are generated in hydraulic amplifier through combined action of speed governor and extraction pressure controller.

2.2.3 CONTROL VALVE ACTUATORS (SERVO MOTORS):

Servo motors position the HP and LP control valves corresponding to the HP and LP secondary oil pressures generated by hydraulic amplifier. Servo motor mainly consists of a pilot valve, a power cylinder and a feedback system. Upon change in secondary oil pressure, pilot valve provides oil passages to and from power cylinder. The movement of power piston is transmitted to the control valves through levers. The feedback lever resets the pilot valve, to its neutral position. The power piston occupies new position corresponding to changed secondary oil pressure. The system is such that the increase in secondary oil pressure causes the control valves to open. Hence interruption of secondary oil pressure causes the control valves to close.

2.2.4 EMERGENCY STOP VALVE AND STARTING DEVICE:

The emergency stop valve is of quick closing type. The valve is actuated by means of a starting device. The stop valve consists of a spring-loaded piston and piston device which is connected to the valve cone through a spindle. For opening the stop valve, start-up oil from starting device is admitted to the space above the spring-loaded piston, by operating the starting device. Due to start-up oil pressure, the piston moves towards the piston disc and forms a tight seal against each other. Oil from trip oil circuit is then admitted to the space under the piston disc and the space above the piston is connected to oil drain. The trip oil now forces both the piston disc and piston to the outer position thereby opening the stop valve. As long as the trip oil pressure is maintained, the piston and the piston disc cannot be separated by spring forces. The stop valve is closed only when the trip oil pressure drops substantially. On a loss of trip oil pressure, the pressure of secondary oil from trip oil circuit drops to zero, thus causing control valves to close. This arrangement provides a two-fold protection against steam entering the turbine.

2.2.5 NON-RETURN EXTRACTION STEAM VALVES (QUICK CLOSING):

In the extraction steam line, non-return quick closing flop valves have been provided, which prevents reverse flow of steam into the turbine. Also on turbine trip non-return valve gets closed by its actuator, which in turn acts at the loss of trip oil pressure. Change over valve helps in quick draining of oil from non-return valve actuator.

2.2.6 LOAD LIMITING DEVICE:

Load limiting device is provided on the LP quick closing NRV trip oil line. This device ensures minimum cooling steam flow through LP turbine. If turbine trips or if LP secondary oil pressure is below 2.42 kg/cm^2, the trip oil will be drained and quick closing NRV gets closed due to spring action.

2.2.7 ELECTRO HYDRAULIC TURBINE CONTROL GOVERNING SYSTEM

System consists of speed controller, load (power) controller, frequency controller, extraction pressure controller, and power import/export controller. Turbo Generator is rolled and synchronized by means of speed controller. After synchronization load controller is made active.

2.2.7.1 Speed Control:

The actual value of speed is acquired in digital form by a solid state system measured in three channel system. A toothed disc mounted on the turbine shaft causes fluctuations in magnetic flux at 3 independent hall probes. The change in flux is converted into voltage and then converted into speed value. The pulses of the three channels are monitored continuously. In the event of fault on a channel the control system continues to work without interruption. The defective channel is switched out electronically and fault alarm is initiated. The control system continues to function normally even when two of the three pickups have failed. Failure of a channel is indicated selectively on the front panel of the evaluation module and the display can be cancelled only when the fault has been rectified. After the evaluation circuitry, the frequency is converted into an analog value and fed to the speed controller. At the same time the actual value of speed is also fed to a limiter stage which initiates a signal to the remote tripping gear before the trip speed is exceeded. This signal acts in parallel with the Mechanical-Hydraulic over speed trip. The speed set point is adjusted by speed reference from EHTC panel by means of raise/lower push buttons. In the event of an emergency trip, the speed set point is set automatically to -1% and when the generator circuit breaker is open, to 100%.

2.2.7.2 Power (load) Control: The actual value of power is obtained with a load transducer, which produces a signal of 4 to 20 mA corresponding to 0 to 30 MW from the instrument transformer currents and voltages. Load controller can be used in synchronized mode only.

2.2.7.3 Power Import/Export Control:

Power import/export controller is meant for maintaining constant power import or export with grid on auto as per set point by changing load on selected TG. The set point from power import/export controller will take over control as soon as it acquires an instantaneous value greater than load reference of selected TG. The set point is equalized with the time dependent value. (The value, whichever is higher between load reference of selected TG and set point of power import/export controller, is considered for controlling).

2.2.7.4 Frequency Control:

The actual frequency is acquired by a frequency transducer. It converts frequency of 45 to 55Hz into 4 to 20 mA. The frequency set point can be adjusted from EHTC panel by adjusting frequency reference. In case, plant comes to island mode, it automatically gets activated overriding speed and load controllers. A connection for an automatic synchronizing device is provided to synchronize the plant to the grid. In parallel operation, the frequency influence is set to zero automatically in a step less way. Auto tracking frequency is adjusted to a minimum limit of 49 Hz, below which tracking will not be done and in the event of islanding machine tries to keep the frequency at 49 Hz.

2.2.7.5 Extraction Pressure Control:

There are two controllers for extraction pressure control.

Extraction pressure limiter

Extraction pressure controller

Extraction pressure set point is adjusted by extraction pressure controller from EHTC panel. Extraction pressure limiter is adjusted between 0 to 100% from EHTC panel. Extraction pressure limiter overrides extraction pressure controller. Extraction pressure controller becomes inoperative when extraction pressure limiter is set to zero percent.

2.2.7.6 Constant Valve Control:

The constant valve control facility has the following functions

To maintain the pre-set power constant during extraction pressure control action.

To maintain the extraction pressure constant during change in valve position affected by the speed, frequency or power controllers.

2.2.8 BOILER CONTROL MECHANISM:

Similar to the controls provided to TGs Boilers are also provided with different controls. The main control is the main steam pressure controller which maintains the main steam header pressure by controlling the coal feeder speeds which regulates the coal flow to the mills i.e. controls the fuel in put to the boilers. The main steam header is combined header of both steam generators. Hence there is a provision for selecting all the operating coal feeders in both SGs and any of the coal feeders. Pressure variations will be lesser in the case of selection of more number of operating coal feeders in auto. Primary air flow of the corresponding coal feeder can be selected to auto control to take care of the variable primary air flows requirements corresponding to coal flow variations. Another important control is the air flow control or oxygen flow control. Corresponding to the variations in input fuel to boilers there is a need to maintain the fuel to air flow ratio. With fuel input control variations the air flow will be controlled based on the oxygen levels in the flue gas. The control output varies the speed of the forced draft fans and in turn maintains the oxygen levels which ensure perfect combustion in the furnace and at the same time maintains the unburnt carbon levels within limits. With steam flow variations there will be corresponding variations in the boiler drum level which is to be maintained at constant predefined level to avoid starvation of boiler tubes as well as carry-over of water in to the turbine system. Hence drum level control based on three elements is also provided.

2.3 PROBLEMS DEVELOPED AFTER INTEGRATION WITH RENEWABLE ENERGY

Before solar plant addition as stated the operation was optimised. With solar addition, the power export agreement for 12 MW was entered with the state grid. The intention is that whenever solar generation is available it can be exported to the grid. In the absence of the power export it demands reduction of power generation from TGs as electrical power requirement is constant. This results in the reduction of HP and LP steam flows from the turbines and opening of HPPRDS and LP PRDS leading to system in efficiencies. This also results in to reduction of boiler loadings below a minimum level of 60% which needs oil support. This is as per original design of boilers to avoid furnace disturbances and tripping of boiler. To obviate all these problems power export agreement to the tune of 12 MW is made. The balance of the power when solar is not available or solar generation below 12 MW will be augmented by increasing correspondingly generation from the TGs through condensing mode. But when solar plant is integrated with existing cogeneration system, even though export agreement is made for 12 MW following effects on the system is noticed.

As the solar energy is variable in nature, there is continuous variation of boiler and TG steam flows as follows

a) To maintain export to grid constant whenever solar power generation varies it is mandatory to vary the TG power generation levels. For example, with sudden increase of solar power, power export increases. So power export /import controller comes in to line and generates the control signals to reduce the power generation from the selected TGs. For reducing the power generation from the TGs, steam input to the TG gets reduced. The HP and LP control valves gets close to reduce the TG power. To maintain the HP extraction pressure constant LP control valve gets close, thereby pressurizing the HP chamber. Hence HP pressure can be maintained. The LP stage pressure is controlled by the control valve external to the turbine. During the above process there will be a continuous variation of TG inlet flows, pressures, power generation, HP and LP pressures along with solar plant generation levels. The reverse phenomenon happens with sudden reduction of solar insolation levels. The continuous variation of the parameters may lead to system inefficiencies and system Instability.

b) With TG inlet flow corresponding variations in the boiler steam flows takes place. For example, with reduction in TG inlet flows, the main steam header pressure increase than set value. To maintain the constant steam header pressure, the controller generates the signals to reduce the selected coal feeder speeds and in turn reduces the steam generation from boiler. With variation in the coal flow to the coal mills primary air flows varies to maintain the mill differential and mill outlet air temperatures. Correspondingly the total air flow to the furnace also reduces to maintain the oxygen levels in the flue gas. Reverse will be the case with decrease in solar power generation. Hence there will be continuous variation of fuel and air to the furnace that causes furnace instability leading to furnace disturbances and increase in unburnt residues. This increases the system inefficiencies and furnace stability problems.

c) The variations of boiler pressures in turn effects the TG parameters. Hence the variations are closed cycle i.e. increase of solar generation varies the TG parameters which in turn varies boiler parameters and this in turn again varies the TG parameters. The variations will be continuous and will not become steady as mostly the solar generation levels vary continuously and do not allow the controller to stabilize. The variations are appreciable during large variations in solar generation. Thus the cogeneration plant which was operating very steady and stable before the integration with solar has become unstable and introduced inefficiencies after integration.

Above situation further worsened and a big threat has come in the way of co-generation plant operation which snatched the advantages of co-generation plant and solar plant. Even though 12 MW export agreement exists with the grid, state load dispatch center (SLDC) is giving schedules based on the demand requirement i.e. whenever there is less demand SLDC is asking for 25 % , 50 %, 75% back downs. Sometimes during non-peak hours or rainy season even there is 100% back down also from the grid i.e. resulting in to zero export condition. Whenever a power export demand is less than the solar generation it is essential to decrease the generation on the TGs to maintain zero export condition as no revenue will be paid beyond the scheduled quantity. At 100 % back down, the inefficiencies may occur with solar generation. Reducing the TG generation below 60% of the MCR reduces the stage flows drastically. This makes the HP and LP flows cannot be maintained from the TG extractions and maintained by opening the HPPRDS and LPPRDS. Hence getting the process steam from PRDS is uneconomical and losing the advantages of cogeneration systems and reduces the plant efficiency drastically.

In addition to the TG inefficiencies above operation introduces the inefficient operation of boilers also. The boilers are designed for operation of the steam generators without oil support above 60 % load only. Hence whenever the steam generation requirements are coming down, the furnaces start getting disturbed. To obviate this oil guns are cut in. The oil support at low boiler loads operation increased the steam generation cost. The curtailment of export from grid side results the co-generators operation troublesome.

Hence to obviate above deficiencies co-generation plant is regulating the solar whenever a power export demand is less than solar generation. It means whenever there is no export requirement from grid side it is switching off the solar panels i.e. reverting back to the operation of the plant before solar addition. But this is also an inefficient way as the prime motto off setting up solar plant is defeated and not meeting the renewable power producing obligation for which purpose solar is added. Utilizing the fossil fuels for electricity generation when renewable energy is available is a drain to the natural resources of fossil fuels. It is aiding the environmental degradation also. This case study is a lesson to the cogenerating systems and to be wise before opting renewable energy integration.

2.4 SUMMARY

In this chapter a case study is considered where RE is integrated in an existing cogeneration plant. Detailed description along with various control philosophies adopted is presented which helps in analysing the problems developed after integration. The post operational constraints developed after integration are presented in detail so as to understand the post integration issues.

CHAPTER-3

LITERATURE REVIEW

3.1 LITERATURE REVIEW

Initially the literature review is made to understand the integration problems faced by cogeneration plants. However, integration problems associated with grid and the main challenges/problems and the remedial solutions are available from various papers on the integration of renewable energy. Conventional power plants are switching to inefficient operation of the plant as well as experienced equipment failures. This is mainly due to sudden injection of a renewable energy in to grid which demands reduction of the generation on conventional turbo generators leading to sudden reduction of load on the steam generators (Boilers). This is causing the overall reduction of heat rate of a power plant, thermal stresses on major equipment of turbo generator and boilers wear & tear of systems, higher cycling costs. This case will be further worsened when renewable energy availability during the off-peak period as conventional plants have to reduce their generation levels below a minimum level of the generation where boilers will land into unstable operation resulting in tripping of units. All the above may offset the savings gained from renewable energy [6]. After summarizing the main challenges associated with the integration of RE further review is carried out to know the methodology adopted to find the feasible solutions to above. In order to accommodate large scale renewable generation and to address associated challenges, the following measures are identified [7].

-Strong grid interconnection to encourage power balancing areas

-Forecasting of renewable generation on different time scale.

-Flexible generation, an ancillary services, etc. for supply balancing

-Pocket wise RE generation development should be prioritized so that transmission infrastructure available in the pocket can be utilized optimally.

-Establishment of Renewable Energy Management Centers (REMC) equipped with advanced forecasting

-Smart grid application and Demand- side management

-Demand response and storage for load balancing

-Deployment of synchro phasor technology PMUs / WAMs on pooling stations and interconnection with centralized control centers through fiber optic communication for real time information, monitoring and control.

Even though the above solutions are mostly concentrated on infrastructure development to accommodate RE, challenges associated with the main problem of the variable nature of the renewable energy is addressed by most of the authors and proposed energy storage systems as the viable option. The various energy systems that were proposed are,

- Battery Energy Storage Systems (BESS)
- Fly wheels
- Thermal storage systems
- Fuel Cells
- Stored Magnetic Energy Systems (SMES)
- Super capacitors
- Pumped Hydro Energy Storage (PHES)
- Compressed energy systems

Storage systems utilizing the above technologies require the development of models considering the different design parameters. In case of Solar PV systems, battery energy storage system is one of the options. Economic aspects of BESS to reduce the power fluctuations of a large solar PV system to be arrived based on the critical parameters. The main parameters are charging/discharging, battery capacity and type of the battery. The type of battery can be taken up only after economic study as BESS is a costly option and requires maintenance and replacement at regular intervals [8]. However, other options like reduction of power fluctuations by installing a dump load and by operating below MPP absorb the power fluctuations from variable energy [8]. But these methods lead to revenue loss or non-utilization of cheaper energy or cleaner energy. Another is a novel idea of solar electrolysis power cogeneration system which utilizes the solar energy to electrolysis of water to power a fuel cell [9]. The energy produced with fuel cells can be fed to the grid during peak hours. Hydrogen generation option with wind power and using the hydrogen as a vehicle fuel than reconverting the hydrogen back to electricity [9] is also a good option. However, the hydrogen storage and transportation issues are to be looked into. Utilizing the hydrogen generated in fuel cells as used in the hybrid power generation can be another option with both solar as well as wind. Another energy storage option of pumped hydroelectric storage where the water stored at a higher elevation is used for power production through hydro turbines during peak hours and the same water will be pumped back during off-peak hours / whenever renewable energy is available [10]. But there is a limitation of this method PHS requires significant land areas with suitable topography.

Concerning wind power utilization predominant option is compressed air energy storage systems. State-space model for compressor air technology developed which monitors the storage dynamics at any state of time in terms of the reservoir pressure and mass of the compressed air stored. Model is simulated to address the variability issue in one of the wind farms and this is used to generate data at different wind pressures [11]. Hybrid power plant where two or more energy resources are used simultaneously out of which one source is variable renewable energy source is an option for absorbing the variable nature of the renewable energy and to smooth power fluctuations [12] developed thermodynamic models of turbine/ compressor/generator and the results are tabulated for various conditions using MATLAB/Simulink. Super capacitor energy storage for wind energy applications is another option and by considering the wind energy and storage energy management algorithm to smooth out the short-term variations in wind power is developed [13]. Models for optimal control of battery energy storage for wind farm dispatch developed considering basic battery equations. A control strategy is developed for optimal use as the Battery Energy Storage System (BESS) is an expensive option for wind power dispatch. Mathematical problem for optimal control is developed by, considering the state of charge, capacity, and deep discharge parameters. The method developed is simulated using the two battery models and verified by carrying out simulations using Power System Computer-Aided Design (PSCAD) [14]. Compressed air energy system for trigeneration based on electrical energy peak load shifting i.e. Demand-side management is another option. Direct expansion of the compressed air is proposed for cooling power, heating power recovery in the process of compression and storage. Based on the working principle of compressed air storage theoretical analysis of the thermodynamic system model is established [15].

Based on the literature study, it is concluded that the best option to maximize the utilization of installed capacity of renewable energy is to store the RE beyond a break-even point and to reutilize the same during the non RE period.

Hence, initially BEP estimation is taken up by using the real time data. The actual problem of switching over to inefficient mode of operation is analyzed by using the onsite data. Literature survey is made to collect the in house data of design criteria and limits of cogeneration plant operation. The technical on site data of various operation parameters are obtained before the integration of renewable energy. The same data is collected after integration of renewable energy and operating at 100% and 50% of renewable energy generation. The data is critically analyzed for critical parameters like HP and LP PRDS opening, reduction in HP and LP extraction steam flows from turbine extractions and steam flow reductions from steam generators. The analysis revealed, even though LP PRDS opening has increased with renewable energy injection, the main deviation is observed in steam flow reduction from steam generators below the design threshold limit. This has resulted in to oil firing to support the coal flame stability, resulting increase in cost of steam generation. Observed the increase in heat rate of the system also, resulting in inefficiency. As the in-house data was available for 50 % and 100% loads only, the exact point at which RE generation the plant is switching to inefficient mode could not be ascertained. Hence to ascertain the exact point at which RE generation, the system is switching in to inefficient mode, the on line data is collected by conducting the experiments. The generation from turbo generators is decreased in steps of 1 MW, which is equivalent to injection of 1 MW RE. The required technical data is collected and the experiments are continued till the full installed RE generation equivalent MW is imported from the grid i.e. reduction of generation on turbo generators. From on line data collected, the exact break-even point at which system is switching to inefficient mode is established. The break-even point is the exact point below which steam generation flow is falling below the design threshold value.

To validate the BEP obtained through practical experimentation, BEP is estimated by developing an algorithm using heuristic techniques. Literature survey is made to identify the various heuristic techniques available and the suitability to the present application. Based on the literature survey, opted forward approach technique as the most suitable to reach the goal in steps with intermediate goals [16].In the process of developing mathematical modeling and methodology development literature review is made to establish theoretical concepts and related governing equations. Based on cogeneration concepts on heat rate establishment of CHP plants [17], and thermal analysis of thermal plants [18] established equations governing theoretical power generation in turbines [19]. Literature on concepts of internal rate of return/ Newton Raphson’s empirical formula [20 - 21] guided to establish an algorithm/flow chart to establish a BEP. From the mathematical modeling and the equations developed, an algorithm is developed. The algorithm is run using MATLAB in iterative process. The initial data to initiate the algorithm and the design limitations are obtained from the real time data of the industry considered. As the results obtained from heuristic technique is within limits obtained from practical real time data the methods are validated.

After validation of BEP through theoretical method developed, literature survey is carried out to select suitable storage device to maximize efficient utilization of RE. To make a comparative analysis of various Energy Storage Technologies (ESTs) available to suggest suitable storage option for the present application, comprehensive literature survey is made.

The relevant literatures available on ESTs and standard publications are considered for literature review.

Stage wise methodology adopted in literature is indicated in figure 3.1.

Initially under stage 1 “Technology mapping” is adopted where gathered the information related to available technologies, principals involved and their suitability for various applications. The various technologies available are described in detail.

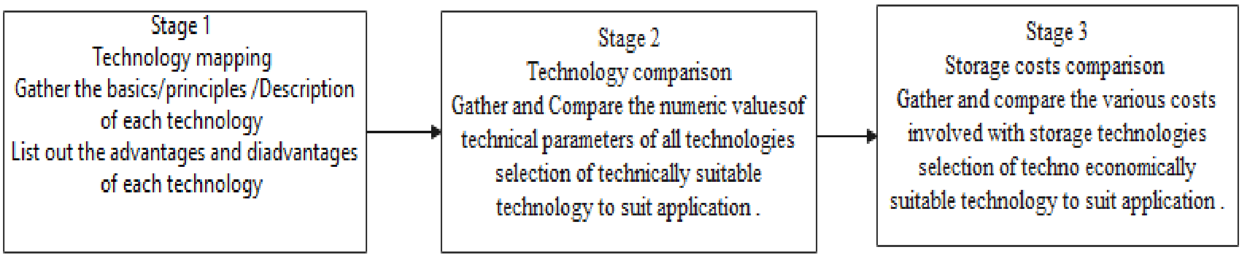

Figure 3.1 Methodology adapted to select suitable storage technology [22]

The main purpose of technology mapping adopted is to increase the awareness and knowledge about the storage technologies to come out with various advantages and disadvantages associated with these technologies. In stage 2 all the data related to numeric values of common parameters corresponding to each technology available in various literatures is collected and used as a tool to facilitate the first evaluation for comparison of technologies. The main technical parameters considered are power, energy ratings, specific energy, energy density, power density, storage period, efficiency, discharge time, daily self-discharge, response time, lifetime, technology maturity etc. Based on the data, comparison analysis is carried out and suitable storage option on technical evaluation is arrived. The data collected is analyzed and the most suitable storage device from the technically suitable is arrived. In stage 3 data related to power cost, energy cost, total capital cost per unit of power rating in Rs/kW, total capital cost per unit of storage capacity in Rs/kWh and total life cycle costs are collected from literature review. In stage 4, with cost data collected and utilizing net energy analysis based on two energy ratios i.e., the electrical energy stored on invested and overall energy efficiency ratio the most techno economical storage device is opted. In stage 1 from the literature available in [22-33] obtained information on basic concepts and principle involved with each technology. From the study, the design and operational parameters of each technology is obtained to ensure the suitability of storage mechanism to a particular application. Similarly, the hindrance factors of design limitations and operational constraints which makes the usage of technology for a particular application is also studied. Advantages and disadvantages of each technology are analyzed as this information gives which technologies are ideal in different situations and applications. In stage 2 the relevant numeric values of critical design and operational parameters from literatures [22-24], [27-29], [31] are considered on various technical parameters for comparison analysis. Wherever the values are differing from different literatures the average values or values with appropriate correction factors are considered. Based on study in stage 1 and the data generated in stage 2 technically feasible storage technologies are filtered out from the available options. In stage 3 literature related to various costs associated with the storage technologies is considered. Cost comparison of different energy storage technologies uses two main approaches viz. Total Capital Cost (TCC) and Life Cycle Cost (LCC) [34]. Main elements of total capital costs include Power Conversion Systems (PCS), storage section and Balance of Plant (BOP) [34]. LCC accounts for all costs of fixed Operation and Maintenance (O&M), variable O&M, replacement, recycling, disposal and TCC. Study on Levelized Costs of Storage (LCOS) for three battery technologies namely lithium ion, lead acid and vanadium flow are carried out in [35] including sensitivity analysis to project the future costs up to 2030.Costs and performance of parameters of battery storage technologies, pumped storage hydro, fly wheels, compressed air energy storage and ultra-capacitors is compared in [36] for 2018 and projections up to 2025 is made. However, in latest report [37] the comparisons are made for 2020 and projected out to 2030. Further studies on two energy ratios i.e., the Electrical Energy Stored on Invested ($ESOI_e$) and the overall energy efficiency ratio [38] and the data on energy return on investment [39] also considered to finalize the suitable energy storage option for the present application.

Electricity storage costs are predicted in literature [40] for future up to 2030 and main salient features are, total installation costs in case of Li-ion shall fall by 54%-61% by 2030, costs of other battery storage technologies also expected the fall in trend. Installation costs of flow batteries are expected to drop by two thirds by 2030[40]. Hence these aspects can be considered in future even though at present deferred due to cost factors as these offers operational advantages of operation at ambient temperatures. High temperature sodium Sulphur and sodium nickel chloride batteries costs also anticipated to fall by 56%-60% [40]. Fly wheel and compressed air energy storage technologies costs expected to fall by 35 % and 17 % respectively by 2030 [40]. Literature [41] focused on reduction of storage costs to meet the estimated cost targets and cost minimization demonstrated by storage system operation. RE is utilized in hydrogen production and demonstrated the fuel cell technology [42].

After establishing suitable storage device, technical literature survey is made to design the storage system including design of control logic.

After identifying suitable energy storage, designing the capacity rating and modeling of energy storage and discharge devices was explored in the literature study. Design and simulation of a PV system operating in grid-connected and stand-alone modes for areas subjected to daily grid blackouts are presented in [43], which helped in the estimation of solar power generation from available radiation data. Power and energy rating considerations with the integration of flow battery with solar PV and residential load are presented in [44], which helped in arriving at a battery capacity and rating estimation based on the estimated solar power above BEP. Estimation of solar insulation and power generation of PV systems using previous day weather data [45] and the relationship between solar irradiance and power generated by PV panels [46] are considered for guiding to predict the solar power based on weather data. Modeling of temperature and solar radiation effects on PV panel power in [47] helped in considering the correction factors on estimated solar power. Modeling, control, and simulation of battery storage, PV-wave energy hybrid renewable power generation systems were presented in [48]. Optimal charge/discharge scheduling of battery storage interconnected with residential PV Systems [49] are also considered for modeling the battery storage system. A flow chart is developed to coordinate between frequency support and capacity factor tracking, resulting in behavior closer to a conventional power generation plant in [50]. An energy management strategy for a hybrid stand-alone plant to supply controllable loads is proposed. A fuzzy management algorithm was developed to control a BESS which ensured the maximum use of RE generation in [51]. A rule-based algorithm is developed in a BESS integrated with a solar system, taking into account the operating constraints of the BESS, such as state of charge limits, charge/discharge current limits, and a lifetime of batteries.

The algorithm mainly focused on optimal utilization of the BESS so that solar power is dispatched smoothly to supply loads as forecasted [52]. Based on the concepts, a control algorithm was developed to control the charge and discharge cycles of the battery system to the present application. The storage capacity is determined based on the intensive literature study. Data regarding the solar radiation levels on a minute-wise, hourly, and daily basis is considered from the industry’s Automatic Weather Station (AWS) to determine capacity. The cost data of the battery bank is taken from the present market trend and payback and savings are estimated.

The battery energy storage capacity and voltage rating were designed by utilizing the PV power equations. The algorithm was developed based on the literature survey of rule based systems. The various conditions of the present application are considered while developing the algorithm. The charging of the battery bank is considered beyond the BEP of solar generation. The State of Charge (SOC) of the batteries after the completion of discharge is taken as a reference for charging. The amount of charge for every one minute is integrated and rules are defined such that the charging of BESS gets terminated on SOC reaching 100% or completion of the charging cycle. Similarly, the discharge cycle starts based on pre-set discharge timer and the SOC of the BESS is taken as a reference from the final SOC value at the end of the charging cycle. SOC diminishes every 5 min based on the discharge rate at a constant value.

The discharge cycle is completed based on predefined rules of either SOC of BESS is reaching 20% or completion of the discharge timer. The methodology developed takes care of the life of the battery as deep charging or overcharging is not allowed by the algorithm.

Power balance equations are framed based on the design storage device selected. Ensured the design capacity of the storage device is adequate as the one minute power charging values are within acceptable limits.

Finally, the research resolved the major problems developed in a CHP plant after integration. Estimation of BEP and design of suitable storage capacity to store the RE beyond BEP prevented deviation from optimality conditions. This made the system optimization at full solar capacity possible without affecting the efficiency of the cogeneration plant.

The research is extended further and guide lines are established to design the future industrial cogeneration plants by integrating with RE with suitable energy storage device. Literature survey is carried out to gather the concepts and conventional cogeneration plants design. However the present conventional designs are not optimized fully as compromised either to meet fully the electrical load or thermal loads. Most of the plants are of extraction cum condensing designs instead of fully optimized designs of back pressure turbine systems. Systems without PRDS are preferred in new design. From the research carried out and the literature study, the new design concepts of industrial cogeneration systems are developed by integrating with RE and adopting suitable energy storage device.

3.2 DESCRIPTION OF AVAILABLE ENERGY STORAGE TECHNOLOGIES

Energy storage technologies have become popular mainly due to enhanced utilization of renewable energy in recent days. Due to intermittent nature of renewable energy, these ESTs have become key components for replacing the conventional fossil fuel plants with Renewable Energy Sources (RES). In addition to these, the storage devices have become essential in existing cogeneration plants due to post operational constraints after integration with RE. However, the suitability of storage device depends on the type of application for which it is being used. Hence to make a comparative analysis between various storage options to determine suitable storage option, study on storage technologies has become essential with a focus on advantages and disadvantages of each technology.

Basically the energy storage technologies can be classified under 5 broad categories based on the form of energy stored in the system and each category can be sub divided as follows.

1). Electrochemical storage
  i. Lithium – ion battery
  ii. Nickel Cadmium (Ni-Cd) battery
  iii. Sodium sulfur battery
  iv. Lead acid battery
  v. Redox flow battery

2). Mechanical storage
  i. Compressed air energy storage
  ii. Pumped hydro energy storage
  iii. Fly wheel energy storage

3).Chemical storage
  i. Hydrogen
  ii. Methane

4). Thermal storage
  i. Sensible heat storage
  ii. Latent heat storage
  iii. Thermo-chemical energy storage

5). Electrical Storage
  i. Electrostatic energy storage including capacitors and super capacitors
  ii. Magnetic / current energy storage including SMES

Another way of classification of energy technologies is the direct and indirect storage [29]. Electrical storage in capacitors/super capacitors and SMES comes under direct storage. In indirect storage reservoirs are used for storage. The reservoirs can be either artificial or natural. Batteries and fly wheels come under artificial type whereas pumped hydro and compressed air storage comes under natural reservoir type.

3.2.1. ELECTROCHEMICAL ENERGY STORAGE (ECES):

ECES is the generic name for Batteries [22] which are used for energy storage. Batteries are electrochemical devices which convert the stored energy into electrical energy. Batteries can be classified as primary and secondary. Primary batteries are non-rechargeable whereas secondary batteries are chargeable. For large scale industrial and energy storage applications mainly for renewable energy storage where energy charging and discharging is prime requirement, chargeable batteries are used. During charging, a direct current is converted into chemical energy and during discharging chemical energy is converted back in to direct current [24]. Batteries can also be either solid state or flow type [22]. Battery storage does not depend on geographic features [35].

3.2.1.1 Lithium-Ion Batteries (LIB): Lithium-ion batteries can be cobalt based or phosphate based. Phosphate based is more recent technology and is more efficient than cobalt based, and requires further development [21] .LIB consists of a positive electrode (cathode) of lithium oxides, a negative electrode (anode) of graphite and an electrolyte of a lithium salt and organic solvent [22]. Applicability of LIB is limited to small electronic equipment and not appropriate to stationery applications due to decreased performance and high cost [27]. Low density of Lithium and large electrode potential gives an advantage of low weight and high operating voltage [22].

3.2.1.2 Nickel cadmium Batteries: Nickel cadmium battery is a rechargeable battery using nickel oxide hydroxide and metallic cadmium as electrodes. But these batteries offer good cycle life and performance at low temperatures. Have ability to deliver their full rated capacity at high discharge rates (discharging in one hour or less). However, the materials are more costly than that of the lead acid batteries and the cells have high self-discharge rates. These batteries are being used currently or power tools, portable devices, emergency lighting, telecoms and generator starting applications and not preferred in large scale power systems due to its high cost and memory effect problems [31].

3.2.1.3 Sodium Sulphur Batteries (SSB): Sodium Sulphur batteries consist of two active materials; molten sulfur as the positive electrode and molten sodium as the negative electrode [22]. SSB technology involves high operating temperatures of around 300^{o}c [23]. Both sodium and sulfur are corrosive in nature, hence prone to corrosion problems. As SSB operates at high temperature makes suitable for large scale industry applications [22]. The Na-S batteries is used for high power energy management such as the smoothing the output power mainly wind farms, load leveling and peak shaving [31]

3.2.1.4 Lead acid batteries: Lead acid battery technology is the oldest, cheapest, well developed and widely used rechargeable electrochemical energy storage device and a popular choice as a backup power supply in a range of kW to tens of MWs [31]. Lead Acid Batteries normally consists of lead oxide (PbO2) cathodes and lead (Pb) anodes immersed in sulfuric acid (H2SO4) [22]. These Batteries are designed to operate at ambient temperatures. Operating at lower temperatures than designed increases the life cycle but decreases the rated capacity and reverse is the case when operation at high temperatures than designed [23]. Lead sulphate is the product formed on both electrodes during discharge. Hence these batteries should not be overcharged or undercharged for a prolonged time [28]. These batteries with quite low density provide a large current which is a great advantage in many applications.

3.2.1.5 Redox Flow Batteries (RFB): In Redox flow batteries two liquid electrolytes are pumped to the opposite sides of the electrochemical cell. The two liquid electrolytes contain dissolved metal ions as active masses and they stay dissolved in the fluid electrolyte, hence no phase change of these active masses takes place. The negative and the positive redox species are contained in separate storage tanks and are separated by an ion-selective membrane. Redox-active ions undergo reduction or oxidation reactions when they are in contact or very near the current collector [22]. The technology is still in the early phases of commercialization compared to more mature battery systems such as Li-ion and lead-acid [36].

3.3 MECHANICAL STORAGE:

In mechanical storage, either potential or kinetic energy is converted into electrical energy by using physical movements. Fly wheel is an example of kinetic energy storage whereas compressed air energy storage and pumped hydro energy storage comes under potential energy storage.

3.3.1 COMPRESSED AIR ENERGY STORAGE (CAES):

CAES is based on air being pumped by an air compressor run by an electric motor during periods of low demands (off-peak) and the stored compressed air is used to run the turbine to generate electricity during periods of high demands (peak-load) [22]. Two processes are existing in CAES namely diabatic and adiabatic and are indicated in figures 3.2 and 3.3 respectively [22].

In diabatic process, during off peak period’s air is compressed and the heat generated in the compression process is removed in a heat exchanger (air cooler). The cooled air is stored in an underground storage vessel. During peak periods or when energy is required, the stored compressed air is expanded in a turbine to generate electricity. As the air cools down due to its expansion in a turbine and may freeze the turbine, air must be heated in a combustion chamber by burning a conventional fuel or biofuel before admitting into turbine. In this process as the air is heated by using external fuel, the overall efficiency is less than adiabatic process.

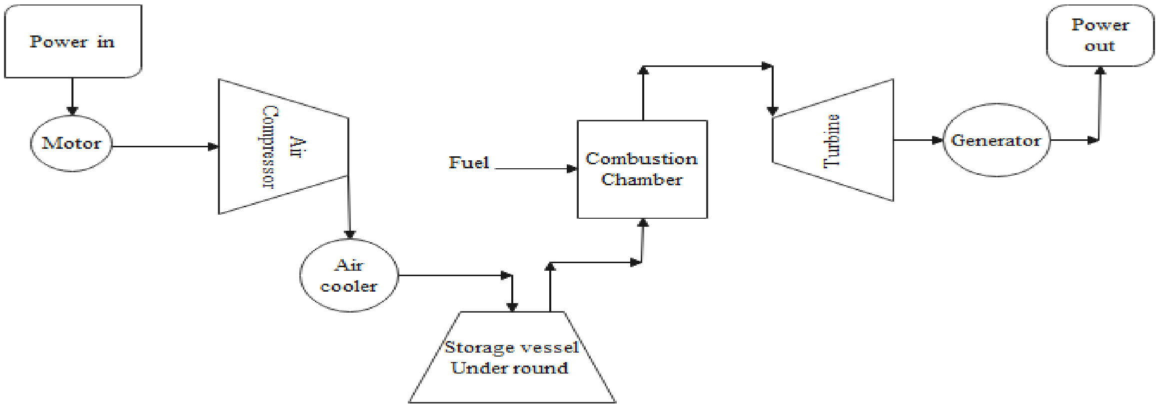

Figure 3.2 Schematic diagram of diabatic CAES system [22]

In adiabatic process, the heat generated in the compression process is stored to reduce or eliminate the energy loses during the compression processes. The stored heat is utilized to heat the compressed air to heat before admitting into the turbine. As this process is eliminating the additional heat requirement, the efficiency of the storage system improves considerably.

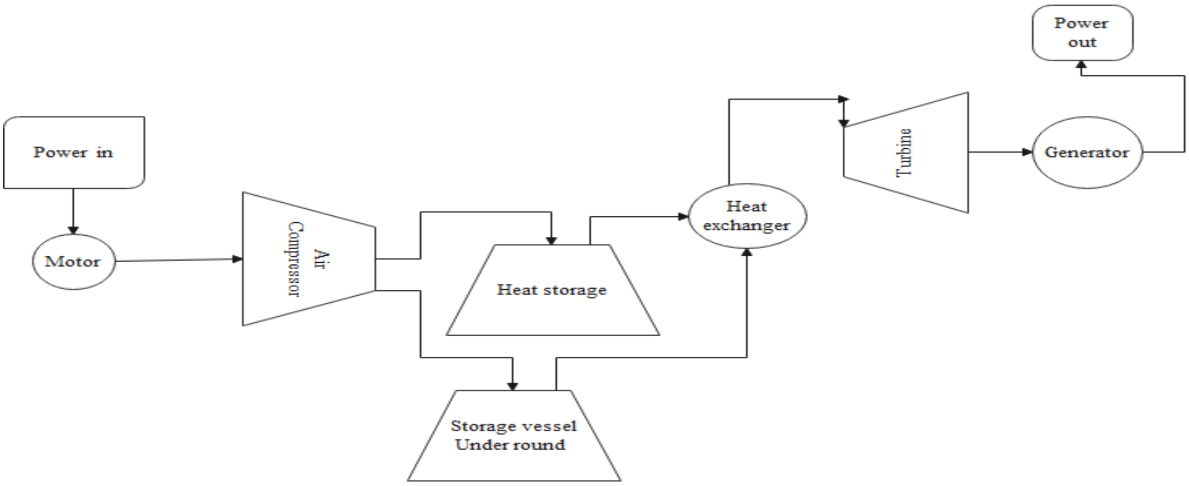

Figure 3.3 Schematic diagram of adiabatic CAES system [22]

The compressed air can also be used in gas turbine engine to produce electricity. This is a hybrid compressed air energy system and is like a conventional gas power plant. In a conventional gas power plant, up to 60% of the output from the plant is used to compress the air. The remaining 40% is directed to the generator. In hybrid compressed air system, the stored compressed air removes the need for this, increasing the efficiency of the gas plant up to 70% [30].

3.3.2 PUMPED HYDRO ENERGY STORAGE (PHES):

PHES systems, water are pumped to an uphill reservoir from a low-level reservoir during periods of low demands. This process is followed by discharging the stored water back to the lower reservoir during periods of peak demands. The discharged water then drives the generator to produce electricity when needed. The same generator is being used for pumping the water uphill, consequently used as a reversible pump-turbine [22].

3.3.3 FLYWHEEL:

Flywheel is equivalent to a mechanical battery, simply a mass rotating about its axis. Fly wheel absorbs electric energy from the source to store it as rotational kinetic energy and then deliver to a load at the appropriate time, in the form that meets the load needs [23]. Fly wheels are generally used for applications requiring short discharge time, normally for voltage and frequency stabilization [29].

3.4 CHEMICALSTORAGE:

An endothermic chemical reaction absorbs energy to form chemical bonds to produce high-energy products where as during exothermic reactions a lower-energy product and energy is released. Hence these chemical reactions can be utilized to store energy in the bonds of chemical compounds (atoms and molecules) by utilizing electricity and heat to use them for a future energy supply. Hydrogen and methane are two different technologies available under chemical storage [22].

3.4.1 HYDROGEN:

Hydrogen can be produced either by natural gas reformation with steam or by the electrolysis of water in to oxygen and hydrogen. Even though reforming of natural gas is more common, but environmental point of view electrolysis of water is more convenient. As electrolysis of water is less efficient, producing hydrogen from renewable power is preferred. The stored hydrogen can be converted back to heat or electricity in an internal combustion engine or a fuel cell [22].However, the hydrogen and fuel cell combination is low efficiency option as presently the efficiencies of electrolyzer and fuel cells are around 70% and 50% respectively [24]. Hence, the overall efficiency and the huge capital costs are the major barriers in commercialization of hydrogen-based systems [34]

3.4.2 METHANE:

Methane can be produced using hydrogen by a methanation reaction i.e. the Sabatier process. In the Sabatier process methane and water are produced when hydrogen reacts with carbon dioxide (CO_2) [22] and increase the stability and energy density of the storage media [34].

3.5 THERMAL STORAGE:

Thermal energy storage systems can be low and high temperature systems. The low temperature systems can be further divided in to aquifer low temperature energy systems, which are not preferable for electricity generation and another type cryogenic energy storage which is under developing stage only [28]. High temperature systems store thermal energy by heating or cooling as storage medium. The stored energy can be used either for cooling or heating applications as well as for power generation. Sensible heat, latent heat and chemical reactions are the three options available under thermal storage.

3.5.1 SENSIBLE HEAT STORAGE (SHS):

SHS store thermal energy by cooling or heating either a liquid or a solid and the capacity of the storage depends on the specific heat of the storage medium [22]. Water tanks and aquifer storage systems are the most common water-based storage systems. In water tank systems hot water tank with high thermal insulation to avoid thermal losses is used to store the solar energy via a solar collector.

3.5.2 LATENT HEAT STORAGE (LHS):

LHS store thermal energy in a Phase Change Materials (PCMs). PCM change phase at a certain temperature called Phase Change Temperature (PCT) i.e. when the temperature is beyond PCT, the chemical bonds gets break up on supply of energy (endothermic reaction) and the material changes from solid to liquid. Similarly, as the temperature decrease, the material will return to a solid state by releasing the energy (exothermic reaction). By controlling the temperature rate it is possible to store the energy. In order to store energy in the form of cold, the process can be reversed. The storage capacity is greater for LHS than for SHS [22].

3.5.3 THERMO CHEMICAL ENERGY STORAGE (TCES):

TCES refers to storing thermal energy using chemical reactions. When two or more components are combined in to a chemical compound, heat will be released. Similarly, on supplying heat, the compound can be broken and gets divided. The divided components are then stored separately until a demand arises. During peak periods or whenever energy required the components are reunited into a chemical compound and heat is released. The storage capacity depends on the heat of reaction. Main constraint with SHS and LHS are heat losses with time. As TCES enables to store for long duration, makes suitable for large-scale electricity generation. However, TCES technologies are under development and demonstration stage and further improvements are necessary to make this technology commercially available [22].

3.6 ELECTRICAL STORAGE:

Electrical energy storage can be either in the form of electrostatic like in capacitors and super capacitors or in the form of magnetic/current storage like super conducting magnetic energy storage [28].

3.6.1 CAPACITORS:

Capacitors store electrical energy in the form of electrical charge accumulated on their plates. However, the stored energy can be quickly released from the capacitor as capacitors have low internal resistance. Hence, capacitors are often used in systems that generate large load spikes [22]. But capacitors have limited storage potential due to low energy density and superseded by super capacitors in large scale applications [28].

3.6.2 SUPER CAPACITORS (ULTRA CAPACITOR):

Super Capacitors are the latest innovation devices in the field of electrical energy storage. In comparison with a battery or a traditional capacitor, the super capacitors have high power and energy density. Normally Super capacitors are electrochemical double layer capacitors that store energy between two plates or metals and separated by a dielectric. When a voltage is applied across the plates, capacitors work in direct current [22].

3.6.3 SUPER CONDUCTING MAGNETIC ENERGY STORAGE SYSTEMS (SMES):

SMES store energy in the magnetic field created by the flow of direct current in a coil of cryogenically cooled, superconducting material. When more coils are added to increase the power capacity, coolant is necessary to keep the machine operable, resulting increase in cost.

3.7 TECHNICAL CHARACTRISTICS OF ENERY STORAGE SYSTEMS:

The main technical characteristics of energy storage systems based on which the selection of a storage depends are [24],

1. Storage capacity is the quantity of available energy after charging and the usable energy depends upon the Depth of Discharge (DOD). DOD is the limit up to

which storage device can be discharged which is based on minimum charge state required.

2. Power rating is the system's maximum power output under normal operating conditions. Normal discharge rate of a storage system can be referred as the design, nominal or power rating of a system.
3. Emergency power capability is the feature of a storage system which can deliver higher output for short durations. However, at higher rates of discharge, storage efficiency gets reduced with an increase in equipment damage compared to operation at normal power rating.
4. Autonomy or discharge duration autonomy is the maximum time that storage device can deliver its rated output without recharging and depends on DOD and operational conditions.
5. Energy density is the amount of energy that an energy storage device can store for a given volume or mass and important when space available is limited and valuable.
6. Power density is the amount of power that an energy storage device can deliver for a given volume or mass.
7. Space requirement of a storage device depends on the power and energy density of a storage system and dictates the floor area or space requirement.
8. Efficiency or storage system round trip efficiency is the amount of energy delivered by the system relative to the amount of energy that is stored. Efficiency estimation must be based on one or more realistic cycle's operation.
9. Durability or lifetime is the number of charge - discharge cycles of operation that a storage device is designed or can with stand without performance deterioration. All storage systems can deteriorate because of fatigue or wear and depends on type, operating conditions and other variables pertaining to storage technology. Shallow discharge i.e., discharging a small portion of stored energy is less damaging than a deep discharge i.e., discharging most or all the stored energy. Hence lifetime strongly linked to the amplitude of the cycles
10. Reliability is an important factor as normally as it is a guarantee of on demand service and should be reliable as necessary to cater the required application.
11. Response time is the time required to charge the storage device from no charge to full charge. The storage device must respond rapidly if it is provided capacity margin in lieu of transmission and distribution (T & D) as T & D equipment

respond instantly depending on demand. However, in case of storage energy delivery in lieu of generation capacity the response need not be quicker as normally generation responds relatively slow.

12. Ramp rate is the rate at which power output changes and a guiding characteristic for many of the applications.
13. Charge rate is the rate at which energy can be stored. If storage cannot recharge quickly, it may be delayed in absorbing the surplus energy from the system, hence it defeats the purpose for which it provided.
14. Energy retention is the amount of time storage device can retain the charge which depends mainly on self-discharge i.e., the phenomenon of dissipating energy even though storage is not in use. Storage devices based on mechanical means are prone to self-discharge. Normally retention time and self-discharge is inversely proportional. This characteristic may be less important for applications where storage is used frequently.
15. Transportability is important because if storage is transportable, it can be relocated to the location where it is needed, or benefits are important. Transportability may significantly enhance the life cycle benefits.
16. Power conditioning is required by some storage technologies and uses Power Conditioning Unit (PCU) to modify electricity to have necessary voltage and form.
17. Power quality may be affected by the use of PCUs. In general power output from a storage device should have an acceptable power factor, voltage variations within tolerable limit of 5% to 8%, wave form as close as possible to sine wave and harmonics within limits.
18. Modularity is the attractive feature of storage device as helps in increase or decreases the storage capacity and may be helpful in maintenance point of view also.
19. Reactive power capability indicates the VAR support. Mostly storage systems inherently do not possess reactive power capability. However reactive power capability equipment can be added, if required with moderate incremental costs.
20. Feasibility and adaptation to the generating source needs to closely adopt the storage system to the type of application and to the type of production. Harmonization with the network is essential.

21. Monitoring, control and communication equipment ensures quality and safety of storage levels. Many storage applications warrant control signals to ramp up or ramp down of power in proportion to the requirement. It may necessitate more sophisticated algorithms also.
22. Interconnection facility shall be available with storage technologies in case of grid connected applications. Storage device should be in accordance with IEEE standard 1547 with distribution level of applications.
23. Operating constraints relates to safety aspects (explosions, waste generation, release of unsafe substances to environment, etc.) and operational conditions (temperature, pressure, etc.). These constraints can influence the choice of storage technology.
24. Environmental aspects of the storage system are more important where environmental safety is given priority than energy costs. Storage devices should not produce harmful pollutants that degrade the environment .to the extent possible and the materials used should be recyclable.

The technical characteristics of various energy storage systems are compared in table 3.1,

Table 3.1 Comparison of technical characteristics of energy storage systems

Energy storage device Main Cat.	Energy storage device Sub Cat.	Capacity [MWh]	Power rating [MW]	Discharge time	Energy density [Wh/kg]	Power density [W/kg]	Efficiency [%]	Lifetime [Years]	Cycle Life [cycles]	Self-discharge per day	Storage duration	Response time	Discharge duration at max. power	Maturity	Operating temperature	Environment influence
I. Electrochemical storage (Battery energy storage systems)	Lithium-ion	0.25-25[22]	0.001-0.1 [22]	Minutes-hours [24]	75-200 [24]	150-315 [24]	85 – 100 [22]	5-15 [24]	1000-4500 [22]	0.1%-0.3% [24]	Minutes-Days [24]	20ms-sec [31]	1-8 hrs [23]	Commercialized [22]		---
	Nickel cadmium		0 – 40 [24]	Seconds-hours [24]	50-75 [24]	150-300 [24]		10-20 [24]	2000-2500 [24]	0.2%-0.6% [24]	Minutes-Days [24]	20ms-Sec [31]	1-8 hrs [23]	Very mature [31]		---
	Sodium sulfur	≤ 300[22]	1-50 [22]	Seconds-hours [24]	150-240 [24]	150-230 [24]	75 – 90 [22]	10-15 [24]	2500 [22]	≈20% [24]	Seconds-hours [24]	1ms-sec [31]	1-8 hrs [23]	Commercialized [22]		----
	Lead acid	0.25-50[22]	0-40 [22]	Seconds-hours [24]	30-50 [24]	75-300 [24]	70 – 90 [22]	5-15 [24]	500-1000 [22]	0.1%-0.3% [24]	Minutes-Days [24]	5-10ms [31]	1-8 hrs [23]	Mature	High 0-100^{0}F[23]	Negative [24]
	Redox flow	≤ 10 [22]	0.03-7[22]	Seconds-hours [24]	10-30 [24]	-----	75 – 85 [22]	5-10 [24]	12000 [22]	Small [24]	Hours-months [24]	Sec [31]	1-8 hrs [23]	Demo [22]		Negative [24]
II. Mechanical energy storage	Compressed air storage	≤250 [22]	5-300[22]	1 – 24 hours [24]	30-60 [24]	-----	60 – 79 [22]	20-40 [24]	8000 – 12000[22]	Small [24]	Hours-months [24]	1-15min [31]	4-24 hrs [23]	Demo [22]	Normal atm [23]	Negative [24]
	Pumped hydro storage	≤ 5000 – 140000[22]	<3100[22]	1 – 24 hours [24]	0.5-1.5 [24]	-----	65 – 82 [22]	40-60 [24]	10000 - 30000[22]	Very small [24]	Hours-months [24]	Sec-min [31]	12 hrs [23]	Mature	Normal atm [23]	Negative [24]
	Fly wheel Storage		0 - 0.25 [24]	ms-15 min [24]	10-30 [24]	400-1500 [24]	93-95 [28]	≈ 15 [24]		100% [24]	Seconds - minutes [24]	<4ms-sec [31]	Minutes-1 hour [23]	Commercializing [31]	Normal atm [23]	Almost none [24]

Table 3.1 Comparison of technical characteristics of energy storage systems (Cont.)

Energy storage device Main Cat.	Energy storage device Sub Cat.	Capacity [MWh]	Power rating [MW]	Discharge time	Energy density [Wh/kg]	Power density [W/kg]	Efficiency [%]	Lifetime [Years]	Cycle Life [cycles]	Self-discharge per day	Storage duration	Response time	Discharge duration at max. power	Maturity	Operating temperature	Environment influence
III. Chemical storage	Hydrogen fuel cell	Varies [22]	Varies [22]	Seconds-24 hours	800-10000[24]	500+ [24]	20 – 50 [22]	5-15 [24]	----	Almost zero [24]	Hours-months [24]	Good <1Sec [28]	Hours as needed [23]	Commercializing [31]	50-120^0 c [23]	Benign[24]
	Methane storage	Varies [22]	Varies [22]			-----	28 – 45 [22]	---	----	---	Hours-months [24]	---	Hours as needed	Demo [22]		---
IV. Thermal storage	Sensible heat storage	---	0.001-10[22]	1 – 8 hours [24]	80-120 [24]	-----	50 – 90 [22]	10-20 [24]	----	0.5% [24]	Minutes-Days [24]	----		Commercialized [22]		Small [24]
	Latent heat storage	----	0.001-1 [22]	1 – 24 hours [24]	80-200 [24]	-----	75 – 90 [22]	5-15 [24]	----	0.5–1.0 % [24]	Minutes-months [24]	----		Commercialized [22]		Small [24]
	Thermo-chemical	----	0.01 - 1 [22]	1 – 8 hours [24]	150-250[24]	10-30 [24]	75 –100 [22]	20-40 [24]	----	0.5–1.0 % [24]	Minutes-Days [24]	----		Commercalized [22]		---
V. Electrical storage	Capacitors storage		0 – 0.05 [24]	Millisecs-60min [24]	0.05-5	≈100000 [24]	60-65 [28]	≈5 [24]	50000 + [24]	40% [24]	Seconds -hours [24]	Very fast [28]		Developed [28]		Small [24]
	Super capacitors		0 – 0.3 [24]	ms -60 min [24]	20+ [24]	100000+[24]	90-95 [28]	10-30 [24]	100000 + [24]	20-40% [24]	Seconds -hours [24]	8 ms [31]		Commercializing [33]		Small [24]
	SCMS Storage		0.1 – 10 [24]	Millisecs-8 secs [24]	0.50.5-5 [25]	50500 -2000 [24]	95-98 [28]	20+ [24]	1000 100000 + [24]	10 -1 10-15 % [8][24]	Minutes-hours [24]	<100 <100 ms [31]		Commercializing [31]		Negative [24]

3.8 ECONOMIC CHARACTERISTICS OF ENERGY STORAGE SYSTEMS:

Based on the technical characteristics suitability feasible energy storage systems can be selected to a particular application. However to select the most economical storage system from the technically suitable option study on economic aspects of storage system is essential. As the present application is related to electrical energy storage, study on cost analysis of Electrical Energy Storage (EES) systems is considered.

Cost analysis of the EES systems is based on two main approaches i.e. Total Capital Cost (TCC) and Life Cycle Cost (LCC) [34]. Normally the TCCs of EES systems mainly consist of purchase, installation and commissioning of EES unit comprising of Power Conversion System (PCS), Energy storage section and Balance of Plant (BOP). PCS may consists of power interconnection equipment for charging and discharging with different characteristics and storage section mainly include the storage medium containment equipment like battery banks, air tanks (CAES), reservoirs (PHS) etc.[34]. BOP may include the project engineering, grid integration facilities, monitoring and control equipment etc. Normally PCS related costs are expressed in per unit of capacity i.e. €/kW, whereas energy related costs in per unit of energy stored or delivered i.e.€/kWh and BOP costs in per unit of power (€/kW) or in energy (€/kWh) where, € is used for EURO currency [34].

TCC can be calculated per unit of output power rating, (Ccap) as indicated in eq. (3.1).

$$C_{cap} = C_{PCS} + C_{BOP} + C_{stor} \times h \quad (€ / kW) \quad \text{----------------------------------} \quad (3.1)$$

While C_{PCS}, C_{BOP}, and C_{stor} represent unitary costs of PCS, BOP, and storage compartment (€ /kWh), respectively, h is the charging/discharging time.

LCC is more appropriate to compare different EES systems, as it accounts for the all expenses like fixed operation and maintenance costs, variable operation and maintenance costs, replacement costs, disposal costs, recycling costs and total capital costs.

Annualized Life Cycle Costs (ALCC) is the LCC expressed in Levelized annual costs in (€/ kW-yr) i.e. the yearly payment an organization should maintain for all the services of EES, including loan payments and upfront of the capital costs.

Hence, is the Levelized ($C_{LCC.a}$) can be expressed as indicated in equation (3.2) [34],

$$ALCC= C_{LCC.a} = C_{cap.a}+ C_{O\&M.a}+ C_{R.a} + C_{DR.a}(€/ kW\text{-}yr) \quad \text{--------------} \quad (3.2)$$

Where, $C_{cap.a}$ is annualized TCC and expressed by equation 3.3 and 3.4 [34],

$$C_{cap.\ a} = TCC \times CRF \quad (€/ kW\text{-}yr) \quad \text{---------------------------} \quad (3.3)$$

$$\text{Where, } CRF = \text{capital recovery factor} = i\ (1+i)^T / (1+i)^T - 1 \quad \text{-----------------} \quad (3.4)$$

Where, i is the interest rate during the life time T

$C_{O\&M.a}$ is the total annual operation and maintenance costs and given in eq. (3.5) [34].

$$C_{O\&M.a} = C_{FOM.a} + C_{VM} \times n \times h \quad \text{(€ / kW –yr.) --- (3.5)}$$

Where, CFOM.a= annualized costs of fixed O & M, C_{VOM} = Variable operation and maintenance costs, n= number of discharge cycles per year and h = Yearly operating hours

Similarly, $C_{R.a}$ is the annualized replacement costs of EES systems and given by eq.3.6 [34],

$$C_{R.a} = CRF \times \sum_{K=1}^{r} (1 + i)^{-kt} \times [(C_R \times h)/ \eta_{sys}] \quad \text{(€ / kW –yr.) -------------------- (3.6)}$$

Where r = replacement period in years, C_R = the future cost of replacement in €/kWh, k= Discharge time in hours and η_{sys} is overall system efficiency for one full cycle at the rated depth of discharge (DOD). Similarly, $C_{DR.a}$ is the annualized disposal and recycling costs (C_{DR}) are represented by eq. (3.7) [34],

$$C_{DR.a} = C_{DR} \times [i/ (1+i)^{T} – 1] \quad \text{(€/ kW –yr.) ---------------------------------- (3.7)}$$

Levelized cost of electricity (LCOE) can be expressed by equation 3.8[34],

$$LCOE = ALCC / \text{Yearly operating hours} = C_{LCC.a}/ (n \times h) \quad \text{(€ / kWh) ------------- (3.8)}$$

The net levelized cost of storage (LCOS) can be obtained by Eq. 3.9[34]. This way, the cost of employing EES can be calculated despite the price of electricity,

$$LCOS = LCOE – \text{(Price of charging power/overall efficiency) (€ / kWh) ------------ (3.9)}$$

The economic characteristics of the energy storage systems are indicated in table 3.2

Table 3.2 Comparison of economic characteristics of energy storage systems [34]

S. No	Electrical Energy Storage System	Average Cost of PCS €/kW	Average Cost of storage system €/ kWh	Average TCC * € / kW	Average Fixed O & M costs €/ kW-yr.	Average Variable O & M costs €/MWh.	Replacement Costs €/ kWh	ALCC ** €/kW-yr.	LCOE €/ MWh
1	PHS	513	68	1406	4.6	0.22	----	239	120
2	CAES under above	843 846	40 109	893 1315	3.9 2.2	2.2 3.1	-----	269 319	134 159
3	Fly wheel	302	---	867	5.2	2.0	----	---	
4	Lead acid	378	618	1923	3.4	0.37	172	646	323
5	NaS	366	298	2254	3.6	1.8	180	487	244
6	Li-ion	463	795	1160	6.9	2.1	369	493 for T & D	617 for T & D
7	VRFB	490	467	2512	8.5	0.9	130	706	353
8	Ni cd	239	780	1093	10.9	11	525	842	421
9	Super capacitors	----	-----	229	-----	---	---	-----	-----
10	SMES	----	-----	218	-----	---	---	------	-----
11	Hydrogen Fuel cell	-----	3.67	3243	25.1	----	----	385 for T& D	481
12	Hydrogen GT	-----	130	1570	34.7	---	---	333 for T & D	416

* 1) Total Capital Cost (TCC) of large scale EES system per unit of normal power rating based on equation 2[34].

2) The costs are for typical size of each system which is not same for all technologies.

****** ALCC **costs** based on 250 cycles per year, 8 % interest rate and 8 h discharge time [34].

3.9 SUMMARY

Literature survey carried out systematically to resolve the practical problems developed after integration with RE in an identified cogeneration industry is presented. Literature survey is made on stage wise to resolve the issues. Even though most of the data is collected from the internal data of the industry, the external literature survey helped in providing the general guide lines like identifying the suitable heuristic techniques. In depth analysis of techno economic factors of various energy storage technologies is carried out to explore suitable storage technology for the present application. The literature survey is also the base for developing equations to establish BEP.

CHAPTER-4

BEP ESTIMATION BY REAL – TIME / ONSITE DATA

4.1 REMEDIAL SOLUTIONS TO THE PROBLEMS DEVELOPED AFTER INTEGRATION WITH RENEWABLE ENERGY:

To come out of the situations raised due to the integration of solar energy, the following options are considered to establish a feasible solution.

As the plant is switching to inefficient operation when a full solar plant is in service, it was decided to keep a part load of the solar plant only i.e. up to which efficiencies are being maintained. Stopping solar generation is resulting in the non-utilization of green energy and consuming the fossil fuels. Hence, the prime objective of establishing renewable energy is defeated. At the same time, the renewable power purchase obligation is also not fulfilled. Hence, the following cases are analyzed for study.

CASE I: In this case, considered full solar generation, by reducing correspondingly the generation on TGs with a corresponding reduction of load on the steam generators. This requires oil support. Following strategies are assumed

a) To minimize the effect on both steam generators with a reduction in TG load, one SG can be kept on fixed load i.e. around 60 % MCR. The entire steam flow variations due to solar have to be absorbed by the other boiler. By this only one boiler requires the oil support and a maximum of 4 burners are required for coal mills on light load operation.

b) Similarly the generation of one TG has to be maintained constant i.e. at 60 % MCR i.e. 18 MW. In this the extractions from at least one TG will not get affected. The other TG generation has to be reduced depending on the solar generation. The extraction steam that comes down has to be compensated through PRDS.

4.2 COST-BENEFIT ANALYSIS:

By operating the plant as stated above, developed the cost-benefit analysis with generalized formulae. Followed the following methodology to establish the cost-benefit analysis

1. Estimate the cost of oil by accounting for the number of oil guns taken to stabilize the furnace. The capacity of the oil guns and the oil cost per MT are the main parameters for consideration. Equation 4.1 indicates the total oil cost per hour.
2. Total MW loss due to the reduction of HP and LP steam flows from the Turbine are calculated by accounting for the actual quantity of HP and LP

iii. Steam reduction from turbine extractions and diverting to HP and LP PRDS stations. The HP and LP MW loss is calculated using the enthalpy drop across the HP and LP parts of the turbine. Equation 4.2, 4.3, and 4.4 indicates MW loss due to HP, LP, and total loss due to both HP and LP respectively.

iv. The net MW reduction on TGs due to solar generation can be the difference between total solar generation and total MW loss due to HP and LP PRDS openings. Equation 4.5 indicates the net MW reduction on TGs.

v. The net reduction of steam on the boilers can be obtained from the steam rate (steam factor). Equation 4.6 indicates the Net reduction of steam on the boilers.

vi. The quantity of coal savings due to the reduction of steam demand from boilers can be calculated by accounting for the factor evaporation ratio. The evaporation ratio is the amount of steam generated in MT per MT of fuel i.e. coal consumed. Equation 4.7 indicates the amount of coal saved due to the reduction of steam demand from boilers.

vii. As oil firing is added to stabilize the furnace, there will be corresponding savings in coal. Hence, the equivalent coal saved due to oil firing can be accounted for by considering the calorific values of both oil and coal. Equation 4.8 indicates the coal savings due to oil firing.

viii. The total coal saving on account of steam demand reduction and oil firing can be the summation of coal saved due to steam reduction and oil firing.

ix. Based on the cost of coal per MT, the total saving in cost on account of coal reduction is represented by equation 4.9

x. Now the total cost benefit is the difference of a reduction in cost saving on account of coal and additional cost incurred due to oil firing. Equation 4.10 indicates the total cost benefit in rupees per hour.

xi. If the total cost-benefit value is negative it indicates the loss and profit if the value is positive.

Above is the generalized procedure that can be applied to similar cases. Following are the parameters assumed to develop the equations

N= Number of oil guns taken to stabilize the furnace

$Q_{\text{oil gun}}$ = Design flow rate of the oil gun in MT/hr

TQ_{oilfired} = Total Quantity of oil fired = N x $Q_{\text{oil gun}}$

C_{oil} = Cost of oil in Rs per MT

Total Cost of oil (TOC) fired in Rs/hr= $TQ_{oilfired} \times C_{oil}$ -------------------------- (4.1)

Q_{hp} = HP Steam flow reduction from HP turbine extraction in MT/hr

Q_{lp} = LP Steam flow reduction from LP turbine extraction in MT/hr

H_{inlet} = Turbine steam enthalpy in kcal/hr at turbine inlet pressure and temperature

H_{HPE} = HP steam enthalpy in kcal/hr at turbine HP extraction pressure and temperature

H_{LPE} = LP steam enthalpy in kcal/hr at turbine LP extraction pressure and temperature

K = Conversion factor to convert heat energy to electrical energy in kcal/hr/kW=860

PL_{HP} = Power generation loss due to HP steam reduction from turbines in MW

PL_{LP} = Power generation loss due to LP steam reduction from turbines in MW

$TPL_{HP\&LP}$ = Total Power generation loss due to both HP and LP steam reduction from Turbines in MW

Now, $PL_{HP} = Q_{hp} [H_{inlet} - H_{HPE}] / K$ MW--- (4.2)

$PL_{LP} = Q_{lp} [H_{inlet} – H_{LPE}] / K$ MW--- (4.3)

$TPL_{HP\&LP} = PL_{HP} + PL_{LP}$ MW--- (4.4)

$SP_{generation}$ = installed solar power generation in MW

$TGP_{reduction}$ = Net power reduction on TGs due to solar injection in MW

$= (SP_{generation} – TPL_{HP\&LP})$ ----------------------------- (4.5)

SR_{boiler} = Design steam rate of boiler in MT/MW

$SR_{reduction}$ = Steam reduction on boilers in MT

$= TGP_{reduction} \times SR_{boiler}$ -------- (4.6)

ER_{boiler} = Design evaporation rate of boiler

$QOCS_{steam\ reduction}$ = Quantity of Coal Saved due to Steam reduction from boilers in MT

$= SR_{reduction} / ER_{boiler}$ --- (4.7)

CV_{oil} = Calorific Value of oil in kcal/kg

CV_{coal} = Calorific Value of coal in kcal/kg

$CF_{oil\ to\ coal}$ = Conversion Factor to convert oil quantity to equivalent coal quantity in MT

$= CV_{oil} / CV_{coal}$

$QOCS_{oilfiring}$ = Quantity of coal saved due to oil firing in MT

$= CF_{oil\ to\ coal} \times TQ_{oilfired}$ --------------------- (4.8)

C_{coal} = Cost of Coal in Rs per MT

TCCS = Total Coal Cost Saved in Rs = $[(QOCS_{steamreduction} + QOCS_{oilfiring})] \times C_{coal}$ -------- (4.9)

Total Cost Benefit/loss (TCB) in Rs/hr = (TCCS - TOC)

If the numerical value of TCB is positive it is a profit otherwise it is a loss.

4.3 ESTIMATION OF TOTAL COST BENEFIT

The estimation of total cost benefit is carried out for the case (i) operation by the above developed methodology.

Case I: when solar generation is 12 MW (Peak)

The Plant operation data is given in Table 4.1

Table 4.1 Plant operation data with 12 MW solar plant in service

S. No	Description	Nil export & solar generation 12 MW	Remarks
i)	2 Steam generators with Main steam generation	330 MT/hr	Boiler 1 165 MT/hr Boiler 2 135 MT/hr
ii)	2 Turbo generators with total power generation	19 MW	TG 1 15.5 MW TG 2 3.5 MW
iii)	Auxiliary Turbo Generator power generation	4.0 MW	
iv)	Power Export	Nil	
v)	Power Import, if any	Nil	
vi)	Steam through HP PRDS	105MT/hr	
vii)	Steam through LP PRDS	10 MT/hr	
viii)	HP steam consumption before/after de-superheating	210 / 245 MT/hr	TG 1 Extraction 105/MT/hr HPPRDS 105/MT/hr
ix)	LP steam consumption before/after de-superheating	20./25 MT/hr	TG 1 Extraction 10/MT/hr LPPRDS 10/MT/hr
x)	Condensate flow	70 MT/hr	TG1 55MT/hr TG 2 15 MT/hr

a) Oil cost for 4 oil guns: Assuming each oil gun consumes 300 kg/hr

Total oil consumption for 4 oil guns=1.2 MT/hr

Cost of oil/MT=Rs. 30,000/-

Total cost of oil /hour=Rs 1.2*30,000=Rs 36,000/-

MW Loss due to HP PRDS opening = 105(794-747)/860 = 5.74 MW

Where TG inlet steam enthalpy = 794 kcal/kg

HP extraction steam enthalpy = 747 kcal/kg

MW Loss due to LP PRDS opening = 10(794-694)/860 = 1.16 MW

Where TG inlet steam enthalpy = 794 kcal/kg

LP extraction steam enthalpy = 694 kcal/kg

Resultant steam reduction on steam generators;

Total loss due to HP & LP PRDS opening = (5.74+1.16) =6.9 MW

Equivalent MW reduction= (12.0-6.9) MW=5.1 MW

Equivalent Steam reduction= =5.1*5 =25.5 MT/hr

Coal consumption /MT of steam= 5 MT

Hence coal saved due to steam reduction on steam generators= 25.5/5=5 MT/hr

Cost of coal per MT = Rs 3500 /-

Cost benefit due to coal saving= Rs 5*3500/-=Rs17, 500/-

f) Calorific value of oil =10,000 kcal/kg

Calorific value of coal=4,000 kcal/kg

Ratio of oil to coal calorific value = 2.5:1

Hence 4oil guns oil quantity of 1.2 MT/hr is equivalent to 2.5*1.2 MT of coal i.e. 3 MT of coal

Hence coal saving due to oil firing=Rs 3*3,500/-= Rs 10,500/-

Net saving due to coal= (e+f) =Rs (17,500 + 10,500) =Rs 28,000/-

Hence total benefit by keeping all 12 MW solar panels in service = (g-a)

= Rs (28,000-36,000) = Rs (-) 8,000/-

As the result is negative it indicates loss by going full solar generation.

Hence this indicates by keeping a full solar plant, there is no financial gain. Moreover, as solar is variable in nature, the average power generation comes to around only 6 MW. Hence keeping the solar plant in service will not be economical as loss through HP and LP PRDS by this mode of operation is coming around 6.9 MW which is more than solar generation.

4.4 ESTIMATION OF BEP BY REAL TIME/ON-SITE DATA

As the case (i) operation i.e. keeping full solar capacity is proven uneconomical based on cost -benefit analysis, the operation strategy as stated in case ii) is considered. Practical experiments are carried out and based on the data collected, BEP is estimated.

Case ii): From the above, integration of RE with co-generation plants has proven uneconomical and it is better to meet the RPPO obligation by purchasing Renewable Energy Certificates (RECS) from the market instead of going for huge investments and involving a lot of process variations.

However, as the solar plant is already set up without so much of study and without anticipating the hurdles, the second option is to study the feasibility of utilizing partial solar plant capacity available which is something better than nothing.

For this, the break-even point of solar generation utilization can be obtained by practically experimenting. Theoretically the break-even point is the point beyond which reduction of steam generation on SG demands oil support and the HPPRDS opening is optimum. Here assumed the variation of load on both TGs in parallel based on the solar generation. To find out the break-even point, it is better to conduct a practical experiment by switching the solar panels one by one. Observe for deviation of optimality conditions i.e. opening of HP PRDS valves or steam generator load falling below the minimum threshold limit. Here contrast to case i) the load on both the TGs has to be varied in parallel based on the solar generation variations i.e. increase or decrease have to be done on both TGs equally . Similarly, the load on the steam generators should be varied on both the steam generators equally instead of on one steam generator as in the case of case i).

With the practical experiment conducted, the break-even point is worked out as 6.3 MW i.e. 50% of the solar plant capacity, and the parameters are indicated in table 4.2.

Table 4.2 Plant operation data with 6.3 MW (BEP) solar plant in service

S. No	Description	Nil export & solar generation 6.3 MW	Remarks
i)	2 Steam generators with Main steam generation	317 MT/hr	Boiler 1 159 MT/hr Boiler 2 158 MT/hr
ii)	2 Turbo generators with total power generation	25.5 MW	TG 1 13.0MW TG 2 12.5 MW
iii)	Auxiliary Turbo Generator power generation	3.5 MW	
iv)	Power Export	Nil	
v)	Power Import ,if any	Nil	
vi)	Steam through HP PRDS	NIL	
vii)	Steam through LP PRDS	7.2 MT/hr	
viii)	HP steam consumption before/after de-superheating	210 / 245 MT/hr	TG 1 Extraction 105/MT/hr TG 2 Extraction 105/MT/hr
ix)	LP steam consumption before/after de-superheating	30.2/35 MT/hr	TG 1 Extraction 11.5 /MT/hr TG 2 Extraction 11.5 /MT/hr LPPRDS 7.2 /MT/hr
x)	Condensate flow	70 MT/hr	TG1 55MT/hr TG 2 15 MT/hr

From the above, it is observed that at 6.3 MW solar, Resultant steam reduction on steam generators = (330-317) =13 MT/hr

Hence coal saved due to steam reduction on steam generators = 13/5 =2.6 MT/hr (considering 1 ton of coal generates 5 MT/hr). Cost benefit due to coal saving= Rs 2.6*3500/-=Rs9, 100/- Cost of coal per MT = Rs 3500 /-

Further increase of solar generation results in oil support as steam generation levels of both boilers are at verge (60% MCR), hence uneconomical as explained under case i). Hence the break-even point is 6.3 MW and operation above 6.3 MW is not economical, and hence part-load operation of solar is economical and recommended.

Experiment is further continued to find out the cost savings below the 6.3 MW and data recorded is presented in Table 4.3, and represented graphically in Fig 4.1.

Table 4.3 Cost benefit analysis results

S. No	Solar generation in MW	Total steam generation in MT/hr	Steam reduction on boilers with solar in MT/hr	Cost saving due to steam reduction in Rs
1	6.3	317	13	9100
2	6.0	320	10	7000
3	5.5	321.6	8.4	5880
4	5.0	319	11 #	7700
5	4.5	321	9	6300
6	4.0	323.8	6.2	4340

#Steam reduction is increased as LP PRDS got closed fully. But cost saving is still maximum at 6.3 Mw only even though LP PRDS is partially open.

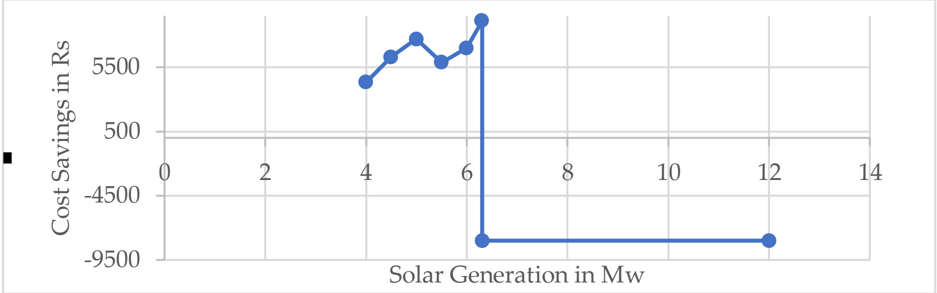

Figure 4.1 Cost savings in Rs Vs solar generation in MW.

From the above it is observed that at 6.3 MW solar the LP PRDS valves got opened by around 68 %. This is equivalent to 7.2 MT/hr of LP steam as per the LP PRDS valve characteristic. The LP PRDS opening even though it decreases the benefit of solar generation but still it is in advantageous position as compared to case i)

Further increase of solar generation, leads to HPPRDS opening and furnace instability resulting in oil firing support which is uneconomical as explained under case i)

Hence it appears that part load operation of solar is economical. However, following are the other issues related with the operation of the plant

If a plant comes to islanding due to predefined external grid conditions/grid fault conditions, suddenly TGs have to take additional generation. Sudden additional load on TGs is equal to solar generation available before islanding. This is due to prevailing logic, as solar panels will go out of service with islanding. The interlock of solar plant switching off with plant islanding is to ensure smooth operation of TGs and SGs. No problems are expected, if grid frequency is maintained around 50 Hz. In case of grid operating at low frequency, problems arise as TGs may trip on under frequency. This may results in total supply failure of the plant. Hence, it envisaged logic modification in case of low frequency operation. The auto off feature has to be defeated in case of low frequency operation. The solar panels shall be switched off manually one by one after stabilizing the TGs generation.

4.5 RENEWABLE ENERGY INTEGRATION CHALLENGES – SOLUTIONS

The main problem of plant operation switching into inefficiency is addressed and BEP is estimated as above. The other minor challenges associated with RE integration are discussed under case iii) and case iv).

Case iii): The main problem of integration of Renewable energy with co-generation plants is continuous variation of process parameters. The remedial solutions for mitigation of the variations can be achieved through controller's modification as explained below.

The boiler pressure variations can be reduced by giving a feed forward signal to the master pressure controller. The feed forward signal can be from measured variable of solar irradiance/ insolation level. Normally the master pressure controller works on the feedback of the actual steam pressure. If solar insolation level is used as a feed forward signal to master pressure controller, the controller initiates action prior to actual variations in steam pressure. Hence, proactive action of controller helps in reduction of variations of steam generator outlet pressures. Similarly for import/ export controller also feed forward signal of solar insolation can be used to stabilize the TG parameters.

Case iv): In addition to the above, ideal solution can be connecting the solar plant independently to the grid, provided state electricity companies accept an agreement to export renewable energy. In the present case study considered state authorities have not accepted due to technical limitations.

Other option is to search for customers who need either heat load or electrical energy. Wheeling of power to nearby industries is the better option in case of requirement. Agreements shall be made such a way that nearby industries have to be attracted by offering lower prices than conventional power as the solar generation is cheaper. With this we can get the benefit of RPPOs also.

Following are the other options that can be adopted after detailed analysis of techno commercial feasibility

a) Installation of ozonizer: The water required normally in the process plants requires treatment before using the process. Generally chlorine and other chemicals are used for the purpose of disinfection. Ozone is very strong oxidizer and a powerful disinfecting property. A very small concentration of ozone in water makes the free from bacteria, virus etc. much faster and with lesser concentration in a most effective manner.

Today there are four recognition methods of ozone production

- Corona discharge
- UV Radiation
- Electrolysis
- Radiochemical
- Any one method, which requires electrical energy can be adopted based on techno commercial feasibility. Hence, the water treatment can be planned whenever solar energy production is more than utilization. With this there are two fold advantages.
- Chemicals can be saved resulting in to the cost of water treatment
- The solar energy utilization will be better and this will fulfill the RPPO obligation also

b) Utilization of solar energy:

Hydrogen is an ideal replacement for fossil fuels such as coal, oil and natural gas in furnaces, internal combustion engines, turbines and jet engines. Today, the research is concentrated on hydrogen and development efforts on hydrogen as an alternative fuel. In future the transport sector may depend on fuel cells which convert hydrogen efficiently (back) to electricity. The application spectrum of fuel cells is vast. They have the potential to replace conventional power generators such as combustion engines or even large batteries in cars, buses; Forklift Trucks (FLTs), submarines, and backup and power plants.

Hydrogen can be produced using a number of different processes. Thermo chemical processes use heat and chemical reactions to release hydrogen from organic materials such as fossil fuels and biomass. Water (H_2O) can be split into hydrogen (H_2) and oxygen (O_2) using electrolysis or solar energy. Microorganisms such as bacteria and algae can produce hydrogen through biological processes.

Electrolyzer use electricity to split water into hydrogen and oxygen. This technology is well developed and available commercially. Hence the solar power can be utilized for the generation of hydrogen

The above methods that suit can be adopted for the full utilization of solar plant

4.6 CONCLUSION:

With the above experiences the future co-generation plants have to be designed so that they can absorb the solar generation. System should be designed in such a way to cater the variable solar in a better way. Boilers capacity should be designed so as to operate them without oil support even with full solar capacity. Similar should be the case with Turbine extractions also i.e. even with solar energy at full level turbines design should be in such a way that they give required extractions without PRDS opening.

CHAPTER-5

BEP ESTIMATION BY HEURISTIC FORWARD CHAINING APPROACH

5.0 INTRODUCTION

In an existing cogeneration plant where renewable energy is integrated, the full capacity utilization of renewable energy introduces inefficiencies. Through practical experimentation, the break-even point, i.e., the point beyond which renewable energy utilization becomes inefficient is established. However, establishing the break-even point practically necessitates steady state operation at various renewable energy generations. This affects the regular operation and the established break-even point depends on the system parameters at which experimented. Hence, a systematic methodology based on the heuristic forward chaining approach is adopted to establish the break-even point. An algorithm/flow chart is developed based on the turbo-generator load and extraction pressure controller’s behaviour. Theoretical equations are developed to obtain the high and low-pressure extraction flows, by accounting minimum flow through the low-pressure part of a turbine as well as to the condenser. Based on the extraction flows and the load on steam generator, optimality conditions are established. An iterative technique is adopted and the iteration process is terminated when any one of the predefined optimality conditions are deviated. The accurate value of a break-even point is obtained using Newton Raphson’s empirical formula. The break-even point obtained is compared with the results obtained from practical experimentation. The break-even point obtained by this method can be applied at different operating parameters and at different modes of operation. Even though the model developed is system/case-based, it applies to various cogeneration systems by adopting the concerned design and technical parameters.

5.1. FACTORS AFFECTING OPERATION OF CHP BEYOND BEP

With solar injection, the load controller reduces the load on TGs as total plant load is constant. Hence, both HP and LP control valves gets close resulting fall in HP and LP extraction pressures. LP extraction pressure after the control valve is maintained by regulating the control valve provided externally. Similarly, the HP extraction pressure controller maintains the stage pressure by increasing the HP valve and reducing the LP valve. Hence, results in further decrease in steam flow through the LP part of the turbine [53]. Finally, the saturation stage occurs at a particular steam flow to TG resulting in drop of LP extraction pressure. The LP steam pressure to process plant is maintained constant by supplying the deficit LP steam flow through LP PRDS. Hence, the first LPPRDS starts opening with a reduction of TG load. With the further injection of solar, the steam flow through the LP part of the turbine reaches the minimum threshold value. Hence, the HP extraction pressure controller becomes ineffective to ensure the minimum steam flow through LP part of the turbine. Hence, further opening of HP control valve and closing of LP control valve gets defeated resulting in HPPRDS opening. Hence, with an injection of renewable energy, part of HP and LP process steam flows through HPPRDS and LPPRDS respectively. HPPRDS and LPPRDS opening is an inefficient operation. Similarly, load reduction on TG may result in a fall of SG output below the threshold value. Hence, demands oil support due to furnace disturbances. Oil firing is not economical and results in increase in operation cost. Hence, the first key factor for inefficient operation is the part supply of HP/LP steam to the process plant through HP/LP PRDS. The second key factor for uneconomical operation is the reduction of SG load below a minimum threshold value. Supplying steam from PRDS is scratching the main advantage of co-generation. Hence, with PRDS opening, we are losing efficient cogeneration power. The difference in losing cost between cogeneration power and condensing power is much lower than the gain in the cost of solar power generation. Solar power generation cost is very low. Hence, it appears PRDS opening can be allowed based on the cost point of view and energy security point of view. Further increase in PRDS opening results in further inefficient operation. The boilers stability worsens in such a way that it is very uneconomical to continue the operation. Hence, to maintain the heat rate and boilers stability, the load on TG cannot be allowed to reduce beyond certain point. Hence, RE generation cannot be absorbed by the system beyond certain point, forcing to switch off the part of RE.

Hence, to maximize the efficient utilization of solar energy, it is economical to store the solar energy beyond the point where the system is becoming inefficient or uneconomical. The stored renewable energy can be utilized during the non-RE period. However, the conversion losses depend on the energy storage system adopted. Major energy storage technologies available are mainly based on mechanical, electrical, thermal, and chemical [27]. Specification and performance characteristics of these systems depend on the technology adopted. Efficiency of these systems varies widely from 35% (Hydrogen–fuel cell technology) to 95% (Fly wheel technology) [28]. Hence, for the arriving optimality condition, an average efficiency of 65% is considered. However, the exact value of efficiency can be considered based on the actual storage system adopted.

Consider Power loss due to HP and LP extraction flows reduction = X

Throttling loss in HP/LP PRDS = 2% of X = 0.02 X

Increase in solar generation = Y

The condition for first key factor of HP/LP PRDS opening is economical if, $[(X) + 0.02 X] > 0.35Y$ i.e. $1.02X > 0.35Y$

The second key factor is the load on steam generators and the condition for the constraint is

SG Steam flow > Minimum threshold value

Hence, it is worth to estimate the BEP, i.e., the point up to which the system can absorb the solar without introducing inefficiencies or becomes uneconomical. Even though the BEP is calculated for a particular industry, it may not be constant throughout the period as it depends on many process parameters like SG outlet pressure and temperature, total plant load, process, steam requirements, power export limitations, etc. [18]. However, the variations cannot be expected much as most of the process parameter loops are on auto. Similarly, the process thermal and electrical load requirements maintain constant once the system gets stabilized.

5.2 HEAT RATE OF A TURBINE AND SIGNIFICANCE ON SYSTEM EFFICIENCY

The heat rate of a turbine is the amount of heat required in Kilo Calories (KCal) to produce 1 Kilo Watt hour (kWh) [17]. Normally, conventional steam turbine systems (condensing type turbines) account for more kcal than backpressure type or extraction cum condensing type turbines. The main reason for better heat rate in backpressure or extraction cum condensing type turbines is due to the utilization of latent heat of the extraction steam in process industry. Hence, the same heat content is not accounted in power generation. However, in the case of condensing type, the entire steam is condensed in a condenser. Hence, the total latent heat condensed is accounted in power generation. Systems with less heat rate are more efficient than those with high heat rate as the efficiency of a co-generation system is inversely proportional to heat rate [1][17]. Normally cogeneration systems are designed with a particular heat rate depending on the process thermal as well as electrical load requirements. Hence, the selection of cogeneration systems is based on heat to power ratio [1]. The various cogeneration systems available are backpressure, extraction cum backpressure, extraction cum condensing type, double extraction type cum condensing, etc.

Any deviation in operation from the designed co-generation system parameters will alter the heat to power ratio, hence the efficiency of the system [17]. Hence, in cogeneration systems where renewable energies are integrated may lead to inefficiencies as renewable power injection reduce the power generation from turbo generators. The reduction of power generation from the turbine results in the reduction of inlet steam flow and in turn the reduction of extraction flows. As the process thermal requirements are constant, the deficit extraction steam shall be met by HPPRDS/LPPRDS. Once the steam is met from PRDS, the turbine heat rate will come down resulting in more steam consumption per kWh generation. Hence, the system shifts towards inefficiency.

5.3 TG CONTROLS MECHANISM- EFFECT ON HEAT RATE

Extractions cum condensing type turbine systems are provided with additional controls than the conventional type. This is mainly due to extraction pressures are to be maintained constant as per process requirement. Additional controls provided also ensure the minimum steam flow to LP part of the turbine to avoid starvation effects [4]. Hence, the main controls provided in the TG system are power/speed control, HP, and LP extraction pressure control. In addition to the TG controls, the co-generation plants/captive power plants are provided with a master import/export controller to maintain the total import/export constant. HP and LP control valves gets signals from these controllers. Speed /power controller maintains the TG generation constant by operating both HP and LP control valves in the same direction. To reduce TG generation, the HP and LP control valves get close so that the steam flow reduction in the HP and LP parts of the turbine remains constant [4] [[5]. HP extraction pressure controller maintains the HP pressure constant by operating the HP and LP control valves in the opposite direction. If HP pressure falls below a set value, the HP control valve gets open more and LP control valve gets close. This ensures the increase in power generation in HP part of the turbine gets lowered in LP part of the turbine. The ratio module provided determines the ratio of HP and LP control valves opening. Master import and export controller generates the signal to operate the power controller to maintain the import/export constant. Based on the variations in HP pressure, the HP pressure controller maintains the pressure without affecting the power generation. Normally, the second extraction pressure control is uncontrolled, i.e., controlled externally through a control valve. However, the interlocks to the LP control valve ensure the minimum steam flow through the LP part of the turbine. Quick closing NRV in the LP extraction line ensures minimum flow to the condenser beyond LP stage extraction. The NRVs gets close fully to avoid last stage blades starvation. The control mechanisms ensure safe operation of turbine systems as well as maintain the constant parameters at predefined set value. While maintaining the parameters and ensuring safety, the system may shift towards inefficiency.

5.4 HEURISTIC FORWARD CHAINING/REASONING APPROACH TECHNIQUE

The heuristic technique is a definite or deterministic and informed search technique that systematically explores the problem under a constant searching rule. When a problem is known and wants to obtain the solution in advance, the heuristic method suggests using known features of the given problem to obtain a good solution. Even though heuristic techniques may not yield accurate results, approximate solutions can be obtained in the case of complex problems.

Guess and check (iteration method), forward and backward chaining/reasoning, systematic listing, modeling, etc. are some heuristic techniques. When based on the available data a decision is taken, it is called forward chaining. With forward chaining, it makes use of the existing data along with the inference rules to extract more data until a certain goal is reached. The inference engine will iterate through the process of obtaining new data to eventually satisfy the goal. The working is based on the real-world implementation of the if-then clause. It works from an initial state and reaches the goal state [16]. It converts facts to first-order logic and variables are framed based on the available facts or rules. If based on the decision the initial state is fetched, then it is called backward chaining. Backward chaining is a decision-driven or goal-driven inference technique, whereas the forward technique is a data-driven inference technique.

Figure 5.1 represents the typical heuristic forward chaining/reasoning tree.

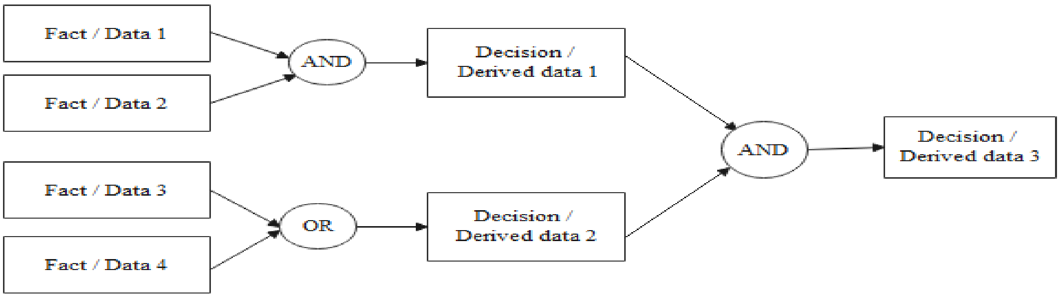

Figure 5.1 Typical Heuristic Forward Chaining/Reasoning Tree [16]

In the present case, as the goal is to determine at what point the optimality conditions are deviating, the forward approach technique, and other techniques of systematic listing, modeling, and iteration are adopted. With the available technical data of various control mechanisms and their behavior during load reduction on TGs, various first-order equations are developed. Optimality conditions are derived based on known technical limitations and safety interlocks. Finally, with the help of the iteration process, the optimality conditions are verified for the deviation until the break-even point is obtained.

5. 5 METHODOLOGY ADOPTED TO DETERMINE BEP

RE injection in a RE integrated CHP plant, the import/export controller reduces the TG generation resulting in steam reduction. The reduction of steam depends on the heat rate of the system. From the heat rate, the steam rate, i.e., MT /kWh, which is the equivalent main steam generation from the boiler, can be obtained by dividing the heat rate in kcal /kWh with the heat addition in boilers in kcal/MT. The following methodology is adopted

1) Assume RE of unit value, say, 1 MW is injected into the system, which makes the TG generation gets reduced proportionately. The power controller initially reduces the inlet steam flow equivalent to the steam rate of a turbine to absorb the RE.

2) With inlet steam reduction, the HP stage pressures falls. The HP pressure controller maintains the pressure by opening the HP control valve and reducing the LP control valve in the ratio of 0.60 / 0.40. The increase of steam in the HP part of the turbine is more than a reduction in the LP Part of the turbine as HP power generation is less than LP power generation per MT of steam by design. The drop-in stage pressure is linear with the inlet steam flow. Hence, based on the drop-in pressure, the equivalent compensation flow can be estimated. Drop-in pressure is compensated by increasing the HP steam flow by 0.60 parts and decreasing the LP steam flow by 0.40 parts. Hence, with RE injection, LP extraction steam reduction is more than HP.

3) Reduction in steam flow through the LP part of the turbine causes a fall in LP stage pressure. However, the extraction pressure can be compensated up to a certain level by the control valve provided externally. Based on the minimum and maximum LP extraction flows corresponding to the LP part of steam flow, a first-order straight line equation can be obtained. The control valve controllability and safety constraint of ensuring minimum steam flow through the last stage blades of the turbine are the conditions considered. Hence, the LP extraction and LPPRDS flows can be estimated.

4) Now the system occupies a different state of HP and LP flows at a new TG generation with corresponding changes in steam flow through the turbine and SG.

5) With the new values of data, the two optimality conditions corresponding to SG flow and total HP and LP PRDS loss are to be checked for any deviation.

6) In the case of no optimality condition is deviated, the new heat rate of the system shall be obtained.

7) Repeat the process by admitting another unit value of RE injection into the system. The system parameters change like above and stabilize with new HP and LP steam

flows at different energy generations. As there is more reduction of LP steam, a stage will reach where LP extraction pressure cannot be maintained even with the full opening of the control valve. Hence, the LP pressure starts falling leading to LP PRDS opening to maintain the LP steam for process and for internal use. With this, the system starts drifting towards inefficiency as the heat rate of the system starts falling. Thus, the first key factor initiator responsible for the inefficient operation is the LPPRDS opening.

8) With the further injection of RE, a stage arises such that the HP controller signal gets saturated in a downward direction. LP control valve cannot close further to ensure the minimum flow through the LP part of the turbine (60 MT/hr). Hence, the HP stage pressure cannot be maintained with a further reduction of power generation .The power controller dominates and reduces the inlet steam to maintain power reduction. The HP pressure cannot be compensated as the HP pressure controller has saturated, resulting HPPRDS opening to maintain the process flow. Hence, the second key factor responsible for the inefficient operation is HP PRDS opening.

9) With the further injection of RE, the HP and LP PRDS openings increase further as the stage pressure cannot be maintained due to reduction in inlet steam flow.

10) In case of steam flow through the LP part of the turbine beyond LP extraction falls to a minimum value of 45 MT/hr., the quick closing NRV in the LP extraction line gets close to protect LP stage blades resulting in complete LP steam through PRDS only.

11) Another key factor of boiler steam flow falling below a threshold value may occur depending on the prior steam generation. This can happen even before the start of LPPRDS or HPPRDS opening.

12) Developing a BEP with a direct RE system connected in line is a difficult task as the variation in RE is variable. Moreover, it may not give sufficient time to establish a steady state, so that the parameters cannot be noted for optimality condition checking.

13) Hence, to develop the BEP, the strategy adopted is to reduce TG generation and estimating the inlet, HP, and LP flow variations and then checking for optimality conditions. The process shall be repeated iteratively until any optimality condition gets deviated.

14) An accurate BEP shall be estimated using the Newton Rapson’s empirical formula [20, 54].

5.6 FORWARD CHAINING /REASONING TREE TO ESTABLISH BEP

Based on the methodology developed, step-by-step procedure to establish a forward chaining/reasoning approach tree to find the BEP is represented in Figure 5.2.

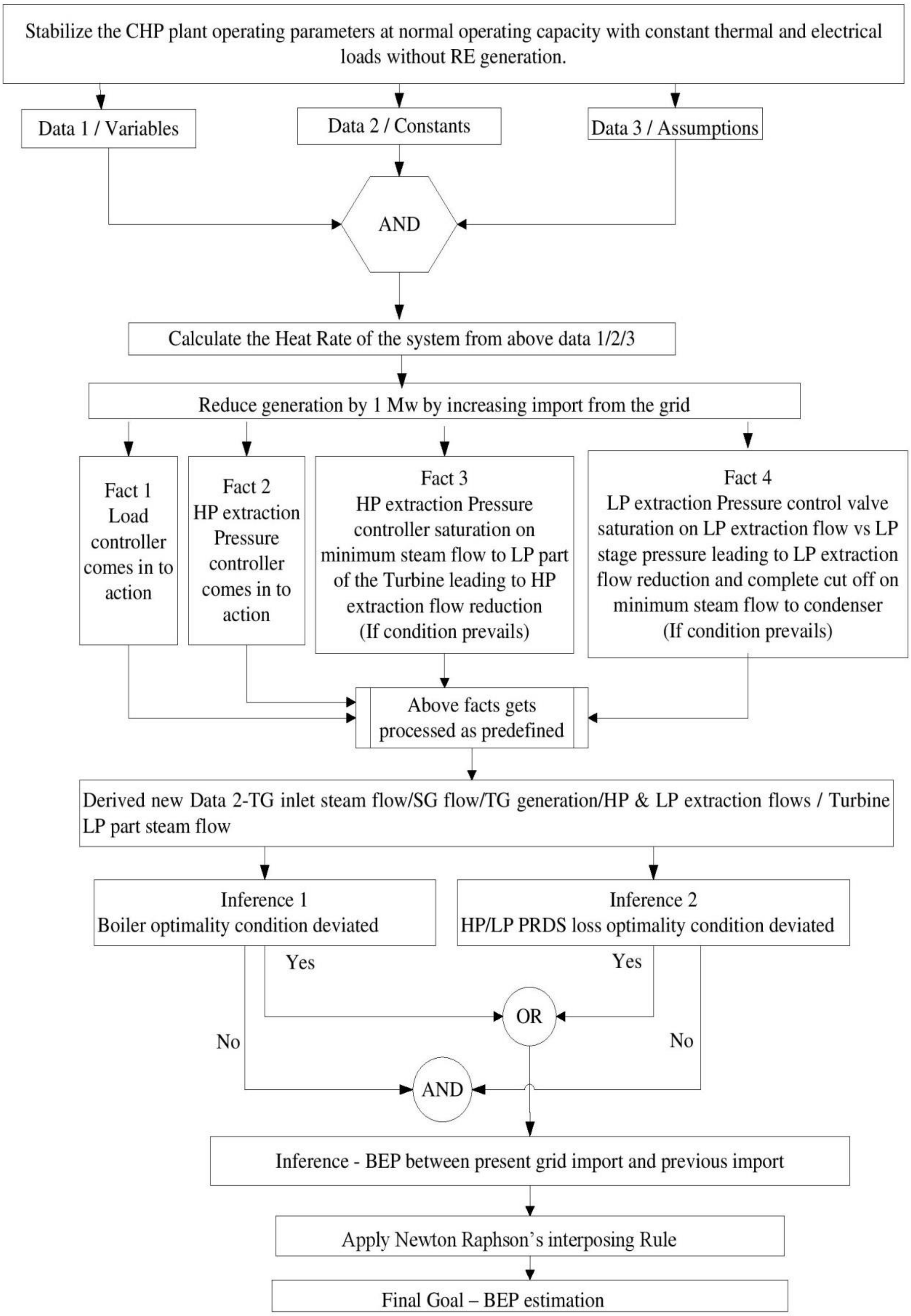

Figure 5.2 Forward chaining/Reasoning tree to establish BEP

5.7 MATHEMATICAL MODEL TO ESTIMATE BREAK-EVEN POINT

Based on the methodology and stepwise procedure, a mathematical model is developed as shown in Figure 5.3. The identified variables and constants to arrive at the equations based on predicted controller actions and system safety interlocks are indicated in Table 5.1. As the mathematical model developed is based on theoretical concepts based on the system behaviour with a rejection of load on TG, the model is also called theoretical modeling.

Table 5.1 Variables and constants identified

Variables	Constants
SGF_i = Steam Generator Flow at instant i TGF_i = Turbo Generator Flow at instant i HR_i = Heat Rate of a system at instant i SR_i = Steam Rate of a system at instant i $HPEXF_i$ = HP Extraction Flow through turbine at instant i $LPEXF_i$ = LP Extraction Flow through turbine at instant i $HPPRDSF_i$ = HPPRDS Flow at instant i $LPPRDSF_i$ = LPPRDS Flow at instant i $HPPSF_i$ = HP Part Steam Flow of a turbine at instant i $LPPSF_i$ = LP Part Steam Flow of a turbine at instant i $PLHPX_i$ = Power Loss in MW due to steam flow through HP PRDS $PLLPX_i$ = Power Loss in MW due to steam flow through LP PRDS PLTXi=Total Power loss in MW due to steam flow through both HP & LP PRDS $HPSPP_i$ = HP Steam to Process Plant at 32 kg/cm^2, 238 °C $LPSPP_i$ = LP Steam to Process Plant at 8 kg/cm^2, 178 °C $DMWF_i$ = DM Water Flow to deaerator BEP = Break-even Point GIM_i =Grid Importat instant i EG_i = Electrical Generation in MW $BFWF_i$ = Boiler Feed Water Flow at instant i $PLHPX_i$ = Total power loss due to HP PRDS opening $PLLPX_i$ = Total power loss due to LP PRDS opening	TGE =Turbo Generator inlet steam Enthalpy at 100 kg/cm^2, 480 °C = 794 kcal/kg HPSE = Turbo Generator HP Extraction Steam Enthalpy at 32 kg/cm^2, 347 °C = 747 kcal/kg LPSE = Turbo Generator LP Extraction Steam Enthalpy at 8 kg/cm^2, 238 °C = 694 kcal/kg 1Kwh=860 kcal DMWE= DM Water Enthalpy = 33 kcal/kg HPRCF= HP Return Condensate Flow =150 MT/hr. LPRCF=LP Return Condensate Flow =20 MT/hr. HPRCE= HP Return Condensate Flow Enthalpy= 235 kcal/kg LPRCE= LP Return Condensate Flow Enthalpy= 100 kcal/kg DMWE= DM Water Enthalpy=33 kcal/kg BFWE=Boiler Feed Water Enthalpy=158 kcal/kg X= Renewable Energy installed capacity in MW= 12

While developing the model assumed, following parameters will remain constant throughout the plant operation and any minor changes will not contribute an appreciable change in the break-even point.

HPPS =HP Steam to process plant in T/hr.

LPPS= LP Steam to process plant in T/hr.   PL = Total Plant load in MW

SGFT= SG outlet steam Flow and Temperature   TGFT=TG inlet steam Flow and Temperature

Assumed entire HP extraction is utilized in the process industry and LP extraction in the process as well as feed water heating. The amount of steam required for heating will vary based on the SG load. Figure 5.3 represents the modeling of a typical cogeneration system. Mathematical equations are derived based on the theoretical concepts and mass flow balancing. Variables with subscript 2i indicate the values of variables at the next iteration.

i) Mathematical equation of Heat rate (HR_i) is obtained through Eqs. (5.1a-5.1c).

HR_i =Heat rate of a system in kcal/kWh

$$=1/EG_i[\{(TGF_i \times TGE) + (HPRCF \times HPRCE) + (LPRCF \times LPRCE) + (DMWF_i \times DMWE)\}- \{(HPEXF_i \times HPSE) + (LPEXF_i \times LPSE) + (BFWF_i \times BFWE)\}] \quad \text{-(5.1 a)}$$

$$=1/EG_i\ [\{(794TGF_i) + (150 \times 235) + (20 \times 100) + (33DMWF_i)\} - \{(747HPEXF_i) + (694LPEXFi) + (158BFWF_i)\}] \text{ ----------------- -----------------------------------(5.1 b)}$$

$$= 1/EG_i\{(37250+794TGF_i + 33DMWF_i) - (747HPEXF_i + 694\ LPEXF_i + 58BFWF_i)\}\text{(5.1c)}$$

Where TGFi, $HPEXF_i$, LPEXFi and EG_i are the initial values of the data collected after plant stabilization.

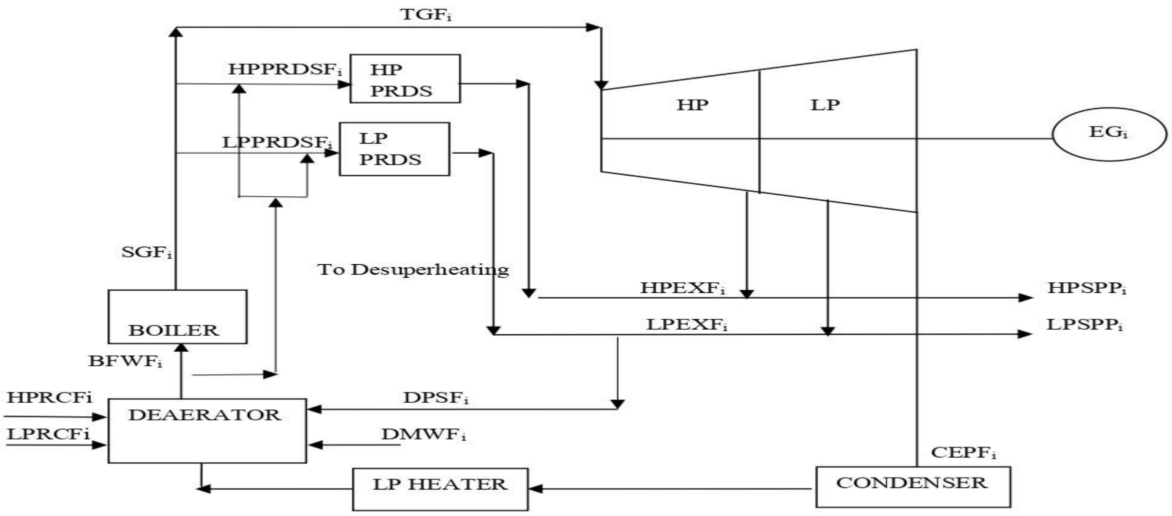

Figure 5.3 Modeling of a typical cogeneration system

ii) Total steam flow from the steam generator (SGF_i) can be obtained from Eq. (5.2).

$$SGFi = TGF_i + 0.78\ HPPRDSF_i + 0.7\ LPPRDSF_i \quad \text{----------------------- (5.2)}$$

Where $HPPRDSF_i$ and $LPPRDSF_i$ are the initial values.

In establishing the mass flow equation, the correction factor 0.78 and 0.7 is considered to account the equivalent main steam flow corresponding to HP and LP PRDS flows, respectively. Considered the equal amounts of main steam and desuperheating water. Correction factor of equivalent main steam corresponding to HPPRDS steam

= (Enthalpy of HP steam at 32 kg/cm^2, 347 $^\circ$C) / (Enthalpy of Main steam at 105 kg/cm^2, 485 °C + Enthalpy of desuperheating water at 105 kg/cm^2, 160 °C)= 747/ (794 + 160) = 0.78

Similarly, correction factor of equivalent main steam corresponding to LPPRDS steam

= (Enthalpy of LP steam at 8 kg/cm^2, 238 °C) / (Enthalpy of Main steam at 105 kg/cm^2, 485 °C + Enthalpy of desuperheating water at 105 kg/cm^2, 160 °C) = 694/ (794 + 160) = 0.73

However, 95% of this factor is considered as around 5% of energy loss is accounted for LP extraction circuit via an externally mounted LP control valve and 8 kg/cm^{2}piping circuit. Hence, the correction factor of equivalent Main steam corresponding to LPPRDS steam = 0.95 × 0.73 = 0.70

The desuperheating water is accounted for BFP feed water as it is fed from BFP discharge.

Initially, i.e., at the beginning of the first iteration, it is assumed that the total steam flow from the SG is more than the minimum threshold limit. The steam flow through the HPPRDS and LPPRDS are not deviating from the HP and LP optimality conditions.

iii) Values of Boiler feed water flow, CEP flow, Deaerator pegging steam flow, and DM water flow can be obtained from the Eqs. (5.3-5.6) based on the mass balance,

$BFWF_i = 1.005\ SGF_i + 0.22\ HPPRDSF_i + 0.3\ LPPRDSF_i$ ------- (5.3)

$LPSTC = CEPF_i = LPPSF_i - LPEXF_i$ ---------------------------- (5.4)

$DPSF_i = 0.08\ SGF_i$ -- (5.5)

$DMWF_i = \{BFWF_i - (HPRCF + LPRCF + DPSF_i + CEPF_i)\}$

$= \{BFWF_i - (150 + 20 + DPSF_i + CEPF_i)\}$

$= \{BFWF_i - (170 + DPSF_i + CEPF_i)\}$ ------------------ (5.6)

iv) The Steam rate of a system SR_i in MT/MWh is equal to HR_i divided by the heat added in kcal per MT of steam in a steam generator as represented by Eq. (5.7).

$SR_i = HRi/ 630$--(5.7)

Based on SR the inlet steam through turbo generator varies.

v) Steam flow through HP and LP Part of a turbine can be obtained from Eqs. (5.8, 5.9).

$HPPSF_i = TGF_i$---(5.8)

$LPPSF_i = TGF_i - HPEXF_i$ --(5.9)

vi) Now to simulate the condition of RE addition, import from the grid is increased in steps, by 1MW, so that the new import from the grid can be by Eq. (5.10).

$GIM_{2i} = GIM_i + 1$ -- (5.10)

vii) Injection of RE into the system, results in the reduction of TG generation and the corresponding steam flow through HP and LP parts of the turbine is as follows,

Initially, steam in the HP and LP part of the turbine gets reduced by equal to the steam rate (SR) due to the power controller action. Later, HP extraction pressure controller increases HP part steam flow by 60% and reduces the LP part of steam flow further by 40% of steam rate, resulting in an overall steam reduction in HP part by 0.4 times of SR and LP part by 1.4 times of SR. Thus, the new Steam flow through HP part of the turbine can be expressed by mathematical Eq. (5.11).

$$TGF_{2i} = HPPSF_{2i} = TGF_{i} - 0.4\ SR_{i} \tag{5.11}$$

viii) By incorporating the design minimum steam flow condition through LP part of the turbine, i.e., 60 MT/hr, the flow through LP part is governed by Eqs. (5.12, 5.13)

$$LPPSF_{2i} = (HPPSF2i - HPEXF_{i} - SR_{i}) \tag{5.12}$$

When $(HPPSF2i - HPEXF_{i} - 1.0\ SR_{i}) > 60$

$$\text{otherwise} \quad LPPSF_{2i} = 60 \tag{5.13}$$

ix) HP extraction flow also varies to maintain the minimum flow through the LP part of the turbine, based on which HP extraction flow through the turbine and HPPRDS can be from Eqs. (5.14-5.16) .The difference of steam flow through HPPRDS can be by Eq. (5.17).

$$HPEXF_{2i} = HPEXF_{i} \text{ when } TGF_{2i} - HPEXF_{i} > 60 \tag{5.14}$$

$$\text{Otherwise} \qquad HPEXF_{2i} = HPEXF_{i} - \{60 - (TGF_{2i} - HPEXF_{i})\} \tag{5.15}$$

$$HPPRDSF_{2i} = HPPRDSF_{i} + (HPEXF_{i} - HPEXF_{2i}) \tag{5.16}$$

$$DOHPPRDSF_{2i} = HPPRDSF_{2i} - HPPRDSF_{i} \tag{5.17}$$

Where $DOHPPRDSF_{2i}$ is the difference of steam flow through HPPRDS between two successive instant values, i.e., between instants i and 2i

x) Based on the guiding factor of minimum steam flow through LP stage blades after LP extraction, LP extraction flow through a turbine and LPPRDS flow can be by the Eq. (5.18).

$$\text{If } (LPPSF_{2i} - LPEXF_{i}) < 45 \text{ then } LPEXF2i = 0 \tag{5.18}$$

Otherwise, LP extraction is dictated by the equation generated based on the steam flow through the LP part of the turbine. One point is the minimum flow condition, i.e., at 45 MT/hr of LP part of the steam flow the LP extraction is zero as the quick closing NRV on LP extraction line gets close. Another point on the straight line is the condition based on the maximum controllability of the LP control valve, which is equal to 40 MT/hr steam flow corresponding to the LP part of the steam flow of 120 MT/hr.

The equation generated by the above two points is expressed by Eq. (5.19).

$$LPEXF_{2i} = (0.5LPPSF_{2i} - 22.5) \tag{5.19}$$

Hence, the LP extraction flow is either zero or a value equal to Eq. (5.19). Hence, Steam flow through LP extraction, is the minimum of the two values obtained by Eqs. (5.18 , 5.19).

After obtaining steam flow through LP extraction, Eq. (5.20) governs the steam flow through LPPRDS and the difference of steam flow through LPPRDS by Eq. (5.21).

$$LPPRDSF_{2i} = LPPRDSF_i + (LPEXF_i - LPEXF_{2i}) \quad \text{--------------- (5.20)}$$

$$DOLPPRDSF_{2i} = LPPRDSF_{2i} - LPPRDSF_i \quad \text{-------------------(5.21)}$$

Where $DOLPPRDSF_{2i}$ is the difference of steam flow through LPPRDS between two successive instant values, i.e., between instant i and 2i

Xi) Assuming the cutoff steam either from HP or from LP extraction contributes an additional power to TG as the cutoff steam flows to a condenser. The load controller comes into play and reduces the steam to TG corresponding to the increase in power. Steam reduction based on load controller action is given by Eq. (5.22).

$$TGF_{3i} = TGF2i - 1.1\ SR_i\ (0.163\ DOLPPRDSF_{2i} + 0.224\ DOHPPRDSF_{2i}) \quad \text{--- (5.22)}$$

Where 0.163 and 0.224 accounts for the power generation by LP and HP extraction cut-off steam based on the conventional thermodynamic concepts [5, 12].

HP part of the power = (794 -747) / 860 = 55 kW

Power due to up to LP extraction part of the turbine = (794 - 694) / 860 = 116 kW

Power due to LP extraction to exhaust of the turbine = (694 - 554) / 860 = 163 kW

Factor 1.1 is considered to account for further action of the extraction pressure controller, which will further reduce the LP part of steam flow and extraction flow reduction.

xii) Revised SG flow can be calculated by Eq. (5.23) and accordingly the revised DM water, Boiler feed water, CEP, and deaerator pegged steam flow can be calculated by Eqs. (5.3-5.6).

$$SGF_{2i} = TGF_{2i} + 0.78\ HPPRDSF_{2i} + 0.7\ LPPRDSF_{2i} \quad \text{------------------ (5.23)}$$

xiii) Optimality conditions can be checked to ensure efficient operation, based on Newton Raphson's empirical formula used in the IRR method [16, 54]. Eq. (5.24) gives an empirical formula to obtain IRR.

$$IRR = LR + [\{NPV\ at\ LR \times (HR - LR)\}/ (NPV\ at\ LR - NPV\ at\ HR)] \quad \text{---- (5.24)}$$

Where IRR = Internal rate of return and NPV = Net present value, LR = lower rate and HR = Higher rate

Based on the above, just like NPV at the higher rate is less, in the case of SGF_{2i} is less than the threshold value, then SGF_{2i} value is less than SGF_i. However, here the difference of (SGF_i - 320) or (320 - SGF_{2i}) can be more or less than others depending on the flow variations. Hence, the maximum of values (SGF_i - 320) or (320 -SGF_{2i}) shall be considered.

Boiler optimality condition can be checked using the threshold value of 320 MT/hr and BEP conditions in the case of SGF2i is less than 320 MT/hr is by Eqs. (5.25, 5.26).

However, $(GIM_{2i} - GIM_i) = 1$ if the import is assumed to increase by 1 MW in each iteration. Hence,

$$BEP_{SGFY} = GIM_i + \frac{[\{\text{Maximum of } (SGF_i - 320) \text{ or } (320 - SGF_{2i})\} (GIM_{2i} - GIM_i)]}{(SGF_i - 320) + (320 - SGF_{2i})} \tag{5.25}$$

$$BEP_{SGFY} = GIM_i + \frac{\text{Maximum of } (SGF_i - 320) \text{ or } (320 - SGF_{2i})}{(SGF_i - 320) + (320 - SGF_{2i})} \tag{5.26}$$

$BEP_{SGFN} = X = 12$, i.e., the value equal to the maximum renewable energy capacity

Where BEP_{SGFN} is the value of BEP when the optimality condition based on SG flow is not deviated, i.e., SG flow is more than a threshold value. BEP_{SGFY} is the value of BEP when the optimality condition based on SG flow is deviated i.e., SG flow is less than a threshold value. In the case of SG flow is more than a threshold value, then both BEP_{SGFY} and BEP_{SGFN} are considered as 12, i.e., the value equal to the maximum RE capacity

$BEP_{SGFY} = X = 12$ $\quad\quad$ $BEP_{SGFN} = X = 12$

xiv) Checking for Total HPPRDS opening optimality condition,

Power loss reduction due to reduction of HP extraction flow = $X_{hp} = (TGE - HPSE) / 860$

$= (794 - 747) / 860 = 0.055$ MW

Throttling loss in HP PRDS =2% of $X_{hp} = 0.02\ X_{hp}$, hence the total power loss due to HPPRDS opening can be expressed by Eqs. (5.27, 5.28) and the revised total power loss due to steam flow difference through HPPRDS can be given by Eq. (5.29).

$PLHPX_i = (DOHPPRDSF_i) \times 1.02\ X_{hp} = 0.0561\ DOHPPRDSF_i$ ------- (5.27)

However, $DOHPPRDSFi = HPPRDSF_i$ as the initial value of HPPRDSF to be considered as a change in HPPRDS flow only due to non-availability of prior status.

Hence, $PLHPXi = 0.0561\ HPPRDSF_i$ -------------------------- (5.28)

Similarly, $PLHPX_{2i} = 0.0561\ DOHPPRDSF_{2i}$ ---------------------------- (5.29)

Similarly, Checking for LPPRDS opening optimality condition,

Power loss reduction due to reduction of LP extraction flow = $X_{lp} = (TGE - LPSE) / 860$

$= (794-694) / 860 = 0.116$ MW

Throttling loss in LP PRDS =2% of $X_{lp} = 0.02\ X_{lp}$. Hence, the total power loss due to LPPRDS opening is governed by Eqs. (5.30, 5.31) and the revised total power loss due to steam flow difference through LPPRDS can be given by Eq. (5.32).

Hence, $PLLPX_i = (DOLPPRDSF_i) \times 1.02\ X_{lp} = 0.1183\ DOLPPRDSF_i$ ----------- (5.30)

However, $DOLPPRDSF_i = LPPRDSF_i$ as the initial value of LPPRDSF to be considered as a change in LPPRDS flow only due to non-availability of prior status

Hence, $PLLPXi = 0.1183\ LPPRDSF_i$ ----------------------------- (5.31)

Similarly, $PLLPX_{2i} = 0.1183\ DOLPPRDSF_{2i}$ --------------------------- (5.32)

Now total power loss due to both HP and LP PRDS opening = $PLTX_{2i}$ = ($PLHPX_{2i}$ + $PLLPX_{2i}$) and the total PRDS optimality condition is the total power loss due to both HP and LP PRDS openings.

Total PRDS optimality condition using the threshold value of 0.35 MW based on the storage loss assumed and the optimality condition deviated is expressed by Eqs. (5.33, 5.34).

$$BEP_{PLTY} = GIM_i + \frac{[\{\text{Max. of } (0.35 - PLTX_i) \text{ or } (PLTX_{2i} - 0.35)\}(GIM_{2i} - GIM_i)}{(0.35 - PLTX_i) + (PLTX_{2i} - 0.35)} \qquad (5.33)$$

However, (GIM_{2i} - GIM_i) = 1 if the import is assumed to increase by 1 MW in each iteration. Hence,

$$BEP_{PLTY} = GIM_i + \frac{\text{Maximum of } (0.35 - PLTX_i) \text{ or } (PLTX_{2i} - 0.35)}{(0.35 - PLTX_i) + (PLTX_{2i} - 0.35)} \qquad (5.34)$$

$BEP_{PLTN} = X = 12$, i.e., the value equal to the maximum RE capacity, where BEP_{PLTN} is the value of BEP when the optimality condition based on the total power loss due to HP & LP PRDS opening flow is not deviated i.e., the total power loss due to HP & LP PRDS opening is less than a threshold value. BEP_{PLTY} is the value of BEP when the optimality condition based on the total power loss due to HP & LP PRDS opening is deviated i.e., total power loss due to HP & LP PRDS opening is more than a threshold value.

In case of total power loss due to HP & LP PRDS opening is less than a threshold value, then both BEP_{PLTY} and BEP_{PLTN} are considered as 12, i.e., the value equal to the maximum Renewable energy capacity

$BEP_{PLTN} = X = 12$ $\qquad$ $BEP_{PLTY} = X = 12$

xv) The Minimum value of break-even points of optimality conditions is compared either to arrive BEP or to continue the iteration cycle and expressed by mathematical Eq. (5.35).

In the case of Min value of (BEP_{SGFN}, BEP_{PLTN}, BEP_{SGFY}, and BEPPLTY) is less than 12,

then $BEP = \text{Min}\ (BEP_{SGFN}, BEP_{PLTN}, BEP_{SGFY}, BEP_{PLTY})$ ---------- ---------- (5.35)

Otherwise, continue the iteration cycle after replacing 2i values to i values till BEP maximum installed RE capacity is obtained or the maximum number of cycles. In case of maximum number of cycles the complete installed capacity can be utilized without effecting optimality.

5.8 HEURISTIC FORWARD APPROACH ALGORITHM

Based on the mathematical equations derived based on a typical cogeneration model, an algorithm is developed as indicated in Figure 5.4

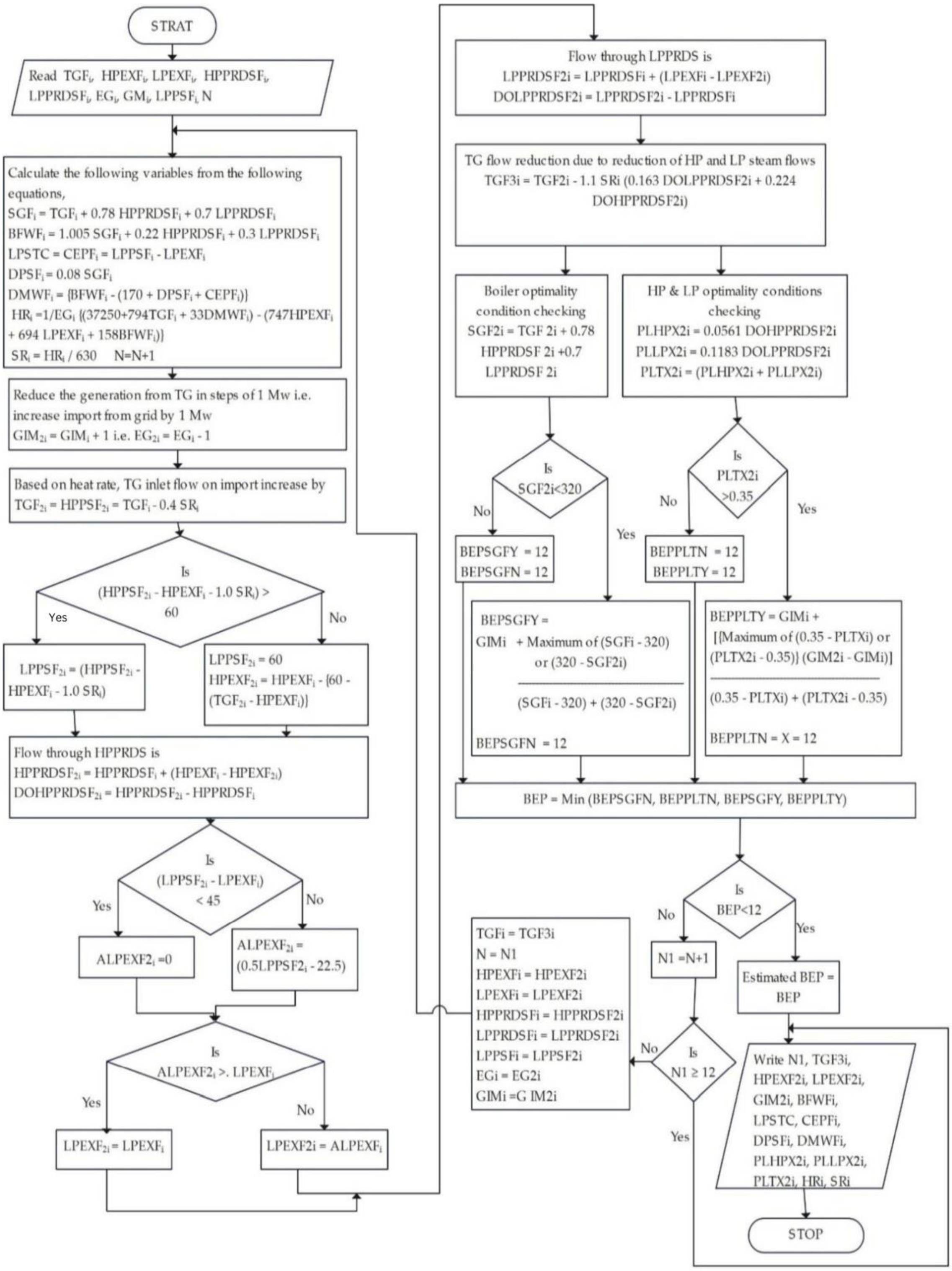

Figure 5.4 Flowchart to estimate BEP using mathematical modeling

5. 9 BEP ESTIMATION USING MATLAB – ANALYSIS OF RESULTS

The algorithm developed is executed using mat lab with the initial data collected from the industry. The MATLAB program to estimate the BEP is presented in appendix A.3. The initial values of variables for the identified RE integrated cogeneration plant for two SG and two TG operations are presented in Table 5.2. These values are taken after stabilization of the plant without RE injection into system. The MATLAB results obtained after simulation for the two SG and two TG operations (100% process plant in operation) are indicated in appendix A.3.1.

Table 5.2 Initial values of variables

Parameters	EG_i	GIM_i	TGF_i	$HPEXF_i$,	$LPEXF_i$,	$HPPRDSF_i$,	$LPPRDSF_i$	$LPPSF_i$
Unit	MW	MW	MT/hr	MT/hr	MT/hr	MT/hr	MT/hr	MT/hr
Initial values	31	0	330	210	35	0	0	120

After the execution of the algorithm, it is found that the BEP is 6.8718 MW based on one of the optimality conditions, i.e., the SG flow is falling below the threshold limit of 320 MT/hr. Table 5.3 presents the main data generated through mat lab execution.

From the data, it is observed that steam generator flow between 6 and 7 MW import is falling below the threshold value of 320 MT/hr as SGF value at 6 MW import is 321.4145 MT/hr and at 7 MW import is 319.8127 MT/hr. Utilizing Newton Raphson’s empirical formula [20], the break-even point is obtained.

Table 5.3 Data generated after execution of the algorithm through MATLAB

Parameters	N=0	N=1	N=2	N=3	N=4	N=5	N=6	N=7
SGFi	330	328.620	327.2553	325.867	324.4363	322.953	321.414	319.8127
TGFi	330	328.620	326.7955	324.731	322.5367	320.242	317.854	315.3673
HPPSFi	330	328.620	326.7955	324.731	322.5367	320.242	317.854	315.3673
LPPSFi	120	115.17	113.69	111.75	109.57	107.25	104.83	102.30
HPEXFi	210	210	210	210	210	210	210	210
LPEXFi	35	35	34.34	33.38	32.29	31.13	29.91	28.65
DMWFi	50.25	53.80	53.57	53.54	53.63	53.77	52.92	52.48
HPPRDSFi	0	0	0	0	0	0	0	0
LPPRDSFi	0	0	0.66	1.62	2.71	3.87	5.09	6.35
DOHPPRDSFi	0	0	0	0	0	0	0	0
DOLPPRDSFi	0	0	0.66	0.97	1.09	1.16	1.21	1.26
EGi	31	30	29	28	27	26	25	24
GIMi	0	1	2	3	4	5	6	7
LPSTC/CEPFi	85	80.17	79.34	78.38	77.29	76.13	74.91	73.65
BFWFi	331.65	330.26	329.09	327.98	326.87	325.73	324.55	321.72
PLHPXi	0	0	0	0	0	0	0	0
PLLPXi	0	0	0.08	0.11	0.13	0.14	0.14	0.15
PLTXi	0	0	0.08	0.11	0.13	0.14	0.14	0.15
DPSFi	26.40	26.29	26.18	26.07	25.95	25.84	25.71	25.58
HRi * e+03	2.1731	2.2203	2.2687	2.3214	2.3775	2.4369	2.4999	2.5750
SRi	3.4494	3.5243	3.6012	3.6847	3.7737	3.8681	3.9681	4.0873

From the above, it is seen that in both the methods i.e., mathematical modeling and practical experimentation, the optimality condition of SG flow is falling below the threshold limit of 320 MT/hr. LPPRDS flow started opening when the import is around 2 MW and the opening increased further with the import. However, the optimality condition for LPPRDS flow has not deviated until the end of iteration. Optimality condition depends on the system's initial operating conditions. Here, as the SG flow is nearer to the threshold value, the optimality condition of SG flow deviated first and decided the BEP. Figure 5.5 indicates the effect of TG generation & Grid import/ RE injection on Turbine heat rate and steam rate.

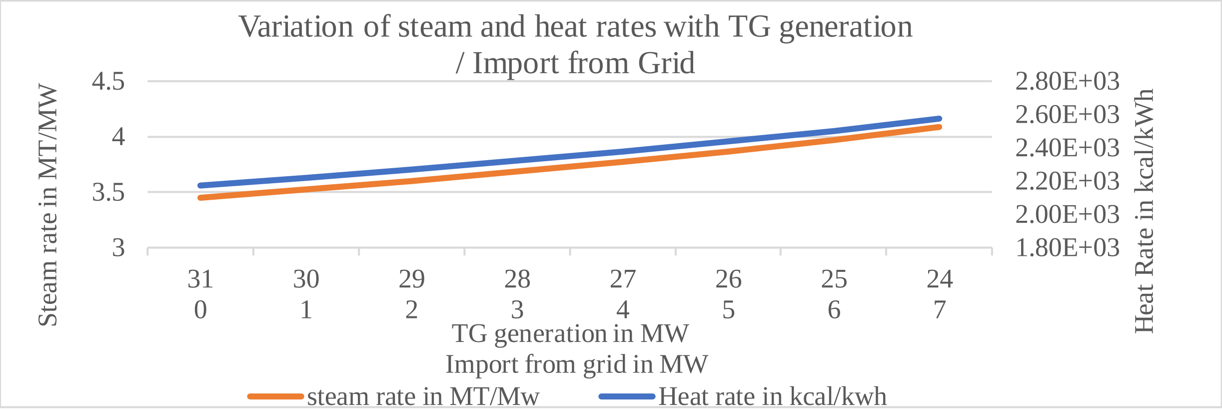

Figure 5.5 Effect of TG generation & Grid import/ RE injection on Turbine Heat Rate and steam rate

From the above, it is observed that with the reduction of TG generation, TG heat rate and steam rate are increasing continuously indicating the system is shifting towards inefficiency. With further reduction of TG generation, the heat and steam rate further reduces and finally approaches the standard value of conventional power plants due to HP and LP extractions cut off. The same phenomenon is indicated with grid import/RE injection into the system as TG generation gets reduced with RE injection, i.e., with grid import. Figure 5.6 indicates the effect of TG generation & Grid import/ RE injection on SG output and LPPRDS flow.

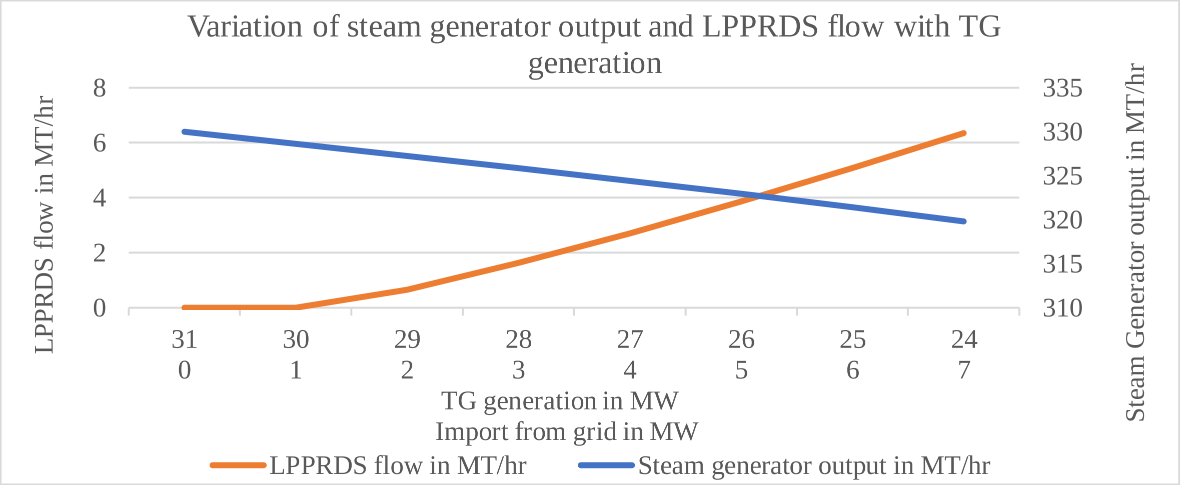

Figure 5.6 Effect of TG generation & Grid import/ RE injection on LP PRDS flow and steam generator output

From above, the steam generation is also continuously decreasing with the reduction of TG generation or with grid import/RE injection. The system is shifting towards inefficiency and consuming more steam to produce 1 MW. The steam reduction is possible as the increase in steam due to inefficiency is offset by the net saving on steam due to the RE generation. Similarly, with the reduction of TG generation, LPPRDS started opening and increasing continuously due to LP extraction reduction of TG due to inlet steam flow reduction. The plots obtained are supporting the practical observations.

5.10 COMPARISION OF RESULTS WITH REAL TIME / ONSITE RESULTS

The data obtained from the execution of the algorithm thorough MATLAB are compared with the real time/online data. The BEP is estimated as 6.3 MW beyond which the steam generator flow is falling below a threshold limit of 320 MT/hr. Practical data presented under table 4.2 is taken for comparison purpose and indicated in Table 5.4. The practical values are compared with the algorithm values at the same BEP (6.3 MW). The algorithm values at 6.3 MW were obtained through MATLAB interpolation coding using the data under Table 5.3. The comparisons of results are represented in Table 5.4.

Table 5.4 Comparison of results with real time/on site results

S. No	Parameter	Unit	Comparison	
			Data obtained through MATLAB interpolation using data under table 5.3	Data obtained through practical experimentation
			At 6.3 MW	At 6.3 MW
1	SG Flow	MT/hr	320.9340	317
2	HP Extraction Flow	MT/hr	210	210
3	LP Extraction Flow	MT/hr	29.5343	27.8
4	HPPRDS Flow	MT/hr	0	0
5	LPPRDS Flow	MT/hr	5. 7	7.2
6	TG generation	MW	24.7	25.5
7	Import/RE generation	MW	6.3	6.3
8	Break-even Point	MW	6.8718	6.3

LPPRDS flow obtained through the algorithm is equivalent to LP extraction conditions. The practical value of LPPRDS flow is equivalent to the process temperature conditions. The correction factor is applied to equate both to similar conditions.

LPPRDS flow was obtained through MATLAB interpolation using data under table 5.3 = 5.4657 MT/hr. LP PRDS steam enthalpy is 666 kcal/kg at 8 kg/cm^2, 178^{o}C of LP steam (practical experiment condition).LP PRDS steam enthalpy is 694 kcal/kg at 8 kg/cm^2, 238^{o}C of LP steam (algorithm condition).

Hence, algorithm LPPRDS flow equivalent to practical condition=5.46578(694/666) =5.7 MT/hr. From the tabulated values in Table 5.4, a graphical representation is made. Figure 5.7

gives a comparative indication of BEP, TG generation, LPPRDS flow, and SG flow obtained through practical experimentation and mathematical modeling.

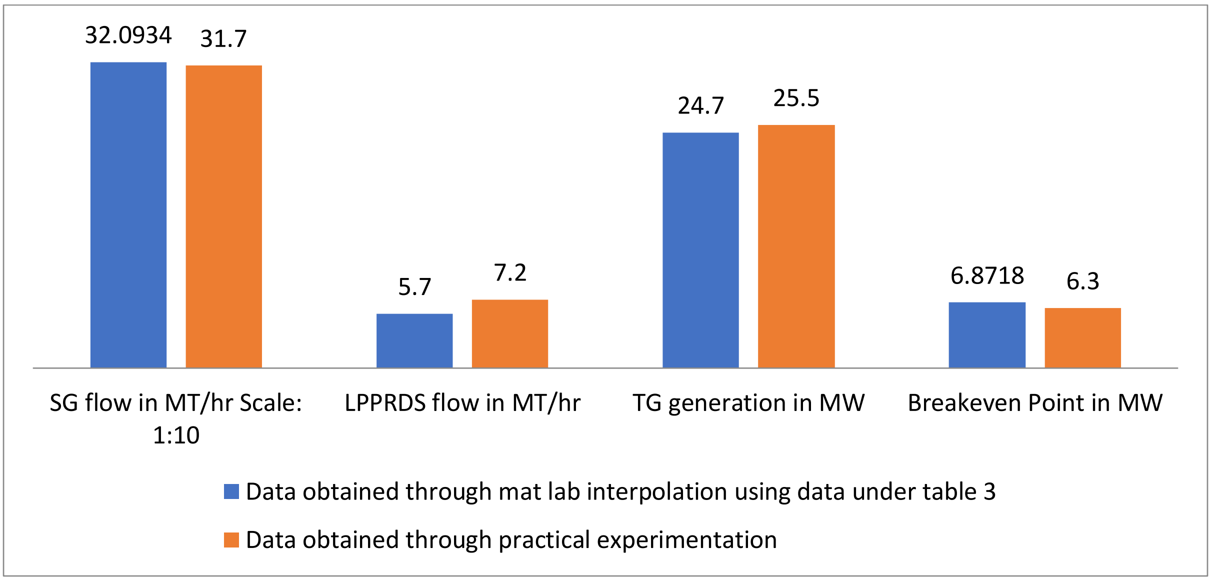

Figure 5.7 Comparison of main parameters obtained throughmathematical modeling and Real time/online

The above difference can be expected as practically the parameters like SG outlet, TG inlet, extraction, and exhaust pressure and temperature cannot be maintained constant always. These will vary depending on many parameters like fuel quality, grid frequency and process plant variations. These values are assumed constant during algorithm development. Hence, the algorithm developed is validated and useful to establish BEP in cogeneration plants integrated with renewable energy.

The theoretical method is further validated by estimating the BEP with the practical data obtained for another mode of operation. In this mode of operation only 50% of the process plant is considered. Hence, only one SG and one TG is sufficient to cater the power and process steam requirements. Practically it is observed with solar generation of 7 MW, the HP extraction from the TG is drastically falling. Hence, indicating a total PRDS loss is exceeding a threshold limit. With MATLAB simulation the BEP obtained is 6.9175 MW, hence further validated the theoretical method adopted. The output data obtained with MATLAB simulation is presented in appendix A.3.2.

5. 11 SUMMARY

The practical problem being faced by a cogeneration plant after integration with RE is presented. BEP is estimated practically by conducting the experiments and collecting the on line data. The BEP estimation is by practical observation of optimality conditions deviation. The point at which furnace is getting disturbed and demanding oil support is accounted as

BEP. Beyond BEP the operation is not economical due to oil support and reduction of extraction flows. The BEP estimation by practical experimentation is accurate as the result is physical variation of the system conditions. But the disadvantage with practical method is limitations in conducting the experiment. Practical experimentation may demand to vary the operating conditions. This may result in to unstable operation and may lead to tripping also. Also, the result obtained is not common for all systems as depends on operating parameters and design parameters. Hence a heuristic approach algorithm is developed based on the equations developed. The equations are developed based on system behaviour with RE injection. The response of the system in sequence is considered and accordingly the equations are developed. The algorithm developed is executed using MATLAB. The results and BEP obtained using heuristic algorithm is validated by comparing with practical experimentation results. Further the heuristic approach is validated using another mode of operation also. Hence, the BEP estimated by this method can be a tool to many of the cogeneration plants integrated with RE and facing similar problems. It is a guiding tool to CHP industry planning to go for RE integration. With prior BEP estimation, cogeneration plants can optimize the storage capacity, which will enhance the optimum utilization of RE. Future upcoming cogeneration plants with RE integration design can be optimized in a better way utilizing the techniques presented. With optimized techniques, many players incline towards RE utilization. This results in an increase in the percentage share of RE utilization, which helps in environment safeguarding and savings in fossil fuel consumption. However, continuous variations in parameters can also be accounted if linked to real-time control mode. However, real time control mode is tedious and cumbersome and may not be required as normally the CHP plant operation is stable and steady.

CHAPTER-6

TECHNO ECONOMIC ANALYSIS OF ENERGY STORAGE TECHNOLOGIES FOR SELECTION OF SUITABLE STORAGE DEVICE

6.0 INTRODUCTION

When RE is added to an existing cogeneration system, introduced system inefficiencies. The inefficiencies are due to deviation in the design / optimum operating parameters with RE injection. Hence, to maximize efficient utilization of RE capacity, it is proposed to store the RE beyond break-even point i.e., the point beyond which optimality conditions are deviating. The stored energy can be utilized during peak periods or whenever RE generation is less than the break-even point. However, estimation of break-even point depends on optimality conditions which depends on the co-generation system considered. Renewable energy utilization and overall system efficiency can be significantly improved by adopting techno economic energy storage system. Hence, a review of comparative study between various energy storage techniques is carried out. Based on the form of energy stored in the system total 5 categories of storage options viz. electrochemical, mechanical, chemical, thermal and electrical storage systems are considered. Advantages and disadvantages of the various storage technologies and the numeric values like capacity, duration of storage, type of storage, lifetime, response time, duration of discharge at maximum power level, specific energy, energy density, efficiency etc. are presented in chapter 3. Based on the data from the literature, suitability of each technology is analyzed on technical parameters. It is concluded electro chemical and hydrogen storage technologies are suitable to present application. Further study on total capital and life cycle costs, net energy analysis is carried out. The two energy ratios viz electrical energy stored on invested and the overall energy efficiency are considered in net energy analysis. Based on this economic study it is concluded lead acid batteries can be best suitable storage option. The methodology presented for determination of suitable energy storage technology can be a guiding principle for various cogeneration systems and grid connected RE systems.

6.1 ADVANTAGES AND DISADVANTAGES OF ENERGY STORAGE SYSTEMS:

Based on the technical and economic characteristics of various energy storage systems, the advantages and disadvantages of storage technologies are summarized in table 6.1

Table 6.1 Advantages and Disadvantages of energy storage systems

Energy storage device		Advantages	Disadvantages
Main category	Sub category		
I. Electro chemical storage (Battery energy storage systems)	Lithium-ion	High energy to weight ratio, No memory effect and long lifetime [21] High discharge rate at maximum power level [29] Low self-discharge not exceeding 8% per month [31] Can handle hundreds of charge / discharge cycles [23]	Expensive and relatively low efficient [29] Limited to small electronic component [27]. Limited resources of Lithium [21] High temperatures quicken the capacity loss [29] Cause significant environmental-social-and health impacts [22].
	Nickel cadmium	High efficiency, unaffected by DOD, very low maintenance, small self-discharge of 10% per month, operates over a wide range of -40^0 C to 50^0 C [31].	Impact on the environment and have memory impact problem [31]. High cost
	Sodium sulfur	Long lifecycle, fast response, high recyclability, high pulse power capability [31] Specific energy is high [22] High energy density [28] Delivers 100% coulombic efficiency [23]	Highly corrosive behavior High production cost High operating temp. High self-discharge per day [28]
	Lead acid	Can provide high current High efficiency, high reliability, low self-discharge rate, fast response time, easy recyclability, high specific power, No block wise or cell wise battery management required [31]. High response to changes in power demand and have low stand by losses [23] Mature technology	Contains toxic substance Short life time, low energy density, poor performance at low temperature, high maintenance and environmental impact [31] Reduction of capacity at low temperatures [23]
	Redox flow	Short time to fully charge Suitable for large applications with high energy and power density [28] Easy to upgrade [28] High design flexibility Fully charged/discharged without loss of capacity	Low specific energy High cost and immature for utility applications [28] Electrical current leakage Mechanical parts (pumping systems) make system miniaturization difficult [24]
II. Mechanical energy storage	Compressed air storage	Large storage capability and power output [29] Long life (reservoir, compressor, turbine) Capable of black starts and high discharge duration at maximum power output [29]	Geological requirement, High investment cost [22] Small footprint on surface (underground storage) Slow response time [29] Efficiency is relatively low 40%-75% [29] Low storage density, hence, requires very large storage areas.
	Pumped hydro storage	Mature technology, Very long lifetime [22]. Capable of black starts, environmentally safe, very high storage capacity, low start up time [29]	Geographical restrictions, Long construction time, Low energy density, High surface footprint [29] Relatively low efficient [29] ranging 60% in old plants to 78% in new units [23]

Table 6.1 Advantages and Disadvantages of energy storage systems (Cont…)

Energy storage device		Advantages	Disadvantages
Main category	Sub category		
	Fly wheel Storage	Long life, High efficiency, High specific power, High output potential Fast response time can handle high power levels [29].	Low specific energy. Provide power for only few seconds or minutes. Safety concerns due to high speed rotor Energy loss due to friction, relatively low discharge time at maximum power level [29] High self-discharge rate [31].
III. Chemical storage	Hydrogen storage fuel cell	Can store long time, No emission (coupled to renewable sources) [22]	Low efficiency, Require costly components [22]
	Methane storage	Can store long time, Easy to store, Long distance transport available [22]	Low efficiency [22]
IV. Thermal storage	Sensible heat storage	Simple application with available materials, Long life time, Cost-effective, Can store longtime [22]	Large volume needed, Geological requirements, Heat loss to the ambient [22]
	Latent heat storage	Small volumes, High storage density (within a small temp). [22]	Low thermal conductivity, which results in slow charge and discharge rates [28] Corrosive nature of material [22]
	Thermo-chemical storage	Long distance transport available, High efficiency, Highly compact energy storage [22]	Expensive, Technically complex, High capital cost [22]
V. Electrical storage	Capacitors storage	Can charge and accumulate energy quickly. Can deliver the stored energy quickly. Losses are small compared to other storage medium. Long service life and low (or no) maintenance.	Self-discharge rate. Gradual voltage loss.
	Super capacitors storage	Long life cycle, Short charge/discharge time without the risk of overcharging [28]	High cost, Energy storage per unit weight is low. Low energy storage capacity. Require power electronics due to variations in voltage during discharge. Hence increasing complexity [28]. Super capacitors aren't well-suited for long-term energy storage
	SCMS	Fast response time Great instantaneous efficiency High power availability	High operating cost Power availability for brief period of time

6.2 SELECTION OF SUITABLE STORAGE DEVICE BASED ON TECHNO ECONOMIC ANALYSIS OF STORAGE SYSTEMS:

The suitability of each technology to present case study of a RE integrated cogeneration plant is carried out and presented in table 6.2.

Table 6.2 Selection criteria of suitable energy storage device

Energy storage device		Study on suitability to present application	**Suitability**
Main category	Sub category		
I. Electro chemical storage (Battery energy storage systems)	Lithium-ion	High energy density, long life time and relatively high efficiency are the main factors for utilization as energy storage.	Suitable
	Nickel cadmium	High efficiency, good performance at low temperatures. Due to high cost and memory effect problems, presently being used in power tools, portable devices, telecom etc.	Suitable
	Sodium sulfur	Most proven technology in MW scale. Suitable for large scale industry, high power energy management applications	Suitable
	Lead acid	Lead acid batteries are one among low cost energy storage system. Provides large current with quite low density is a great advantage in many applications.	Suitable
	Redox flow	Flow batteries may have lower costs in larger scales. Still in the early phases of commercialization.	Suitable
II. Mechanical energy storage	Compressed air storage	Requires special geological sites, high capital costs, long construction time, needs gas fuel input/gas turbine system, contaminant emission. Also mainly demonstration and have limited commercial maturity. Hence not suitable for small capacities for present application.	Not suitable
	Pumped hydro storage	Normally suitable for high capacity units 100-5000MW. Have disadvantages of location limited, long lead time >10 years, requires special sites for upper and lower water reservoirs, high capital cost and long construction time. Hence not suitable for present application.	Not suitable
	Fly wheel Storage	Even though have better life cycle than batteries, main drawback is it provides power for only few seconds or minutes. Large standby losses and high initial cost. This is applicable for high power and short duration requirements. Not suitable for present application.	Not suitable
III. Chemical storage	Hydrogen storage fuel cell	Normally hydrogen is produced through electrolysis and utilized using fuel cells. The relatively low overall efficiency and huge capital costs are two major barriers in commercial implementation of hydrogen based storage in grid scale applications.	Suitable.
	Methane storage	Hydrogen produced through electrolysis is converted in to methane by reacting with CO_2. But the efficiency is very low around 33%-40%.Mostly suitable for large scale applications. Not suitable for present application.	Not suitable
IV. Thermal storage	Sensible heat storage	As 12 MW solar power plant is established in an existing cogeneration plant to meet RPPO, hence needs electrical energy storage only and not in the form of thermal energy. Hence not suitable.	Not suitable
	Latent heat storage		Not suitable
	Thermo-chemical storage		Not suitable
V. Electrical storage	Capacitors storage	Capacitors are limited in their energy storage potential due to low capacity and energy density.	Not suitable
	Super capacitors storage	Even though helps in minimizing voltage and power fluctuations when connected with grid, they are expensive. Limited due to low energy density. To minimize variations in voltage during discharging require power electronics which enhances system complexity. Also storage period time is from seconds to hours only, hence makes unsuitable.	Not suitable
	Super Conducting Magnetic Storage	Main applications are for transient and dynamic compensation as release energy rapidly resulting in voltage stability. System limitations arise from cooling water requirements. Main constraint for present application is power availability for brief period of time. Hence not suitable	Not suitable

From the above it is observed that Electro chemical energy storage devices and hydrogen storage and utilizing in fuel cells are suitable energy storage devices for the present application.

6.3 SELECTION OF HYDROGEN OR BATTERIES FOR ENERGY STORAGE BASED ON NET ENERGY ANALYSIS

To compare regenerative hydrogen fuel cell **(**RHFC) with battery storage, two energy return ratios i.e., the electrical energy stored on invested (ESOIe) and the overall energy efficiency are considered. ESOIe is the ratio of electrical energy returned by the device over its lifetime to the electrical-equivalent energy required to build the device. The overall energy efficiency is the ratio of electrical energy returned by the device over its lifetime to total lifetime electrical-equivalent energy input into the system. ESOIe depends on characteristics of cycle life, depth of discharge and cradle-to-gate electrical embodied energy of storage devices [38]. Table 6.3 indicates ESOIe ratios of various battery storage devices.

Table 6.3 ESOIe ratios of various battery storage devices [38]

S.No	Energy storage system	Life cycle λ	Depth of discharge D	Cradle- to- gate electrical embodied energyε_e	ESOIe λ D /ε_e
1	Lithium-ion battery	6000	80	136	35
2	Sodium sulfur battery	4750	80	146	26
3	Lead acid battery	700	80	96	5.8
4	Redox flow battery	2900	100	208	14
5	Zinc bromide battery	2750	80	151	15

ESOIe ratio of Hydrogen fuel cell is 59 [38], hence highest compared with battery storage devices. Hence based on this economic factor, hydrogen storage appears economical. But the overall energy efficiency of hydrogen fuel cell is around 33 % only, considering the alkaline electrolyzer efficiency of 70% and fuel cell efficiency of 47%. However, the battery energy storage systems overall efficiencies ranges from 75%-90%. Hence, the round-trip efficiency of fuel cell technology must improve drastically. Hence, for the present application battery storage is preferable. Hydrogen/Fuel cell technology can be thought of with further improvement in efficiency.

6.4 SELECTION OF BATTERY STORAGE DEVICE TYPE BASED ON TECHNO ECONOMIC ANALYSIS

Out of the 4 battery technologies discussed, Lithium ion batteries proven to be advantageous for electric traction of vehicles, power tools and intermittently available RE. Applicability of LIB is limited to small electronic equipment and not appropriate to stationery applications due to decreased performance and high cost [27]. LCOE of Li ion battery is high compared to other battery technologies, hence not economical also. Even though sodium sulfur batteries have LCOE low compared to other battery technologies, SSB technology involves high operating temperatures of around 300^{o}c [23] and both sodium and sulfur are corrosive in nature, hence not considered. Flow batteries technology is not fully developed and still at immature stage. LCOE is more than lead acid batteries. Based on these not considered for the present application. Nickel cadmium batteries are being used currently for power tools, portable devices, emergency lighting, telecoms and generator starting applications. These are not preferred in large scale power systems due to its high cost and memory effect problems. LCOE is also more than lead acid batteries. Hence, Lead acid batteries with LCOE of 323 €/ MWh [34] and matured technology with many advantages is considered for the application.

6.5 OUTCOME OF TECHNO ECONOMIC ANLYSIS OF ENERGY STORAGE TECHNOLOGIES

Based on the techno economic analysis carried out, it is concluded that the lead acid battery storage is most suitable storage device for the present application. Most of the literatures are also indicating that the BESS is most proven technology for the grid related solar integration issues and the battery storage is helping in stabilizing the solar intermittent variations. Even though the direct literatures on the present application are not available, reference [54] indicated battery energy storage systems are increasingly used to help integration of solar power in to grid. Similarly, the reference [55] presented optimum design of PV systems with battery energy storage systems. Hence, present literatures are also supporting the selection of lead acid battery storage for the present application.

6.6 SUMMARY

Suitable storage technology for the present application is arrived based on in depth analysis of techno economic factors of various energy storage technologies. Techno economic analysis (based on tables 3.1, 3.2, 6.1, 6.2, and on overall energy efficiency ratio) and the methodology adopted can be a tool to determine suitable energy storage technologies for different type of industrial applications. Storage of energy will be a major issue in future as future energy needs will be met by renewable energy due to depletion of fossil fuels and associated environment threats. However, the economic factors as well as technical issues with storage technologies are variable as development of materials and invention/ improvement of technologies alters the economic and technical factors. Hence, selection of techno economically suitable storage option requires periodical review.

CHAPTER-7

DESIGN OF STORAGE SYSTEM TO OPTIMIZE RENEWABLE ENERGY

7.0 INTRODUCTION

To design and estimate the capacity of a storage system i.e., AH rating of a battery bank, the data of solar radiation levels pertaining to the area is taken as the guiding factor. Table 7.1 indicates the average solar radiation levels of the horizontal and tilted planes in kWh/m^2/day for the 3 consecutive financial years.

Table 7.1 Monthly average data of solar radiation for three years

S. No	Period	Total solar radiation (kWh/m^2/Month)		Average radiation (GHI) (kWh/m^2/Day) based on total monthly solar radiation	Average radiation (GTI) (kWh/m^2/Day) based on total monthly solar radiation
		Horizontal plane (GHI)	Tilted plane (GTI)		
1	April 2018	183.04	181.11	6.101	6.037
	April 2019	189.46	184.57	6.315	6.152
	April 2020	181.74	183.24	6.058	6.108
2	May 2018	185.81	173.75	5.994	5.605
	May 2019	181.78	167.01	5.864	5.387
	May 2020	173.786	188.449	5.609	6.079
3	June 2018	143.03	130.71	4.768	4.357
	June 2019	147.79	133.77	4.926	4.459
	June 2020	136.83	149.79	4.561	4.993
4	July 2018	99.84	94.17	3.221	3.038
	July 2019	127.77	112.5	3.928	3.629
	July 2020	120.745	115.568	3.895	3.728
5	August 2018	98.79	94.56	3.187	3.050
	August 2019	111.57	106.44	3.597	3.434
	August 2020	87.296	90.923	2.816	2.933
6	September 2018	146.30	148.26	4.877	4.942
	September 2019	118.21	118.90	3.940	3.963
	September 2020	145.83	144.96	4.861	4.832
7	October 2018	169.01	187.42	5.452	6.046
	October 2019	144.66	157.02	4.666	5.065
	October 2020	150.66	139.066	4.860	4.486
8	November 2018	144.48	174.85	4.816	5.828
	November 2019	142.86	170.06	4.762	5.669
	November 2020	115.62	135.93	3.854	4.431
9	December 2018	111.75	138.25	3.605	4.460
	December 2019	125.76	153.57	4.057	4.957
	December 2020	118.606	131.967	3.826	4.257
10	January 2019	136.20	166.52	4.394	5.372
	January 2020	135.53	163.92	4.372	5.288
	January 2021	120.652	134.416	3.892	4.336
11	February 2019	141.97	162.91	5.070	5.818
	February 2020	148.82	167.96	5.132	5.792
	February 2021	149.632	158.452	5.344	5.659
12	March 2019	180.20	190.41	5.813	6.142
	March 2020	181.11	190.10	5.842	6.132
	March 2021	181.04	189.751	5.840	5.561

The above data is taken from AWS (Automatic Weather Station) mounted within the solar plant of kendriya chemical refinery (refuted central government organization) and communicates the data to control room through data monitoring system. The latitude and longitude of the area is 17.9311^0 N and 80.8156^0 E respectively. The location comes under bhadradri kothagudem district of Telangana state.

From the above it is observed that months of April 2018, October 2018, March 2019, April 2019, March 2020, April 2020 and May 2020, average global tilted incidence values i.e. GTI in kWh/m2/day are exceeding 6 kWh/m^2/day. Hence, to arrive at the maximum daily global tilted incidence radiation recorded, the day wise data of GTI values recorded in AWS for the above months is represented in Table 7.2

Table 7.2 Daily average data of solar radiation for the months of April 2018, October 2018, March 2019, April 2019, March 2020, April 2020 and May 2020

Day in a month	Daily global tilted incidence ,GTI in kWh/m^2/day						
	April 2018	October 2018	March 2019	April 2019	March 2020	April 2020	May 2020
1	6.02	6.28	5.80	5.78	6.18	5.72	6.49
2	6.21	6.50	6.15	6.41	4.87	6.3	6.03
3	5.70	6.32	5.64	6.41	5.84	4.56	6.45
4	5.78	6.79	6.33	5.92	5.38	6.18	6.43
5	5.97	6.73	5.12	5.87	5.82	6.61	6.18
6	5.67	6.57	6.68	5.64	4.78	5.98	6.52
7	5.47	6.02	6.38	6.12	4.19	6.18	5.97
8	4.88	6.67	4.64	6.14	6.61	5.44	6.65
9	6.28	5.08	5.41	5.24	5.76	6.29	6.69
10	6.63	5.13	6.27	5.95	6.55	6.79	1.74
11	6.67	3.62	6.72	5.78	6.25	6.69	6.50
12	6.31	5.44	5.99	6.23	6.76	6.33	6.36
13	6.77	6.41	6.53	6.46	6.78	6.48	6.55
14	6.44	5.16	6.46	6.42	5.60	6.3	6.75
15	5.42	3.95	6.45	6.32	6.76	6.27	6.65
16	6.67	5.87	6.64	6.79	6.78	6.37	6.52
17	6.68	6.01	6.65	6.48	6.68	6.31	6.61
18	5.86	6.22	6.75	6.52	6.79	6.1	5.68
19	6.37	6.54	6.52	6.38	6.16	5.43	4.58
20	5.62	6.47	5.51	5.95	6.28	6.26	5.95
21	5.85	6.36	6.34	5.83	6.36	6.58	6.62
22	6.44	6.02	5.16	6.14	5.13	6.49	6.52
23	6.01	5.91	6.43	6.52	6.28	6.62	6.78
24	4.72	5.41	6.12	6.65	6.74	6.24	6.42
25	6.42	6.05	6.37	6.29	6.55	5.29	5.15
26	6.14	6.68	6.23	6.27	6.79	6.67	5.98
27	6.24	6.78	6.13	5.66	6.75	6.48	6.47
28	5.98	6.65	6.28	6.15	6.56	6.15	6.56
29	5.86	6.72	6.34	6.32	6.19	6.52	6.42
30	6.03	6.56	6.41	6.11	5.99	6.6	5.04
31	----	6.50	5.96	---	5.85	---	5.18
Total /Month in kWh/m^2/Month	181.11	187.42	190.41	184.57	190.10	186.23	188.44

The day wise average radiation levels data for the identified months having maximum monthly average radiation levels and represented in table 7.2 is represented graphically in figure 7.1

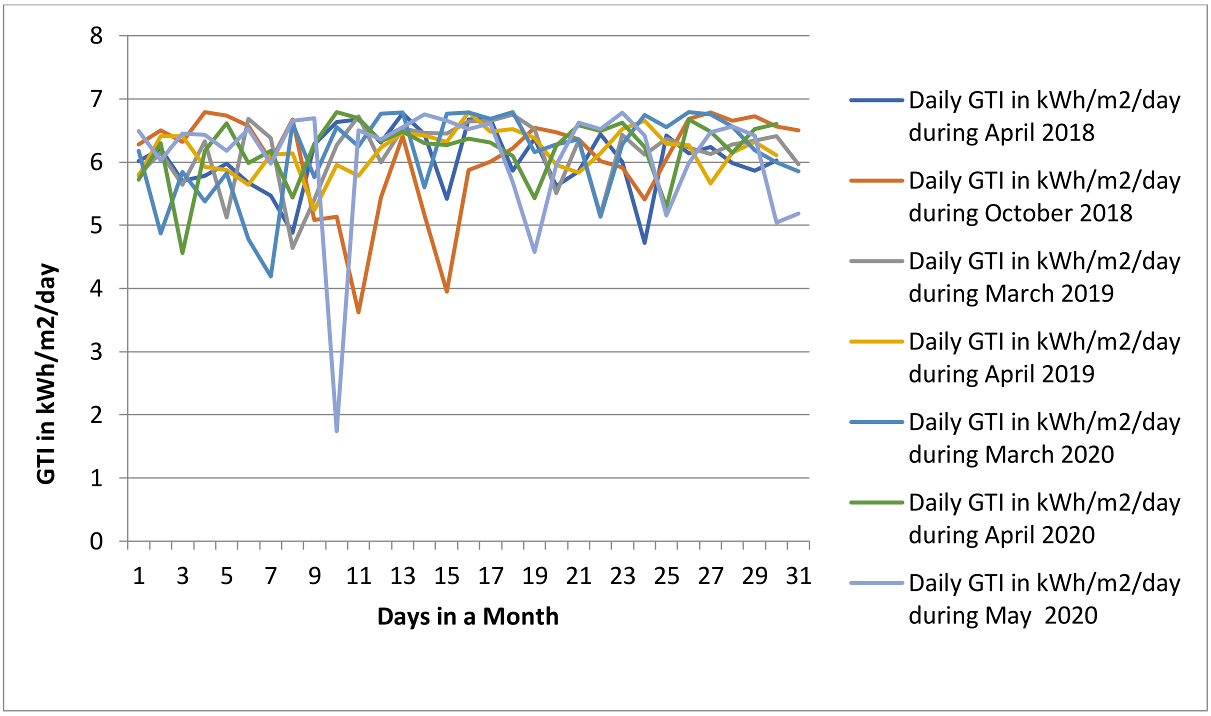

Figure 7.1 Daily average solar radiation levels for the months of April 2018, October 2018, March 2019, April 2019, March 2020, April 2020 and May 2020.

7.1 PV OUTPUT POWER ESTIMATION USING GHI/GTI

Based on the solar radiation per day, the DC power generated from the PV system can be estimated. The DC power generated mainly depends on different factors, including PV peak power at standard test conditions of (STC), solar radiation, and cell temperature and is represented by Equation (7.1).

$$P_{PVout}=P_{PVpeak}\times(G/G_{ref})\times[1+K_t(T_c-T_{ref})]\text{---------------------------------}(7.1)$$

where P_{PVout} is the output power of the PVarray , P_{PVpeak} is the power of the PV array at STC, G is solar radiation in W/m^2, G_{ref} is solar radiation at STC amounting to 1000W/m^2, K_t is the temperature coefficient of mono and polycrystalline Si cells amounting to $K_t = 3.\ 7\times10^{-3}$/°C, Tref is the reference temperature at STC amounting to 25 °C, and T_C is the cell temperature.

Hence to estimate the design capacity of the storage system, the available minute wise GTI data of 16th April 2019 is considered. From the minute wise radiation levels the solar power output is estimated using the equation 7.1. Table A.1.1 indicates the minute-wise solar radiation data from 6 AM to 7 AM on 16th April 2019. The power generation on minute wise basis is estimated based on equation 7.1. G/Gref indicates G/1000 and temperature compensation factor which is 3.7/1000 and T_{ref} is the temperature 25^0c. Figure 7.2 is the graphical representation of the solar power generation between 6 AM & 7 AM on 16th April 2019 based on the data presented in appendix (Table A.1.1).

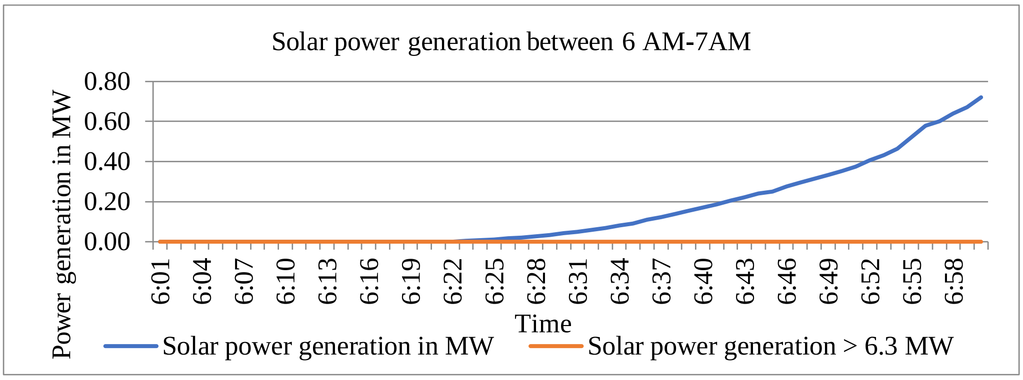

Figure 7.2 Solar generation between 6:00 a.m.–7:00 a.m.

Figure7.3 is the graphical representation of the solar power generation between 7 AM & 8 AM on 16th April 2019 based on the data presented in appendix (Table A.1.2)

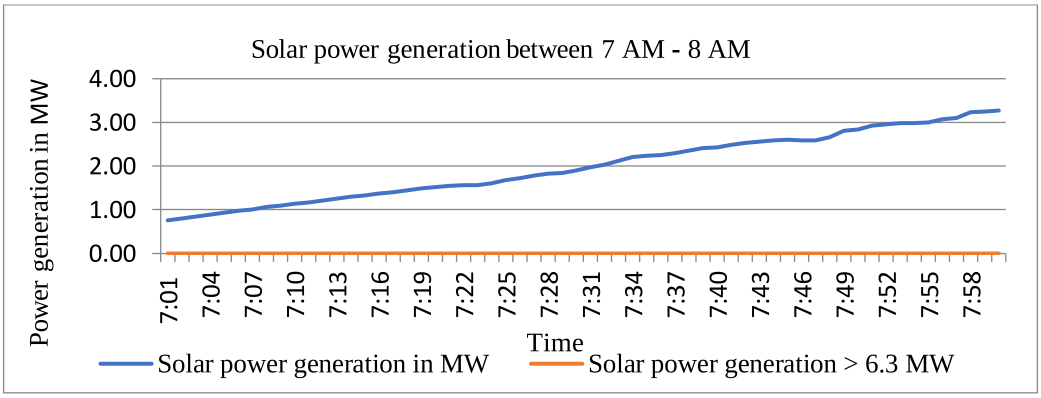

Figure 7.3 Solar generation between 7:00 a.m.–8:00 a.m.

Figure7.4 is the graphical representation of the solar power generation between 8AM & 9 AM on 16th April 2019 based on the data presented in appendix (Table A.1.3)

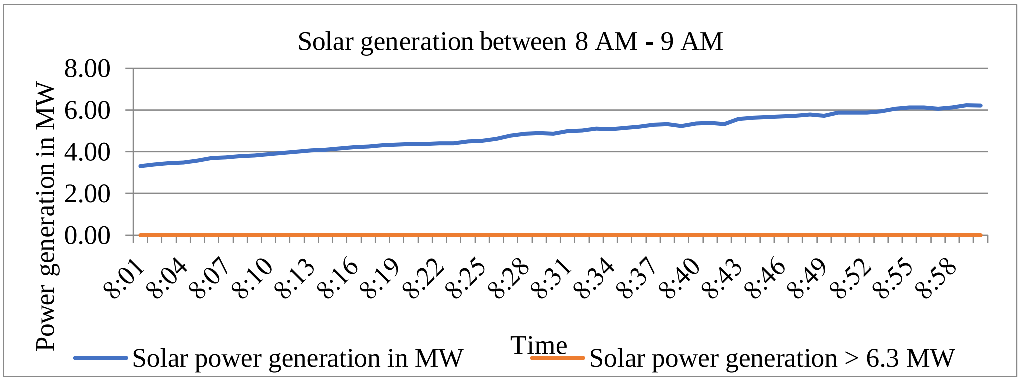

Figure 7.**4** Solar generation between 8:00 a.m.–9:00 a.m.

Figure7.5 is the graphical representation of the solar power generation between 9 AM & 10 AM on 16th April 2019 based on the data presented in appendix (Table A.1.4)

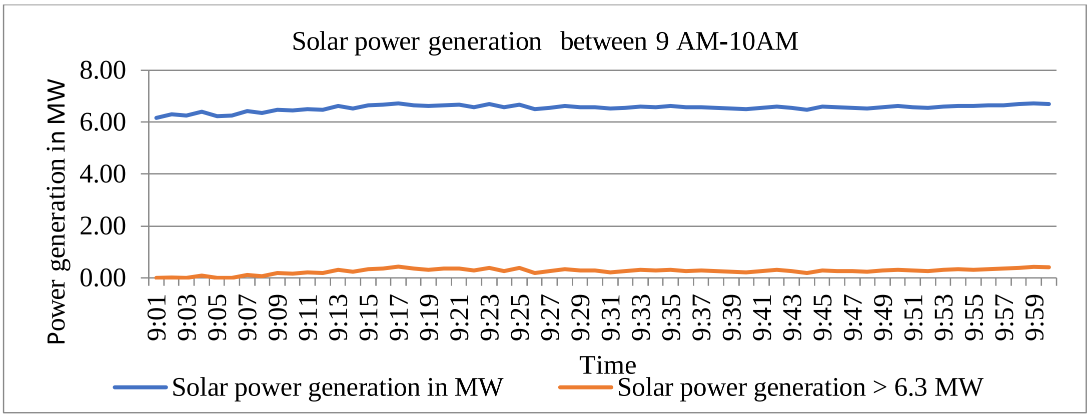

Figure 7.5 Solar generation between 9:00 a.m.–10:00 a.m.

Figure7.6 is the graphical representation of the solar power generation between 10 AM & 11 AM on 16th April 2019 based on the data presented in appendix (Table A.1.5)

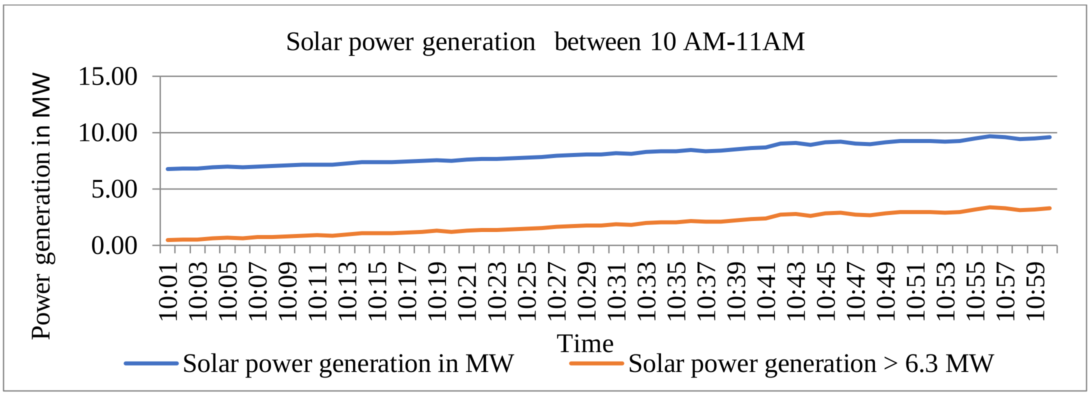

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Figure 7.6 .Solar generation between 10:00 a.m.–11:00 a.m.

Figure 7.7 is the graphical representation of the solar generation between 11 AM & 12 PM on 16th April 2019 based on the data presented in appendix (Table A.1.6).

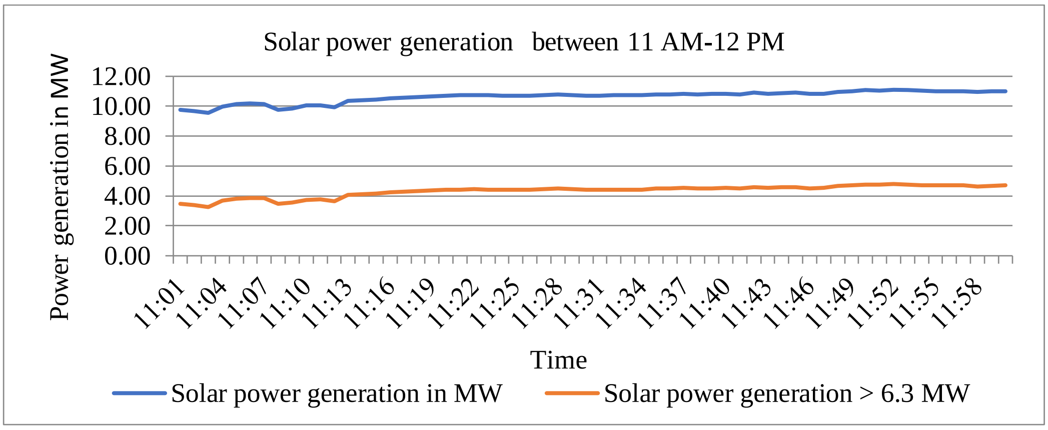

Figure 7.7 Solar generation between 11:00 a.m.–12:00 p.m.

Figure 7.8 is the graphical representation of the solar power generation between 12 PM &1PM on 16th April 2019 based on the data presented in appendix (Table A.1.7).

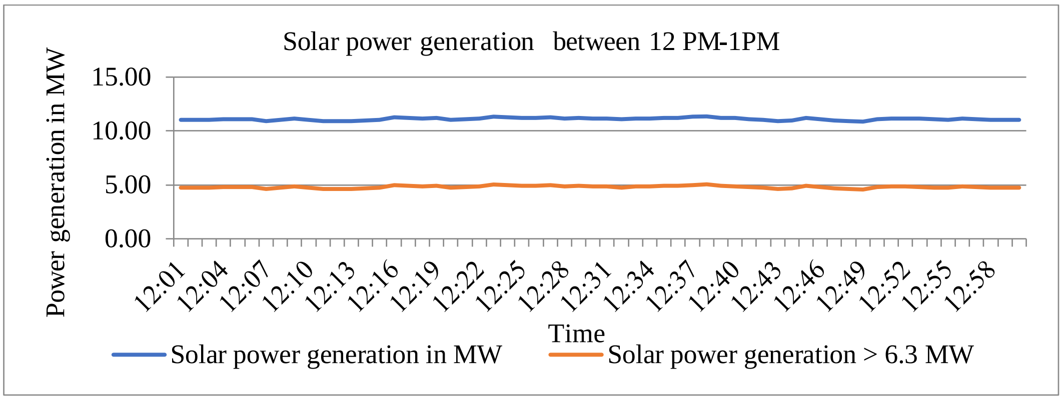

Figure 7.8 Solar generation between 12:00 p.m.–1:00 p.m.

Figure7.9 is the graphical representation of the solar power generation between 1 PM & 2 PM on 16th April 2019 based on the data presented in appendix (Table A.1.8).

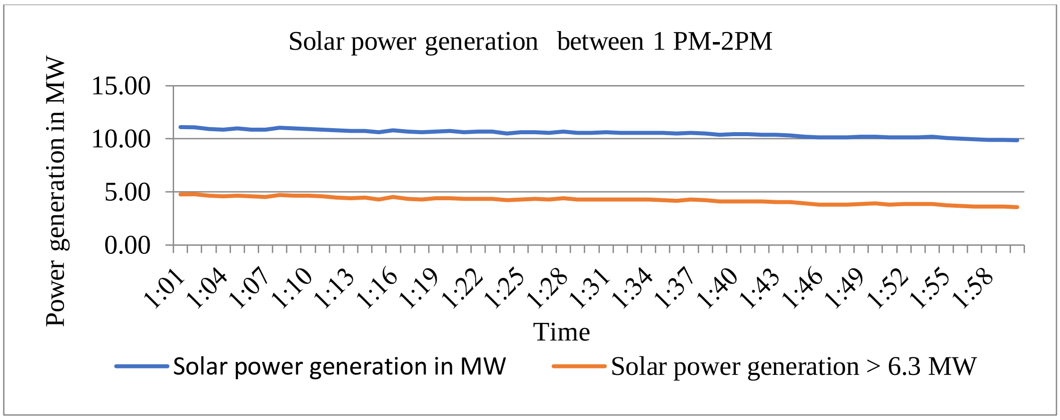

Figure 7.9 Solar generation between 1:00 p.m.–2:00 p.m.

Figure7.10 is the graphical representation of the solar power generation between 2 & 3 PM on 16th April 2019 based on the data presented in appendix (Table A.1.9).

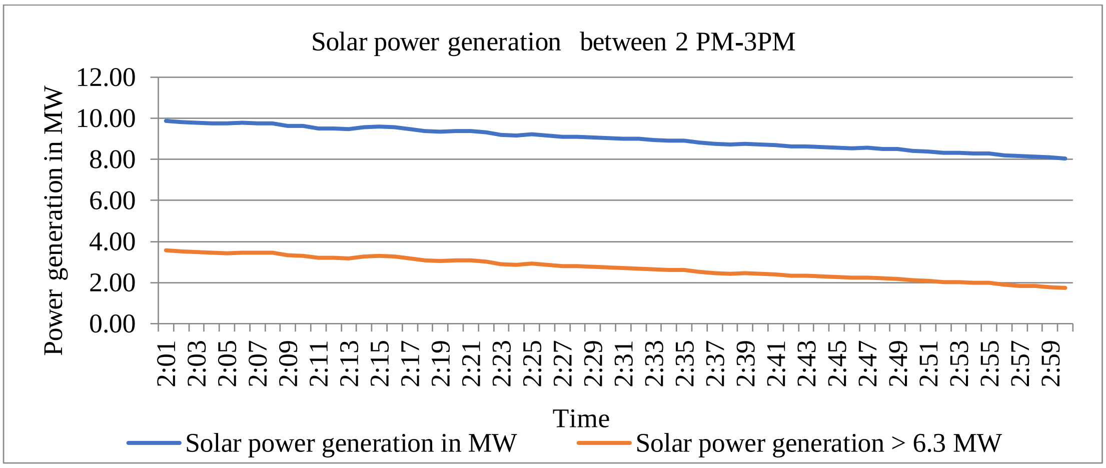

Figure 7.10 Solar generation between 2:00 p.m.–3:00 p.m.

Figure7.11 is the graphical representation of the solar power generation between 3 PM & 4 PM on 16th April 2019 based on the data presented in appendix (Table A.1.10).

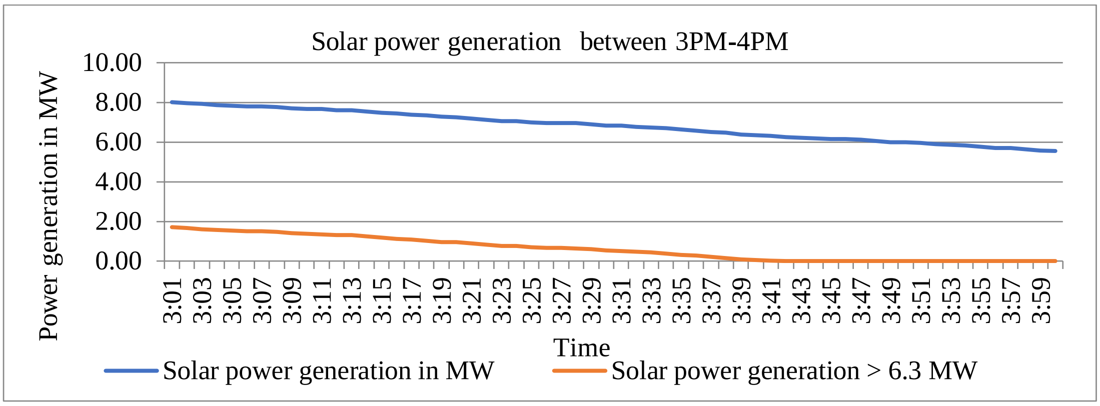

Figure 7.11 Solar generation between 3:00 p.m.–4:00 p.m.

Figure7.12 is the graphical representation of the solar power generation between 4 PM & 5 PM on 16th April 2019 based on the data presented in appendix (Table A.1.11).

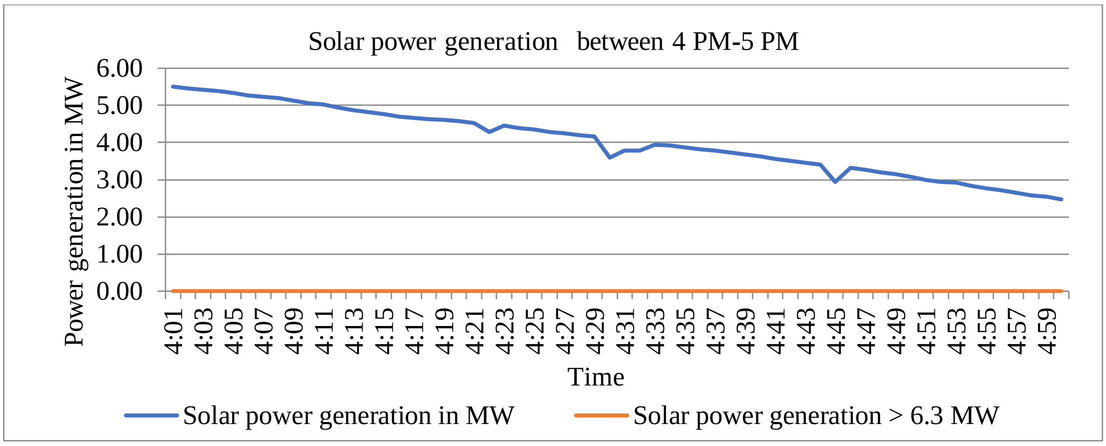

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Figure 7. 12 Solar generation between 4:00 p.m.–5:00 p.m.

Figure7.13 is the graphical representation of the solar power generation between 5 PM & 6 PM on 16th April 2019 based on the data presented in appendix (Table A.1.12).

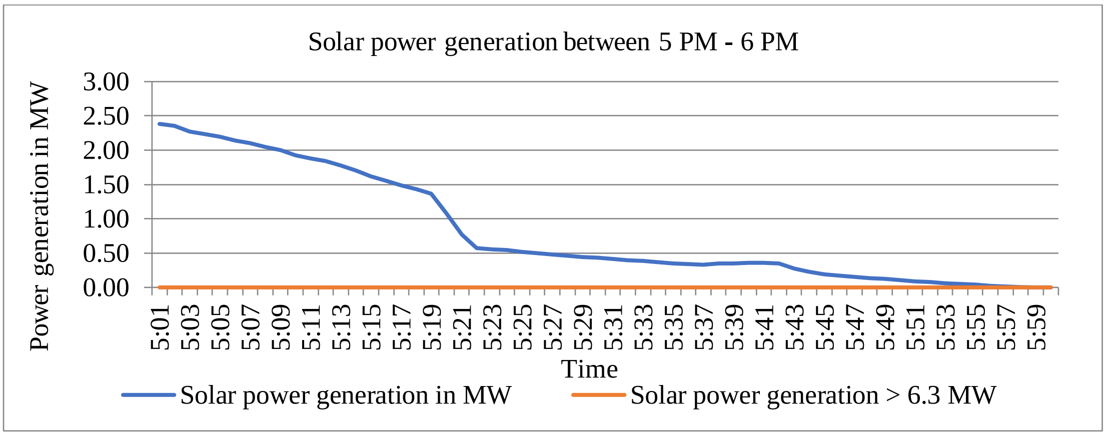

Figure 7.13 Solar generation between 5:00 p.m.–6:00 p.m.

7.2 ESTIMATION OF STORAGE CAPACITY

Based on minute wise estimated solar generation, the hourly average solar power in MWh is obtained. Table 7.3 summarizes the hourly average values of GHI, GTI and the hourly average solar power generation. The solar generation beyond BEP is also estimated and the data is indicated in table 7.3

Table 7.3 Hourly average data of solar radiation for maximum radiation day in a year

S. No	Time	GHI(Wh/ m^2)	GTI(Wh/ m^2)	Average temperature in ^{0}C	Estimated solar average power in MWh	Estimated solar average power in MW> BEP (6.3 MW)
1	6.01 AM-7.00 AM	11.16	12.44	13.88	0.16	0
2	7.01AM-8.00 AM	130.41	163.14	19.5	1.99	0
3	8.01 AM-9.00 AM	345.78	421.08	33.18	4.88	0
4	9.01AM-10.00 AM	583.51	586.41	43.55	6.55	0.258
5	11.01 AM-11.00 AM	741.26	753.43	50.84	8.17	1.87
6	11.01 AM-12.00 AM	809.46	983.85	51.94	10.63	4.33
7	12.01 AM-1.00PM	881.64	1029.49	52.31	11.11	4.8
8	1.01 PM -2.00 PM	846.55	974.78	52.23	10.52	4.22
9	2 .01PM -3.00 PM	721.06	827.71	50.03	9.01	2.71
10	3.01 PM -4.00 PM	516.76	617.24	47.21	6.79	0.61
11	4 .01PM -5.00 PM	283.37	354.91	39.54	4.02	0
12	5.01 PM -6.00 PM	56.93	69.65	29.57	0.81	0
Total		5927.89	6794.13	--	74.64	18.798

Figure 7.14 indicates the hourly average values of GTI and corresponding generation of the power based on Equation 7.1.

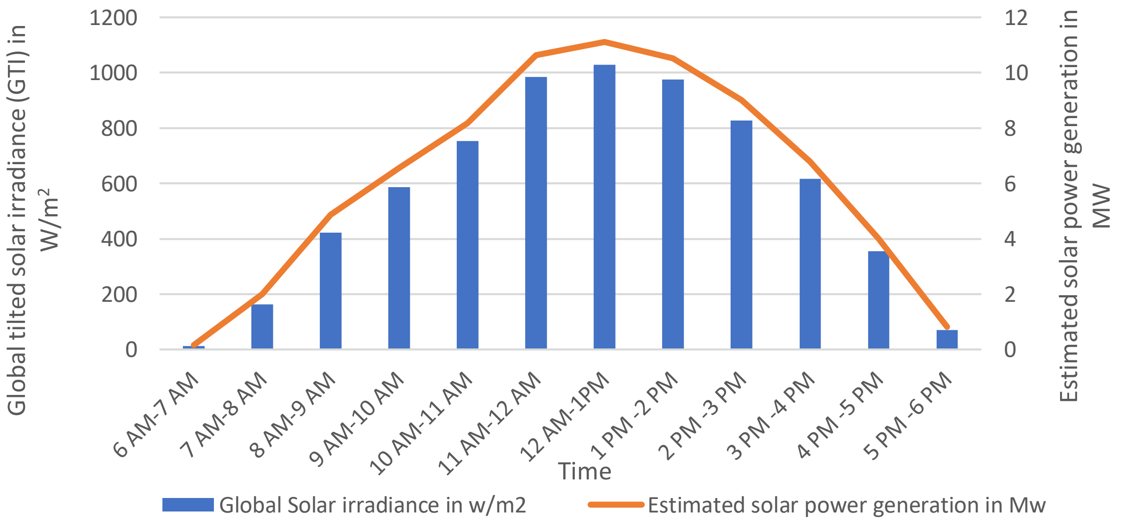

Figure 7.14 Hourly variations of GTI and solar power generations in a day

From the above, solar generation is exceeding BEP for 7 hours in a day, necessitating energy storage for 7 hours only, and the total solar energy to be stored is 18.8 MWh.

For better life expectancy of the batteries, considered batteries discharge up to 20% of capacity. Hence, the capacity of the batteries shall be 23.5 MWh which is equivalent to 3.357 MW @ 7 hrs solar for storage. The solar capacity to be stored is 5.7 MW. Table 7.4 indicates the comparison of standard external battery bank storage capacity with reference to solar capacity. The data is obtained from the basics of solar systems integration basics [56]

Table 7.4 Comparison of standard external battery bank storage capacity with reference to solar capacity

S. No	External Data available			Literature Reference	Proposed Data			Remarks
	Battery bank storage capacity in MW/MWh	Solar plant capacity in MW	Percentage of battery bank storage capacity with reference to installed solar plant		Battery bank storage capacity in MW/ MWh	Solar plant capacity in MW Excluding BEP	Percentage of battery bank storage capacity with reference to installed solar plant	
1	60/240 @4hrs	100	60	www.energy.gov/solar/articles/solar-plus-storage-101[56]	3.357/ 23.5@7 hrs	5.7	58.9	Difference of 1.1 % only
2	13/52@4 hrs	13	100	www.energy.gov/solar/articles/solar-plus-storage-101[56]	3.357/ 23.5@7hrs	5.7	58.9	Difference of 41.1 % as storage is planned to accommodate other sources of power on the grid

From the above it is validated that the capacity of the battery bank is within standard values. Two battery banks are assumed, the capacity of each battery bank is 1.96 MWh and the AH rating is 5800 amps based on 340 VDC.

Hence, deep cycle tubular 2V, 3000 AH @C5 rating of two battery banks in parallel to each inverter is assumed.

7.3 STORAGE SYSTEM LAYOUT

Battery banks proposed for energy storage beyond BEP is connected to the existing system. Figure 7.15 indicates the arrangement of the storage system.

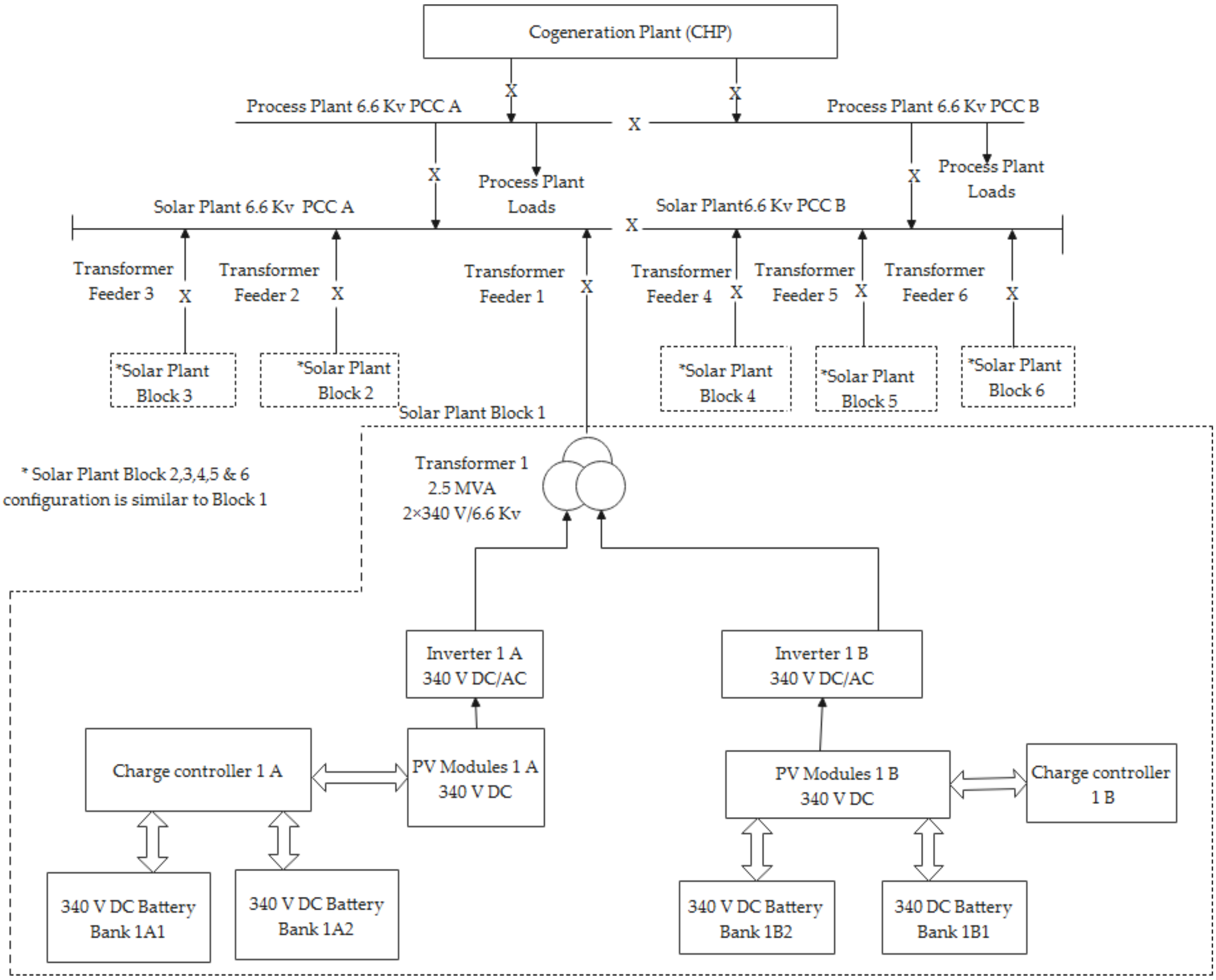

Figure 7.15 Block diagram of the cogeneration system with proposed battery energy storage.

7.4 MATHEMATICAL MODEL TO BALANCE ENERGY FLOWS

Figure 7.16 represents the mathematical model to balance the energy flows between energy sources and the electrical storage device to meet the plant electrical load. Following variables represent the model

Following is the nomenclature used in mathematical model developing

P_{solar} =power generation from solar plant

CHP_{PG} = Power generation from Cogeneration (CHP) plant in MW

P_{TGs} =Power generation from the Turbo Generators

P_{load1}= Power requirement by process plant

P_{load2} = Power requirement by cogeneration plant

PL = Total Power requirement by load

$$= P_{load1} + P_{load2}$$

$P_{\text{solar-load DC}}$ = DC Power flow to Inverter from solar plant

= $P_{\text{solar-load}} + P_{\text{Discharge}}$

As the control system of storage device is designed such that discharge from the storage device takes place when solar generation is absent completely, hence either $P_{\text{solar-load}}$ or $P_{\text{Discharge}}$ presents at any time.

$P_{\text{solar-load AC}}$ = AC Power flow to load from solar plant

= LF * $P_{\text{solar-load}}$ Where LF is the loss factor accountable Inverter

However, as the loss factor is accounted in performance ratio (PR) of PV system, $P_{\text{solar-load AC}}$ is considered as $P_{\text{solar-load}}$ only.

$P_{\text{Discharge}}$ = Power flow from storage device

P_{GIM} = Power import from grid

P_{GEX}= Power export to grid

ESD_{SOC} = state of charge of electrical storage device in MW

% ESD_{SOC} = state of charge of electrical storage device in percentage

Figure 7.16 indicates the mathematical model developed to indicate the various energy flows with energy storage system

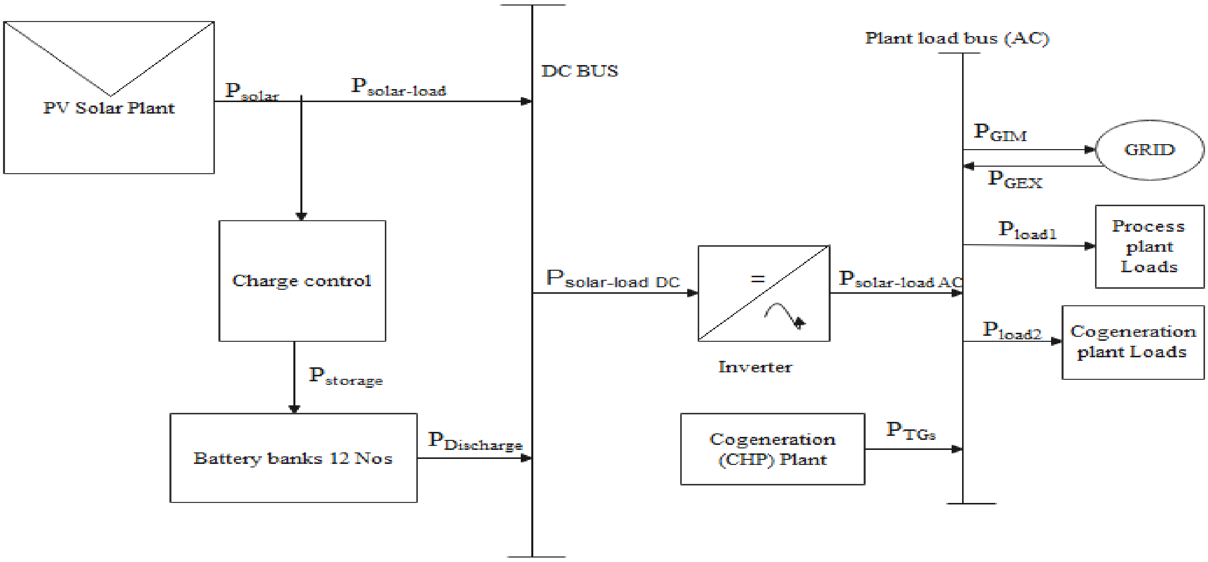

Figure 7.16 Mathematical model to balance energy flows.

The mathematical equations that govern the energy flows is obtained by balancing the energy generation from CHP and Solar plant to meet the plant load. However to optimize the plant operation, the solar energy above BEP is designed for storage. The stored energy from the storage device is utilized during non-solar period i.e. during night time at a constant discharge rate.

The mathematical equations that govern the energy flows during day time i.e. the period when solar power is available normally is,

The charging power to electrical storage device is represented by eqs.7.2a, 7.2b and 7.2c

$$P_{storage} = 0 \text{ if } P_{solar} < BEP \text{ i.e. } 6.3 \text{ MW} \text{ -------------------------------- } (7.2a)$$

$$= P_{solar} - BEP \text{ if } P_{solar} > BEP \text{ i.e. } 6.3 \text{ MW} \text{--------- ---------- } (7.2b)$$

$$= 0 \text{ if } \% \ ESD_{SOC} \geq 100 \ \% \text{------------------------------------- } (7.2c)$$

The power flow to load from solar plant is represented by Eqs 7.3a and 7.3b,

$$P_{solar\text{-}load} = P_{solar} \text{ if } P_{solar} < BEP \text{ i.e. } 6.3 \text{ MW} \text{ -------------------------- } (7.3a)$$

$$= 6.3 \text{ if } P_{solar} > BEP \text{ i.e. } 6.3 \text{ MW} \text{-------------------------- } (7.3b)$$

The power generation from Cogeneration (CHP) plant in MW is represented by Eqs 7.4a and 7.4b,

$$CHP_{PG} = P_{TGs} = P_{load} - P_{solar\text{-}load} - (P_{GIM} - P_{GEX}) \text{ with export or import --------------- } (7.4a)$$

$$= P_{load} - P_{solar\text{-}load} \text{ under floating condition i.e. with no export or import------- } (7.4b)$$

The state of charge of electrical storage device in MW is represented by Eqs 7.5 and 7.6,

$$ESD_{SOC} = \int_{t1}^{t2} ESDCP \, dt \text{ ------ -------------------------------- } (7.5)$$

$$\% \ ESD_{SOC} = ESD_{SOC} / ESD_{capacity} \text{ -- } (7.6)$$

Discharge of storage device is considered in night time i.e. during the period when solar is not available and at constant rate of K in MW is represented by Eqs 7.7a and 7.7b,

$$CHP_{PG} = PL - k \text{ if } \% \ ESD_{SOC} > 20\% \text{ and discharge timer is ON------------------------ } (7.7a)$$

$$= PL \text{ if} \% \ ESD_{SOC} \leq 20\% \text{ -- } (7.7b)$$

7.5 CONTROL OF STORAGE SYSTEM

The storage system can be controlled based on the algorithm proposed in Figure 7.17.The charging of battery storage takes place whenever solar generation exceeds BEP. To have a simple control mechanism, the discharge is planned at the night for a period of 8 h. In the algorithm-developed discharge cycle is assumed for 8 h and the Discharge Timer (DT) gets switched on auto as per the time set, for example, 8 p.m. and discharge gets terminated as per the identified preconditions. The charging cycle will start based on the solar system's wake-up. To avoid intermediate switch over from the charging mode due to any partial cloudy conditions, the Charging Timer (CT) is preset to get switched off at 19.30 h after waking up in the morning. State of charge of batteries during charging time (SOC_{CT}) and during discharge time (SOC_{DT}) are considered based on battery charging current (I_{bc}) and battery discharging current (I_{bd}). Hence, the algorithm is developed to suit the present scenario, and the charging cycle and discharge cycle are made independent.

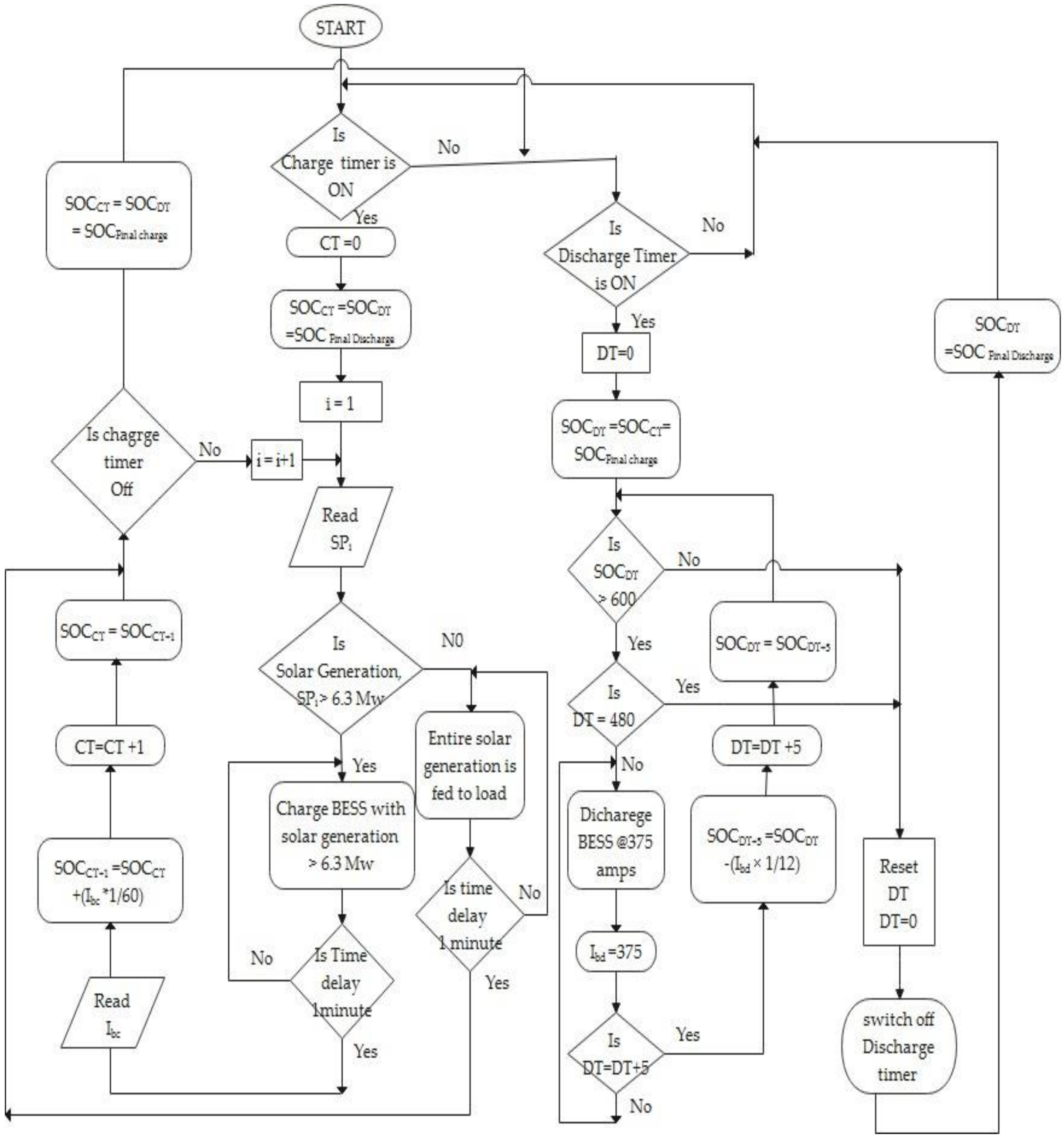

Figure 7.17 Control algorithm of Storage system.

7.6 MATHEMATICAL MODEL SIMULATION ALGORITHM

An algorithm is developed to simulate the energy flows based on the mathematical equations developed in section 7.4. Figure 7.18 indicates the algorithm to generate the energy flows with input data.

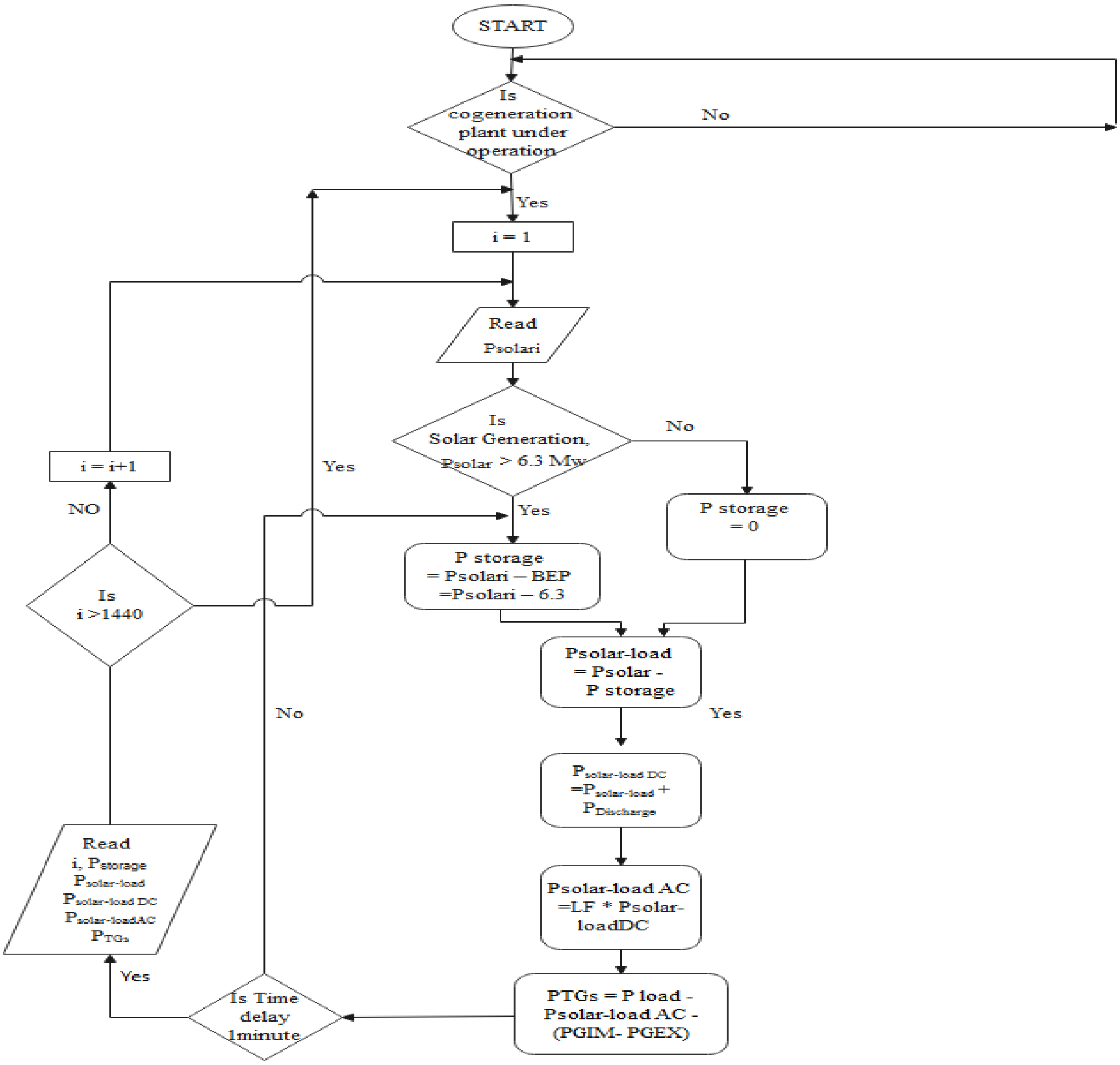

Figure 7.18 Algorithm to establish energy flows based on solar generation

From the solar irradiance data, the solar power generation and energy flows are obtained by using the mat lab coding using the algorithm developed and mathematical equations. The mathematical model developed is simulated using the estimated solar generation from the minute wise solar radiation data to compute the energy flows. The data is indicated in appendix A2.

With this rating, the 1 min charging data is verified, and the charging current does not exceed 600 amps except in a few instances which are also within 3% overload.

7.7 ENERGY STORAGE DEVICE CHARGING AND DISCHARGING PATTERN

Based on minute wise energy balancing data, the hourly charging pattern of storage device is obtained. Table 7.5 summarizes the hourly average values of charging/Discharging. Fig 7.19 indicates the storage device Charging/Discharge pattern on hourly basis.

Table 7.5 Hourly average values of charging/Discharge of storage device in AH

Time	SOC in %	Charging of storage device in AH	Time	SOC in %	Discharge of storage device in AH
6:00 AM	20	600	7:00 PM	97.7311	2931.93
7:00 AM	20	600	8:00 PM	97.7311	2931.93
8:00 AM	20	600	9:00 PM	87.731	2631.93
9:00 AM	20	600	10:00 PM	77.731	2331.93
10:00 AM	20.01389	600.4167	11:00 PM	67.731	2031.93
11:00 AM	28.8412	865.236	12:00 AM	57.731	1731.93
12:00 AM	46.8239	1404.72	1:00 AM	47.731	1431.93
1:00 PM	66.4546	1993.64	2:00 AM	37.731	1131.93
2:00 PM	83.977	2519.31	3:00 AM	27.731	831.93
3:00 PM	95.2297	2856.89	4:00 4M	20	600
4:00 PM	97.7311	2931.93	5:00 AM	20	600
5:00 PM	97.7311	2931.93	6:00 AM	20	600
6:00 PM	97.7311	2931.93			

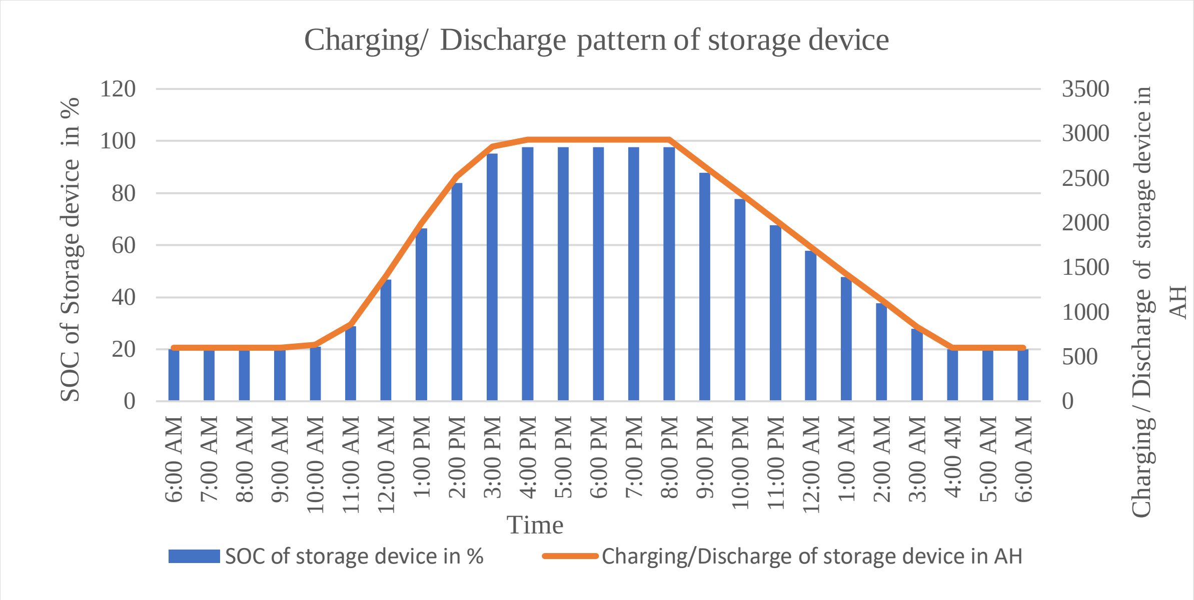

Figure 7.19 Charging/ Discharge pattern of a storage device

7.8 VALIDATION OF SOLAR GENERATION:

The solar generation estimated based on equation 7.1 and tilted irradiation data is validated from the actual generation based on energy meter readings. The daily solar generation recorded is 64450 units on April 16 in 2019. Table 7.6 indicates the estimated solar generation and the actual solar energy generated.

Table 7.6 Comparison of estimated and actual solar generation

Solar generation estimated		Actual solar generation			
Time	Estimated solar generation in kWh	Outgoing Feeder I		Outgoing Feeder II	
6 AM-7AM	160	Previous Meter Reading (MWh)	33654.250	Previous Meter Reading (MWh)	32002.850
7 AM-8AM	1990				
8 AM-9AM	6210				
9 AM-10AM	6550	Current Meter Reading (MWh)	33686.750	Current Meter Reading (MWh)	32034.800
10 AM-11AM	8170				
11 AM-12PM	10630				
12 PM-1PM	11110	Difference (MWh)	32.500	Difference (MWh)	31.950
1 PM-2PM	10520				
2 PM-3PM	9010	MF	1000	MF	1000
3 PM-4PM	6790	Energy Generation (kWh)	32,500	Energy Generation (kWh)	31,950
4 PM-5 PM	4020				
5 PM-6 PM	810	Total actual Solar generation in Kwh			64,450
Total estimated solar generation	75970				
Difference of solar generation between actual and estimated in KWh					11520
Percentage difference of solar generation between actual and estimated					15.16388

The design performance ratio of the PV system considered is 13.65%. The performance ratio (PR) is defined as a measure of the quality of a PV plant. PR can be a quality factor also. The PR is stated as a percentage and describes the relationship between the actual and theoretical energy outputs of the PV plant. The difference of 1.5 % from design can be acceptable as the performance of system depends on factors like cleanliness of solar panels, meter accuracy errors etc.

7.9 MONETARY BENEFITS

From Table 7.3, it can be observed that on a maximum solar radiation day, the total GTI is 6794.13 Wh/m^2/day and the expected solar generation is 74.64 MWh. From Table 7.1, the total yearly GTI for the year April 2019 to March 2020 is 1825.82 kWh/m^2/year. Hence, the total MWh generation in a year is 20058.37 MWh. Out of this, 50% of generation i.e., 10,029.19 MWh, is unutilized, as 50% of the solar panels were switched off to maintain optimality conditions. Hence, by using energy storage, a net monetary benefit of Rs 5.0146 crores is envisaged by considering the unit charge @ Rs 5 per unit. The expenditure can be 8.61 crores by considering the cost of 2 V, 3000 Ah cell @ Rs 20,000. Figure 7.20 indicates the comparison of monetary benefits due to RE utilization beyond BEP.

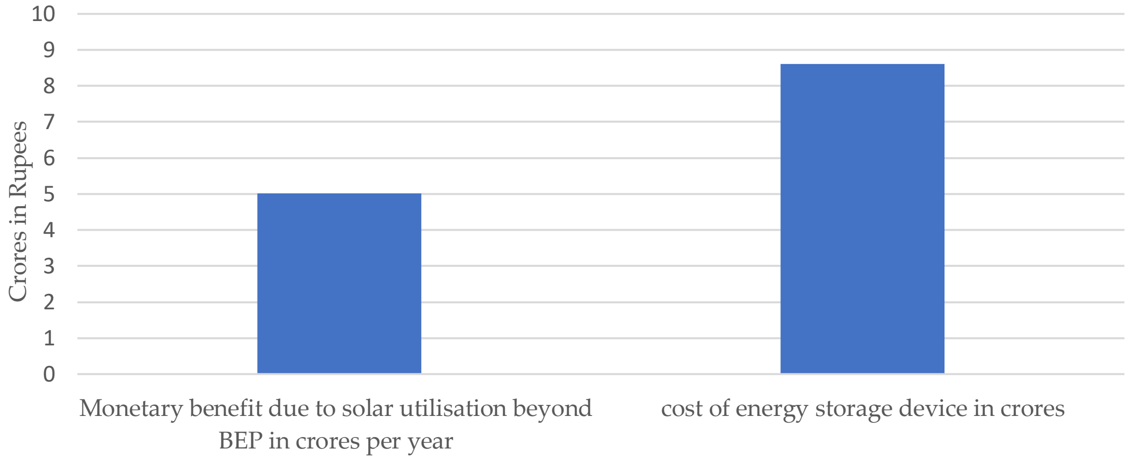

Figure 7.20 Comparison of monetary benefits due to RE utilization beyond BEP

Hence, the simple payback period is 1.72 years, which is well below the acceptable payback period of 3 years for any financial projects. In addition to the financial savings, other benefits like meeting the RPPO obligations and reduction in Co_2 emissions strengthens the proposed scheme.

7.10 SUMMARY

The post-operational constraints developed on integration of solar plant with existing cogeneration plant are effectively optimized by establishing BEP by practical and theoretical methods. Suitable storage device is selected and the capacity is designed based on the available data. The control mechanism of the storage device is also proposed. The payback period of the storage system proposed is arrived and proven economical. The methodology adopted in this paper is a guiding tool for designing storage systems for similar applications. Storage of energy will be a major issue in the future as future energy needs are by RE due to depletion of fossil fuels and associated environmental threats.

The outcome of this research presented a solution to the integration of renewable energy challenges faced by many industries. The energy share will definitely shift from the utilization of conventional fuels to renewables, which benefits society at large. This helps in improvement of energy security and sustainable growth, and at the same time protects the environment from further degradation.

CHAPTER-8

INDUSTRIAL COGENERATION PLANTS DESIGN OPTIMIZATION BY INTEGRATING WITH RENEWABLE ENERGY

8.0 INTRODUCTION

Cogeneration is the simultaneous generation of two different forms of energy from a single source. Normally, when thermal as well as electrical energies are required in process industries like chemical, paper, steel etc., cogeneration systems are preferred. Generating these energies independently is energy inefficient process; hence, cogeneration is the viable option. However, depending on the requirement of heat and electrical loads, industries have adopted different conventional designs. This paper proposed the improvements to the existing conventional cogeneration designs. New design aspects are suggested to optimize the cogeneration plants by integrating with RE. Increase in the efficiency of RE integrated cogeneration plants results in drastic savings in fossil fuels. Hence, enhances the energy security and at the same time protects the environment from degradation.

8.1 CONVENTIONAL DESIGN CHOICES OF COGENERATION SYSTEMS

In topping cycle cogeneration, maximum efficiency depends on the requirement of thermal and electrical energy in the process industry. Design shall be chosen in such a way that either a backpressure or extraction cum backpressure turbines meet the requirement of both thermal and electrical loads. The major savings in the back-pressure co-generation systems are due to utilization of latent heat in the process, hence maximum fuel saving. Backpressure co-generation systems best suits when the power generation obtained through the turbines with the process steam requirement matches with the plant demand. But in most of the cases both requirements cannot be met exactly. Mostly either thermal energy or electrical power demand by the process may be either less or excess.

Depending on the thermal and electrical energy requirements the selection of most of the cogeneration systems presently existing in industries are, based on the following choices

8.1.1 Base electrical load matching:

Cogeneration system designed ensures to meet the minimum electricity demand from the cogeneration. The grid will meet any further variations in electricity demand. If thermal energy generated by cogeneration is less than requirement, it will met by additional boilers/ Pressure Reducing and De-Superheating stations (PRDS). In case thermal energy generated is more, the same is exported to neighbouring industries.

8.1.2 Base thermal load matching:

The cogeneration system is designed to produce the minimum thermal energy requirement of process industry. Whenever thermal energy demand is higher, additional boilers/ PRDS are used to meet the requirements. If the electricity generated is less/more with base thermal requirement, it will be met by grid import/export.

8.1.3 Electrical load matching:

In this design, the process industry is completely independent with grid system i.e. it is stand-alone system. If the thermal energy generated with cogeneration is less, then it will be met by additional boilers/PRDS and if it is more same will be supplied to nearby process industries or it will be wasted.

8.1.4 Thermal load matching:

In this, the cogeneration system is designed to meet the thermal energy requirement at any time i.e. process industry does not depend on additional boilers. The electricity produced by the cogeneration during at any period is less than the demand, it will be by the grid import and similarly if it is excess to demand, it will be exported to the grid.

The choice of a cogeneration system from the above options depends mainly on the power to heat ratio of a process industry. Hence, the heat to power ratio of an industry guides the cogeneration system to be adopted.

8.2 DISADVANTAES OF CONVENTIONAL COGENERATION SYSTEMS

From the above it is observed that, no design is fully optimized as both energy and thermal requirements are not fully met by the cogeneration system adopted. In every design, either electricity or thermal energy partly depends on external sources. If parts of electricity demands are not met by design, same depends on the grid which indicates system is not optimized fully. Similarly, if the part of thermal energy is not met by the system it depends on additional boilers/ PRDS, which is not an optimized design. The selection of a particular cogeneration system depends on heat to power ratio and should match with the cogeneration characteristic. For higher heat to power ratio normally back pressure cogeneration systems gets matched and these systems have highest efficiency ranging from 84%-92% [1].With fall in heat to power ratios other cogeneration systems like extraction cum condensing , Gas turbine, combined cycle and reciprocating systems will match with fall in efficiencies. Table 8.1 summarizes the action plans at different operating conditions and disadvantages associated with each conventional design choices available.

Table 8.1 Summary of conventional topping cycle cogeneration systems design

Case no	Conventional design choices	Expected conditions during operation	Action plans	Disadvantages
I	Base electrical load matching	i) Electrical load demand is more than generated due to intermittent process fluctuations	i) Import from grid	i) System is not optimized fully
		ii) Electrical load demand is less than generated due to intermittent process fluctuations	ii) Export to grid. Normally on, free of cost, as firm export order with grid may not be feasible as constant export is not possible.	ii) Inadvertent export may lead to uneconomical
		iii)Thermal energy requirement is more than obtained with cogeneration systems	iii)Additional thermal energy shall be obtained through PRDS /additional boilers	iii) Supply of steam through PRDS is an inefficient process
		iv) Thermal energy requirement is less than obtained with cogeneration systems	iv) a) Excess thermal energy can be supplied to nearby industries if available	iv) a) Interdependent on nearby industry
			b) This may be less heat to power ratio of process industry other designs like extraction cum condensing type / combined cycle with extraction cum condensing steam turbine design shall be adopted such that excess electrical demand is met by condensing mode	b) Electrical energy produced through condensing mode is an inefficient process compared to cogeneration
			c) If nearby industries are not available excess thermal energy to be vented/wasted	c)Wastage of thermal energy
II	Base thermal load matching	Thermal energy demand is more than base thermal load due to intermittent process fluctuations	i) Additional thermal energy shall be obtained through PRDS /additional boilers	Supply of steam through PRDS is an inefficient process
		ii) Thermal energy demand is less than base thermal load due to intermittent process fluctuations	ii)a) Excess thermal energy can be supplied to nearby industries if available	Interdependent on nearby industry
			b) if nearby industries requiring thermal energy not available excess thermal energy to be vented/wasted	Wastage of thermal energy
		iii) Base electrical load requirement is more than obtained with cogeneration systems	iii) a) Import from the grid	System is not optimized fully
			b) This may be less heat to power ratio of process industry other designs like extraction cum condensing type / combined cycle with extraction cum condensing steam turbine design shall be adopted such that excess electrical demand is met by condensing mode	Electrical energy produced through condensing mode is an inefficient process compared to cogeneration
		iv) Base electrical load requirement is less than obtained with cogeneration systems	iv) a) Export to the grid with an export agreement with grid	Can be economical with agreement
			b) If export agreement is not possible , cogeneration system design based on base electrical to be adopted	Disadvantages as mentioned under case I

Case no	Conventional design choices	Expected conditions during operation	Action plans	Disadvantages
III	Electrical load matching (stand-alone system)	i) Thermal energy requirement is more than obtained corresponding to electrical load generation ii) Thermal energy requirement is less than obtained corresponding to electrical load generation	i) Additional thermal energy shall be obtained through PRDS /additional boilers ii)a) Excess thermal energy can be supplied to nearby industries if available b) if nearby industries requiring thermal energy not available excess thermal energy to be vented/wasted	Supply of steam through PRDS is an inefficient process Interdependent on nearby industry Wastage of thermal energy
IV	Thermal load matching (No additional boilers/PRDS)	Electrical load demand is more than generated corresponding to thermal energy requirement ii) Electrical load demand is less than generated corresponding to thermal energy requirement	i) Import from grid ii) Export to grid. Normally on, free of cost, as firm export order with grid may not be feasible as constant export is not possible.	System is not optimized fully Inadvertent export may lead to uneconomical

8.3 COGENERATION SYSTEMS DESIGN OPTIMIZATION BY INTEGRATING WITH RENEWABLE ENERGY AND UTILISING THE ENERGY STORAGE TECHNOLOGIES

From the above it is observed that scope is available to further optimize the cogeneration systems. Co-generation systems can be integrated with RE systems like solar, wind, hydro etc. for generation of electrical energy. This can be utilized during the operating conditions of power import. Similarly when low heat to power ratio prevails, the cogeneration systems can be designed to meet the heat load. This avoids the less efficient extraction cum condensing turbines/ gas turbines to generate the electrical power through condensing mode/conventional power generation mode. The excess of electrical energy required can be generated by RE sources. Similarly whenever thermal energy generated by cogeneration is less than the requirement, the surplus can be produced through renewable thermal energy route like solar thermal power/ solar water heating systems.

As the RE generation is intermittent in nature, the generated electrical or thermal energies may not match with demand. Hence it necessitates the use of energy storage devices so that whenever RE generated is more than required it can be stored and the same can be utilized. The storage devices is also required during operating conditions of power export or surplus thermal energy, as the stored electrical or thermal energy can meet the requirements. Hence, this avoids the inefficient operation of inadvertent power export or supplying steam to nearby industries.

Thus, the cogeneration plants design can be optimized in a better way by integrating with RE along with suitable energy storage device. However the selection of energy storage technology depends on the process plant requirements and application. Hence, study is made regarding advantages and disadvantages of the various storage technologies available. The numeric values like Capacity, duration of storage, type of storage, lifetime, response time, duration of discharge at maximum power level, specific energy, energy density, efficiency etc are also considered. Further economic study is also made based on total capital and life cycle costs so as to select the optimum storage technology.

8.4 DESIGN OF RENEWABLE ENERGY INTEGRATED COGENERATION SYSTEMS:

Based on the inefficiencies in the conventional cogeneration systems and study of energy storage systems, new optimized designs are proposed by integrating with renewable energy. The various designs that can be opted under various operating conditions and advantages with the optimized RE integrated cogeneration plants is given in table 8.2

Table 8.2 Advantages of optimized renewable energy integrated topping cycle cogeneration systems

Case no	Conventional design choices	Expected conditions during operation with conventional design	New proposed design to meet the Expected conditions during operation with conventional design	Action Plan	Advantages
I	Base electrical load matching	i) Electrical load demand is more than generated due to intermittent process fluctuations	i) Install the RE generation (Electrical) plant including the energy storage. The capacity of the plant shall be to meet the peak demand over base electrical load.	Utilize the generation from RE sources. If RE generation is surplus, store the excess energy and import from energy storage device in case RE generated is not sufficient to meet the demand.	i) System is optimized fully as not being imported from grid which was case with conventional design
		ii) Electrical load demand is less than generated due to intermittent process fluctuations	Install the energy storage device so that it can be used during peak periods. In case stored energy is surplus, can be utilized for production of RE fuels like Hydrogen / Methane etc.	ii) Store the surplus electrical energy and utilize it during peak requirement.	ii) System is optimized fully as no inadvertent export to grid which was the case with conventional design

Case no	Conventional design choices	Expected conditions during operation with conventional design	New proposed design to meet the Expected conditions during operation with conventional design	Action Plan	Advantages
		iii)Thermal energy requirement is more than obtained with cogeneration systems	iii) Install the renewable thermal energy generation facility including thermal energy storage preferably solar thermal /water heating /through electrode boilers utilizing the electrical energy from RE sources. The capacity of the plant shall be to meet thermal energy demand over generated through cogeneration.	.iii) Additional thermal energy required shall be utilized from generated through RE route	iii) System is optimized fully as no supply of steam through PRDS/through additional boilers which was case with conventional design
		iv) Thermal energy requirement is less than obtained with cogeneration systems	iv) Design the cogeneration for base thermal energy and generate the deficit electrical energy required through RE sources along with storage facility. Capacity of the plant shall be to meet the deficit requirement over the electricity produced from cogeneration.	iv) Utilize the deficit electrical energy from RE /storage device.	iv) System is optimized fully as not interdependent on nearby industry and not required to produce electricity through condensing mode, which was case with conventional design. Wastage of thermal energy not envisaged also.
II	Base thermal load matching	Thermal energy demand is more than base thermal load due to intermittent process fluctuations	i) Install the RE generation (Thermal) plant including the energy storage. The capacity of the plant shall be to meet the peak demand over base thermal load.	i) Additional thermal energy shall be obtained through RE sources. If RE is surplus, store the excess energy and import from energy storage device in case of deficit.	i) System is optimized fully as not being utilized through PRDS, which was case with conventional design.
		ii)Thermal energy demand is less than base thermal load due to intermittent process fluctuations	ii) Install the energy storage (Thermal) so that it can be used during peak periods.	ii) Store the surplus electrical energy and utilize it during peak requirement.	ii) System is optimized fully as not Interdependent on nearby industry and no wastage of thermal energy
		iii)Base electrical load requirement is more than obtained with the cogeneration systems	iii) Install the RE generation (Electrical) plant including the energy storage. The capacity of the plant shall be to meet the peak demand over obtained with cogeneration.	iii) Utilize the generation from RE sources. If RE generation is surplus, store the excess energy and import from energy storage device in case RE	iii) System is optimized fully as electrical energy is not through condensing mode, which was the case with conventional design.

Case no	Conventional design choices	Expected conditions during operation with conventional design	New proposed design to meet the Expected conditions during operation with conventional design	Action plan	Advantages
		iv)Base electrical load requirement is less than obtained with cogeneration systems	iv) Install the energy storage device so that it can be used during peak periods. In case stored energy is surplus, can be utilized for production of RE fuels like Hydrogen / Methane etc.	is not sufficient to meet the demand. iv) Store the surplus electrical energy and utilize it during peak requirement	iv)System is optimized fully as no inadvertent export to grid which was the case with conventional design
III	Electrical load matching (stand-alone system)	i)Thermal energy requirement is more than obtained corresponding to electrical load generation	i) Install the RE generation (Thermal) plant including the energy storage. The capacity of the plant shall be to meet the thermal energy requirement in excess of thermal energy generated with electrical load matching cogeneration.	i) Additional thermal energy shall be obtained through installed RE (thermal)	i) System is optimized fully as no supply of steam through PRDS /through additional boilers which was the case with conventional design
		ii)Thermal energy requirement is less than obtained corresponding to electrical load generation	ii) Design for thermal load matching and install RE generation (electrical) including storage. The capacity of the plant shall be to meet the additional electrical energy requirement over generated through cogeneration.	ii)Additional electrical energy required than generated from cogeneration is obtained from installed RE	ii) System is optimized fully as not Interdependent on nearby industry and no wastage of thermal energy
IV	Thermal load matching (No additional boilers/PRDS)	Electrical load demand is more than generated corresponding to thermal energy requirement	i) Install the RE generation (Electrical) plant including the energy storage. The capacity of the plant shall be to meet the demand over obtained with cogeneration.	i) Utilize the generation from RE sources. If RE generation is surplus, store the excess energy and import from energy storage device in case RE generated is not sufficient to meet the demand.	i) System is optimized fully as electrical energy is not imported from grid, which was the case with conventional design.
		Electrical load demand is less than generated corresponding to thermal energy requirement	ii) Install the electrical energy storage device so that it can be used during peak periods. In case stored energy is surplus, can be utilized for production of RE fuels like Hydrogen / Methane etc.	ii) Store the surplus electrical energy and utilize it during peak requirement production of RE fuels.	System is optimized fully as electrical energy is not exported to grid, which was the case with conventional design.

8.5 BOTTOMING CYCLE:

Mostly the bottoming cycle is used to recover the waste heat from the process. Generally, this approach can be adopted in process industries that utilize high heat at high temperature like in furnaces and kilns. Instead of exhausting, the waste heat from the process it can be utilized for generation of electricity using waste heat recovery boilers and condensing / backpressure turbines depending on thermal energy requirement. In this cycle also two cases arise and the table 8.3 indicates summary of conventional bottoming cycle cogeneration systems design.

Table 8.3 Summary of conventional bottoming cycle cogeneration systems design

Energy requirements by process industry	Conventional design choices	Expected conditions during operation	Action plans	Disadvantages
Require both thermal as well as electrical	Similar to topping cycles i.e. 4 cases can prevail as mentioned in table 8.1	Similar to topping cycles i.e. 4 cases can prevail as mentioned in table -8.1	Similar to topping cycles i.e. 4 cases can prevail as mentioned in table 8.1	Similar to topping cycles i.e. 4 cases can prevail as mentioned in table 8.1
Requires only electrical energy	Producing electrical energy using cogeneration systems like gas turbine cycle/combined cycle/steam turbines with condensing mode. No extraction /backpressure systems due to absence of thermal energy requirement.	i) Electrical energy demand is more than generated ii) Electrical energy demand is less than generated	i) Import from grid ii) Export to grid if firm export agreement with grid is feasible	i) System is not optimized fully as dependent on grid which may not be reliable ii) In case of no firm export agreement with grid , energy to be wasted / vented

Based on the above conventional systems design, RE integrated cogeneration systems are proposed in table 8.4

Table 8.4 Advantages of optimized renewable energy integrated bottoming cogeneration systems

Conventional design choices	Expected conditions during operation with conventional design	New proposed design to meet the Expected conditions during operation with conventional design	Action Plan	Advantages
Similar to topping cycles i.e. 4 cases can prevail as mentioned in table 8.2	Similar to topping cycles i.e. 4 cases can prevail as mentioned in table 8.2	Similar to topping cycles i.e. 4 cases can prevail as mentioned in table 8.2	Similar to topping cycles i.e. 4 cases can prevail as mentioned in table 8.2	Similar to topping cycles i.e. 4 cases can prevail as mentioned in table 8.2

Conventional design choices	Expected conditions during operation with conventional design	New proposed design to meet the Expected conditions during operation with conventional design	Action Plan	Advantages
Producing electrical energy using cogeneration systems like gas turbine cycle/combined cycle/steam turbines with condensing mode. No extraction /backpressure systems due to absence of thermal energy requirement.	i) Electrical energy demand is more than generated	i) Install the RE generation (Electrical) plant including the energy storage. The capacity of the plant shall be to meet the demand over obtained with cogeneration.	i) Utilize the generation from RE sources. If RE generation is surplus, store the excess energy and import from energy storage device in case RE generated is not sufficient to meet the demand.	i) System is optimized fully as electrical energy is not imported from grid, which was case with conventional design.
	ii) Electrical energy demand is less than generated	ii) In case of firm export order it can be continued. In case of export with grid not feasible, then install energy storage device	ii) the energy stored can be utilized for peak requirements or generate hydrogen /methane for commercial marketing	ii) system can be optimized fully as no energy wastage

8.6 ANALYTICAL SOLUTION FOR INDUSTRIAL COGENERATION PLANT DESIGN OPTIMIZATION

Analytical analysis for the RE integration cogeneration plants optimization is presented based on the proposed new designs.

BASE ELECTRICAL LOAD MATCHING:

The conventional cogeneration plants design based on base electrical load matching can be optimized by following the new design concepts as listed. In the new design, the capacity selection of RE can be estimated as indicated

With base electrical load design the main issues are the electrical load demand is either more or less than the base electrical load.

Assume,

Average electrical load above base load over period of one day in MW = X_{av}

Average electrical load below base load over period of one day in MW = Y_{av}

There can be two cases,

Case I:

$X_{av} > Y_{av}$ i.e. in this case the average cycle demand above base load is more than the average cycle demand below base load. So the electrical energy below the base load can be stored to utilize the same during the peak cycle.

Hence, the RE generation required = $X_{av} - Y_{av}$ -- (8.1)

Assume efficiency of renewable energy plant in percentage = η

The capacity of RE plant in MW = $[(X_{av} - Y_{av}) / (\eta/100)]$-------------------------------(8.2)

Based on the minute wise RE generation levels, the peak energy below base load & the demand, the battery storage capacity, the charging and discharging pattern shall be designed.

Case II:

$X_{av} < Y_{av}$ i.e. in this case the average cycle demand above base load is less than the average cycle demand below base load. So the electrical energy below the base load can be stored to utilize the same during the peak cycle. The average cycle demand above base load can be met fully by the storage capacity; it doesn't require any RE capacity addition. Based on the minute wise the energy levels below base load to be stored, the battery storage capacity, the charging and discharging pattern shall be designed.

ELECTRICAL LOAD MATCHING:

In case of cogeneration systems while matching electrical load, two conditions can arise

Case i:

Thermal energy generation is more than required if back pressure turbine system is adopted. There should be a consumer of excess thermal energy to nearby. If no taker of thermal energy, the conventional design is extraction cum condensing type turbine cogeneration systems. Hence, part of electrical energy is met by condensing mode which is not efficient. New design proposes to generate thermal energy required through back pressure turbine system. The excess energy requirement is met by RE. The RE generation is equivalent to power generation through condensing mode.

In the proposed design, the capacity selection of RE can be estimated as indicated.The thermal energy requirements of process plant can be met by number of extractions at different pressures and temperatures. Based on the steam flow requirements and enthalpies, the power generated while meeting the thermal energy requirements can be estimated as follows.

Assume the following,

Turbine inlet steam flow T/hr = Q_{tint}

1st extraction steam flow T/hr = Q_{ext1}

2nd extraction steam flow T/hr = Q_{ext2}

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nth extraction steam flow T/hr = Q_{extn}

Turbine inlet steam pressure Kg/cm^2 = P_{tint}

1st extraction steam pressure Kg/cm^2 = P_{ext1}

2^{nd} extraction steam pressure $Kg/cm^2 = P_{ext2}$

----

n^{th} extraction steam pressure $Kg/cm^2 = P_{extn}$

Turbine inlet steam temperature $^0C = t_{tint}$

1^{st} extraction steam temperature $^0C = t_{ext1}$

2^{nd} extraction steam temperature $^0C = t_{ext2}$

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n^{th} extraction steam temperature $^0C = t_{extn}$

Inlet Steam enthalpy corresponding to P_{tint} & $t_{tint} = h_{tint}$

Inlet Steam enthalpy corresponding to P_{ext1} & $t_{ext1} = h_{ext1}$

Inlet Steam enthalpy corresponding to P_{ext2} & $t_{ext2} = h_{ext2}$

Inlet Steam enthalpy corresponding to P_{extn} & $t_{extn} = h_{extn}$

Assume Turbine efficiency in percentage = η_{turb}

Total power that can be generated through the turbine if back pressure system adopted is, P_{gen}

$$= [\{Q_{tint}(h_{tint} - h_{ext1}) + (Q_{tint} - Q_{ext1})(h_{ext1} - h_{ext2}) + \text{--------------------------} + (Q_{extn\,(n-1)} - Q_{extn})(h_{ext\,(n-1)} - h_{extn})\}\ \{\eta turb/860\}]MW \text{--------------------------------------} (8.3)$$

Total Power demand = P_{demand}

$$\text{Renewable energy plant requirement} = [(P_{demand} - P_{gen}) / (\eta/100)] \text{--------------------} (8.4)$$

Based on the minute wise RE generation levels, and the demand utilization, the battery storage capacity, the charging and discharging pattern shall be designed.

Case II:

Thermal energy generation is less than required if back pressure turbine system is adopted. The extra thermal energy can be met by additional boilers/PRDS. The new design suggests the thermal energy generation through RE thermal route.

8.7 RE INTEGRATED DESIGN PROPOSAL FOR AN IDENTIFIED COGENERATION INDUSTRY

The identified cogeneration industry in figure 2.1 is designed with conventional design of base electrical load as industry requirement is uninterrupted thermal and electrical energies. As thermal energy obtained with cogeneration is more than demand and no nearby industries to take the thermal energy, system is designed with extraction cum condensing cogeneration. The additional electrical energy required than obtained from extraction mode is generated through condensing mode; hence system is not optimized fully. As discussed under case I iv) under topping cycle, instead of going for double extraction condensing type turbine, the additional electrical power requirement can be met through RE route with suitable energy storage device. This further optimizes the system towards sustainable energy and environmental security. Figure 8.1 indicates the new design proposed in an identified conventional design cogeneration plant associated with chemical industry.

Total power that can be generated through the turbine (assuming 90% turbine efficiency) if back pressure system adopted is,

= {255(794-742) +35(742-698)} x {0.9/860} = {(255x52) + (35x44)} x {0.9/860} MW

= (13,260+1540) x (0.9/860) MW = (14800) x (0.9/860) MW = 15.48 MW say 15 MW

Total Electrical energy requirement = 35 MW

Hence Renewable energy requirement =20MW

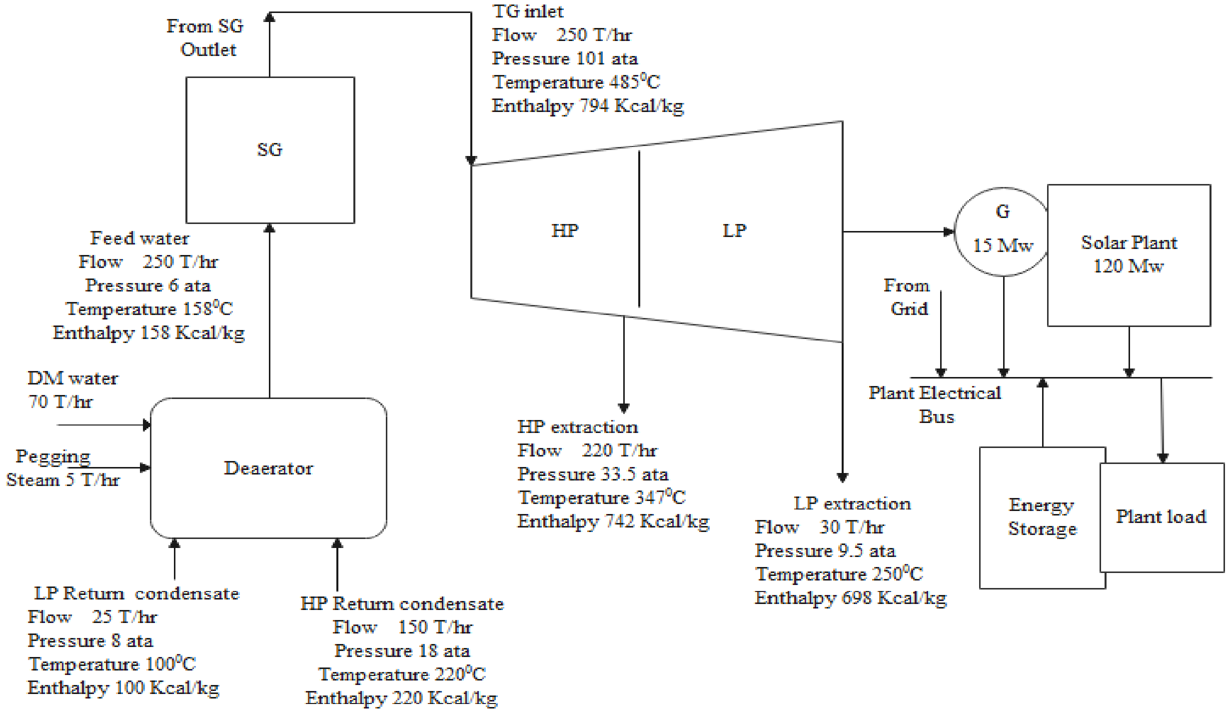

Figure 8.1Design optimization of conventional cogeneration systems by adopting Renewable energy

Total heat addition in the steam generator is,

= 250 × (794 - 158) Mcal/hr = 159000 Mcal/hr

Total input energy to steam generator considering steam generator efficiency of 85% is,

= (159000÷ 0.85) Mcal/hr = 187058 Mcal/hr

Total amount of coal consumed by industry considering calorific value of coal 5000 Kcal/Kg = (187058 ÷ 5000) MT/hr = 37.4 MT/hr

Hence, by adopting RE integrated cogeneration design industry is benefitted by around 17.8 MT/hr of coal consumption i.e. 32.24% of coal saving when compared with case of independently meeting the thermal and electrical energy requirements. Similarly when compared with extraction cum condensing cogeneration system, realized coal savings of 12 Mt/hr i.e.24.3% hence, helping in energy security and minimizing the environmental degradation.

8.8 RESULTS AND DISCUSSION:

The study is aimed on improving the efficiency of cogeneration plants and the new design aspects are suggested to minimize the fossil fuel utilization. This results in saving of fossil fuels to ensure energy security and minimize the environmental degradation. The requirement of fossil fuel (Coal) for all 3 designs is estimated. The data collected from an identified conventional cogeneration industry designed for base electrical load is used. The results are tabulated in table 8.5

Table 8.5 Comparison of performance indicators of industrial cogeneration systems

S. No	Parameter	Systems adopted to meet the thermal and electrical energy		
		Independent	cogeneration	RE integrated cogeneration
1	Input energy in Mcal/hr	275976	246918	187058
2	Thermal energy in Mcal/hr	142950	142950	142950
3	Electrical energy in Mcal/hr	30100	30100	12900
4	Total output energy in Mcal/hr	173050	173050	155850
5	Energy utilization factor	62.7	70.1	83.3
6	Fossil Fuel (coal) consumption in MT/hr	55.2	49.4	37.4
7	Percentage of coal consumption	100	89.5	67.8
8	Carbon dioxide emission in tons/hr	81	72.5	54.9
9	Percentage of carbon dioxide emission	100	89.5	67.8

From the table it is observed that the energy utilization factor is drastically improved to 83.3 % with RE integrated cogeneration plant. The energy utilisation factor is the percentage of useful output energy (combined electrical and thermal output energy) to the input energy. Both thermal and electrical energies are expressed in Mcal/hr by converting electrical energy to heat energy (1 kWh=860 calories). The coal consumption also reduced to 67.8% with RE integration. As the coal consumption has reduced, the CO_2 emissions in to atmosphere also have reduced proportionately. The carbon dioxide emissions in MT/hr are calculated assuming the 40% carbon content in the coal. The emission levels and the coal consumption vary depending on the type of coal used due to variation in percentage of constituent elements and calorific values.

The Energy utilization factor, fossil fuel consumption levels and CO_2 emissions in to atmosphere are indicated in the figure 8.2

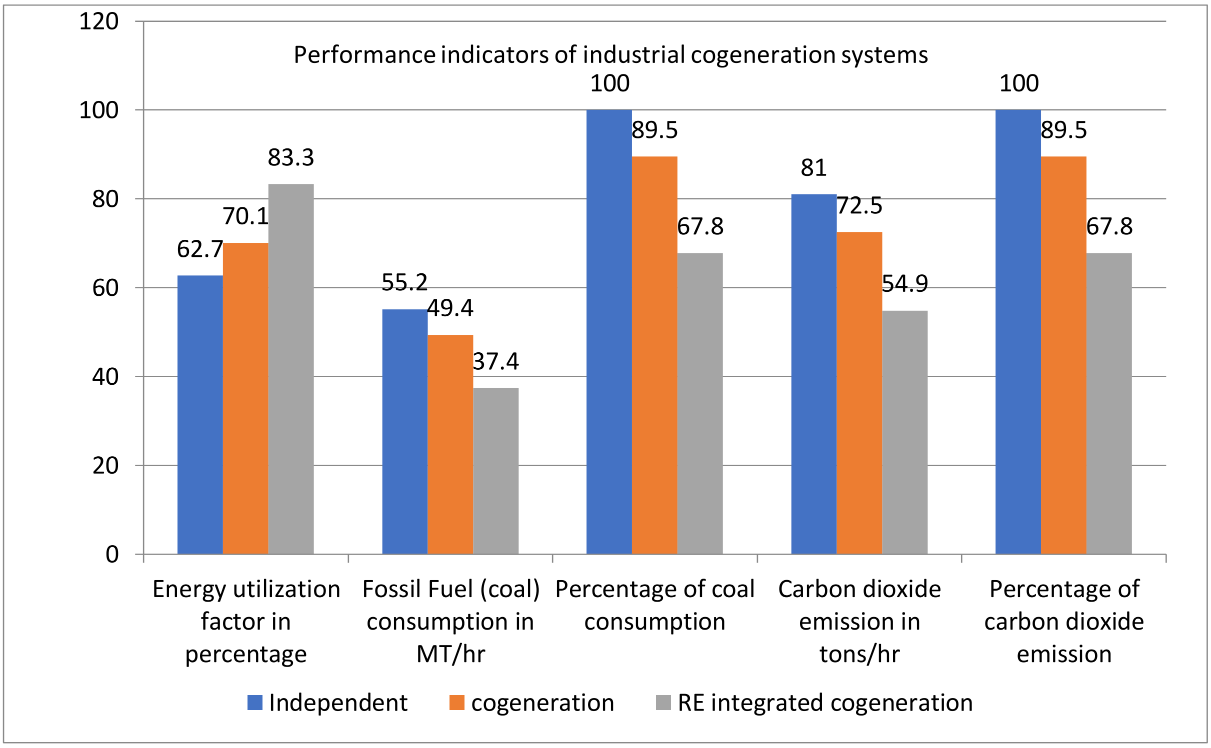

Figure 8.2 Comparison of industrial cogeneration systems performance indicators

8.9 SUMMARY

Most of the energy intensive industries utilize cogeneration systems to meet thermal as well as electrical energies. It was emphasized to integrate with RE to optimize the energy utilization further. Energy utilization factor drastically improved, resulting in reduction of fossil fuels which helps in energy security and at the same time reduction in environmental pollution. This can be an initial step in achieving zero carbon emissions. However, as most of the RE technologies are at developing stage, the development of these technologies along with energy storage technologies will definitely encourage the industries to opt the new designs proposed. The utilization of the proposed designs in forthcoming cogeneration plants will definitely reduce the fuel inputs along with a drastic reduction of energy costs, paving the way for energy and environmental security.

CHAPTER-9

CONCLUSION AND FUTURE SCOPE

9.0 RESEARCH OUTCOMES:

The research topic chosen is practical industrial problems that are developed after the addition of renewable energy based on guidelines under RPPO (renewable power purchase obligation). Research concentrated on an investigation to find out the remedial solutions to the challenges faced by co-generation plant in an identified industry and following are the research outcomes. Break-even point is estimated by real time/on site data. Real time data is obtained by practically running the system at different energy imports i.e. simulated the conditions when the renewable energy gets injected in to the system .The data collected is analyzed for any deviations in design parameters which results in to inefficient operation or uneconomical. From the real time data it is observed that total steam generation from steam generators is falling below the threshold limit demanding an oil support. Hence, it is concluded it is uneconomical to utilize the renewable energy beyond a certain point. Even though BEP is established using real time data, this is valid for the system considered only as the design conditions and the optimality condition limits vary from system to system. Hence, a standard method is developed based on the heuristic forward approach. Mathematical model is developed and the equations are developed based on theoretical concepts and considering the design conditions and limitations. Standard algorithm is developed based on heuristic forward approach techniques and the developed mathematical equations. Using the initial data the algorithm developed is executed using MATLAB. The algorithm was run iteratively, till any of the optimality condition deviated. The results are tabulated and the BEP is obtained. The results obtained from the heuristic approach method are compared with the results obtained from real time method. The variations in values obtained from these two methods are within limits, hence validated the methods developed. Both the techniques can be adopted to obtain the BEP for any cogeneration plants. The standard mathematical model developed can be a best tool and suits to any type of CHP plants, by modifying the model based on the system adopted. Similarly, the equations are to be modified based on the system design conditions and limitations pertaining to the system adopted. The same methodology can be adopted by CHP plants facing similar problems after integration with RE.

After establishing the BEP, research concentrated on the effective utilization of the RE beyond BEP. From the literature review, it is concluded to store the energy beyond BEP and utilize the same during non RE period or during the time when RE generation is below the BEP. Hence an elaborate literature review is carried out to identify the various emery storage technologies available. Based on the technical characteristics of the energy storage devices, the advantages and disadvantages of each technology are derived. Financial aspects are also considered and the data is collected. From the technical and financial aspects, the suitability of each technology to the present application is studied and concluded lead acid batteries suits best for the case study considered.

After considering the suitable storage device, the capacity design of storage device including voltage rating and ampere hour capacity played an important role in the research. To determine the storage capacity the total solar radiation data of global horizontal incidence (GHI) and global tilted incidence (GTI) values per month is collected for 3 consecutive calendar years of 2018, 2019 and 2020. From the data, it is analyzed that during the months of April 2018, October 208, March 2019, April 2019, March 2020, April 2020 and May 2020, the average radiation values are exceeding 6 kWh/m^2/Day based on the total monthly radiation levels.. To identify the maximum radiation levels per day, the GTI data is collected on day wise basis for the months of April 2018, October 208, March 2019, April 2019, March 2020, April 2020 and May 2020. From the analysis of the data collected on day wise, it is observed that the maximum radiation level of GTI is recorded on April 16th 2019 and the recorded value is 6.79 kWh /m^2 /Day. To estimate the capacity of storage device, the total solar generation on April 16th 2019 on minute wise is accounted. To estimate the minute wise solar power generation, the standard power equation 7.1 is considered. The minute wise solar radiation values, the average cell temperatures corresponding to April 16th 2019 are obtained from the weather station mounted for the purpose of solar plant. All the solar data is collected from the 12 MW solar plant integrated with an identified cogeneration plant only. From the estimated solar generation levels on minute wise, the total energy to be stored greater than BEP is estimated. As the storage device considered is lead acid batter bank system, for better battery life expectancy, only 80% discharge is considered. Accordingly, the battery capacity is designed 20 % more than the estimated. By considering the optimum battery bank voltage of 340 V DC the ampere hour capacity is estimated. Total 24 Nos battery banks of each 3000 amps is considered and lay out is also designed. The control scheme for charging and discharging is also designed and an algorithm is prepared. Based on the one minute power generation levels, the energy flows are balanced and indicated. The charging values of the storage device on minute wise indicated the charging current not exceeded the current rating of battery bank based on 5 hour rating except in few cases which is also within the permissible value of 3%.Hence, validated the design capacity of the storage device.

The estimated total solar generation is also validated from the recorded energy meter readings. The difference of 1.5% is arrived by considering the designed solar cells performance ratio of 13.65%, which is within limits by accounting the meter accuracy values. Finally in the research, the monetary benefits are also accounted by considering the monetary savings that is due to the utilization of solar energy beyond BEP and the cost of the energy storage device. The payback period arrived is 1.72 years, which is well within the acceptable values.

9.1 FUTURE SCOPE OF RESEARCH:

Integration challenges faced by the cogeneration plants are latest and newly developed problems. Many cogeneration plants associated with process industries are not coming forward to set up RE generation plants. The main reasons for not going RE generation are the RE technologies and storage systems are costly. The variable nature of renewable energy and the technologies are not fully developed can also be the added reasons. Hence many cogenerators are trying to fulfill the RPPO obligation through purchase of RECs or paying penalties. Hence much of the literatures are not available on similar type of problems. The challenges experienced and noticed in this thesis are unique in nature. The ideas developed in this thesis like BEP estimation by practical experimentation/online data, development of heuristic forward approach algorithm are innovative ideas. The heuristic forward approach algorithm is validated by comparing with the practical experimental results. The method is further validated by considering the operation strategy of 1 boiler and 1 TG operation at 50% of process load.

In view of above, the thesis lacks in comparison of the results with other literatures or similar type of problems experienced. The graphical and tabular results could not be compared with other papers. Hence, the future scope of the work mainly involves the following,

i) Identifying the RE integrated cogeneration plants

ii) Study of the challenges faced and inefficiencies caused at full installed capacity.

iii) Carrying out the cost benefit analysis by the developed methodology and formulae in the thesis

iv) BEP estimation utilizing the heuristic forward approach algorithm and the corresponding initial values of the system considered.

v) Validate the results by comparing with test results of the thesis.

Most of the cogeneration systems designs are based on conventional concepts of base thermal load matching , base electrical load matching, electrical load matching (stand-alone systems) and thermal load matching (no additional boilers/PRDS).All these designs are not optimized fully as utilizing partly condensers or additional boilers/ PRDS systems. The research intended to optimize the RE integrated system, optimized the system fully by utilizing the RE to the maximum by utilizing the energy storage concepts. Tables 8.2 and 8.4 indicated the new design concepts to optimize the cogeneration systems by integrating with RE and utilizing the energy storage devices. It is also demonstrated to optimize the identified cogeneration industry further by adding more RE and enhancing the storage device capacity. The energy utilization factor improved drastically resulting in the reduction of coal consumption and carbon dioxide emissions. The various design approaches presented is very much useful and contributes in minimizing the natural fossil fuels degradation as well as minimizes environmental degradation also.

Hence future scope of research involves the optimization of cogeneration plants utilizing RE integration. The research gives a boost to many industries/ grid players to come forward to establish renewable energy generation.

9.2 SUMMARY:

The research presented a solution to optimize the conventional cogeneration systems. By utilizing the concepts presented in selection of energy storage devices, capacity estimation of energy storage, the energy share will shift from conventional fuels to renewables which benefit the society at large. This helps in energy security improvement and sustainable growth and at the same time protects the environment from further degradation.

Research Publications

Published Journal (Scopus) Papers

1. Manikyala Rao, A.V.R.N.B., Singh, A.K., “Optimization and Control of Renewable Energy Integrated Cogeneration Plant Operation by Design of Suitable Energy Storage System,”*Energies***2022**, Volume 15, Issue 13, 4590. https://doi.org/10.3390/en15134590

Published Conference Papers

1. Rao, A.M., Singh, A.K., “Case study on Renewable energy integration challenges with Captive / Cogeneration plants and optimization of plant operation,” In: Proceedings of the 3rd International Conference on intelligent circuits and systems, (ICICS 2020), June 26-27, 2020, CRC press Taylor & Francis group, London, New York: pp. 11-19

2. Ankem V R N B Manikyala Rao and Dr. Amit Kumar Singh, “Cogeneration Plants Design Optimization by Integrating them with Renewable Energy towards Sustainable Energy and Environmental Security,” in the International Conference on Intelligent and innovative technologies in Computing, Electrical and Electronics (IITCEE 2023) held on January 27-28th, 2023organized by IEEE Bangalore section at BNM Institute of Technology, Bengaluru, India, DOI: 10.1109 / IITCEE57236.2023.10090890, Publisher: IEEE

Conference papers presented

1. Ankem V R N B Manikyala Rao and Dr. Amit Kumar Singh, “Techno economic analysis of energy storage technologies for selection of suitable device and design of storage system to optimize renewable energy integrated cogeneration plant,” in the 4th International e-Conference on Intelligent Circuits and Systems (ICICS 2022) held on April 8-9th, 2022 organized by School of Electronics and Electrical Engineering at Lovely Professional University, Punjab.

APPENDIX A

A.1 MINUTE WISE SOLAR DATA

The solar radiation data of 16thApril 2019 is collected from 6 AM to 6 PM. Based on the equation 7.1, the solar output is estimated. Tables A.1.1 to A.1.12 indicate the minute wise solar radiations and the estimated solar power.

Table A.1.1 Minute wise data of solar radiation from 6 AM to 7 AM

Time AM	GTI (W/m2)G	Temperature T ^{0}C	G/Gref i.e. (G/1000) W/m2	Temp Compensation factor 3.7*(T-25)/1000	Solar power generation MW	Solar Power > 6.3 MW
6:01	0.00	13.56	0.00	-0.04	0.00	0
6:02	0.00	13.54	0.00	-0.04	0.00	0
6:03	0.00	13.52	0.00	-0.04	0.00	0
6:04	0.00	13.52	0.00	-0.04	0.00	0
6:05	0.00	13.55	0.00	-0.04	0.00	0
6:06	0.00	13.63	0.00	-0.04	0.00	0
6:07	0.00	13.67	0.00	-0.04	0.00	0
6:08	0.00	13.68	0.00	-0.04	0.00	0
6:09	0.00	13.68	0.00	-0.04	0.00	0
6:10	0.00	13.65	0.00	-0.04	0.00	0
6:11	0.00	13.64	0.00	-0.04	0.00	0
6:12	0.00	13.60	0.00	-0.04	0.00	0
6:13	0.00	13.58	0.00	-0.04	0.00	0
6:14	0.00	13.61	0.00	-0.04	0.00	0
6:15	0.00	13.65	0.00	-0.04	0.00	0
6:16	0.00	13.65	0.00	-0.04	0.00	0
6:17	0.00	13.67	0.00	-0.04	0.00	0
6:18	0.00	13.66	0.00	-0.04	0.00	0
6:19	0.00	13.65	0.00	-0.04	0.00	0
6:20	0.00	13.64	0.00	-0.04	0.00	0
6:21	0.00	13.62	0.00	-0.04	0.00	0
6:22	0.00	13.62	0.00	-0.04	0.00	0
6:23	0.36	13.62	0.00	-0.04	0.00	0
6:24	0.65	13.62	0.00	-0.04	0.01	0
6:25	0.93	13.60	0.00	-0.04	0.01	0
6:26	1.29	13.58	0.00	-0.04	0.02	0
6:27	1.65	13.56	0.00	-0.04	0.02	0
6:28	2.16	13.55	0.00	-0.04	0.03	0
6:29	2.59	13.54	0.00	-0.04	0.03	0
6:30	3.38	13.55	0.00	-0.04	0.04	0
6:31	3.95	13.59	0.00	-0.04	0.05	0
6:32	4.81	13.62	0.00	-0.04	0.06	0
6:33	5.46	13.63	0.01	-0.04	0.07	0
6:34	6.54	13.63	0.01	-0.04	0.08	0
6:35	7.33	13.64	0.01	-0.04	0.09	0
6:36	8.69	13.66	0.01	-0.04	0.11	0
6:37	9.84	13.70	0.01	-0.04	0.12	0
6:38	11.14	13.78	0.01	-0.04	0.14	0
6:39	12.50	13.87	0.01	-0.04	0.16	0
6:40	13.72	13.96	0.01	-0.04	0.17	0
6:41	15.02	14.02	0.02	-0.04	0.19	0
6:42	16.38	14.06	0.02	-0.04	0.20	0
6:43	17.82	14.07	0.02	-0.04	0.22	0

Time AM	GTI (W/m2)G	Temperature T ^{0}C	G/Gref i.e. (G/1000) W/m2	Temp Compensation factor 3.7*(T-25)/1000	Solar power generation MW	Solar Power > 6.3 MW
6:44	19.18	14.08	0.02	-0.04	0.24	0
6:45	20.19	14.10	0.02	-0.04	0.25	0
6:46	22.13	14.12	0.02	-0.04	0.28	0
6:47	23.71	14.13	0.02	-0.04	0.30	0
6:48	25.22	14.17	0.03	-0.04	0.31	0
6:49	26.80	14.21	0.03	-0.04	0.33	0
6:50	28.31	14.25	0.03	-0.04	0.35	0
6:51	30.17	14.29	0.03	-0.04	0.38	0
6:52	32.55	14.34	0.03	-0.04	0.41	0
6:53	34.56	14.41	0.03	-0.04	0.43	0
6:54	37.36	14.48	0.04	-0.04	0.47	0
6:55	41.96	14.58	0.04	-0.04	0.52	0
6:56	46.48	14.69	0.05	-0.04	0.58	0
6:57	48.21	14.78	0.05	-0.04	0.60	0
6:58	51.44	14.89	0.05	-0.04	0.64	0
6:59	53.88	14.98	0.05	-0.04	0.67	0
7:00	57.98	15.14	0.06	-0.04	0.72	0

Table A.1.2 Minute wise data of solar radiation from 7 AM to 8 AM

Time AM	GTI (W/m2) G	Temperature T ^{0}C	G/Gref i.e. (G/1000) W/m2	Temp Compensation factor 3.7*(T-25)/1000	Solar power generation MW	Solar Power > 6.3MW
7:01	58.04	15.27	0.06	-0.04	0.76	0
7:02	58.42	15.39	0.06	-0.04	0.80	0
7:03	58.88	15.51	0.07	-0.04	0.84	0
7:04	59.98	15.57	0.07	-0.03	0.89	0
7:05	60.87	15.72	0.07	-0.03	0.93	0
7:06	61.07	15.77	0.08	-0.03	0.97	0
7:07	64.30	15.94	0.08	-0.03	1.00	0
7:08	67.75	16.02	0.09	-0.03	1.06	0
7:09	71.34	16.17	0.09	-0.03	1.10	0
7:10	74.79	16.29	0.09	-0.03	1.13	0
7:11	78.24	16.40	0.09	-0.03	1.17	0
7:12	80.75	16.52	0.10	-0.03	1.21	0
7:13	85.57	16.61	0.10	-0.03	1.25	0
7:14	88.51	16.77	0.10	-0.03	1.29	0
7:15	91.60	16.91	0.11	-0.03	1.33	0
7:16	94.69	17.06	0.11	-0.03	1.37	0
7:17	97.64	17.20	0.11	-0.03	1.40	0
7:18	101.01	17.36	0.12	-0.03	1.44	0
7:19	104.61	17.48	0.12	-0.03	1.49	0
7:20	107.56	17.67	0.12	-0.03	1.52	0
7:21	110.72	17.83	0.13	-0.03	1.55	0
7:22	113.45	17.98	0.13	-0.03	1.56	0
7:23	116.97	18.12	0.13	-0.03	1.57	0
7:24	121.13	18.25	0.13	-0.02	1.61	0
7:25	123.14	18.41	0.14	-0.02	1.68	0
7:26	125.80	18.57	0.14	-0.02	1.72	0
7:27	126.66	18.73	0.15	-0.02	1.79	0
7:28	127.52	18.89	0.15	-0.02	1.83	0
7:29	130.61	19.03	0.15	-0.02	1.84	0
7:30	136.36	19.18	0.16	-0.02	1.90	0
7:31	140.02	19.33	0.16	-0.02	1.98	0
7:32	145.56	19.45	0.17	-0.02	2.03	0

Time AM	GTI (W/m2) G	Temperature T ^{0}C	G/Gref i.e. (G/1000) W/m2	Temp Compensation factor 3.7*(T-25)/1000	Solar power generation MW	Solar Power > 6.3 MW
7:33	149.36	19.65	0.17	-0.02	2.13	0
7:34	150.23	19.84	0.18	-0.02	2.21	0
7:35	155.40	20.01	0.18	-0.02	2.24	0
7:36	161.58	20.11	0.18	-0.02	2.26	0
7:37	165.75	20.25	0.19	-0.02	2.29	0
7:38	173.79	20.39	0.19	-0.02	2.36	0
7:39	180.33	20.53	0.20	-0.02	2.41	0
7:40	183.57	20.69	0.20	-0.02	2.43	0
7:41	184.86	20.89	0.20	-0.02	2.49	0
7:42	187.88	21.03	0.21	-0.01	2.54	0
7:43	192.98	21.27	0.21	-0.01	2.56	0
7:44	197.94	21.42	0.21	-0.01	2.59	0
7:45	199.09	21.70	0.21	-0.01	2.61	0
7:46	204.22	21.92	0.21	-0.01	2.59	0
7:47	208.36	22.12	0.21	-0.01	2.59	0
7:48	210.47	22.31	0.22	-0.01	2.66	0
7:49	213.05	22.48	0.23	-0.01	2.80	0
7:50	214.78	22.67	0.24	-0.01	2.84	0
7:51	213.27	22.89	0.24	-0.01	2.93	0
7:52	213.70	23.10	0.24	-0.01	2.96	0
7:53	219.52	23.26	0.25	-0.01	2.98	0
7:54	231.58	23.53	0.25	-0.01	2.99	0
7:55	235.03	23.76	0.25	0.00	3.00	0
7:56	241.92	24.00	0.26	0.00	3.07	0
7:57	244.72	24.25	0.26	0.00	3.10	0
7:58	246.66	24.51	0.27	0.00	3.23	0
7:59	247.52	24.78	0.27	0.00	3.25	0
8:00	248.60	24.98	0.27	0.00	3.27	0

Table A.1.3 Minute wise data of solar radiation from 8 AM to 9 AM

Time AM	GTI (W/m2) G	Temperature T ^{0}C	G/Gref i.e. (G/1000) W/m2	Temp Compensation factor 3.7*(T-25)/1000	Solar power generation MW	Solar Power > 6.3 MW
8:01	276.40	25.33	0.28	0.00	3.31	0
8:02	283.94	25.61	0.28	0.00	3.40	0
8:03	287.39	25.74	0.29	0.00	3.44	0
8:04	292.77	26.09	0.29	0.00	3.50	0
8:05	300.74	26.34	0.30	0.00	3.59	0
8:06	308.93	26.63	0.31	0.01	3.68	0
8:07	313.45	26.83	0.31	0.01	3.74	0
8:08	318.41	26.98	0.32	0.01	3.79	0
8:09	322.07	27.23	0.32	0.01	3.83	0
8:10	326.82	27.35	0.33	0.01	3.89	0
8:11	332.85	27.60	0.33	0.01	3.96	0
8:12	336.30	27.81	0.34	0.01	3.99	0
8:13	342.55	28.05	0.34	0.01	4.06	0
8:14	346.85	28.35	0.35	0.01	4.11	0
8:15	352.45	28.68	0.35	0.01	4.17	0
8:16	356.54	28.93	0.36	0.01	4.22	0
8:17	359.34	29.19	0.36	0.02	4.25	0
8:18	365.81	29.42	0.37	0.02	4.32	0
8:19	369.26	29.75	0.37	0.02	4.35	0

Time AM	GTI (W/m2) G	Temperature T ^{0}C	G/Gref i.e. (G/1000) W/m2	Temp Compensation factor 3.7*(T-25)/1000	Solar power generation MW	Solar Power > 6.3 MW
8:20	371.84	30.07	0.37	0.02	4.38	0
8:21	373.13	30.35	0.37	0.02	4.39	0
8:22	376.15	30.68	0.38	0.02	4.42	0
8:23	375.72	30.92	0.38	0.02	4.41	0
8:24	383.91	31.23	0.38	0.02	4.50	0
8:25	386.92	31.66	0.39	0.02	4.53	0
8:26	395.97	31.96	0.40	0.03	4.63	0
8:27	409.98	32.26	0.41	0.03	4.79	0
8:28	417.09	32.59	0.42	0.03	4.86	0
8:29	419.68	32.86	0.42	0.03	4.89	0
8:30	419.04	33.34	0.42	0.03	4.87	0
8:31	428.52	33.73	0.43	0.03	4.98	0
8:32	433.26	34.07	0.43	0.03	5.02	0
8:33	441.45	34.37	0.44	0.03	5.11	0
8:34	438.87	34.68	0.44	0.04	5.08	0
8:35	445.98	35.03	0.45	0.04	5.15	0
8:36	450.72	35.36	0.45	0.04	5.20	0
8:37	460.20	35.57	0.46	0.04	5.31	0
8:38	462.36	35.80	0.46	0.04	5.33	0
8:39	453.96	36.14	0.45	0.04	5.22	0
8:40	465.59	36.30	0.47	0.04	5.35	0
8:41	468.61	36.40	0.47	0.04	5.39	0
8:42	464.95	36.73	0.46	0.04	5.34	0
8:43	484.34	36.95	0.48	0.04	5.56	0
8:44	491.68	37.19	0.49	0.05	5.63	0
8:45	494.26	37.49	0.49	0.05	5.66	0
8:46	498.58	37.82	0.50	0.05	5.70	0
8:47	501.17	38.00	0.50	0.05	5.72	0
8:48	505.69	38.14	0.51	0.05	5.77	0
8:49	502.89	38.43	0.50	0.05	5.73	0
8:50	516.46	38.66	0.52	0.05	5.88	0
8:51	515.16	38.84	0.52	0.05	5.87	0
8:52	515.59	38.98	0.52	0.05	5.87	0
8:53	521.84	39.08	0.52	0.05	5.94	0
8:54	533.26	39.25	0.53	0.05	6.06	0
8:55	537.79	39.40	0.54	0.05	6.11	0
8:56	539.51	39.52	0.54	0.05	6.13	0
8:57	533.48	39.68	0.53	0.05	6.05	0
8:58	539.29	39.76	0.54	0.05	6.12	0
8:59	549.20	39.88	0.55	0.06	6.23	0
9:00	547.69	39.98	0.55	0.06	6.21	0

Table A.1.4 Minute wise data of solar radiation from 9 AM to 10 AM

Time AM	GTI (W/m2) G	Temperature T^{0}C	G/Gref i.e.(G/1000) W/m2	Temp Compensation factor 3.7*(T-25)/1000	Solar power generation MW	Solar Power > 6.3MW
9:01	544.03	40.01	0.54	0.06	6.17	0
9:02	556.10	39.89	0.56	0.06	6.31	0.01
9:03	552.00	39.82	0.55	0.05	6.26	0
9:04	564.30	39.83	0.56	0.05	6.40	0.1
9:05	549.65	39.89	0.55	0.06	6.23	0
9:06	551.60	40.02	0.55	0.06	6.25	0
9:07	566.68	40.14	0.57	0.06	6.42	0.12

Time AM	GTI (W/m2) G	Temperature T^0C	G/Gref i.e.(G/1000) W/m2	Temp Compensation factor 3.7*(T-25)/1000	Solar power generation MW	Solar Power > 6.3MW
9:08	561.08	40.29	0.56	0.06	6.35	0.05
9:09	573.58	40.42	0.57	0.06	6.49	0.19
9:10	571.42	40.51	0.57	0.06	6.46	0.16
9:11	575.52	40.55	0.58	0.06	6.51	0.21
9:12	572.93	40.72	0.57	0.06	6.48	0.18
9:13	585.86	40.83	0.59	0.06	6.62	0.32
9:14	578.75	40.79	0.58	0.06	6.54	0.24
9:15	587.80	40.74	0.59	0.06	6.64	0.34
9:16	589.96	40.82	0.59	0.06	6.67	0.37
9:17	595.77	41.12	0.60	0.06	6.72	0.42
9:18	589.75	41.24	0.59	0.06	6.65	0.35
9:19	587.60	41.54	0.59	0.06	6.62	0.32
9:20	591.48	41.76	0.59	0.06	6.66	0.36
9:21	593.21	42.07	0.59	0.06	6.67	0.37
9:22	585.88	42.41	0.59	0.06	6.58	0.28
9:23	596.46	42.66	0.60	0.07	6.69	0.39
9:24	586.33	42.79	0.59	0.07	6.57	0.27
9:25	595.81	43.02	0.60	0.07	6.67	0.37
9:26	580.30	43.21	0.58	0.07	6.49	0.19
9:27	586.55	43.39	0.59	0.07	6.56	0.26
9:28	592.79	43.49	0.59	0.07	6.63	0.33
9:29	589.12	43.69	0.59	0.07	6.58	0.28
9:30	589.99	43.79	0.59	0.07	6.59	0.29
9:31	583.96	43.86	0.58	0.07	6.52	0.22
9:32	587.62	43.97	0.59	0.07	6.56	0.26
9:33	592.80	44.16	0.59	0.07	6.61	0.31
9:34	591.51	44.40	0.59	0.07	6.59	0.29
9:35	594.09	44.51	0.59	0.07	6.61	0.31
9:36	590.01	44.66	0.59	0.07	6.57	0.27
9:37	591.73	44.87	0.59	0.07	6.58	0.28
9:38	590.44	45.07	0.59	0.07	6.56	0.26
9:39	588.93	45.18	0.59	0.07	6.54	0.24
9:40	585.48	45.21	0.59	0.07	6.50	0.2
9:41	590.65	45.26	0.59	0.07	6.56	0.26
9:42	594.96	45.34	0.59	0.08	6.60	0.3
9:43	591.09	45.48	0.59	0.08	6.56	0.26
9:44	584.84	45.62	0.58	0.08	6.48	0.18
9:45	594.75	45.62	0.59	0.08	6.59	0.29
9:46	592.59	45.70	0.59	0.08	6.57	0.27
9:47	592.59	45.83	0.59	0.08	6.56	0.26
9:48	590.43	45.96	0.59	0.08	6.54	0.24
9:49	594.10	45.99	0.59	0.08	6.58	0.28
9:50	597.99	46.06	0.60	0.08	6.62	0.32
9:51	594.54	46.15	0.59	0.08	6.58	0.28
9:52	593.25	46.16	0.59	0.08	6.56	0.26
9:53	597.56	46.27	0.60	0.08	6.61	0.31
9:54	600.57	46.60	0.60	0.08	6.63	0.33
9:55	600.14	46.88	0.60	0.08	6.62	0.32
9:56	602.30	46.95	0.60	0.08	6.64	0.34
9:57	603.59	47.07	0.60	0.08	6.65	0.35
9:58	608.12	47.37	0.61	0.08	6.69	0.39
9:59	611.35	47.54	0.61	0.08	6.72	0.42
10:00	610.28	47.73	0.61	0.08	6.71	0.41

Table A.1.5 Minute wise data of solar radiation from 10 AM to 11 AM

Time AM	GTI (W/m2) G	Temperature T^0C	G/Gref i.e. (G/1000) W/m2	Temp Compensation factor 3.7*(T-25)/1000	Solar power generation MW	Solar Power > 6.3 MW
10:01	616.32	47.79	0.62	0.08	6.77	0.47
10:02	619.33	48.03	0.62	0.09	6.80	0.5
10:03	621.92	48.13	0.62	0.09	6.82	0.52
10:04	630.75	48.11	0.63	0.09	6.92	0.62
10:05	634.41	48.06	0.63	0.09	6.96	0.66
10:06	633.76	48.15	0.63	0.09	6.95	0.65
10:07	639.58	48.25	0.64	0.09	7.01	0.71
10:08	641.95	48.46	0.64	0.09	7.03	0.73
10:09	647.55	48.63	0.65	0.09	7.09	0.79
10:10	655.75	48.92	0.66	0.09	7.17	0.87
10:11	657.26	49.12	0.66	0.09	7.18	0.88
10:12	656.40	49.27	0.66	0.09	7.17	0.87
10:13	666.09	49.38	0.67	0.09	7.27	0.97
10:14	674.28	49.53	0.67	0.09	7.36	1.06
10:15	675.14	49.55	0.68	0.09	7.37	1.07
10:16	678.59	49.55	0.68	0.09	7.40	1.1
10:17	680.96	49.63	0.68	0.09	7.43	1.13
10:18	686.99	49.77	0.69	0.09	7.49	1.19
10:19	695.83	49.92	0.70	0.09	7.58	1.28
10:20	691.09	50.13	0.69	0.09	7.52	1.22
10:21	698.84	50.42	0.70	0.09	7.60	1.3
10:22	706.17	50.69	0.71	0.10	7.67	1.37
10:23	707.03	50.87	0.71	0.10	7.67	1.37
10:24	711.99	50.95	0.71	0.10	7.72	1.42
10:25	717.37	51.07	0.72	0.10	7.78	1.48
10:26	723.84	51.13	0.72	0.10	7.85	1.55
10:27	733.53	51.23	0.73	0.10	7.95	1.65
10:28	739.35	51.28	0.74	0.10	8.01	1.71
10:29	745.82	51.19	0.75	0.10	8.08	1.78
10:30	746.26	51.29	0.75	0.10	8.08	1.78
10:31	757.46	51.55	0.76	0.10	8.20	1.9
10:32	753.38	51.78	0.75	0.10	8.14	1.84
10:33	765.66	51.94	0.77	0.10	8.27	1.97
10:34	770.83	51.85	0.77	0.10	8.33	2.03
10:35	774.29	51.77	0.77	0.10	8.37	2.07
10:36	783.34	51.85	0.78	0.10	8.47	2.17
10:37	775.38	51.95	0.78	0.10	8.38	2.08
10:38	780.55	52.05	0.78	0.10	8.43	2.13
10:39	790.43	51.85	0.79	0.10	8.54	2.24
10:40	798.31	51.62	0.80	0.10	8.64	2.34
10:41	801.17	51.04	0.80	0.10	8.69	2.39
10:42	833.40	50.80	0.83	0.10	9.05	2.75
10:43	835.55	50.81	0.84	0.10	9.07	2.77
10:44	824.10	51.10	0.82	0.10	8.93	2.63
10:45	842.72	51.14	0.84	0.10	9.13	2.83
10:46	849.88	51.14	0.85	0.10	9.21	2.91
10:47	833.41	51.06	0.83	0.10	9.04	2.74
10:48	829.83	51.53	0.83	0.10	8.98	2.68
10:49	844.15	51.84	0.84	0.10	9.12	2.82
10:50	858.46	52.06	0.86	0.10	9.27	2.97
10:51	860.61	52.39	0.86	0.10	9.28	2.98
10:52	858.47	52.66	0.86	0.10	9.25	2.95

Time AM	GTI (W/m2) G	Temperature T^{0}C	G/Gref i.e. (G/1000) W/m2	Temp Compensation factor 3.7*(T-25)/1000	Solar power generation MW	Solar Power > 6.3 MW
10:53	855.60	52.91	0.86	0.10	9.21	2.91
10:54	863.48	53.20	0.86	0.10	9.28	2.98
10:55	883.53	53.40	0.88	0.11	9.49	3.19
10:56	900.71	53.24	0.90	0.10	9.68	3.38
10:57	892.83	53.16	0.89	0.10	9.60	3.3
10:58	877.08	53.25	0.88	0.10	9.42	3.12
10:59	880.66	53.38	0.88	0.11	9.46	3.16
11:00	896.40	53.68	0.90	0.11	9.62	3.32

Table A.1.6 Minute wise data of solar radiation from 11AM to 12 PM

Time AM	GTI (W/m2) G	Temperature T ^{0}C	G/Gref i.e. (G/1000) W/m2	Temp Compensation factor 3.7*(T-25)/1000	Solar power generation MW	Solar Power > 6.3 MW
11:01	912.16	53.91	0.91	0.11	9.77	3.47
11:02	906.43	54.39	0.91	0.11	9.69	3.39
11:03	893.54	54.37	0.89	0.11	9.56	3.26
11:04	930.78	53.87	0.93	0.11	9.98	3.68
11:05	943.67	53.55	0.94	0.11	10.13	3.83
11:06	946.53	53.24	0.95	0.10	10.17	3.87
11:07	942.24	52.92	0.94	0.10	10.14	3.84
11:08	908.59	52.89	0.91	0.10	9.78	3.48
11:09	913.58	52.66	0.91	0.10	9.84	3.54
11:10	932.20	52.45	0.93	0.10	10.05	3.75
11:11	930.77	51.91	0.93	0.10	10.06	3.76
11:12	918.60	51.62	0.92	0.10	9.94	3.64
11:13	957.26	51.37	0.96	0.10	10.37	4.07
11:14	961.55	51.28	0.96	0.10	10.42	4.12
11:15	965.14	51.53	0.97	0.10	10.44	4.14
11:16	973.73	51.71	0.97	0.10	10.53	4.23
11:17	978.74	51.78	0.98	0.10	10.58	4.28
11:18	982.32	51.51	0.98	0.10	10.63	4.33
11:19	983.75	51.15	0.98	0.10	10.66	4.36
11:20	986.61	51.01	0.99	0.10	10.70	4.4
11:21	988.76	50.95	0.99	0.10	10.73	4.43
11:22	993.05	51.15	0.99	0.10	10.76	4.46
11:23	990.91	51.28	0.99	0.10	10.73	4.43
11:24	988.05	51.46	0.99	0.10	10.70	4.4
11:25	990.20	51.43	0.99	0.10	10.72	4.42
11:26	990.92	51.57	0.99	0.10	10.72	4.42
11:27	995.92	51.83	1.00	0.10	10.76	4.46
11:28	998.07	51.83	1.00	0.10	10.79	4.49
11:29	993.78	51.83	0.99	0.10	10.74	4.44
11:30	990.20	51.85	0.99	0.10	10.70	4.4
11:31	990.93	51.88	0.99	0.10	10.71	4.41
11:32	993.08	52.01	0.99	0.10	10.73	4.43
11:33	994.51	52.21	0.99	0.10	10.73	4.43
11:34	993.79	52.14	0.99	0.10	10.73	4.43
11:35	998.80	51.63	1.00	0.10	10.80	4.5
11:36	995.94	51.27	1.00	0.10	10.79	4.49
11:37	998.81	51.22	1.00	0.10	10.82	4.52
11:38	996.67	51.28	1.00	0.10	10.80	4.5
11:39	998.83	51.53	1.00	0.10	10.81	4.51
11:40	1002.41	51.92	1.00	0.10	10.83	4.53
11:41	1001.70	52.26	1.00	0.10	10.81	4.51

Time AM	GTI (W/m2) G	Temperature T ^{0}C	G/Gref i.e. (G/1000) W/m2	Temp Compensation factor 3.7*(T-25)/1000	Solar power generation MW	Solar Power > 6.3 MW
11:42	1011.01	52.53	1.01	0.10	10.90	4.6
11:43	1004.56	52.39	1.00	0.10	10.83	4.53
11:44	1008.15	52.35	1.01	0.10	10.87	4.57
11:45	1011.01	52.50	1.01	0.10	10.90	4.6
11:46	1003.84	52.63	1.00	0.10	10.81	4.51
11:47	1005.99	52.34	1.01	0.10	10.85	4.55
11:48	1013.87	51.76	1.01	0.10	10.96	4.66
11:49	1016.01	51.06	1.02	0.10	11.02	4.72
11:50	1019.59	50.65	1.02	0.09	11.07	4.77
11:51	1018.87	50.77	1.02	0.10	11.06	4.76
11:52	1023.17	50.92	1.02	0.10	11.10	4.8
11:53	1021.02	50.95	1.02	0.10	11.08	4.78
11:54	1016.72	51.10	1.02	0.10	11.02	4.72
11:55	1018.15	51.48	1.02	0.10	11.02	4.72
11:56	1018.13	51.66	1.02	0.10	11.01	4.71
11:57	1019.56	51.80	1.02	0.10	11.02	4.72
11:58	1013.12	52.11	1.01	0.10	10.94	4.64
11:59	1017.41	52.03	1.02	0.10	10.99	4.69
12:00 PM	1017.41	51.71	1.02	0.10	11.00	4.7

Table A.1.7 Minute wise data of solar radiation from 12 PM to 1 PM

Time PM	GTI (W/m2) G	Temperature T ^{0}C	G/Gref i.e. (G/1000) W/m2	Temp Compensation factor 3.7*(T-25)/1000	Solar power generation MW	Solar Power > 6.3 MW
12:01	1022.42	51.61	1.02	0.10	11.06	4.76
12:02	1019.56	51.66	1.02	0.10	11.03	4.73
12:03	1021.71	51.70	1.02	0.10	11.05	4.75
12:04	1026.71	51.88	1.03	0.10	11.10	4.8
12:05	1026.00	52.00	1.03	0.10	11.08	4.78
12:06	1028.87	52.06	1.03	0.10	11.11	4.81
12:07	1013.11	52.19	1.01	0.10	10.93	4.63
12:08	1025.29	52.36	1.03	0.10	11.06	4.76
12:09	1034.60	52.81	1.03	0.10	11.14	4.84
12:10	1029.59	53.26	1.03	0.10	11.06	4.76
12:11	1018.84	53.74	1.02	0.11	10.93	4.63
12:12	1020.99	54.30	1.02	0.11	10.92	4.62
12:13	1020.27	54.56	1.02	0.11	10.90	4.6
12:14	1027.44	54.52	1.03	0.11	10.98	4.68
12:15	1028.16	53.93	1.03	0.11	11.02	4.72
12:16	1046.77	53.25	1.05	0.10	11.25	4.95
12:17	1043.19	52.73	1.04	0.10	11.23	4.93
12:18	1033.89	52.57	1.03	0.10	11.14	4.84
12:19	1038.19	52.47	1.04	0.10	11.19	4.89
12:20	1025.30	52.51	1.03	0.10	11.05	4.75
12:21	1028.16	52.68	1.03	0.10	11.07	4.77
12:22	1035.32	52.42	1.04	0.10	11.16	4.86
12:23	1050.36	52.34	1.05	0.10	11.33	5.03
12:24	1045.35	52.59	1.05	0.10	11.26	4.96
12:25	1043.92	52.86	1.04	0.10	11.24	4.94
12:26	1041.05	53.02	1.04	0.10	11.20	4.9
12:27	1047.50	53.29	1.05	0.10	11.25	4.95
12:28	1038.19	53.34	1.04	0.10	11.15	4.85
12:29	1040.33	52.97	1.04	0.10	11.19	4.89

Time PM	GTI (W/m2) G	Temperature T ^{0}C	G/Gref i.e. (G/1000) W/m2	Temp Compensation factor 3.7*(T-25)/1000	Solar power generation MW	Solar Power > 6.3 MW
12:30	1034.61	52.68	1.03	0.10	11.14	4.84
12:31	1033.16	52.52	1.03	0.10	11.14	4.84
12:32	1028.15	52.85	1.03	0.10	11.07	4.77
12:33	1033.16	52.53	1.03	0.10	11.13	4.83
12:34	1030.30	51.66	1.03	0.10	11.14	4.84
12:35	1033.88	50.91	1.03	0.10	11.22	4.92
12:36	1033.17	50.72	1.03	0.10	11.22	4.92
12:37	1040.33	50.53	1.04	0.09	11.30	5
12:38	1043.91	50.29	1.04	0.09	11.35	5.05
12:39	1031.73	50.46	1.03	0.09	11.21	4.91
12:40	1031.02	50.91	1.03	0.10	11.19	4.89
12:41	1022.41	51.15	1.02	0.10	11.08	4.78
12:42	1019.55	51.38	1.02	0.10	11.04	4.74
12:43	1006.66	51.34	1.01	0.10	10.90	4.6
12:44	1010.96	51.23	1.01	0.10	10.95	4.65
12:45	1035.30	51.22	1.04	0.10	11.22	4.92
12:46	1028.14	51.67	1.03	0.10	11.12	4.82
12:47	1018.83	52.06	1.02	0.10	11.00	4.7
12:48	1015.25	52.56	1.02	0.10	10.94	4.64
12:49	1009.52	52.75	1.01	0.10	10.87	4.57
12:50	1030.29	52.78	1.03	0.10	11.09	4.79
12:51	1035.30	52.59	1.04	0.10	11.16	4.86
12:52	1037.45	52.66	1.04	0.10	11.18	4.88
12:53	1033.86	52.92	1.03	0.10	11.12	4.82
12:54	1029.57	53.17	1.03	0.10	11.07	4.77
12:55	1026.71	52.96	1.03	0.10	11.05	4.75
12:56	1032.44	52.36	1.03	0.10	11.13	4.83
12:57	1027.43	51.94	1.03	0.10	11.10	4.8
12:58	1018.85	51.67	1.02	0.10	11.02	4.72
12:59	1017.42	51.30	1.02	0.10	11.02	4.72
1:00	1018.84	51.27	1.02	0.10	11.04	4.74

Table A.1.8 Minute wise data of solar radiation from 1 PM to 2 PM

Time PM	GTI (W/m2) G	Temperature T ^{0}C	G/Gref i.e. (G/1000) W/m2	Temp Compensation factor 3.7*(T-25)/1000	Solar power generation MW	Solar Power > 6.3 MW
1:01	1023.14	51.37	1.02	0.10	11.08	4.78
1:02	1024.57	51.51	1.02	0.10	11.09	4.79
1:03	1012.41	51.67	1.01	0.10	10.95	4.65
1:04	1005.96	51.87	1.01	0.10	10.87	4.57
1:05	1015.99	52.09	1.02	0.10	10.97	4.67
1:06	1008.12	52.25	1.01	0.10	10.88	4.58
1:07	1004.54	52.21	1.00	0.10	10.84	4.54
1:08	1021.01	52.19	1.02	0.10	11.02	4.72
1:09	1016.71	52.30	1.02	0.10	10.97	4.67
1:10	1013.85	52.57	1.01	0.10	10.93	4.63
1:11	1010.27	52.63	1.01	0.10	10.88	4.58
1:12	1000.96	52.56	1.00	0.10	10.79	4.49
1:13	995.95	52.54	1.00	0.10	10.73	4.43
1:14	997.38	52.54	1.00	0.10	10.75	4.45
1:15	984.50	52.44	0.98	0.10	10.61	4.31
1:16	1002.40	52.43	1.00	0.10	10.81	4.51
1:17	990.22	52.41	0.99	0.10	10.68	4.38

Time PM	GTI (W/m2) G	Temperature T ^{0}C	G/Gref i.e. (G/1000) W/m2	Temp Compensation factor 3.7*(T-25)/1000	Solar power generation MW	Solar Power > 6.3 MW
1:18	984.49	52.40	0.98	0.10	10.62	4.32
1:19	990.94	52.32	0.99	0.10	10.69	4.39
1:20	993.79	52.23	0.99	0.10	10.72	4.42
1:21	986.63	52.04	0.99	0.10	10.66	4.36
1:22	986.63	52.00	0.99	0.10	10.66	4.36
1:23	988.77	52.17	0.99	0.10	10.67	4.37
1:24	975.89	52.30	0.98	0.10	10.53	4.23
1:25	982.32	52.17	0.98	0.10	10.60	4.3
1:26	983.04	51.90	0.98	0.10	10.62	4.32
1:27	980.16	51.97	0.98	0.10	10.59	4.29
1:28	990.90	52.03	0.99	0.10	10.70	4.4
1:29	979.44	52.14	0.98	0.10	10.57	4.27
1:30	977.30	51.85	0.98	0.10	10.56	4.26
1:31	979.45	51.61	0.98	0.10	10.60	4.3
1:32	975.87	51.25	0.98	0.10	10.57	4.27
1:33	975.87	51.17	0.98	0.10	10.58	4.28
1:34	975.15	51.18	0.98	0.10	10.57	4.27
1:35	972.99	51.26	0.97	0.10	10.54	4.24
1:36	967.98	51.32	0.97	0.10	10.48	4.18
1:37	974.42	51.19	0.97	0.10	10.56	4.26
1:38	971.56	51.19	0.97	0.10	10.53	4.23
1:39	960.82	51.20	0.96	0.10	10.41	4.11
1:40	962.25	51.35	0.96	0.10	10.42	4.12
1:41	965.12	51.71	0.97	0.10	10.44	4.14
1:42	963.67	51.96	0.96	0.10	10.41	4.11
1:43	959.38	52.18	0.96	0.10	10.35	4.05
1:44	957.23	52.42	0.96	0.10	10.32	4.02
1:45	949.35	52.60	0.95	0.10	10.23	3.93
1:46	940.76	52.97	0.94	0.10	10.12	3.82
1:47	942.18	53.22	0.94	0.10	10.13	3.83
1:48	942.18	53.40	0.94	0.11	10.12	3.82
1:49	947.91	53.41	0.95	0.11	10.18	3.88
1:50	949.34	53.22	0.95	0.10	10.20	3.9
1:51	940.75	53.13	0.94	0.10	10.11	3.81
1:52	942.91	53.12	0.94	0.10	10.14	3.84
1:53	945.77	53.03	0.95	0.10	10.17	3.87
1:54	947.92	52.98	0.95	0.10	10.20	3.9
1:55	935.74	52.76	0.94	0.10	10.08	3.78
1:56	927.86	52.70	0.93	0.10	9.99	3.69
1:57	924.29	52.82	0.92	0.10	9.95	3.65
1:58	921.43	52.90	0.92	0.10	9.92	3.62
1:59	922.16	52.90	0.92	0.10	9.92	3.62
2:00	916.43	52.70	0.92	0.10	9.87	3.57

Table A.1.9 Minute wise data of solar radiation from 2 PM to 3 PM

Time PM	GTI (W/m2) G	Temperature T^{0}C	G/Gref i.e. (G/1000) W/m2	Temp Compensation factor 3.7*(T-25)/1000	Solar power generation MW	Solar Power > 6.3 MW
2:01	915.00	52.25	0.91	0.10	9.87	3.57
2:02	907.83	51.54	0.91	0.10	9.82	3.52
2:03	904.25	51.20	0.90	0.10	9.80	3.5
2:04	898.53	51.07	0.90	0.10	9.74	3.44
2:05	898.53	51.12	0.90	0.10	9.74	3.44
2:06	901.40	51.16	0.90	0.10	9.77	3.47

Time PM	GTI (W/m2) G	Temperature T ^{0}C	G/Gref i.e. (G/1000) W/m2	Temp Compensation factor 3.7*(T-25)/1000	Solar power generation MW	Solar Power > 6.3 MW
2:07	901.41	51.26	0.90	0.10	9.77	3.47
2:08	899.98	51.38	0.90	0.10	9.75	3.45
2:09	891.39	51.63	0.89	0.10	9.64	3.34
2:10	889.24	51.76	0.89	0.10	9.61	3.31
2:11	880.65	51.98	0.88	0.10	9.51	3.21
2:12	879.93	52.04	0.88	0.10	9.50	3.2
2:13	876.35	51.91	0.88	0.10	9.47	3.17
2:14	885.66	51.66	0.89	0.10	9.58	3.28
2:15	886.38	51.30	0.89	0.10	9.60	3.3
2:16	882.08	51.13	0.88	0.10	9.56	3.26
2:17	875.63	51.25	0.88	0.10	9.49	3.19
2:18	866.32	51.24	0.87	0.10	9.39	3.09
2:19	862.74	51.27	0.86	0.10	9.35	3.05
2:20	867.03	51.25	0.87	0.10	9.39	3.09
2:21	864.89	51.06	0.86	0.10	9.38	3.08
2:22	857.71	50.86	0.86	0.10	9.31	3.01
2:23	846.97	50.89	0.85	0.10	9.19	2.89
2:24	844.82	50.80	0.84	0.10	9.17	2.87
2:25	849.12	50.79	0.85	0.10	9.22	2.92
2:26	844.11	50.69	0.84	0.10	9.17	2.87
2:27	838.38	50.75	0.84	0.10	9.10	2.8
2:28	836.95	50.51	0.84	0.09	9.10	2.8
2:29	833.38	50.35	0.83	0.09	9.06	2.76
2:30	829.80	50.19	0.83	0.09	9.03	2.73
2:31	828.36	50.06	0.83	0.09	9.02	2.72
2:32	826.24	50.18	0.83	0.09	8.99	2.69
2:33	821.22	50.31	0.82	0.09	8.93	2.63
2:34	821.22	50.46	0.82	0.09	8.93	2.63
2:35	819.79	50.74	0.82	0.10	8.90	2.6
2:36	814.06	50.87	0.81	0.10	8.83	2.53
2:37	806.90	50.69	0.81	0.10	8.76	2.46
2:38	801.89	50.16	0.80	0.09	8.73	2.43
2:39	804.75	50.05	0.80	0.09	8.76	2.46
2:40	801.17	49.84	0.80	0.09	8.73	2.43
2:41	796.16	49.15	0.80	0.09	8.70	2.4
2:42	790.31	48.87	0.79	0.09	8.65	2.35
2:43	787.94	48.43	0.79	0.09	8.64	2.34
2:44	784.49	48.26	0.78	0.09	8.60	2.3
2:45	782.34	48.19	0.78	0.09	8.58	2.28
2:46	779.54	48.20	0.78	0.09	8.55	2.25
2:47	779.32	48.06	0.78	0.09	8.55	2.25
2:48	774.37	47.82	0.77	0.08	8.51	2.21
2:49	772.86	47.80	0.77	0.08	8.49	2.19
2:50	767.25	47.92	0.77	0.08	8.43	2.13
2:51	762.51	48.03	0.76	0.09	8.37	2.07
2:52	758.20	47.99	0.76	0.09	8.32	2.02
2:53	755.83	47.70	0.76	0.08	8.31	2.01
2.54	754.12	47.69	0.75	0.08	8.29	1.99
2:55	754.33	47.74	0.75	0.08	8.29	1.99
2:56	747.01	47.73	0.75	0.08	8.21	1.91
2:57	742.05	47.87	0.74	0.08	8.15	1.85
2:58	741.84	48.13	0.74	0.09	8.14	1.84
2:59	737.09	48.19	0.74	0.09	8.09	1.79
3:00	733.21	48.27	0.73	0.09	8.04	1.74

Table A.1.10 Minute wise data of solar radiation from 3 PM to 4 PM

Time PM	GTI (W/m2) G	Temperature T^0C	G/Gref i.e.(G/1000) W/m2	Temp Compensation factor 3.7*(T-25)/1000	Solar power generation MW	Solar Power > 6.3 MW
3:01	731.25	48.59	0.73	0.09	8.01	1.71
3:02	728.66	48.81	0.73	0.09	7.97	1.67
3:03	724.15	49.07	0.72	0.09	7.92	1.62
3:04	721.35	49.34	0.72	0.09	7.88	1.58
3:05	717.90	49.43	0.72	0.09	7.84	1.54
3:06	716.16	49.60	0.72	0.09	7.81	1.51
3:07	714.44	49.63	0.71	0.09	7.79	1.49
3:08	711.85	49.60	0.71	0.09	7.76	1.46
3:09	705.82	49.47	0.71	0.09	7.70	1.4
3:10	701.94	49.19	0.70	0.09	7.67	1.37
3:11	699.57	48.88	0.70	0.09	7.65	1.35
3:12	695.26	48.77	0.70	0.09	7.61	1.31
3:13	693.75	48.71	0.69	0.09	7.59	1.29
3:14	687.72	48.66	0.69	0.09	7.53	1.23
3:15	682.33	48.56	0.68	0.09	7.47	1.17
3:16	677.59	48.45	0.68	0.09	7.43	1.13
3:17	672.85	47.95	0.67	0.08	7.39	1.09
3:18	666.82	47.68	0.67	0.08	7.33	1.03
3:19	660.35	47.52	0.66	0.08	7.26	0.96
3:20	658.20	47.39	0.66	0.08	7.24	0.94
3:21	651.95	47.36	0.65	0.08	7.18	0.88
3:22	646.56	47.53	0.65	0.08	7.11	0.81
3:23	642.25	47.85	0.64	0.08	7.06	0.76
3:24	642.68	48.12	0.64	0.09	7.05	0.75
3:25	636.22	48.15	0.64	0.09	6.98	0.68
3:26	635.57	48.21	0.64	0.09	6.97	0.67
3:27	633.63	47.97	0.63	0.09	6.96	0.66
3:28	632.34	47.88	0.63	0.08	6.95	0.65
3:29	627.60	47.67	0.63	0.08	6.90	0.6
3:30	621.13	47.52	0.62	0.08	6.83	0.53
3:31	619.42	47.46	0.62	0.08	6.82	0.52
3:32	615.11	47.43	0.62	0.08	6.77	0.47
3:33	611.88	47.44	0.61	0.08	6.73	0.43
3:34	607.79	47.53	0.61	0.08	6.69	0.39
3:35	602.18	47.67	0.60	0.08	6.62	0.32
3:36	597.44	47.85	0.60	0.08	6.56	0.26
3:37	592.91	48.01	0.59	0.09	6.51	0.21
3:38	589.02	48.18	0.59	0.09	6.46	0.16
3:39	582.12	48.10	0.58	0.09	6.39	0.09
3:40	577.38	47.72	0.58	0.08	6.35	0.05
3:41	572.43	47.26	0.57	0.08	6.30	0
3:42	567.25	46.72	0.57	0.08	6.26	0
3:43	562.08	46.49	0.56	0.08	6.21	0
3:44	559.28	46.37	0.56	0.08	6.18	0
3:45	555.62	46.21	0.56	0.08	6.14	0
3:46	555.19	46.18	0.56	0.08	6.14	0
3:47	552.82	46.08	0.55	0.08	6.12	0
3:48	547.44	45.89	0.55	0.08	6.06	0
3:49	540.97	45.59	0.54	0.08	6.00	0
3:50	539.25	45.28	0.54	0.08	5.99	0
3:51	536.66	44.99	0.54	0.07	5.96	0

Time PM	GTI (W/m2) G	Temperature T ^{0}C	G/Gref i.e. (G/1000) W/m2	Temp Compensation factor 3.7*(T-25)/1000	Solar power generation MW	Solar Power > 6.3 MW
3:52	529.55	44.57	0.53	0.07	5.89	0
3:53	524.81	44.24	0.52	0.07	5.85	0
3:54	521.58	43.88	0.52	0.07	5.82	0
3:55	516.41	43.77	0.52	0.07	5.77	0
3:56	510.81	43.62	0.51	0.07	5.71	0
3:57	509.08	43.59	0.51	0.07	5.69	0
3:58	504.13	43.66	0.50	0.07	5.63	0
3:59	499.39	43.64	0.50	0.07	5.58	0
4:00	496.59	43.55	0.50	0.07	5.55	0

Table A.1.11 Minute wise data of solar radiation from 4 PM to 5 PM

Time PM	GTI (W/m2) G	Temperature T ^{0}C	G/Gref i.e. (G/1000) W/m2	Temp Compensation factor 3.7*(T-25)/1000	Solar power generation MW	Solar Power > 6.3 MW
4:01	492.28	43.41	0.49	0.07	5.51	0
4:02	488.19	43.31	0.49	0.07	5.46	0
4:03	483.67	43.15	0.48	0.07	5.41	0
4:04	481.08	42.81	0.48	0.07	5.39	0
4:05	475.70	42.35	0.48	0.06	5.34	0
4:06	469.02	42.15	0.47	0.06	5.27	0
4:07	466.00	42.02	0.47	0.06	5.24	0
4:08	462.33	41.96	0.46	0.06	5.20	0
4:09	455.87	41.94	0.46	0.06	5.13	0
4:10	450.70	42.05	0.45	0.06	5.07	0
4:11	447.47	42.08	0.45	0.06	5.03	0
4:12	440.14	42.13	0.44	0.06	4.95	0
4:13	433.88	42.12	0.43	0.06	4.88	0
4:14	428.50	42.09	0.43	0.06	4.82	0
4:15	423.31	42.05	0.42	0.06	4.76	0
4:16	418.14	41.97	0.42	0.06	4.70	0
4:17	414.26	41.90	0.41	0.06	4.66	0
4:18	411.03	41.68	0.41	0.06	4.63	0
4:19	408.87	41.08	0.41	0.06	4.61	0
4:20	404.99	40.86	0.40	0.06	4.57	0
4:21	400.68	40.68	0.40	0.06	4.53	0
4:22	378.05	40.56	0.38	0.06	4.28	0
4:23	394.21	40.38	0.39	0.06	4.46	0
4:24	386.89	40.12	0.39	0.06	4.38	0
4:25	383.65	40.03	0.38	0.06	4.35	0
4:26	377.83	39.91	0.38	0.06	4.28	0
4:27	374.60	39.85	0.37	0.05	4.25	0
4:28	370.29	39.76	0.37	0.05	4.20	0
4:29	366.84	39.71	0.37	0.05	4.16	0
4:30	316.62	39.62	0.32	0.05	3.59	0
4:31	333.22	39.51	0.33	0.05	3.78	0
4:32	332.79	39.39	0.33	0.05	3.78	0
4:33	345.72	39.20	0.35	0.05	3.93	0
4:34	344.65	39.06	0.34	0.05	3.92	0
4:35	339.48	38.96	0.34	0.05	3.86	0
4:36	334.73	38.89	0.33	0.05	3.81	0
4:37	331.93	38.79	0.33	0.05	3.78	0
4:38	327.19	38.65	0.33	0.05	3.73	0
4:39	323.09	38.52	0.32	0.05	3.68	0
4:40	317.71	38.41	0.32	0.05	3.62	0

Time PM	GTI (W/m2) G	Temperature T ^{0}C	G/Gref i.e. (G/1000) W/m2	Temp Compensation factor 3.7*(T-25)/1000	Solar power generation MW	Solar Power > 6.3 MW
4:41	312.32	38.22	0.31	0.05	3.56	0
4:42	306.93	38.13	0.31	0.05	3.50	0
4:43	302.83	38.03	0.30	0.05	3.46	0
4:44	297.44	37.92	0.30	0.05	3.40	0
4:45	256.70	37.85	0.26	0.05	2.93	0
4:46	290.33	37.71	0.29	0.05	3.32	0
4:47	285.38	37.52	0.29	0.05	3.27	0
4:48	279.13	37.43	0.28	0.05	3.20	0
4:49	275.03	37.30	0.28	0.05	3.15	0
4:50	267.91	37.21	0.27	0.05	3.07	0
4:51	261.66	37.08	0.26	0.04	3.00	0
4:52	256.27	36.88	0.26	0.04	2.94	0
4:53	254.11	36.76	0.25	0.04	2.92	0
4.54	247.21	36.58	0.25	0.04	2.84	0
4:55	241.39	36.37	0.24	0.04	2.77	0
4:56	236.00	36.09	0.24	0.04	2.72	0
4:57	229.96	35.94	0.23	0.04	2.65	0
4:58	224.36	35.73	0.22	0.04	2.59	0
4:59	220.27	35.48	0.22	0.04	2.54	0
5:00	214.01	35.35	0.21	0.04	2.47	0

Table A.1.12 Minute wise data of solar radiation from 5 PM to 6 PM

Time PM	GTI (W/m2)G	Temperature T^{0}C	G/Gref i.e.(G/1000)W/m2	Temp Compensation factor 3.7*(T-25)/1000	Solar power generation MW	Solar Power > 6.3MW
5:01	206.38	35.17	0.21	0.04	2.38	0
5:02	203.50	34.97	0.20	0.04	2.35	0
5:03	196.31	34.70	0.20	0.04	2.27	0
5:04	192.65	34.53	0.19	0.04	2.23	0
5:05	189.56	34.32	0.19	0.03	2.20	0
5:06	185.03	34.15	0.19	0.03	2.15	0
5:07	180.94	33.96	0.18	0.03	2.10	0
5:08	176.56	33.72	0.18	0.03	2.05	0
5:09	171.89	33.58	0.17	0.03	2.00	0
5:10	165.85	33.41	0.17	0.03	1.93	0
5:11	161.32	33.23	0.16	0.03	1.88	0
5:12	157.93	33.05	0.16	0.03	1.84	0
5:13	152.39	32.88	0.15	0.03	1.78	0
5:14	146.00	32.71	0.15	0.03	1.70	0
5:15	138.88	32.55	0.14	0.03	1.62	0
5:16	132.77	32.36	0.13	0.03	1.55	0
5:17	127.09	32.18	0.13	0.03	1.48	0
5:18	122.56	31.99	0.12	0.03	1.43	0
5:19	116.96	31.81	0.12	0.03	1.37	0
5:20	92.16	31.63	0.09	0.02	1.08	0
5:21	65.85	31.44	0.07	0.02	0.77	0
5:22	48.52	31.30	0.05	0.02	0.57	0
5:23	47.44	31.06	0.05	0.02	0.56	0
5:24	46.37	30.86	0.05	0.02	0.54	0
5:25	43.99	30.66	0.04	0.02	0.52	0
5:26	42.63	30.45	0.04	0.02	0.50	0
5:27	40.54	30.26	0.04	0.02	0.48	0

Time PM	GTI (W/m2)G	Temperature T^0C	G/Gref i.e.(G/1000)W/m2	Temp Compensation factor 3.7*(T-25)/1000	Solar power generation MW	Solar Power > 6.3MW
5:28	39.25	30.05	0.04	0.02	0.46	0
5:29	37.52	29.82	0.04	0.02	0.44	0
5:30	36.59	29.61	0.04	0.02	0.43	0
5:31	34.94	29.40	0.03	0.02	0.41	0
5:32	33.57	29.21	0.03	0.02	0.40	0
5:33	32.35	29.02	0.03	0.01	0.38	0
5:34	30.91	28.83	0.03	0.01	0.37	0
5:35	29.47	28.66	0.03	0.01	0.35	0
5:36	28.75	28.48	0.03	0.01	0.34	0
5:37	27.53	28.30	0.03	0.01	0.33	0
5:38	29.76	28.17	0.03	0.01	0.35	0
5:39	29.11	27.94	0.03	0.01	0.35	0
5:40	30.41	27.78	0.03	0.01	0.36	0
5:41	30.48	27.60	0.03	0.01	0.36	0
5:42	28.97	27.41	0.03	0.01	0.34	0
5:43	22.72	27.26	0.02	0.01	0.27	0
5:44	18.76	27.00	0.02	0.01	0.22	0
5:45	16.10	26.80	0.02	0.01	0.19	0
5:46	14.66	26.65	0.01	0.01	0.17	0
5:47	13.01	26.40	0.01	0.01	0.16	0
5:48	11.57	26.20	0.01	0.00	0.14	0
5:49	10.57	26.01	0.01	0.00	0.13	0
5:50	8.99	25.86	0.01	0.00	0.11	0
5:51	7.69	25.63	0.01	0.00	0.09	0
5:52	6.47	25.46	0.01	0.00	0.08	0
5:53	5.32	25.29	0.01	0.00	0.06	0
5.54	4.24	25.11	0.00	0.00	0.05	0
5:55	3.16	24.94	0.00	0.00	0.04	0
5:56	2.16	24.79	0.00	0.00	0.03	0
5:57	1.29	24.63	0.00	0.00	0.02	0
5:58	0.43	24.47	0.00	0.00	0.01	0
5:59	0.00	24.28	0.00	0.00	0.00	0
6:00	0.00	24.12	0.00	0.00	0.00	0

A.2 MINUTE WISE ENERGY BALANCE DATA

Tables A.2.1 to A.2.12 indicates the power balance data obtained including the charging pattern of battery banks on minute wise basis by simulation based on the mathematical equations developed and estimated minute wise solar power from 6 AM to 7 AM, 7 AM to 8 AM, 8 AM to 9 AM, 9 AM to 10 AM, 10 AM to 11 AM, 11 AM to 12 PM, 12 PM to 1 PM,1 PM to 2 PM, 2 PM to 3 PM, 3 PM to 4 PM , 4 PM to 5 PM, and 5 PM to 6 PM respectively. Assumed Plant Load, PL = 35 MW, Plant is under floating condition and loss factor to calculate $\text{Psolar}_{\text{-load AC}}$ is 1 as same is considered in arriving performance ratio of PV system.

Table A.2.1 Energy flows balancing from 6 AM to 7 AM

Time AM	P_{solar} (est.) MW	CHP_{PG} MW	PL MW	$P_{storage}$ MW	ESD_{SOC} AH	% ESD_{SOC}	Charging current		Overload % (5 hr rating)
							Total	Each bank	
6:01	0.00	35	35	0.00	600	20	0.00	0.00	0.00
6:02	0.00	35	35	0.00	600	20	0.00	0.00	0.00
6:03	0.00	35	35	0.00	600	20	0.00	0.00	0.00
6:04	0.00	35	35	0.00	600	20	0.00	0.00	0.00
6:05	0.00	35	35	0.00	600	20	0.00	0.00	0.00
6:06	0.00	35	35	0.00	600	20	0.00	0.00	0.00
6:07	0.00	35	35	0.00	600	20	0.00	0.00	0.00
6:08	0.00	35	35	0.00	600	20	0.00	0.00	0.00
6:09	0.00	35	35	0.00	600	20	0.00	0.00	0.00
6:10	0.00	35	35	0.00	600	20	0.00	0.00	0.00
6:11	0.00	35	35	0.00	600	20	0.00	0.00	0.00
6:12	0.00	35	35	0.00	600	20	0.00	0.00	0.00
6:13	0.00	35	35	0.00	600	20	0.00	0.00	0.00
6:14	0.00	35	35	0.00	600	20	0.00	0.00	0.00
6:15	0.00	35	35	0.00	600	20	0.00	0.00	0.00
6:16	0.00	35	35	0.00	600	20	0.00	0.00	0.00
6:17	0.00	35	35	0.00	600	20	0.00	0.00	0.00
6:18	0.00	35	35	0.00	600	20	0.00	0.00	0.00
6:19	0.00	35	35	0.00	600	20	0.00	0.00	0.00
6:20	0.00	35	35	0.00	600	20	0.00	0.00	0.00
6:21	0.00	35	35	0.00	600	20	0.00	0.00	0.00
6:22	0.00	35	35	0.00	600	20	0.00	0.00	0.00
6:23	0.00	35	35	0.00	600	20	0.00	0.00	0.00
6:24	0.01	34.99	35	0.00	600	20	0.00	0.00	0.00
6:25	0.01	34.99	35	0.00	600	20	0.00	0.00	0.00
6:26	0.02	34.98	35	0.00	600	20	0.00	0.00	0.00
6:27	0.02	34.98	35	0.00	600	20	0.00	0.00	0.00
6:28	0.03	34.97	35	0.00	600	20	0.00	0.00	0.00
6:29	0.03	34.97	35	0.00	600	20	0.00	0.00	0.00
6:30	0.04	34.96	35	0.00	600	20	0.00	0.00	0.00
6:31	0.05	34.95	35	0.00	600	20	0.00	0.00	0.00
6:32	0.06	34.94	35	0.00	600	20	0.00	0.00	0.00
6:33	0.07	34.93	35	0.00	600	20	0.00	0.00	0.00
6:34	0.08	34.92	35	0.00	600	20	0.00	0.00	0.00
6:35	0.09	34.91	35	0.00	600	20	0.00	0.00	0.00
6:36	0.11	34.89	35	0.00	600	20	0.00	0.00	0.00
6:37	0.12	34.88	35	0.00	600	20	0.00	0.00	0.00
6:38	0.14	34.86	35	0.00	600	20	0.00	0.00	0.00
6:39	0.16	34.84	35	0.00	600	20	0.00	0.00	0.00
6:40	0.17	34.83	35	0.00	600	20	0.00	0.00	0.00
6:41	0.19	34.81	35	0.00	600	20	0.00	0.00	0.00
6:42	0.20	34.8	35	0.00	600	20	0.00	0.00	0.00
6:43	0.22	34.78	35	0.00	600	20	0.00	0.00	0.00
6:44	0.24	34.76	35	0.00	600	20	0.00	0.00	0.00
6:45	0.25	34.75	35	0.00	600	20	0.00	0.00	0.00
6:46	0.28	34.72	35	0.00	600	20	0.00	0.00	0.00
6:47	0.30	34.7	35	0.00	600	20	0.00	0.00	0.00
6:48	0.31	34.69	35	0.00	600	20	0.00	0.00	0.00
6:49	0.33	34.67	35	0.00	600	20	0.00	0.00	0.00
6:50	0.35	34.65	35	0.00	600	20	0.00	0.00	0.00
6:51	0.38	34.62	35	0.00	600	20	0.00	0.00	0.00
6:52	0.41	34.59	35	0.00	600	20	0.00	0.00	0.00

Time AM	P_{solar} (est.) MW	CHP_{PG} MW	PL MW	$P_{storage}$ MW	ESD_{SOC} AH	% ESD_{SOC}	Charging current		Overload % (5 hr rating)
							Total	Each bank	
6:53	0.43	34.57	35	0.00	600	20	0.00	0.00	0.00
6:54	0.47	34.53	35	0.00	600	20	0.00	0.00	0.00
6:55	0.52	34.48	35	0.00	600	20	0.00	0.00	0.00
6:56	0.58	34.42	35	0.00	600	20	0.00	0.00	0.00
6:57	0.60	34.4	35	0.00	600	20	0.00	0.00	0.00
6:58	0.64	34.36	35	0.00	600	20	0.00	0.00	0.00
6:59	0.67	34.33	35	0.00	600	20	0.00	0.00	0.00
7:00	0.72	34.28	35	0.00	600	20	0.00	0.00	0.00

Table A.2.2 Energy flows balancing from 7 AM to 8 AM

Time AM	P_{solar} (est.) MW	CHP_{PG} MW	PL MW	$P_{storage}$ MW	ESD_{SOC} AH	% ESD_{SOC}	Charging current		Overload % (5 hr rating)
							Total	Each bank	
7:01	0.76	34.24	35	0.00	600	20	0.00	0.00	0.00
7:02	0.80	34.2	35	0.00	600	20	0.00	0.00	0.00
7:03	0.84	34.16	35	0.00	600	20	0.00	0.00	0.00
7:04	0.89	34.11	35	0.00	600	20	0.00	0.00	0.00
7:05	0.93	34.07	35	0.00	600	20	0.00	0.00	0.00
7:06	0.97	34.03	35	0.00	600	20	0.00	0.00	0.00
7:07	1.00	34	35	0.00	600	20	0.00	0.00	0.00
7:08	1.06	33.94	35	0.00	600	20	0.00	0.00	0.00
7:09	1.10	33.9	35	0.00	600	20	0.00	0.00	0.00
7:10	1.13	33.87	35	0.00	600	20	0.00	0.00	0.00
7:11	1.17	33.83	35	0.00	600	20	0.00	0.00	0.00
7:12	1.21	33.79	35	0.00	600	20	0.00	0.00	0.00
7:13	1.25	33.75	35	0.00	600	20	0.00	0.00	0.00
7:14	1.29	33.71	35	0.00	600	20	0.00	0.00	0.00
7:15	1.33	33.67	35	0.00	600	20	0.00	0.00	0.00
7:16	1.37	33.63	35	0.00	600	20	0.00	0.00	0.00
7:17	1.40	33.6	35	0.00	600	20	0.00	0.00	0.00
7:18	1.44	33.56	35	0.00	600	20	0.00	0.00	0.00
7:19	1.49	33.51	35	0.00	600	20	0.00	0.00	0.00
7:20	1.52	33.48	35	0.00	600	20	0.00	0.00	0.00
7:21	1.55	33.45	35	0.00	600	20	0.00	0.00	0.00
7:22	1.56	33.44	35	0.00	600	20	0.00	0.00	0.00
7:23	1.57	33.43	35	0.00	600	20	0.00	0.00	0.00
7:24	1.61	33.39	35	0.00	600	20	0.00	0.00	0.00
7:25	1.68	33.32	35	0.00	600	20	0.00	0.00	0.00
7:26	1.72	33.28	35	0.00	600	20	0.00	0.00	0.00
7:27	1.79	33.21	35	0.00	600	20	0.00	0.00	0.00
7:28	1.83	33.17	35	0.00	600	20	0.00	0.00	0.00
7:29	1.84	33.16	35	0.00	600	20	0.00	0.00	0.00
7:30	1.90	33.1	35	0.00	600	20	0.00	0.00	0.00
7:31	1.98	33.02	35	0.00	600	20	0.00	0.00	0.00
7:32	2.03	32.97	35	0.00	600	20	0.00	0.00	0.00
7:33	2.13	32.87	35	0.00	600	20	0.00	0.00	0.00
7:34	2.21	32.79	35	0.00	600	20	0.00	0.00	0.00
7:35	2.24	32.76	35	0.00	600	20	0.00	0.00	0.00
7:36	2.26	32.74	35	0.00	600	20	0.00	0.00	0.00
7:37	2.29	32.71	35	0.00	600	20	0.00	0.00	0.00
7:38	2.36	32.64	35	0.00	600	20	0.00	0.00	0.00
7:39	2.41	32.59	35	0.00	600	20	0.00	0.00	0.00
7:40	2.43	32.57	35	0.00	600	20	0.00	0.00	0.00
7:41	2.49	32.51	35	0.00	600	20	0.00	0.00	0.00

Time AM	P_{solar} (est.) MW	CHP_{PG} MW	PL MW	$P_{storage}$ MW	ESD_{SOC} AH	% ESD_{SOC}	Charging current		Overload % (5 hr rating)
							Total	Each bank	
7:42	2.54	32.46	35	0.00	600	20	0.00	0.00	0.00
7:43	2.56	32.44	35	0.00	600	20	0.00	0.00	0.00
7:44	2.59	32.41	35	0.00	600	20	0.00	0.00	0.00
7:45	2.61	32.39	35	0.00	600	20	0.00	0.00	0.00
7:46	2.59	32.41	35	0.00	600	20	0.00	0.00	0.00
7:47	2.59	32.41	35	0.00	600	20	0.00	0.00	0.00
7:48	2.66	32.34	35	0.00	600	20	0.00	0.00	0.00
7:49	2.80	32.2	35	0.00	600	20	0.00	0.00	0.00
7:50	2.84	32.16	35	0.00	600	20	0.00	0.00	0.00
7:51	2.93	32.07	35	0.00	600	20	0.00	0.00	0.00
7:52	2.96	32.04	35	0.00	600	20	0.00	0.00	0.00
7:53	2.98	32.02	35	0.00	600	20	0.00	0.00	0.00
7:54	2.99	32.01	35	0.00	600	20	0.00	0.00	0.00
7:55	3.00	32	35	0.00	600	20	0.00	0.00	0.00
7:56	3.07	31.93	35	0.00	600	20	0.00	0.00	0.00
7:57	3.10	31.9	35	0.00	600	20	0.00	0.00	0.00
7:58	3.23	31.77	35	0.00	600	20	0.00	0.00	0.00
7:59	3.25	31.75	35	0.00	600	20	0.00	0.00	0.00
8:00	3.27	31.73	35	0.00	600	20	0.00	0.00	0.00

Table A.2.3 Energy flows balancing from 8 AM to 9 AM

Time AM	P_{solar} (est.) MW	CHP_{PG} MW	PL MW	$P_{storage}$ MW	ESD_{SOC} AH	% ESD_{SOC}	Charging current		Overload % (5 hr rating)
							Total	Each bank	
8:01	3.31	31.69	35	0.00	600	20	0.00	0.00	0.00
8:02	3.40	31.6	35	0.00	600	20	0.00	0.00	0.00
8:03	3.44	31.56	35	0.00	600	20	0.00	0.00	0.00
8:04	3.50	31.5	35	0.00	600	20	0.00	0.00	0.00
8:05	3.59	31.41	35	0.00	600	20	0.00	0.00	0.00
8:06	3.68	31.32	35	0.00	600	20	0.00	0.00	0.00
8:07	3.74	31.26	35	0.00	600	20	0.00	0.00	0.00
8:08	3.79	31.21	35	0.00	600	20	0.00	0.00	0.00
8:09	3.83	31.17	35	0.00	600	20	0.00	0.00	0.00
8:10	3.89	31.11	35	0.00	600	20	0.00	0.00	0.00
8:11	3.96	31.04	35	0.00	600	20	0.00	0.00	0.00
8:12	3.99	31.01	35	0.00	600	20	0.00	0.00	0.00
8:13	4.06	30.94	35	0.00	600	20	0.00	0.00	0.00
8:14	4.11	30.89	35	0.00	600	20	0.00	0.00	0.00
8:15	4.17	30.83	35	0.00	600	20	0.00	0.00	0.00
8:16	4.22	30.78	35	0.00	600	20	0.00	0.00	0.00
8:17	4.25	30.75	35	0.00	600	20	0.00	0.00	0.00
8:18	4.32	30.68	35	0.00	600	20	0.00	0.00	0.00
8:19	4.35	30.65	35	0.00	600	20	0.00	0.00	0.00
8:20	4.38	30.62	35	0.00	600	20	0.00	0.00	0.00
8:21	4.39	30.61	35	0.00	600	20	0.00	0.00	0.00
8:22	4.42	30.58	35	0.00	600	20	0.00	0.00	0.00
8:23	4.41	30.59	35	0.00	600	20	0.00	0.00	0.00
8:24	4.50	30.5	35	0.00	600	20	0.00	0.00	0.00
8:25	4.53	30.47	35	0.00	600	20	0.00	0.00	0.00
8:26	4.63	30.37	35	0.00	600	20	0.00	0.00	0.00
8:27	4.79	30.21	35	0.00	600	20	0.00	0.00	0.00
8:28	4.86	30.14	35	0.00	600	20	0.00	0.00	0.00
8:29	4.89	30.11	35	0.00	600	20	0.00	0.00	0.00
8:30	4.87	30.13	35	0.00	600	20	0.00	0.00	0.00

Time AM	P_{solar} (est.) MW	CHP_{PG} MW	PL MW	$P_{storage}$ MW	ESD_{SOC} AH	% ESD_{SOC}	Charging current		Overload % (5 hr rating)
							Total	Each bank	
8:31	4.98	30.02	35	0.00	600	20	0.00	0.00	0.00
8:32	5.02	29.98	35	0.00	600	20	0.00	0.00	0.00
8:33	5.11	29.89	35	0.00	600	20	0.00	0.00	0.00
8:34	5.08	29.92	35	0.00	600	20	0.00	0.00	0.00
8:35	5.15	29.85	35	0.00	600	20	0.00	0.00	0.00
8:36	5.20	29.8	35	0.00	600	20	0.00	0.00	0.00
8:37	5.31	29.69	35	0.00	600	20	0.00	0.00	0.00
8:38	5.33	29.67	35	0.00	600	20	0.00	0.00	0.00
8:39	5.22	29.78	35	0.00	600	20	0.00	0.00	0.00
8:40	5.35	29.65	35	0.00	600	20	0.00	0.00	0.00
8:41	5.39	29.61	35	0.00	600	20	0.00	0.00	0.00
8:42	5.34	29.66	35	0.00	600	20	0.00	0.00	0.00
8:43	5.56	29.44	35	0.00	600	20	0.00	0.00	0.00
8:44	5.63	29.37	35	0.00	600	20	0.00	0.00	0.00
8:45	5.66	29.34	35	0.00	600	20	0.00	0.00	0.00
8:46	5.70	29.3	35	0.00	600	20	0.00	0.00	0.00
8:47	5.72	29.28	35	0.00	600	20	0.00	0.00	0.00
8:48	5.77	29.23	35	0.00	600	20	0.00	0.00	0.00
8:49	5.73	29.27	35	0.00	600	20	0.00	0.00	0.00
8:50	5.88	29.12	35	0.00	600	20	0.00	0.00	0.00
8:51	5.87	29.13	35	0.00	600	20	0.00	0.00	0.00
8:52	5.87	29.13	35	0.00	600	20	0.00	0.00	0.00
8:53	5.94	29.06	35	0.00	600	20	0.00	0.00	0.00
8:54	6.06	28.94	35	0.00	600	20	0.00	0.00	0.00
8:55	6.11	28.89	35	0.00	600	20	0.00	0.00	0.00
8:56	6.13	28.87	35	0.00	600	20	0.00	0.00	0.00
8:57	6.05	28.95	35	0.00	600	20	0.00	0.00	0.00
8:58	6.12	28.88	35	0.00	600	20	0.00	0.00	0.00
8:59	6.23	28.77	35	0.00	600	20	0.00	0.00	0.00
9:00	6.21	28.79	35	0.00	600	20	0.00	0.00	0.00

Table A.2.4 Energy flows balancing from 9 AM to 10 AM

Time AM	P_{solar} (est.) MW	CHP_{PG} MW	PL MW	$P_{storage}$ MW	ESD_{SOC} AH	% ESD_{SOC}	Charging current		Overload % (5 hr rating)
							Total	Each bank	
9:01	6.17	28.83	35	0	600	20	0	0	0
9:02	6.31	28.7	35	0.01	600.020	20.0007	29.412	1.225490	0.204248366
9:03	6.26	28.74	35	0	600.020	20.0007	0	0	0
9:04	6.40	28.7	35	0.1	600.225	20.0075	294.12	12.25490	2.04248366
9:05	6.23	28.77	35	0	600.225	20.0075	0	0	0
9:06	6.25	28.75	35	0	600.225	20.0075	0	0	0
9:07	6.42	28.7	35	0.12	600.47	20.0157	352.94	14.70588	2.450980392
9:08	6.35	28.7	35	0.05	600.572	20.0191	147.06	6.127451	1.02124183
9:09	6.49	28.7	35	0.19	600.96	20.032	558.82	23.28431	3.880718954
9:10	6.46	28.7	35	0.16	601.287	20.0429	470.59	19.60784	3.267973856
9:11	6.51	28.7	35	0.21	601.716	20.0572	617.647	25.73529	4.289215686
9:12	6.48	28.7	35	0.18	602.083	20.0694	529.412	22.05882	3.676470588
9:13	6.62	28.7	35	0.32	602.737	20.0912	941.176	39.21569	6.535947712
9:14	6.54	28.7	35	0.24	603.227	20.1076	705.882	29.41176	4.901960784
9:15	6.64	28.7	35	0.34	603.922	20.1307	1000	41.66667	6.944444444
9:16	6.67	28.7	35	0.37	604.677	20.1559	1088.24	45.34314	7.557189542
9:17	6.72	28.7	35	0.42	605.535	20.1845	1235.29	51.47059	8.578431373
9:18	6.65	28.7	35	0.35	606.25	20.2083	1029.41	42.89216	7.14869281
9:19	6.62	28.7	35	0.32	606.904	20.2301	941.176	39.21569	6.535947712

Time AM	P_{solar} (est.) MW	CHP$_{PG}$ MW	PL MW	$P_{storage}$ MW	ESD$_{SOC}$ AH	% ESD$_{SOC}$	Charging current		Overload % (5 hr rating)
							Total	Each bank	
9:20	6.66	28.7	35	0.36	607.639	20.2546	1058.82	44.11765	7.352941176
9:21	6.67	28.7	35	0.37	608.395	20.2798	1088.235	45.34314	7.557189542
9:22	6.58	28.7	35	0.28	608.967	20.2989	823.5294	34.31373	5.718954248
9:23	6.69	28.7	35	0.39	609.763	20.3254	1147.059	47.79412	7.965686275
9:24	6.57	28.7	35	0.27	610.314	20.3438	794.1176	33.08823	5.514705882
9:25	6.67	28.7	35	0.37	611.070	20.3690	1088.235	45.34313	7.557189542
9:26	6.49	28.7	35	0.19	611.458	20.3819	558.8235	23.28431	3.880718954
9:27	6.56	28.7	35	0.26	611.989	20.3996	764.7058	31.86274	5.310457516
9:28	6.63	28.7	35	0.33	612.663	20.4221	970.5882	40.44117	6.740196078
9:29	6.58	28.7	35	0.28	613.235	20.4411	823.5294	34.31372	5.718954248
9:30	6.59	28.7	35	0.29	613.827	20.4609	852.9412	35.53922	5.923202614
9:31	6.52	28.7	35	0.22	614.277	20.4759	647.0588	26.96078	4.493464052
9:32	6.56	28.7	35	0.26	614.808	20.4936	764.7058	31.86274	5.310457516
9:33	6.61	28.7	35	0.31	615.441	20.5147	911.7647	37.99019	6.331699346
9:34	6.59	28.7	35	0.29	616.033	20.5344	852.9411	35.53921	5.923202614
9:35	6.61	28.7	35	0.31	616.667	20.5555	911.7647	37.99019	6.331699346
9:36	6.57	28.7	35	0.27	617.218	20.5739	794.1177	33.08823	5.514705882
9:37	6.58	28.7	35	0.28	617.79	20.593	823.5294	34.31372	5.718954248
9:38	6.56	28.7	35	0.26	618.321	20.6107	764.7058	31.86274	5.310457516
9:39	6.54	28.7	35	0.24	618.811	20.6270	705.8823	29.41176	4.901960784
9:40	6.50	28.7	35	0.20	619.219	20.6406	588.2353	24.50980	4.08496732
9:41	6.56	28.7	35	0.26	619.750	20.6583	764.7058	31.86274	5.310457516
9:42	6.60	28.7	35	0.30	620.363	20.6787	882.3529	36.76470	6.12745098
9:43	6.56	28.7	35	0.26	620.894	20.6964	764.7058	31.86274	5.310457516
9:44	6.48	28.7	35	0.18	621.262	20.7087	529.4117	22.05882	3.676470588
9:45	6.59	28.7	35	0.29	621.854	20.7285	852.9412	35.53922	5.923202614
9:46	6.57	28.7	35	0.27	622.406	20.7468	794.1176	33.08823	5.514705882
9:47	6.56	28.7	35	0.26	622.937	20.7645	764.7058	31.86274	5.310457516
9:48	6.54	28.7	35	0.24	623.427	20.7809	705.8823	29.41176	4.901960784
9:49	6.58	28.7	35	0.28	623.999	20.7999	823.5294	34.31372	5.718954248
9:50	6.62	28.7	35	0.32	624.652	20.8217	941.1764	39.21568	6.535947712
9:51	6.58	28.7	35	0.28	625.224	20.8408	823.5294	34.31372	5.718954248
9:52	6.56	28.7	35	0.26	625.755	20.8585	764.7058	31.86274	5.310457516
9:53	6.61	28.7	35	0.31	626.388	20.8796	911.7647	37.99019	6.331699346
9:54	6.63	28.7	35	0.33	627.062	20.9021	970.5882	40.44117	6.740196078
9:55	6.62	28.7	35	0.32	627.716	20.9238	941.1764	39.21568	6.535947712
9:56	6.64	28.7	35	0.34	628.410	20.9470	1000	41.66666	6.944444444
9:57	6.65	28.7	35	0.35	629.125	20.9708	1029.411	42.89215	7.14869281
9:58	6.69	28.7	35	0.39	629.922	20.9974	1147.058	47.79411	7.965686275
9:59	6.72	28.7	35	0.42	630.780	21.0260	1235.294	51.47058	8.578431373
10:00	6.71	28.7	35	0.41	631.617	21.0539	1205.882	50.24509	8.374183007

Table A.2.5 Energy flows balancing from 10 AM to 11 AM

Time AM	P_{solar} (est.) MW	CHP$_{PG}$ MW	PL MW	$P_{storage}$ MW	ESD$_{SOC}$ AH	% ESD$_{SOC}$	Charging current		Overload % (5 hr rating)
							Total	Each bank	
10:01	6.77	28.7	35	0.47	633.1046	21.1034	1382.35294	57.5980392	9.599673203
10:02	6.80	28.7	35	0.5	634.1258	21.1375	1470.58823	61.2745098	10.2124183
10:03	6.82	28.7	35	0.52	635.1879	21.1729	1529.41176	63.7254902	10.62091503
10:04	6.92	28.7	35	0.62	636.4542	21.2151	1823.52941	75.9803922	12.66339869
10:05	6.96	28.7	35	0.66	637.8023	21.2600	1941.17647	80.8823529	13.48039216
10:06	6.95	28.7	35	0.65	639.1299	21.3043	1911.76470	79.6568627	13.27614379
10:07	7.01	28.7	35	0.71	640.5801	21.3526	2088.23529	87.0098039	14.50163399

Time AM	P_{solar} (est.) MW	CHP_{PG} MW	PL MW	$P_{storage}$ MW	ESD_{SOC} AH	% ESD_{SOC}	Charging current		Overload % (5 hr rating)
							Total	Each bank	
10:08	7.03	28.7	35	0.73	642.0711	21.4023	2147.05882	89.4607843	14.91013072
10:09	7.09	28.7	35	0.79	643.6846	21.4561	2323.52941	96.8137255	16.13562092
10:10	7.17	28.7	35	0.87	645.4616	21.5154	2558.82353	106.617647	17.76960784
10:11	7.18	28.7	35	0.88	647.259	21.5753	2588.23529	107.843137	17.97385621
10:12	7.17	28.7	35	0.87	649.0359	21.6345	2558.82353	106.617647	17.76960784
10:13	7.27	28.7	35	0.97	651.0172	21.7005	2852.94118	118.872549	19.8120915
10:14	7.36	28.7	35	1.06	653.1822	21.7727	3117.64706	129.901961	21.6503268
10:15	7.37	28.7	35	1.07	655.3676	21.8456	3147.05882	131.127451	21.85457516
10:16	7.40	28.7	35	1.1	657.6144	21.9205	3235.29412	134.803922	22.46732026
10:17	7.43	28.7	35	1.13	659.9224	21.9974	3323.52941	138.480392	23.08006536
10:18	7.49	28.7	35	1.19	662.3529	22.0784	3500	145.833333	24.30555556
10:19	7.58	28.7	35	1.28	664.9673	22.1656	3764.70588	156.862745	26.14379085
10:20	7.52	28.7	35	1.22	667.4592	22.2486	3588.23529	149.509804	24.91830065
10:21	7.60	28.7	35	1.3	670.1144	22.3372	3823.52941	159.313725	26.55228758
10:22	7.67	28.7	35	1.37	672.9126	22.4304	4029.41177	167.892157	27.98202614
10:23	7.67	28.7	35	1.37	675.7108	22.5237	4029.41176	167.892157	27.98202614
10:24	7.72	28.7	35	1.42	678.6111	22.6204	4176.47059	174.019608	29.00326797
10:25	7.78	28.7	35	1.48	681.634	22.7211	4352.94118	181.372549	30.22875817
10:26	7.85	28.7	35	1.55	684.7998	22.8267	4558.82353	189.95098	31.65849673
10:27	7.95	28.7	35	1.65	688.1699	22.939	4852.94117	202.205882	33.70098039
10:28	8.01	28.7	35	1.71	691.6626	23.0554	5029.41176	209.558824	34.92647059
10:29	8.08	28.7	35	1.78	695.2982	23.1766	5235.29412	218.137255	36.35620915
10:30	8.08	28.7	35	1.78	698.9338	23.2978	5235.29412	218.137255	36.35620915
10:31	8.20	28.7	35	1.9	702.8145	23.4271	5588.23529	232.843137	38.80718954
10:32	8.14	28.7	35	1.84	706.5727	23.5524	5411.76471	225.490196	37.58169935
10:33	8.27	28.7	35	1.97	710.5964	23.6866	5794.11765	241.421569	40.2369281
10:34	8.33	28.7	35	2.03	714.7426	23.8247	5970.58823	248.77451	41.4624183
10:35	8.37	28.7	35	2.07	718.9706	23.9657	6088.23529	253.676471	42.27941176
10:36	8.47	28.7	35	2.17	723.4028	24.1134	6382.35294	265.931373	44.32189542
10:37	8.38	28.7	35	2.08	727.6511	24.2550	6117.64706	254.901961	42.48366013
10:38	8.43	28.7	35	2.13	732.0016	24.4000	6264.70588	261.029412	43.50490196
10:39	8.54	28.7	35	2.24	736.5768	24.5526	6588.23529	274.509804	45.75163399
10:40	8.64	28.7	35	2.34	741.3562	24.7119	6882.35294	286.764706	47.79411765
10:41	8.69	28.7	35	2.39	746.2377	24.8746	7029.41176	292.892157	48.81535948
10:42	9.05	28.7	35	2.75	751.8546	25.0618	8088.23529	337.009804	56.16830065
10:43	9.07	28.7	35	2.77	757.5123	25.2504	8147.05882	339.460784	56.57679739
10:44	8.93	28.7	35	2.63	762.884	25.4295	7735.29412	322.303922	53.71732026
10:45	9.13	28.7	35	2.83	768.6642	25.6221	8323.52941	346.813725	57.80228758
10:46	9.21	28.7	35	2.91	774.6078	25.8203	8558.82353	356.617647	59.43627451
10:47	9.04	28.7	35	2.74	780.2042	26.0068	8058.82353	335.784314	55.96405229
10:48	8.98	28.7	35	2.68	785.6781	26.1893	7882.35294	328.431373	54.73856209
10:49	9.12	28.7	35	2.82	791.4379	26.3813	8294.11765	345.588235	57.59803922
10:50	9.27	28.7	35	2.97	797.5041	26.5835	8735.29412	363.970588	60.66176471
10:51	9.28	28.7	35	2.98	803.5907	26.7864	8764.70588	365.196078	60.86601307
10:52	9.25	28.7	35	2.95	809.616	26.9872	8676.47059	361.519608	60.25326797
10:53	9.21	28.7	35	2.91	815.5596	27.1853	8558.82353	356.617647	59.43627451
10:54	9.28	28.7	35	2.98	821.6462	27.3882	8764.70588	365.196078	60.86601307
10:55	9.49	28.7	35	3.19	828.1618	27.6054	9382.35294	390.931373	65.15522876
10:56	9.68	28.7	35	3.38	835.0654	27.8355	9941.17647	414.215686	69.03594771
10:57	9.60	28.7	35	3.3	841.8056	28.0602	9705.88235	404.411765	67.40196078
10:58	9.42	28.7	35	3.12	848.1781	28.2726	9176.47059	382.352941	63.7254902
10:59	9.46	28.7	35	3.16	854.6324	28.4878	9294.11765	387.254902	64.54248366
11:00	9.62	28.7	35	3.32	861.4134	28.7138	9764.70588	406.862745	67.81045752

Table A.2.6 Energy flows balancing from 11 AM to 12PM

Time AM	P_{solar} (est.) MW	CHP_{PG} MW	PL MW	Ps_{torage} MW	ESD_{SOC} AH	% ESD_{SOC}	Charging current		Overload % (5 hr rating)
							Total	Each bank	
11:01	9.77	28.7	35	3.47	872.322	29.0774	10205.8823	425.24509	70.8741830
11:02	9.69	28.7	35	3.39	879.246	29.3082	9970.58823	415.44118	69.2401961
11:03	9.56	28.7	35	3.26	885.9045	29.53015	9588.23529	399.50980	66.5849673
11:04	9.98	28.7	35	3.68	893.4208	29.78069	10823.5294	450.98039	75.1633987
11:05	10.13	28.7	35	3.83	901.2435	30.04145	11264.7059	469.36275	78.2271242
11:06	10.17	28.7	35	3.87	909.1479	30.30493	11382.3530	474.26471	79.0441177
11:07	10.14	28.7	35	3.84	916.9911	30.56637	11294.1176	470.58823	78.4313725
11:08	9.78	28.7	35	3.48	924.0989	30.8033	10235.2941	426.47059	71.0784314
11:09	9.84	28.7	35	3.54	931.3293	31.04431	10411.7647	433.82353	72.3039216
11:10	10.05	28.7	35	3.75	938.9886	31.29962	11029.4118	459.55883	76.5931373
11:11	10.06	28.7	35	3.76	946.6684	31.55561	11058.8235	460.78431	76.7973856
11:12	9.94	28.7	35	3.64	954.103	31.80343	10705.8823	446.07843	74.3464052
11:13	10.37	28.7	35	4.07	962.4159	32.08053	11970.5882	498.77451	83.1290849
11:14	10.42	28.7	35	4.12	970.831	32.36103	12117.6470	504.90196	84.1503268
11:15	10.44	28.7	35	4.14	979.2868	32.64289	12176.4705	507.35294	84.5588235
11:16	10.53	28.7	35	4.23	987.9265	32.93088	12441.1765	518.38235	86.3970588
11:17	10.58	28.7	35	4.28	996.6684	33.22228	12588.2353	524.50980	87.4183006
11:18	10.63	28.7	35	4.33	1005.512	33.51708	12735.2941	530.63725	88.4395425
11:19	10.66	28.7	35	4.36	1014.418	33.81392	12823.5294	534.31372	89.0522876
11:20	10.70	28.7	35	4.4	1023.404	34.11348	12941.1765	539.21569	89.8692812
11:21	10.73	28.7	35	4.43	1032.453	34.41509	13029.4118	542.89216	90.4820262
11:22	10.76	28.7	35	4.46	1041.562	34.71874	13117.6471	546.56863	91.0947713
11:23	10.73	28.7	35	4.43	1050.61	35.02035	13029.4118	542.89216	90.4820261
11:24	10.70	28.7	35	4.4	1059.597	35.31991	12941.1765	539.21569	89.8692811
11:25	10.72	28.7	35	4.42	1068.625	35.62084	13000	541.66667	90.2777778
11:26	10.72	28.7	35	4.42	1077.653	35.92176	13000	541.66667	90.2777778
11:27	10.76	28.7	35	4.46	1086.762	36.22541	13117.6471	546.56863	91.0947712
11:28	10.79	28.7	35	4.49	1095.933	36.5311	13205.8823	550.24509	91.7075163
11:29	10.74	28.7	35	4.44	1105.002	36.83339	13058.8235	544.11764	90.6862745
11:30	10.70	28.7	35	4.4	1113.989	37.13295	12941.1764	539.21568	89.8692810
11:31	10.71	28.7	35	4.41	1122.996	37.4332	12970.5882	540.44117	90.0735294
11:32	10.73	28.7	35	4.43	1132.044	37.73481	13029.4117	542.89215	90.4820261
11:33	10.73	28.7	35	4.43	1141.092	38.03641	13029.4117	542.89215	90.4820261
11:34	10.73	28.7	35	4.43	1150.141	38.33802	13029.4117	542.89215	90.4820261
11:35	10.80	28.7	35	4.5	1159.332	38.64439	13235.2941	551.47058	91.9117647
11:36	10.79	28.7	35	4.49	1168.503	38.95008	13205.8823	550.24509	91.7075163
11:37	10.82	28.7	35	4.52	1177.735	39.25782	13294.1176	553.92156	92.3202614
11:38	10.80	28.7	35	4.5	1186.926	39.56419	13235.2941	551.47058	91.9117647
11:39	10.81	28.7	35	4.51	1196.137	39.87124	13264.7058	552.69607	92.1160130
11:40	10.83	28.7	35	4.53	1205.39	40.17966	13323.5294	555.14705	92.5245098
11:41	10.81	28.7	35	4.51	1214.601	40.48671	13264.7058	552.69607	92.1160130
11:42	10.90	28.7	35	4.6	1223.997	40.79989	13529.4117	563.72549	93.9542483
11:43	10.83	28.7	35	4.53	1233.249	41.10831	13323.5294	555.14705	92.5245098
11:44	10.87	28.7	35	4.57	1242.583	41.41945	13441.1764	560.04902	93.3415032
11:45	10.90	28.7	35	4.6	1251.979	41.73263	13529.4117	563.72549	93.9542483
11:46	10.81	28.7	35	4.51	1261.19	42.03968	13264.7058	552.69607	92.1160130
11:47	10.85	28.7	35	4.55	1270.484	42.34946	13382.3529	557.59803	92.9330065
11:48	10.96	28.7	35	4.66	1280.002	42.66672	13705.8823	571.07843	95.1797385
11:49	11.02	28.7	35	4.72	1289.642	42.98807	13882.3529	578.43137	96.4052287
11:50	11.07	28.7	35	4.77	1299.385	43.31283	14029.4117	584.55882	97.4264705
11:51	11.06	28.7	35	4.76	1309.107	43.6369	14000	583.33333	97.2222222
11:52	11.10	28.7	35	4.8	1318.911	43.9637	14117.6470	588.23529	98.0392156

Time	P_{solar} (est.) MW	CHP_{PG} MW	PL MW	$Ps_{storage}$ MW	ESD_{SOC} AH	% ESD_{SOC}	Charging current		Overload % (5 hr rating)
							Total	Each bank	
11:53	11.08	28.7	35	4.78	1328.674	44.28914	14058.8235	585.78431	97.6307189
11:54	11.02	28.7	35	4.72	1338.315	44.61049	13882.3529	578.43137	96.4052287
11:55	11.02	28.7	35	4.72	1347.955	44.93184	13882.3529	578.43137	96.4052287
11:56	11.01	28.7	35	4.71	1357.575	45.25251	13852.9411	577.20588	96.2009803
11:57	11.02	28.7	35	4.72	1367.216	45.57386	13882.3529	578.43137	96.4052287
11:58	10.94	28.7	35	4.64	1376.693	45.88976	13647.0588	568.62745	94.7712418
11:59	10.99	28.7	35	4.69	1386.272	46.20907	13794.1176	574.75490	95.7924836
12PM	11.00	28.7	35	4.7	1395.872	46.52906	13823.5294	575.98039	95.9967320

Table A.2.7 Energy flows balancing from 12PM to 1PM

Time PM	P_{solar} (est.) MW	CHP_{PG} MW	PL MW	$Ps_{storage}$ MW	ESD_{SOC} AH	% ESD_{SOC}	Charging current		Overload % (5 hr rating)
							Total	Each bank	
12:01	11.06	28.7	35	4.76	1404.879	46.82931	235.2941176	9.80392157	1.633986928
12:02	11.03	28.7	35	4.73	1414.54	47.15134	13911.76471	579.656863	96.60947712
12:03	11.05	28.7	35	4.75	1424.242	47.47473	13970.58824	582.107843	97.01797386
12:04	11.10	28.7	35	4.8	1434.046	47.80153	14117.64706	588.235294	98.03921569
12:05	11.08	28.7	35	4.78	1443.809	48.12696	14058.82353	585.784314	97.63071895
12:06	11.11	28.7	35	4.81	1453.633	48.45444	14147.05882	589.460784	98.24346405
12:07	10.93	28.7	35	4.63	1463.09	48.76966	13617.64706	567.401961	94.56699346
12:08	11.06	28.7	35	4.76	1472.812	49.09374	14000	583.333333	97.22222222
12:09	11.14	28.7	35	4.84	1482.698	49.42326	14235.29412	593.137255	98.85620915
12:10	11.06	28.7	35	4.76	1492.42	49.74733	14000	583.333333	97.22222222
12:11	10.93	28.7	35	4.63	1501.877	50.06256	13617.64706	567.401961	94.56699346
12:12	10.92	28.7	35	4.62	1511.313	50.3771	13588.23529	566.176471	94.3627451
12:13	10.90	28.7	35	4.6	1520.708	50.69028	13529.41176	563.72549	93.95424837
12:14	10.98	28.7	35	4.68	1530.267	51.00891	13764.70588	573.529412	95.58823529
12:15	11.02	28.7	35	4.72	1539.908	51.33026	13882.35294	578.431373	96.40522876
12:16	11.25	28.7	35	4.95	1550.018	51.66727	14558.82353	606.617647	101.1029412
12:17	11.23	28.7	35	4.93	1560.087	52.00292	14500	604.166667	100.6944444
12:18	11.14	28.7	35	4.84	1569.973	52.33244	14235.29412	593.137255	98.85620915
12:19	11.19	28.7	35	4.89	1579.961	52.66536	14382.35294	599.264706	99.87745098
12:20	11.05	28.7	35	4.75	1589.663	52.98875	13970.58824	582.107843	97.01797386
12:21	11.07	28.7	35	4.77	1599.405	53.31351	14029.41176	584.558824	97.42647059
12:22	11.16	28.7	35	4.86	1609.332	53.64439	14294.11765	595.588235	99.26470588
12:23	11.33	28.7	35	5.03	1619.605	53.98685	14794.11765	616.421569	102.7369281
12:24	11.26	28.7	35	4.96	1629.736	54.32454	14588.23529	607.843137	101.3071895
12:25	11.24	28.7	35	4.94	1639.826	54.66087	14529.41176	605.392157	100.8986928
12:26	11.20	28.7	35	4.9	1649.834	54.99447	14411.76471	600.490196	100.0816993
12:27	11.25	28.7	35	4.95	1659.945	55.33148	14558.82353	606.617647	101.1029412
12:28	11.15	28.7	35	4.85	1669.851	55.66169	14264.70588	594.362745	99.06045752
12:29	11.19	28.7	35	4.89	1679.838	55.99461	14382.35294	599.264706	99.87745098
12:30	11.14	28.7	35	4.84	1689.724	56.32413	14235.29412	593.137255	98.85620915
12:31	11.14	28.7	35	4.84	1699.61	56.65365	14235.29412	593.137255	98.85620915
12:32	11.07	28.7	35	4.77	1709.352	56.97841	14029.41176	584.558824	97.42647059
12:33	11.13	28.7	35	4.83	1719.217	57.30725	14205.88235	591.911765	98.65196078
12:34	11.14	28.7	35	4.84	1729.103	57.63677	14235.29412	593.137255	98.85620915
12:35	11.22	28.7	35	4.92	1739.152	57.97173	14470.58824	602.941176	100.4901961
12:36	11.22	28.7	35	4.92	1749.201	58.3067	14470.58824	602.941176	100.4901961
12:37	11.30	28.7	35	5	1759.413	58.64712	14705.88235	612.745098	102.124183
12:38	11.35	28.7	35	5.05	1769.728	58.99093	14852.94118	618.872549	103.1454248
12:39	11.21	28.7	35	4.91	1779.757	59.32522	14441.17647	601.715686	100.2859477
12:40	11.19	28.7	35	4.89	1789.744	59.65814	14382.35294	599.264706	99.87745098
12:41	11.08	28.7	35	4.78	1799.507	59.98358	14058.82353	585.784314	97.63071895

Time PM	P_{solar} (est.) MW	CHP_{PG} MW	PL MW	$Ps_{storage}$ MW	ESD_{SOC} AH	% ESD_{SOC}	Charging current		Overload % (5 hr rating)
							Total	Each bank	
12:42	11.04	28.7	35	4.74	1809.189	60.30629	13941.17647	580.882353	96.81372549
12:43	10.90	28.7	35	4.6	1818.584	60.61947	13529.41176	563.72549	93.95424837
12:44	10.95	28.7	35	4.65	1828.082	60.93606	13676.47059	569.852941	94.9754902
12:45	11.22	28.7	35	4.92	1838.131	61.27103	14470.58824	602.941176	100.4901961
12:46	11.12	28.7	35	4.82	1847.976	61.59919	14176.47059	590.686275	98.44771242
12:47	11.00	28.7	35	4.7	1857.575	61.91917	13823.52941	575.980392	95.99673203
12:48	10.94	28.7	35	4.64	1867.052	62.23508	13647.05882	568.627451	94.77124183
12:49	10.87	28.7	35	4.57	1876.387	62.54622	13441.17647	560.04902	93.34150327
12:50	11.09	28.7	35	4.79	1886.17	62.87233	14088.23529	587.009804	97.83496732
12:51	11.16	28.7	35	4.86	1896.096	63.20322	14294.11765	595.588235	99.26470588
12:52	11.18	28.7	35	4.88	1906.064	63.53546	14352.94118	598.039216	99.67320261
12:53	11.12	28.7	35	4.82	1915.909	63.86362	14176.47059	590.686275	98.44771242
12:54	11.07	28.7	35	4.77	1925.651	64.18837	14029.41176	584.558824	97.42647059
12:55	11.05	28.7	35	4.75	1935.353	64.51177	13970.58824	582.107843	97.01797386
12:56	11.13	28.7	35	4.83	1945.218	64.84061	14205.88235	591.911765	98.65196078
12:57	11.10	28.7	35	4.8	1955.022	65.1674	14117.64706	588.235294	98.03921569
12:58	11.02	28.7	35	4.72	1964.663	65.48875	13882.35294	578.431373	96.40522876
12:59	11.02	28.7	35	4.72	1974.303	65.81011	13882.35294	578.431373	96.40522876
1:00	11.04	28.7	35	4.74	1983.985	66.13282	13941.17647	580.882353	96.81372549

Table A.2.8 Energy flows balancing from 1PM to 2PM

Time PM	P_{solar} (est.) MW	CHP_{PG} MW	PL MW	$Ps_{storage}$ MW	ESD_{SOC} AH	% ESD_{SOC}	Charging current		Overload % (5 hr rating)
							Total	Each bank	
1:01	11.08	28.7	35	4.78	2003.402	66.78007	14058.82353	585.784314	97.63071895
1:02	11.09	28.7	35	4.79	2013.186	67.10619	14088.23529	587.009804	97.83496732
1:03	10.95	28.7	35	4.65	2022.683	67.42277	13676.47059	569.852941	94.9754902
1:04	10.87	28.7	35	4.57	2032.017	67.73391	13441.17647	560.04902	93.34150327
1:05	10.97	28.7	35	4.67	2041.556	68.05186	13735.29412	572.303922	95.38398693
1:06	10.88	28.7	35	4.58	2050.91	68.36368	13470.58824	561.27451	93.54575163
1:07	10.84	28.7	35	4.54	2060.183	68.67277	13352.94118	556.372549	92.72875817
1:08	11.02	28.7	35	4.72	2069.824	68.99412	13882.35294	578.431373	96.40522876
1:09	10.97	28.7	35	4.67	2079.362	69.31207	13735.29412	572.303922	95.38398693
1:10	10.93	28.7	35	4.63	2088.819	69.62729	13617.64706	567.401961	94.56699346
1:11	10.88	28.7	35	4.58	2098.173	69.93911	13470.58824	561.27451	93.54575163
1:12	10.79	28.7	35	4.49	2107.344	70.2448	13205.88235	550.245098	91.70751634
1:13	10.73	28.7	35	4.43	2116.392	70.54641	13029.41176	542.892157	90.48202614
1:14	10.75	28.7	35	4.45	2125.481	70.84938	13088.23529	545.343137	90.89052288
1:15	10.61	28.7	35	4.31	2134.284	71.14281	12676.47059	528.186275	88.03104575
1:16	10.81	28.7	35	4.51	2143.496	71.44987	13264.70588	552.696078	92.11601307
1:17	10.68	28.7	35	4.38	2152.442	71.74807	12882.35294	536.764706	89.46078431
1:18	10.62	28.7	35	4.32	2161.266	72.04219	12705.88235	529.411765	88.23529412
1:19	10.69	28.7	35	4.39	2170.232	72.34107	12911.76471	537.990196	89.66503268
1:20	10.72	28.7	35	4.42	2179.26	72.642	13000	541.666667	90.27777778
1:21	10.66	28.7	35	4.36	2188.165	72.93884	12823.52941	534.313725	89.05228758
1:22	10.66	28.7	35	4.36	2197.07	73.23568	12823.52941	534.313725	89.05228758
1:23	10.67	28.7	35	4.37	2205.996	73.5332	12852.94118	535.539216	89.25653595
1:24	10.53	28.7	35	4.23	2214.636	73.82119	12441.17647	518.382353	86.39705882
1:25	10.60	28.7	35	4.3	2223.418	74.11395	12647.05882	526.960784	87.82679739
1:26	10.62	28.7	35	4.32	2232.242	74.40807	12705.88235	529.411765	88.23529412
1:27	10.59	28.7	35	4.29	2241.004	74.70014	12617.64706	525.735294	87.62254902
1:28	10.70	28.7	35	4.4	2249.991	74.9997	12941.17647	539.215686	89.86928105
1:29	10.57	28.7	35	4.27	2258.713	75.29042	12558.82353	523.284314	87.21405229
1:30	10.56	28.7	35	4.26	2267.414	75.58045	12529.41176	522.058824	87.00980392

Time PM	P_{solar} (est.) MW	CHP_{PG} MW	PL MW	$Ps_{storage}$ MW	ESD_{SOC} AH	% ESD_{SOC}	Charging current		Overload % (5 hr rating)
							Total	Each bank	
1:31	10.60	28.7	35	4.3	2276.196	75.87321	12647.05882	526.960784	87.82679739
1:32	10.57	28.7	35	4.27	2284.918	76.16392	12558.82353	523.284314	87.21405229
1:33	10.58	28.7	35	4.28	2293.659	76.45531	12588.23529	524.509804	87.41830065
1:34	10.57	28.7	35	4.27	2302.381	76.74603	12558.82353	523.284314	87.21405229
1:35	10.54	28.7	35	4.24	2311.041	77.0347	12470.58824	519.607843	86.60130719
1:36	10.48	28.7	35	4.18	2319.579	77.31929	12294.11765	512.254902	85.37581699
1:37	10.56	28.7	35	4.26	2328.28	77.60932	12529.41176	522.058824	87.00980392
1:38	10.53	28.7	35	4.23	2336.919	77.89731	12441.17647	518.382353	86.39705882
1:39	10.41	28.7	35	4.11	2345.314	78.17713	12088.23529	503.676471	83.94607843
1:40	10.42	28.7	35	4.12	2353.729	78.45763	12117.64706	504.901961	84.1503268
1:41	10.44	28.7	35	4.14	2362.185	78.73949	12176.47059	507.352941	84.55882353
1:42	10.41	28.7	35	4.11	2370.579	79.01931	12088.23529	503.676471	83.94607843
1:43	10.35	28.7	35	4.05	2378.851	79.29505	11911.76471	496.323529	82.72058824
1:44	10.32	28.7	35	4.02	2387.062	79.56874	11823.52941	492.647059	82.10784314
1:45	10.23	28.7	35	3.93	2395.089	79.83631	11558.82353	481.617647	80.26960784
1:46	10.12	28.7	35	3.82	2402.891	80.09638	11235.29412	468.137255	78.02287582
1:47	10.13	28.7	35	3.83	2410.714	80.35714	11264.70588	469.362745	78.22712418
1:48	10.12	28.7	35	3.82	2418.516	80.61722	11235.29412	468.137255	78.02287582
1:49	10.18	28.7	35	3.88	2426.441	80.88138	11411.76471	475.490196	79.24836601
1:50	10.20	28.7	35	3.9	2434.407	81.1469	11470.58824	477.941176	79.65686275
1:51	10.11	28.7	35	3.81	2442.189	81.4063	11205.88235	466.911765	77.81862745
1:52	10.14	28.7	35	3.84	2450.032	81.66773	11294.11765	470.588235	78.43137255
1:53	10.17	28.7	35	3.87	2457.936	81.93121	11382.35294	474.264706	79.04411765
1:54	10.20	28.7	35	3.9	2465.902	82.19674	11470.58824	477.941176	79.65686275
1:55	10.08	28.7	35	3.78	2473.623	82.45409	11117.64706	463.235294	77.20588235
1:56	9.99	28.7	35	3.69	2481.159	82.70531	10852.94118	452.205882	75.36764706
1:57	9.95	28.7	35	3.65	2488.615	82.95382	10735.29412	447.303922	74.55065359
1:58	9.92	28.7	35	3.62	2496.008	83.20028	10647.05882	443.627451	73.9379085
1:59	9.92	28.7	35	3.62	2503.402	83.44674	10647.05882	443.627451	73.9379085
2:00	9.87	28.7	35	3.57	2510.694	83.68979	10500	437.5	72.91666667

Table A.2.9 Energy flows balancing from 2 PM to 3PM

Time PM	P_{solar} (est.) MW	CHP_{PG} MW	PL MW	$Ps_{storage}$ MW	ESD_{SOC} AH	% ESD_{SOC}	Charging current		Overload % (5 hr rating)
							Total	Each bank	
2:01	9.87	28.7	35	3.57	2526.603	84.2201	10500	437.5	72.91666667
2:02	9.82	28.7	35	3.52	2533.793	84.45975	10352.94118	431.372549	71.89542484
2:03	9.80	28.7	35	3.5	2540.941	84.69804	10294.11765	428.921569	71.4869281
2:04	9.74	28.7	35	3.44	2547.967	84.93225	10117.64706	421.568627	70.26143791
2:05	9.74	28.7	35	3.44	2554.994	85.16645	10117.64706	421.568627	70.26143791
2:06	9.77	28.7	35	3.47	2562.081	85.4027	10205.88235	425.245098	70.87418301
2:07	9.77	28.7	35	3.47	2569.168	85.63895	10205.88235	425.245098	70.87418301
2:08	9.75	28.7	35	3.45	2576.215	85.87383	10147.05882	422.794118	70.46568627
2:09	9.64	28.7	35	3.34	2583.037	86.10123	9823.529412	409.313725	68.21895425
2:10	9.61	28.7	35	3.31	2589.797	86.32658	9735.294118	405.637255	67.60620915
2:11	9.51	28.7	35	3.21	2596.354	86.54513	9441.176471	393.382353	65.56372549
2:12	9.50	28.7	35	3.2	2602.89	86.76299	9411.764706	392.156863	65.35947712
2:13	9.47	28.7	35	3.17	2609.364	86.97881	9323.529412	388.480392	64.74673203
2:14	9.58	28.7	35	3.28	2616.064	87.20213	9647.058824	401.960784	66.99346405
2:15	9.60	28.7	35	3.3	2622.804	87.4268	9705.882353	404.411765	67.40196078
2:16	9.56	28.7	35	3.26	2629.462	87.64875	9588.235294	399.509804	66.58496732
2:17	9.49	28.7	35	3.19	2635.978	87.86593	9382.352941	390.931373	65.15522876
2:18	9.39	28.7	35	3.09	2642.289	88.07631	9088.235294	378.676471	63.1127451
2:19	9.35	28.7	35	3.05	2648.519	88.28396	8970.588235	373.77451	62.29575163

Time PM	P$_{solar}$ (est.) MW	CHP$_{PG}$ MW	PL MW	Ps$_{torage}$ MW	ESD$_{SOC}$ AH	% ESD$_{SOC}$	Charging current		Overload % (5 hr rating)
							Total	Each bank	
2:20	9.39	28.7	35	3.09	2654.83	88.49434	9088.235294	378.676471	63.1127451
2:21	9.38	28.7	35	3.08	2661.121	88.70403	9058.823529	377.45098	62.90849673
2:22	9.31	28.7	35	3.01	2667.269	88.90896	8852.941176	368.872549	61.47875817
2:23	9.19	28.7	35	2.89	2673.172	89.10572	8500	354.166667	59.02777778
2:24	9.17	28.7	35	2.87	2679.034	89.30112	8441.176471	351.715686	58.61928105
2:25	9.22	28.7	35	2.92	2684.998	89.49992	8588.235294	357.843137	59.64052288
2:26	9.17	28.7	35	2.87	2690.86	89.69532	8441.176471	351.715686	58.61928105
2:27	9.10	28.7	35	2.8	2696.578	89.88595	8235.294118	343.137255	57.18954248
2:28	9.10	28.7	35	2.8	2702.297	90.07658	8235.294118	343.137255	57.18954248
2:29	9.06	28.7	35	2.76	2707.935	90.26449	8117.647059	338.235294	56.37254902
2:30	9.03	28.7	35	2.73	2713.511	90.45036	8029.411765	334.558824	55.75980392
2:31	9.02	28.7	35	2.72	2719.066	90.63554	8000	333.333333	55.55555556
2:32	8.99	28.7	35	2.69	2724.561	90.81868	7911.764706	329.656863	54.94281046
2:33	8.93	28.7	35	2.63	2729.932	90.99774	7735.294118	322.303922	53.71732026
2:34	8.93	28.7	35	2.63	2735.304	91.1768	7735.294118	322.303922	53.71732026
2:35	8.90	28.7	35	2.6	2740.614	91.35381	7647.058824	318.627451	53.10457516
2:36	8.83	28.7	35	2.53	2745.782	91.52606	7441.176471	310.04902	51.6748366
2:37	8.76	28.7	35	2.46	2750.806	91.69355	7235.294118	301.470588	50.24509804
2:38	8.73	28.7	35	2.43	2755.77	91.85899	7147.058824	297.794118	49.63235294
2:39	8.76	28.7	35	2.46	2760.794	92.02647	7235.294118	301.470588	50.24509804
2:40	8.73	28.7	35	2.43	2765.757	92.19191	7147.058824	297.794118	49.63235294
2:41	8.70	28.7	35	2.4	2770.659	92.35531	7058.823529	294.117647	49.01960784
2:42	8.65	28.7	35	2.35	2775.459	92.51531	6911.764706	287.990196	47.99836601
2:43	8.64	28.7	35	2.34	2780.239	92.67462	6882.352941	286.764706	47.79411765
2:44	8.60	28.7	35	2.3	2784.936	92.83121	6764.705882	281.862745	46.97712418
2:45	8.58	28.7	35	2.28	2789.593	92.98644	6705.882353	279.411765	46.56862745
2:46	8.55	28.7	35	2.25	2794.189	93.13963	6617.647059	275.735294	45.95588235
2:47	8.55	28.7	35	2.25	2798.784	93.29281	6617.647059	275.735294	45.95588235
2:48	8.51	28.7	35	2.21	2803.298	93.44328	6500	270.833333	45.13888889
2:49	8.49	28.7	35	2.19	2807.771	93.59238	6441.176471	268.382353	44.73039216
2:50	8.43	28.7	35	2.13	2812.122	93.73739	6264.705882	261.029412	43.50490196
2:51	8.37	28.7	35	2.07	2816.35	93.87832	6088.235294	253.676471	42.27941176
2:52	8.32	28.7	35	2.02	2820.476	94.01585	5941.176471	247.54902	41.25816993
2:53	8.31	28.7	35	2.01	2824.581	94.1527	5911.764706	246.323529	41.05392157
2:54	8.29	28.7	35	1.99	2828.645	94.28818	5852.941176	243.872549	40.64542484
2:55	8.29	28.7	35	1.99	2832.71	94.42367	5852.941176	243.872549	40.64542484
2:56	8.21	28.7	35	1.91	2836.611	94.55371	5617.647059	234.068627	39.01143791
2:57	8.15	28.7	35	1.85	2840.39	94.67966	5441.176471	226.715686	37.78594771
2:58	8.14	28.7	35	1.84	2844.148	94.80493	5411.764706	225.490196	37.58169935
2:59	8.09	28.7	35	1.79	2847.804	94.9268	5264.705882	219.362745	36.56045752
3:00	8.04	28.7	35	1.74	2851.358	95.04526	5117.647059	213.235294	35.53921569

Table A.2.10 Energy flows balancing from 3 PM to 4PM

Time PM	P$_{solar}$ (est.) MW	CHP$_{PG}$ MW	PL MW	Ps$_{torage}$ MW	ESD$_{SOC}$ AH	% ESD$_{SOC}$	Charging current		Overload % (5 hr rating)
							Total	Each bank	
3:01	8.01	28.7	35	1.71	2860.385	95.34616	5029.411765	209.558824	34.92647059
3:02	7.97	28.7	35	1.67	2863.796	95.45985	4911.764706	204.656863	34.10947712
3:03	7.92	28.7	35	1.62	2867.104	95.57015	4764.705882	198.529412	33.08823529
3:04	7.88	28.7	35	1.58	2870.332	95.67772	4647.058824	193.627451	32.27124183
3:05	7.84	28.7	35	1.54	2873.477	95.78257	4529.411765	188.72549	31.45424837
3:06	7.81	28.7	35	1.51	2876.561	95.88537	4441.176471	185.04902	30.84150327
3:07	7.79	28.7	35	1.49	2879.604	95.98681	4382.352941	182.598039	30.43300654
3:08	7.76	28.7	35	1.46	2882.586	96.08622	4294.117647	178.921569	29.82026144

Time PM	P_{solar} (est.) MW	CHP_{PG} MW	PL MW	Ps_{torage} MW	ESD_{SOC} AH	% ESD_{SOC}	Charging current		Overload % (5 hr rating)
							Total	Each bank	
3:09	7.70	28.7	35	1.4	2885.446	96.18153	4117.647059	171.568627	28.59477124
3:10	7.67	28.7	35	1.37	2888.244	96.2748	4029.411765	167.892157	27.98202614
3:11	7.65	28.7	35	1.35	2891.001	96.36672	3970.588235	165.441176	27.57352941
3:12	7.61	28.7	35	1.31	2893.677	96.45591	3852.941176	160.539216	26.75653595
3:13	7.59	28.7	35	1.29	2896.312	96.54373	3794.117647	158.088235	26.34803922
3:14	7.53	28.7	35	1.23	2898.824	96.62747	3617.647059	150.735294	25.12254902
3:15	7.47	28.7	35	1.17	2901.214	96.70713	3441.176471	143.382353	23.89705882
3:16	7.43	28.7	35	1.13	2903.522	96.78406	3323.529412	138.480392	23.08006536
3:17	7.39	28.7	35	1.09	2905.748	96.85827	3205.882353	133.578431	22.2630719
3:18	7.33	28.7	35	1.03	2907.852	96.9284	3029.411765	126.22549	21.0375817
3:19	7.26	28.7	35	0.96	2909.813	96.99376	2823.529412	117.647059	19.60784314
3:20	7.24	28.7	35	0.94	2911.733	97.05776	2764.705882	115.196078	19.19934641
3:21	7.18	28.7	35	0.88	2913.53	97.11767	2588.235294	107.843137	17.97385621
3:22	7.11	28.7	35	0.81	2915.185	97.17282	2382.352941	99.2647059	16.54411765
3:23	7.06	28.7	35	0.76	2916.737	97.22456	2235.294118	93.1372549	15.52287582
3:24	7.05	28.7	35	0.75	2918.269	97.27562	2205.882353	91.9117647	15.31862745
3:25	6.98	28.7	35	0.68	2919.658	97.32192	2000	83.3333333	13.88888889
3:26	6.97	28.7	35	0.67	2921.026	97.36753	1970.588235	82.1078431	13.68464052
3:27	6.96	28.7	35	0.66	2922.374	97.41247	1941.176471	80.8823529	13.48039216
3:28	6.95	28.7	35	0.65	2923.702	97.45672	1911.764706	79.6568627	13.27614379
3:29	6.90	28.7	35	0.6	2924.927	97.49757	1764.705882	73.5294118	12.25490196
3:30	6.83	28.7	35	0.53	2926.01	97.53366	1558.823529	64.9509804	10.8251634
3:31	6.82	28.7	35	0.52	2927.072	97.56906	1529.411765	63.7254902	10.62091503
3:32	6.77	28.7	35	0.47	2928.032	97.60106	1382.352941	57.5980392	9.599673203
3:33	6.73	28.7	35	0.43	2928.91	97.63033	1264.705882	52.6960784	8.782679739
3:34	6.69	28.7	35	0.39	2929.707	97.65689	1147.058824	47.7941176	7.965686275
3:35	6.62	28.7	35	0.32	2930.36	97.67867	941.1764706	39.2156863	6.535947712
3:36	6.56	28.7	35	0.26	2930.891	97.69637	764.7058824	31.8627451	5.310457516
3:37	6.51	28.7	35	0.21	2931.32	97.71067	617.6470588	25.7352941	4.289215686
3:38	6.46	28.7	35	0.16	2931.647	97.72156	470.5882353	19.6078431	3.267973856
3:39	6.39	28.7	35	0.09	2931.831	97.72769	264.7058824	11.0294118	1.838235294
3:40	6.35	28.7	35	0.05	2931.933	97.7311	147.0588235	6.12745098	1.02124183
3:41	6.30	28.7	35	0	2931.933	97.7311	0	0	0
3:42	6.26	28.74	35	0	2931.933	97.7311	0	0	0
3:43	6.21	28.79	35	0	2931.933	97.7311	0	0	0
3:44	6.18	28.82	35	0	2931.933	97.7311	0	0	0
3:45	6.14	28.86	35	0	2931.933	97.7311	0	0	0
3:46	6.14	28.86	35	0	2931.933	97.7311	0	0	0
3:47	6.12	28.88	35	0	2931.933	97.7311	0	0	0
3:48	6.06	28.94	35	0	2931.933	97.7311	0	0	0
3:49	6.00	29	35	0	2931.933	97.7311	0	0	0
3:50	5.99	29.01	35	0	2931.933	97.7311	0	0	0
3:51	5.96	29.04	35	0	2931.933	97.7311	0	0	0
3:52	5.89	29.11	35	0	2931.933	97.7311	0	0	0
3:53	5.85	29.15	35	0	2931.933	97.7311	0	0	0
3:54	5.82	29.18	35	0	2931.933	97.7311	0	0	0
3:55	5.77	29.23	35	0	2931.933	97.7311	0	0	0
3:56	5.71	29.29	35	0	2931.933	97.7311	0	0	0
3:57	5.69	29.31	35	0	2931.933	97.7311	0	0	0
3:58	5.63	29.37	35	0	2931.933	97.7311	0	0	0
3:59	5.58	29.42	35	0	2931.933	97.7311	0	0	0
4:00	5.55	29.45	35	0	2931.933	97.7311	0	0	0

Table A.2.11 Energy flows balancing from 4 PM to 5PM

Time PM	P_{solar} (est.) MW	CHP_{PG} MW	PL MW	Ps_{torage} MW	ESD_{SOC} AH	% ESD_{SOC}	Charging current		Overload % (5 hr rating)
							Total	Each bank	
4:01	5.51	29.45	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:02	5.46	29.49	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:03	5.41	29.54	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:04	5.39	29.59	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:05	5.34	29.61	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:06	5.27	29.66	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:07	5.24	29.73	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:08	5.20	29.76	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:09	5.13	29.8	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:10	5.07	29.87	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:11	5.03	29.93	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:12	4.95	29.97	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:13	4.88	30.05	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:14	4.82	30.12	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:15	4.76	30.18	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:16	4.70	30.24	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:17	4.66	30.3	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:18	4.63	30.34	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:19	4.61	30.37	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:20	4.57	30.39	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:21	4.53	30.43	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:22	4.28	30.47	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:23	4.46	30.72	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:24	4.38	30.54	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:25	4.35	30.62	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:26	4.28	30.65	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:27	4.25	30.72	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:28	4.20	30.75	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:29	4.16	30.8	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:30	3.59	30.84	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:31	3.78	31.41	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:32	3.78	31.22	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:33	3.93	31.22	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:34	3.92	31.07	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:35	3.86	31.08	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:36	3.81	31.14	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:37	3.78	31.19	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:38	3.73	31.22	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:39	3.68	31.27	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:40	3.62	31.32	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:41	3.56	31.38	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:42	3.50	31.44	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:43	3.46	31.5	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:44	3.40	31.54	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:45	2.93	31.6	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:46	3.32	32.07	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:47	3.27	31.68	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:48	3.20	31.73	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:49	3.15	31.8	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:50	3.07	31.85	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:51	3.00	31.93	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:52	2.94	32	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:53	2.92	32.06	35	0.00	2931.933	97.7311	0.00	0.00	0.00

Time PM	P_{solar} (est.) MW	CHP_{PG} MW	PL MW	Ps_{torage} MW	ESD_{SOC} AH	% ESD_{SOC}	Charging current		Overload % (5 hr rating)
							Total	Each bank	
4:54	2.84	32.08	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:55	2.77	32.16	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:56	2.72	32.23	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:57	2.65	32.28	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:58	2.59	32.35	35	0.00	2931.933	97.7311	0.00	0.00	0.00
4:59	2.54	32.41	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:00	2.47	32.46	35	0.00	2931.933	97.7311	0.00	0.00	0.00

Table A.2.12 Energy flows balancing from 5 PM to 6PM

Time PM	P_{solar} (est.) MW	CHP_{PG} MW	PL MW	Ps_{torage} MW	ESD_{SOC} AH	% ESD_{SOC}	Charging current		Overload % (5 hr rating)
							Total	Each bank	
5:01	2.38	32.53	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:02	2.35	32.62	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:03	2.27	32.65	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:04	2.23	32.73	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:05	2.20	32.77	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:06	2.15	32.8	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:07	2.10	32.85	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:08	2.05	32.9	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:09	2.00	32.95	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:10	1.93	33	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:11	1.88	33.07	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:12	1.84	33.12	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:13	1.78	33.16	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:14	1.70	33.22	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:15	1.62	33.3	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:16	1.55	33.38	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:17	1.48	33.45	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:18	1.43	33.52	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:19	1.37	33.57	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:20	1.08	33.63	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:21	0.77	33.92	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:22	0.57	34.23	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:23	0.56	34.43	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:24	0.54	34.44	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:25	0.52	34.46	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:26	0.50	34.48	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:27	0.48	34.5	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:28	0.46	34.52	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:29	0.44	34.54	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:30	0.43	34.56	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:31	0.41	34.57	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:32	0.40	34.59	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:33	0.38	34.6	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:34	0.37	34.62	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:35	0.35	34.63	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:36	0.34	34.65	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:37	0.33	34.66	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:38	0.35	34.67	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:39	0.35	34.65	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:40	0.36	34.65	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:41	0.36	34.64	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:42	0.34	34.64	35	0.00	2931.933	97.7311	0.00	0.00	0.00

Time PM	P_{solar} (est.) MW	CHP_{PG} MW	PL MW	Ps_{torage} MW	ESD_{SOC} AH	% ESD_{SOC}	Charging current		Overload % (5 hr rating)
							Total	Each bank	
5:43	0.27	34.66	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:44	0.22	34.73	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:45	0.19	34.78	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:46	0.17	34.81	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:47	0.16	34.83	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:48	0.14	34.84	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:49	0.13	34.86	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:50	0.11	34.87	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:51	0.09	34.89	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:52	0.08	34.91	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:53	0.06	34.92	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:54	0.05	34.94	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:55	0.04	34.95	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:56	0.03	34.96	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:57	0.02	34.97	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:58	0.01	34.98	35	0.00	2931.933	97.7311	0.00	0.00	0.00
5:59	0.00	34.99	35	0.00	2931.933	97.7311	0.00	0.00	0.00
6:00	0.00	35	35	0.00	2931.933	97.7311	0.00	0.00	0.00

A.3 MATLAB PROGRAM TO ESTIMATE BEP

The MATLAB simulation code developed based on algorithm heuristic forward approach algorithm is indicated below.

```
N = N+1
While N<13;
SGFi = TGFi + 0.7 * HPPRDSFi + 0.7 * LPPRDSFi
BFWFi = 1.005*SGFi
LPSTC=LPPSFi-LPEXFi
CEPFi = LPSTC
DPSFi = 0.08* SGFi
DMWFi= [BFWFi - (170 + DPSFi + CEPFi)]
HRi=1/EGi* [(37250+794*TGFi + 33*DMWFi) - (747*HPEXFi + 694 *LPEXFi + 158*BFWFi)]
SRi   = HRi / 630
GIM2i = GIMi +1
EG2i = EGi -1
TGF2i = TGFi - 0.40* SRi
HPPSF2i =TGF2i
X= HPPSF2i - HPEXFi- 1.0 *SRi
if  X>60 LPPSF2i = X
else LPPSF2i = 60
end
if  X> 60 HPEXF2i = HPEXFi
else HPEXF2i = HPEXFi - [60-(TGF2i - HPEXFi)]
end
HPPRDSF2i = HPPRDSFi + (HPEXFi - HPEXF2i)
DOHPPRDSF2i = HPPRDSF2i - HPPRDSFi
if  LPSTC < 45 ALPEXF2i =0
else ALPEXF2i=[(0.50*LPPSF2i)-22.5]
end
W= [ALPEXF2i  LPEXFi]
LPEXF2i= min (W)
LPPRDSF2i = LPPRDSFi + (LPEXFi- LPEXF2i)
DOLPPRDSF2i = LPPRDSF2i - LPPRDSFi
U= [(SRi* DOLPPRDSF2i*0.163) + (SRi* DOHPPRDSF2i*0.224)]
TGF3i=TGF2i -1.10* U
SGF2i = TGF3i + 0.7*HPPRDSF2i+ 0.7*LPPRDSF2i
if  SGF2i < 320, SGFP1=SGFi-320
SGFP2=320-SGF2i
SGFR=SGFP1+SGFP2
SGFQ1=SGFP1/SGFR
```

```
SGFQ2=SGFP2/SGFR
Q1= [SGFQ1   SGFQ2]
SGFQ=max (Q1)
BEPSGFY = GIMi + SGFQ
BEPSGFN = 13
else BEPSGFY = 13
    BEPSGFN = 13
end
PLHPX2i = 0.0561 *DOHPPRDSF2i
PLLPX2i = 0.1183 *DOLPPRDSF2i
PLTX2i= (PLHPX2i+ PLLPX2i)
if  PLTX2i  > 0.35  TPL1=0.35-PLTXi
TPL2=PLHPX2i-0.35
TPLR=TPL1+TPL2
TPLQ1=TPL1/TPLR
TPLQ2=TPL2/TPLR
Q2= [TPLQ1   TPLQ2]
TPLQ=max (Q2)
BEPTPLY = GIMi + TPLQ
BEPTPLN = 13
else  BEPTPLY = 13
BEPTPLN = 13
end
A= [BEPSGFY BEPTPLY BEPSGFN BEPTPLN]
BEP = min (A)
if  BEP< 12,
break
end
TGFi=TGF3i, HPEXFi=HPEXF2i, LPEXFi=LPEXF2i, HPPRDSFi=HPPRDSF2i, LPPRDSFi=LPPRDSF2i,
EGi=EG2i, GIMi=GIM2i, LPPSFi=LPPSF2i
N = N+1
End
```

A.3.1 Two SG& Two TG Operation during 100 % of process plant operation

The initial values of variables during Two SG and Two TG operation (100% of process plant in service) are,
TGFi=330, HPEXFi=210, LPEXFi=35, HPPRDSFi=0, LPPRDSFi=0, EGi=31, GIMi=0, N=0, LPPSFi=120

The output data generated on simulation is tabulated

TGFi = 330	BEP = 13	BEP = 13	BEP = 13
HPEXFi = 210	TGFi = 328.6202	TGFi = 326.7955	TGFi = 324.7297
LPEXFi = 35	HPEXFi = 210	HPEXFi = 210	HPEXFi = 210
HPPRDSFi = 0	LPEXFi = 35	LPEXFi = 34.3431	LPEXFi = 33.3760
LPPRDSFi = 0	HPPRDSFi = 0	HPPRDSFi = 0	HPPRDSFi = 0
EGi = 31	LPPRDSFi = 0	LPPRDSFi = 0.6569	LPPRDSFi = 1.6240
GIMi = 0	EGi = 30	EGi = 29	EGi = 28
N = 0	GIMi = 1	GIMi = 2	GIMi = 3
LPPSFi = 120	LPPSFi = 115.1708	LPPSFi = 113.6863	LPPSFi = 111.7519
N = 1	N = 2	N = 3	N = 4
SGFi = 330	SGFi = 328.6202	SGFi = 327.2553	SGFi = 325.8666
BFWFi = 331.6500	BFWFi = 330.2633	BFWFi = 328.8915	BFWFi = 327.4959
LPSTC = 85	LPSTC = 80.1708	LPSTC = 79.3431	LPSTC = 78.3760
CEPFi = 85	CEPFi = 80.1708	CEPFi = 79.3431	CEPFi = 78.3760
DPSFi = 26.4000	DPSFi = 26.2896	DPSFi = 26.1804	DPSFi = 26.0693
DMWFi = 50.2500	DMWFi = 53.8029	DMWFi = 53.3680	DMWFi = 53.0506
HRi = 2.1731e+03	HRi = 2.2203e+03	HRi = 2.2696e+03	HRi = 2.3235e+03
SRi = 3.4494	SRi = 3.5243	SRi = 3.6025	SRi = 3.6881
GIM2i = 1	GIM2i = 2	GIM2i = 3	GIM2i = 4
EG2i = 30	EG2i = 29	EG2i = 28	EG2i = 27
TGF2i = 328.6202	TGF2i = 327.2105	TGF2i = 325.3545	TGF2i = 323.2545
HPPSF2i = 328.6202	HPPSF2i = 327.2105	HPPSF2i = 325.3545	HPPSF2i = 323.2545
X = 115.1708	X = 113.6863	X = 111.7519	X = 109.5663
LPPSF2i = 115.1708	LPPSF2i = 113.6863	LPPSF2i = 111.7519	LPPSF2i = 109.5663
HPEXF2i = 210	HPEXF2i = 210	HPEXF2i = 210	HPEXF2i = 210
HPPRDSF2i = 0	HPPRDSF2i = 0	HPPRDSF2i = 0	HPPRDSF2i = 0
DOHPPRDSF2i = 0	DOHPPRDSF2i = 0	DOHPPRDSF2i = 0	DOHPPRDSF2i = 0
ALPEXF2i = 35.0854	ALPEXF2i = 34.3431	ALPEXF2i = 33.3760	ALPEXF2i = 32.2832
W = 35.0854 35.0000	W = 34.3431 35.0000	W = 33.3760 34.3431	W = 32.2832 33.3760
LPEXF2i = 35	LPEXF2i = 34.3431	LPEXF2i = 33.3760	LPEXF2i = 32.2832
LPPRDSF2i = 0	LPPRDSF2i = 0.6569	LPPRDSF2i = 1.6240	LPPRDSF2i = 2.7168
DOLPPRDSF2i = 0	DOLPPRDSF2i = 0.6569	DOLPPRDSF2i = 0.9672	DOLPPRDSF2i = 1.0928
U = 0	U = 0.3773	U = 0.5679	U = 0.6570
TGF3i = 328.6202	TGF3i = 326.7955	TGF3i = 324.7297	TGF3i = 322.5318
SGF2i = 328.6202	SGF2i = 327.2553	SGF2i = 325.8666	SGF2i = 324.4336
BEPSGFY = 13	BEPSGFY = 13	BEPSGFY = 13	BEPSGFY = 13
BEPSGFN = 13	BEPSGFN = 13	BEPSGFN = 13	BEPSGFN = 13
PLHPX2i = 0	PLHPX2i = 0	PLHPX2i = 0	PLHPX2i = 0
PLLPX2i = 0	PLLPX2i = 0.0777	PLLPX2i = 0.1144	PLLPX2i = 0.1293
PLTX2i = 0	PLTX2i = 0.0777	PLTX2i = 0.1144	PLTX2i = 0.1293
BEPTPLY = 13	BEPTPLY = 13	BEPTPLY = 13	BEPTPLY = 13
BEPTPLN = 13	BEPTPLN = 13	BEPTPLN = 13	BEPTPLN = 13
A = 13 13 13 13	A = 13 13 13 13	A = 13 13 13 13	A = 13 13 13 13

BEP = 13	BEP = 13	BEP = 13	BEPSGFN = 13
TGFi = 322.5318	TGFi = 320.2318	TGFi = 317.8344	PLHPX2i = 0
HPEXFi = 210	HPEXFi = 210	HPEXFi = 210	PLLPX2i = 0.1503
LPEXFi = 32.2832	LPEXFi = 31.1202	LPEXFi = 29.9021	PLTX2i = 0.1503
HPPRDSFi = 0	HPPRDSFi = 0	HPPRDSFi = 0	BEPTPLY = 13
LPPRDSFi = 2.7168	LPPRDSFi = 3.8798	LPPRDSFi = 5.0979	BEPTPLN = 13
EGi = 27	EGi = 26	EGi = 25	A = 6.8718 13.0 13.0 13.0
GIMi = 4	GIMi = 5	GIMi = 6	BEP = 6.8718
LPPSFi = 109.5663	LPPSFi = 107.2403	LPPSFi = 104.8043	
N = 5	N = 6	N = 7	
SGFi = 324.4336	SGFi = 322.9477	SGFi = 321.4029	
BFWFi = 326.0558	BFWFi = 324.5624	BFWFi = 323.0099	
LPSTC = 77.2832	LPSTC = 76.1202	LPSTC = 74.9021	
CEPFi = 77.2832	CEPFi = 76.1202	CEPFi = 74.9021	
DPSFi = 25.9547	DPSFi = 25.8358	DPSFi = 25.7122	
DMWFi = 52.8179	DMWFi = 52.6065	DMWFi = 52.3956	
HRi = 2.3812e+03	HRi = 2.4424e+03	HRi = 2.5073e+03	
SRi = 3.7797	SRi = 3.8768	SRi = 3.9798	
GIM2i = 5	GIM2i = 6	GIM2i = 7	
EG2i = 26	EG2i = 25	EG2i = 24	
TGF2i = 321.0200	TGF2i = 318.6811	TGF2i = 316.2425	
HPPSF2i = 321.0200	HPPSF2i = 318.6811	HPPSF2i = 316.2425	
X = 107.2403	X = 104.8043	X = 102.2627	
LPPSF2i = 107.2403	LPPSF2i = 104.8043	LPPSF2i = 102.2627	
HPEXF2i = 210	HPEXF2i = 210	HPEXF2i = 210	
HPPRDSF2i = 0	HPPRDSF2i = 0	HPPRDSF2i = 0	
DOHPPRDSF2i = 0	DOHPPRDSF2i = 0	DOHPPRDSF2i = 0	
ALPEXF2i = 31.1202	ALPEXF2i = 29.9021	ALPEXF2i = 28.6314	
W = 31.1202 32.2832	W = 29.9021 31.1202	W = 28.6314 29.9021	
LPEXF2i = 31.1202	LPEXF2i = 29.9021	LPEXF2i = 28.6314	
LPPRDSF2i = 3.8798	LPPRDSF2i = 5.0979	LPPRDSF2i = 6.3686	
DOLPPRDSF2i = 1.1630	DOLPPRDSF2i = 1.2180	DOLPPRDSF2i = 1.2708	
U = 0.7165	U = 0.7697	U = 0.8244	
TGF3i = 320.2318	TGF3i = 317.8344	TGF3i = 315.3357	
SGF2i = 322.9477	SGF2i = 321.4029	SGF2i = 319.7938	
BEPSGFY = 13	BEPSGFY = 13	SGFP1 = 1.4029	
BEPSGFN = 13	BEPSGFN = 13	SGFP2 = 0.2062	
PLHPX2i = 0	PLHPX2i = 0	SGFR = 1.6092	
PLLPX2i = 0.1376	PLLPX2i = 0.1441	SGFQ1 = 0.8718	
PLTX2i = 0.1376	PLTX2i = 0.1441	SGFQ2 = 0.1282	
BEPTPLY = 13	BEPTPLY = 13	Q1 = 0.8718 0.1282	
BEPTPLN = 13	BEPTPLN = 13	SGFQ = 0.8718	
A = 13 13 13 13	A = 13 13 13 13	BEPSGFY = 6.8718	

A.3.2 One SG & One TG Operation during 50 % of process plant operation

The initial values of variables during One SG and One TG operation (50% of process plant in service) are,

TGFi=172, HPEXFi=100, LPEXFi=10, HPPRDSFi=0, LPPRDSFi=10, EGi=19, GIMi=0, N=0, LPPSFi=72

The output data generated on simulation is tabulated

TGFi = 172
HPEXFi = 100
LPEXFi = 10
HPPRDSFi = 0
LPPRDSFi = 10
EGi = 19
GIMi = 0
N = 0
LPPSFi = 72
N = 1
SGFi = 179
BFWFi = 179.8950
LPSTC = 62
CEPFi = 62
DPSFi = 14.3200
DMWFi = 18.5750
HRi = 2.4075e+03
SRi = 3.8214
GIM2i = 1
EG2i = 18
TGF2i = 170.4714
HPPSF2i = 170.4714
X = 66.6500
LPPSF2i = 66.6500
HPEXF2i = 100
HPPRDSF2i = 0
DOHPPRDSF2i = 0
ALPEXF2i = 10.8250
W = 10.8250   10.0000
LPEXF2i = 10
LPPRDSF2i = 10
DOLPPRDSF2i = 0
U = 0
TGF3i = 170.4714
SGF2i = 177.4714
BEPSGFY = 13
BEPSGFN = 13
PLHPX2i = 0
PLLPX2i = 0
PLTX2i = 0
PLTXi = 1.1830
BEPTPLY = 13
BEPTPLN = 13
A = 13 13 13 13
BEP = 13
TGFi = 170.4714
HPEXFi = 100
LPEXFi = 10
HPPRDSFi = 0
LPPRDSFi = 10
EGi = 18
GIMi = 1
LPPSFi = 66.6500
N = 2
SGFi = 177.4714
BFWFi = 178.3588
LPSTC = 56.6500
CEPFi = 56.6500
DPSFi = 14.1977
DMWFi = 22.5111
HRi = 2.4945e+03
SRi = 3.9596
GIM2i = 2
EG2i = 17
TGF2i = 168.8876
HPPSF2i = 168.8876
X = 64.9280
LPPSF2i = 64.9280
HPEXF2i = 100
HPPRDSF2i = 0
DOHPPRDSF2i = 0
ALPEXF2i = 9.9640
W = 9.9640   10.0000
LPEXF2i = 9.9640
LPPRDSF2i = 10.0360
DOLPPRDSF2i = 0.0360
U = 0.0232
TGF3i = 168.8621
SGF2i = 175.8872
BEPSGFY = 13
BEPSGFN = 13
PLHPX2i = 0
PLLPX2i = 0.0043
PLTX2i = 0.0043
PLTXi = 1.1830
BEPTPLY = 13
BEPTPLN = 13
A = 13 13 13 13
BEP = 13
TGFi = 168.8621
HPEXFi = 100
LPEXFi = 9.9640
HPPRDSFi = 0
LPPRDSFi = 10.0360
EGi = 17
GIMi = 2
LPPSFi = 64.9280
N = 3
SGFi = 175.8872
BFWFi = 176.7667
LPSTC = 54.9640
CEPFi = 54.9640
DPSFi = 14.0710
DMWFi = 22.7317
HRi = 2.5828e+03
SRi = 4.0997
GIM2i = 3
EG2i = 16
TGF2i = 167.2222
HPPSF2i = 167.2222
X = 63.1225
LPPSF2i = 63.1225
HPEXF2i = 100
HPPRDSF2i = 0
DOHPPRDSF2i = 0
ALPEXF2i = 9.0613
W = 9.0613   9.9640
LPEXF2i = 9.0613
LPPRDSF2i = 10.9387
DOLPPRDSF2i = 0.9028
U = 0.6033
TGF3i = 166.5586
SGF2i = 174.2157
BEPSGFY = 13
BEPSGFN = 13
PLHPX2i = 0
PLLPX2i = 0.1068
PLTX2i = 0.1068
PLTXi = 1.1873
BEPTPLY = 13
BEPTPLN = 13
A = 13 13 13 13
BEP = 13
TGFi = 166.5586
HPEXFi = 100
LPEXFi = 9.0613
HPPRDSFi = 0
LPPRDSFi = 10.9387
EGi = 16
GIMi = 3
LPPSFi = 63.1225
N = 4
SGFi = 174.2157
BFWFi = 175.0868
LPSTC = 54.0613
CEPFi = 54.0613
DPSFi = 13.9373
DMWFi = 22.0883

HRi = 2.6843e+03	DMWFi = 21.7015	DPSFi = 13.7077	CEPFi = 49.8112
SRi = 4.2608	HRi = 2.7985e+03	DMWFi = 22.1600	DPSFi = 13.5163
GIM2i = 4	SRi = 4.4420	HRi = 2.9358e+03	DMWFi = 21.4708
EG2i = 15	GIM2i = 5	SRi = 4.6600	HRi = 3.0698e+03
TGF2i = 164.8543	EG2i = 14	GIM2i = 6	SRi = 4.8727
HPPSF2i = 164.8543	TGF2i = 162.1114	EG2i = 13	GIM2i = 7
X = 60.5934	HPPSF2i = 162.1114	TGF2i = 161.3938	EG2i = 12
LPPSF2i = 60.5934	X = 57.6693	HPPSF2i = 161.3938	TGF2i = 157.3480
HPEXF2i = 100	LPPSF2i = 57.6693	X = 54.6224	HPPSF2i = 157.3480
HPPRDSF2i = 0	HPEXF2i = 102.1114	LPPSF2i = 54.6224	X = 51.0815
DOHPPRDSF2i = 0	HPPRDSF2i = -2.1114	HPEXF2i = 101.3938	LPPSF2i = 51.0815
ALPEXF2i = 7.7967	DOHPPRDSF2i = -2.1114	HPPRDSF2i = -1.3938	HPEXF2i = 97.3480
W = 7.7967 9.0613	ALPEXF2i = 6.3347	DOHPPRDSF2i = 0.7175	HPPRDSF2i = 2.6520
LPEXF2i = 7.7967	W = 6.3347 7.7967	ALPEXF2i = 4.8112	DOHPPRDSF2i = 4.0459
LPPRDSF2i = 12.2033	LPEXF2i = 6.3347	W = 4.8112 6.3347	ALPEXF2i = 3.0407
DOLPPRDSF2i = 1.2645	LPPRDSF2i = 13.6653	LPEXF2i = 4.8112	W = 3.0407 4.8112
U = 0.8782	DOLPPRDSF2i = 1.4620	LPPRDSF2i = 15.1888	LPEXF2i = 3.0407
TGF3i = 163.8882	U = -1.0423	DOLPPRDSF2i = 1.5235	LPPRDSF2i = 16.9593
SGF2i = 172.4305	TGF3i = 163.2579	U = 1.9062	DOLPPRDSF2i = 1.7705
BEPSGFY = 13	SGF2i = 171.3456	TGF3i = 159.2970	U = 5.8222
BEPSGFN = 13	BEPSGFY = 13	SGF2i = 168.9535	TGF3i = 150.9436
PLHPX2i = 0	BEPSGFN = 13	BEPSGFY = 13	SGF2i = 164.6715
PLLPX2i = 0.1496	PLHPX2i = -0.1184	BEPSGFN = 13	BEPSGFY = 13
PLTX2i = 0.1496	PLLPX2i = 0.1730	PLHPX2i = 0.0403	BEPSGFN = 13
PLTXi = 1.2941	PLTX2i = 0.0545	PLLPX2i = 0.1802	PLHPX2i = 0.2270
BEPTPLY = 13	PLTXi = 1.4436	PLTX2i = 0.2205	PLLPX2i = 0.2094
BEPTPLN = 13	BEPTPLY = 13	PLTXi = 1.4982	PLTX2i = 0.4364
A = 13 13 13 13	BEPTPLN = 13	BEPTPLY = 13	PLTXi = 1.7186
BEP = 13	A = 13 13 13 13	BEPTPLN = 13	TPL1 = -1.3686
TGFi = 163.8882	BEP = 13	A = 13 13 13 13	TPL2 = -0.1230
HPEXFi = 100	TGFi = 163.2579	BEP = 13	TPLR = -1.4917
LPEXFi = 7.7967	HPEXFi = 102.1114	TGFi = 159.2970	TPLQ1 = 0.9175
HPPRDSFi = 0	LPEXFi = 6.3347	HPEXFi = 101.3938	TPLQ2 = 0.0825
LPPRDSFi = 12.2033	HPPRDSFi = -2.1114	LPEXFi = 4.8112	Q2 = 0.9175 0.0825
EGi = 15	LPPRDSFi = 13.6653	HPPRDSFi = -1.3938	TPLQ = 0.9175
GIMi = 4	EGi = 14	LPPRDSFi = 15.1888	BEPTPLY = 6.9175
LPPSFi = 60.5934	GIMi = 5	EGi = 13	BEPTPLN = 13
N = 5	LPPSFi = 57.6693	GIMi = 6	A = 13.0 6.9175 13.0 13.0
SGFi = 172.4305	N = 6	LPPSFi = 54.6224	BEP = 6.9175
BFWFi = 173.2926	SGFi = 171.3456	N = 7	
LPSTC = 52.7967	BFWFi = 172.2024	SGFi = 168.9535	
CEPFi = 52.7967	LPSTC = 51.3347	BFWFi = 169.7983	
DPSFi = 13.7944	CEPFi = 51.3347	LPSTC = 49.8112	

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