Optimal Planning and Operation of CHP within Micro Energy Grids

By

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A thesis submitted to the
Faculty of Graduate and Postdoctoral Affairs
in partial fulfillment of the requirements for the degree of
Master of Applied Science in Engineering

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April, 2016,

Acknowledgments

I would like to thank and offer my sincerest gratitude to my thesis supervisor, Dr. Hossam A. Gabbar, for his encouragement, supervision and support. I cannot imagine having any better advisor for my thesis regarding his knowledge, perceptiveness, and encouragement.

In addition, I would like to thank Dr. Aboelsood Zidan for his technical guidance.

I am indebted, forever, to my family members for their patience, understanding, and endless encouragement during the course of this study.

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Oshawa, Ontario, Canada
February, 2016

Abstract

In this study, an optimal planning with respect to capacity sizes and types of prime movers for CHP systems within micro energy grids has been discussed. The objective is to minimize the total net present cost, carbon dioxide (CO_2) emission, and mono-nitrogen oxides (NO_x) emission for a certain load (electrical or heat) condition. A multi-objective GA (genetic algorithm) was applied to solve the planning problem in order to optimize CHP prime mover types and capacities. Costs, emissions, and efficiencies of CHP prime movers depend on their types, capacity range, and part-load performance. Four candidate CHP prime mover technologies with different characteristics are involved in this study which are; internal combustion engine (ICE), gas turbine (GT), fuel cell (FC), and Stirling engine (SE). The surplus/deficient electricity can possibly be sold to/bought from the main electrical grid, while the remaining heat demand is met from the conventional natural gas based heating units. The approach was applied to four different load type including a typical micro energy grid system as a case study, and the effectiveness of the proposed method was verified. Moreover, a hybrid operational planning algorithm (to maximize primary resource utilization or minimize running cost operation) for CHP prime mover in micro energy grids (MEGs) has been introduced. The proposed operational planning algorithm has been compared with conventional heat and thermal load following modes of operation. The results found the study are very much dependent on the load (heat and electrical) of the system. However, in almost all the scenarios discussed in the study, proposed system with CHP technologies having optimum sizing results is a significant economic and environmental benefit over the conventional energy infrastructure. It is found that, with optimal capacity of PMs, return on investment of the CHP system could be as high as 13% which leads to a payback period of only 7.8 years. Similarly, with the proposed capacity planning tool, maximum achievable CO_2 and NOx emission reduction were 15% and 61% respectively. Moreover, from the case studies it is also seen that, proposed hybrid load following modes were consistently able to maximize PM efficiency and minimize system cost during operation.

Keyword: CHP, Internal Combustion Engine, Fuel Cell, Gas Turbine, Stirling Engine, Genetic Algorithm, Micro Energy Grid, Planning, Operation.

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Nomenclature

P_{LEE}	$\frac{Electrical\ Efficiency\ at\ certain\ load}{Rated\ Electrical\ Efficiency}$
P_{LHE}	$\frac{Heat\ Efficiency\ at\ certain\ load}{Rated\ Heat\ Efficiency}$
P_{ELR}	$\frac{Electrical\ Load}{Rated\ Electrical\ Capacity}$; 0<PELR<1
P_{HLR}	$\frac{Heat\ Load}{Rated\ Heat\ Capacity}$; 0<PHLR<1
$F_j(t)$	Fuel (NG) consumed by the CHP prime mover j at hour t, in (m^3)
$P_j(t)$	Electrical power produced by the CHP prime mover j at hour t, in (kWh)
$\eta_{PL,j}(t)$	Electrical efficiency of the prime mover j at hour t
$\bar{\eta}_{PL,j}(t)$	Heat efficiency of the prime mover j at hour t
$\eta_{j,Rated}$	Rated electrical efficiency of the prime mover j
$\bar{\eta}_{j,Rated}$	Rated heat efficiency of the prime mover j
u	Energy density of the fuel (NG), consumed by the energy generating unit (kWh/m^3); $1kWh - NG = 0.095m^3\ NG$
$P_{j,Rated}$	Rated electrical capacity of the prime mover j
$H_{AHU}(t)$	Heat energy supplied by the auxiliary heating unit (AHU) at hour t, kWh
$F_{AHU}(t)$	Fuel (NG) consumed by the auxiliary heating unit at hour t, in (m^3)
$\bar{\eta}_{AHU}$	Rated efficiency of the auxiliary heating unit
$H_{Load}(t)$	System heat load demand at hour t, kWh
$H_j(t)$	Heat energy produced by the CHP prime mover j at hour t, in (kWh)
$E_{C,j}(t)$	Amount of CO_2 emission by the prime mover j at hour t, kg
$E_{N,j}(t)$	Amount of NOx emission by the prime mover j at hour t, mg
$E_{C,AHU}(t)$	Amount of CO_2 emission by the auxiliary heating unit at hour t, kg
$E_{N,AHU}(t)$	Amount of NOx emission by the auxiliary heating unit at hour t, mg
$E_{C,Grid}(t)$	CO_2 emission associated with the generation of purchased grid electricity at t, kg
$E_{N,Grid}(t)$	NOx emission associated with the generation of purchased grid electricity at t, mg
$k_{C,j}$	CO_2 footprint of prime mover j , kg-CO_2/m^3-NG
$k_{N,j}$	NOx footprint of prime mover j , mg-NOx/kWh-Electricity

$k_{C,Grid}$	CO_2 footprint associated with grid electricity generation , kg-CO_2/ kWh-Electricity
$k_{N,Grid}$	NOx footprint associated with the grid electricity generation , g-NOx/kWh-Electricity
$k_{C,AHU}$	CO_2 footprint of auxiliary heating unit , kg-CO_2/m^3-NG
$k_{N,AHU}$	NOx footprint of Auxiliary heating unit, g-NOx/kWh-Heat
$O_{F1}, O_{F2}\ O_{F3}$	Objective functions for the sizing planning optimization problem
$C_{Op}(t)$	Total operational cost of the system at t
$C_{Pur}(t)$	Cost of purchased energy at hour t
C_{NG}	Natural gas purchase cost, \$/m^3
$C_{O\&M.j}$	Operation and maintenance cost of the prime mover j, \$/kWh-Electricity
$C_{Grid}(t)$	Electricity purchase/sell cost from/to the main grid, \$/kWh
$C_{O\&M,AHU}$	Operation and maintenance cost of auxiliary heating unit, \$/kWh-Heat
$P_{Grid-}(t)$	Electricity sold to the grid at t, kWh
$P_{Grid+}(t)$	Electricity purchases from the grid at t, kWh
$P_{Load}(t)$	Electrical load demand at, t
$P_{Grid,max}$	Maximum power capacity of the grid
$H_{Load}(t)$	Heat load demand at, t
$P_{Load,max}$	Maximum electrical load of the system, kW
$P_{Loss}(t)$	System power loss during hour t, kWh
$P_{Grid,max}$	Maximum capacity of grid, kWh
$H_{Dump}(t)$	Amount of heat energy dumped during the hour t, kWh
t	Specific hour of operation, which is an element of T
T	Set of hourly periods over a year
j	Specific prime mover type, which is an element of G
G	Is the set of all available prime movers
$\Delta H(t)$	Difference between the heat demand and generation at time, t
$\Delta P(t)$	Difference between the electrical load and total power generation by the PMs at, t
C_{ET}	System total running cost during electrical load tracking mode
C_{HT}	System total running cost during heat load tracking mode
η_{ET}	Prime mover efficiency during electrical load tracking mode
η_{HT}	Prime mover efficiency during heat load tracking mode

Acronym Library

AHU	Auxiliary heating unit
CCHP	Combined cooling, heating and power
CHP	Combined heat and power
DEG	Distributed energy generation
DG	Distributed generation
ELR	Electrical load reference
ET	Electrical load tracking
FC	Fuel cell
GA	Genetic algorithm
GT	Gas turbine
HLR	Heat load reference
HT	Heat load tracking
HyT	Hybrid load tracking
ICE	Internal combustion engine
KPI/SPI	Key/System performance indicators
MCT	Maximum cost tracking
MEG	Micro energy grid
MET	Maximum efficiency tracking
MG	Microgrid
MURB	Multi-unit residential building
NG	Natural gas
NGCC	Natural gas combined cycle power plant
O&M	Operation and maintenance
PAFC	Phosphoric acid fuel cells
PM	Prime mover
PMFC	Proton exchange membrane fuel cell
PSO	Particle swarm optimization
ROI	Return on investment
SE	Stirling engine
SOFC	solid oxide fuel cell
T&D	Transmission and distribution

Chapter 1 Introduction

Due to the increasing stress on the diminishing reserve of conventional fossil fuel and ever growing environmental concerns, human race are being obligated to find efficient and sustainable sources of energy. Intense research has been carried out by researches to find such power generation technologies. Studies propose several solutions for the problem. Possible solution includes:

- Finding energy efficient generation technology
- Deploy more renewable sources such as (PV), wind, hydro, geothermal, etc.
- Decreasing fossil fuel consumption
- Reducing the energy demand, etc.

Renewable sources have the potential to provide sustainable energy. However, because of their limitations, renewable sources are still lagging behind to achieve the goal of sustainability. Currently, renewable sources have some limitations such as;

- Lower energy density
- High capital cost
- Limited number of potential sites (wind and hydro)
- Low conversion efficiency
- Intermittent output as they depend on climate conditions (i.e., wind speed and solar irradiance.

One of the drawbacks of renewable sources is, almost all of them generate only electricity. Moreover, heat energy demand is quiet significant and holds a large share of total energy consumption. Renewable sources are unable to meet the heat demand requirement and have the availability issue which is limiting their application in many cases.

Many research indicates that, having a highly efficient energy generation source can potentially reduce the primary fuel consumption and minimize GHG emission at the same time. Cogeneration (CHP) is a potential energy generation technology which generates electricity and heat simultaneously. Because of the efficient utilization of waste heat during power generation, CHP system efficiency can be as high as 90%.

Having a higher energy generation efficiency not only ensures maximum utilization of primary fuel but also significantly reduces the fossil fuel consumption. Less consumption of fossil fuel leads to a significant reduction on the GHG emission. Because of the potential benefits, CHP has been classified as clean and efficient generation technology by U.S. Environmental Protection Agency [1].

Moreover, according to the international energy statistics by U.S energy information administration (EIA), residential and commercial sector has been the dominant energy consumer (34% of total consumption) and largest contributor of GHG emission [2]. Besides, residential and commercial sectors, energy demand mainly include electricity and heat which makes them ideal candidates for CHP application.

During the year 2009, residential space heating has consumed 41.5% and water heating has consumed 17.7% of the total U.S residential energy consumption of 10.18 quadrillion Btu [3]. The remaining 40.8% of the energy was consumed to meet the residential electricity demand. Figure 1-1 depicts the energy consumption trend in U.S residential sector by the end user.

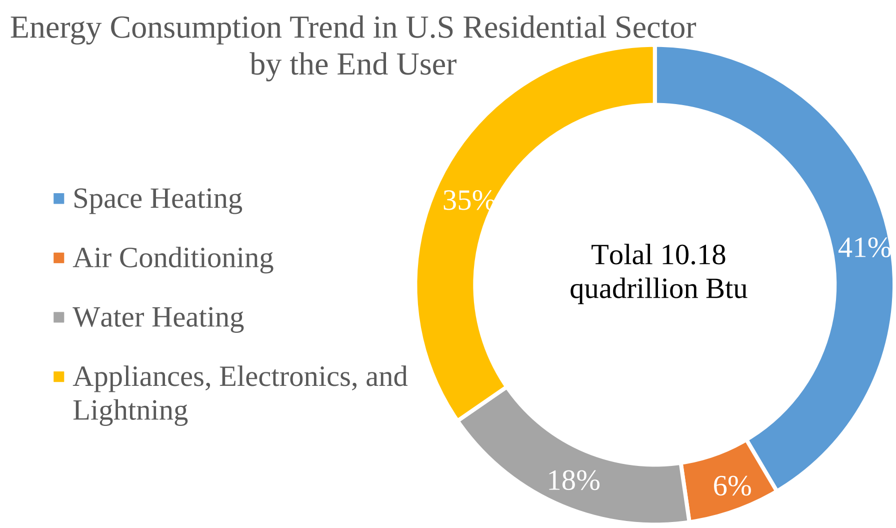

Figure 1-1: Energy Consumption Trend in U.S Residential Sector by the End User.

Similarly, Figure 1-2 shows the contributors of U.S greenhouse gas emission by economic sectors in 2013. The figure depicts that the electricity and transportation was the major sectors of GHG emission causing 31% and 27% of the total emission [4], [5]. Moreover, direct and indirect greenhouse gas (GHG) emissions from U.S. residential and commercial sector resulted around 36% (equivalent to 2250MMT CO_2) of total GHG emissions.

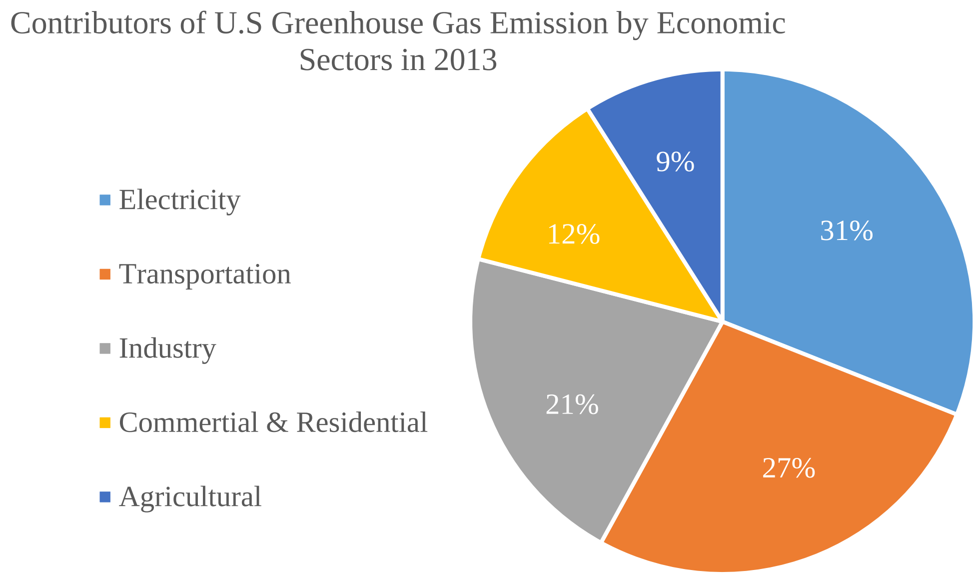

Figure 1-2: Contributors of U.S Greenhouse Gas Emission by Economic Sectors in 2013.

Similar to U.S, Canadian house hold energy requirement is solely classified into heat and electrical energy demand due to its diverse weather condition. Besides, Canadian commercial and residential sector is also a dominant energy consumer and one of the largest GHG contributor [6].

From the above discussion, it appears that, residential and commercial sectors in North America greatly dominates the total energy consumption and GHG emission. Besides, these sectors require both electricity and heat energy at the same time. Having a highly efficient onsite energy generation technology (like CHP) in the residential and commercial sector (main load type in MEG) will help to reduce the fuel consumption and will significantly decrease the emission of harmful gases. However, the application of CHP is not only limited in residential and commercial sectors, they have large potential in industrial sector too.

Therefore, this study focuses on the application of CHP based energy generation system to increase system efficiency and, minimize system cost and GHG emission. The goal of this study is to develop an optimization algorithm to find the optimal size and type of CHP prime movers for a specific load. The objectives are to simultaneously minimize the total net present cost and emission of, carbon dioxide (CO_2), and mono-nitrogen oxides (NO_x). A multi-objective GA (genetic algorithm) was applied to solve the planning problem in order to optimize CHP prime mover types and capacities. The dissertation also asserts the operational planning algorithm for CHP prime mover in micro energy grids (MEGs). Different scenarios has been evaluated with proposed methods to investigate the benefits of CHP technologies over the conventional ones.

1.1 Background

Due to the diminishing fuel reserve and growing environmental concerns, world is in need of highly efficient and environmentally effective energy generation technology. Conventional centralized power plants converts only 30~40% of the primary fuel to generate electricity[7], [8]. Majority portion of the primary fuel energy content is lost as waste heat at the site of electricity generation. As most of the centralized power plants are situated far from the load sites, further energy losses (2~6%) involves [9] in the transmission and distribution (T&D) network, shown in Figure 1-3. Overall, centralized power stations having lower efficiency, require more primary fuel to produce electricity which results in an inefficient utilization of primary resource and increases the emission of carbon dioxide (CO_2). Studies indicate that, having a highly efficient distribution generation system will not only reduce fuel consumption but also decrease GHG emission.

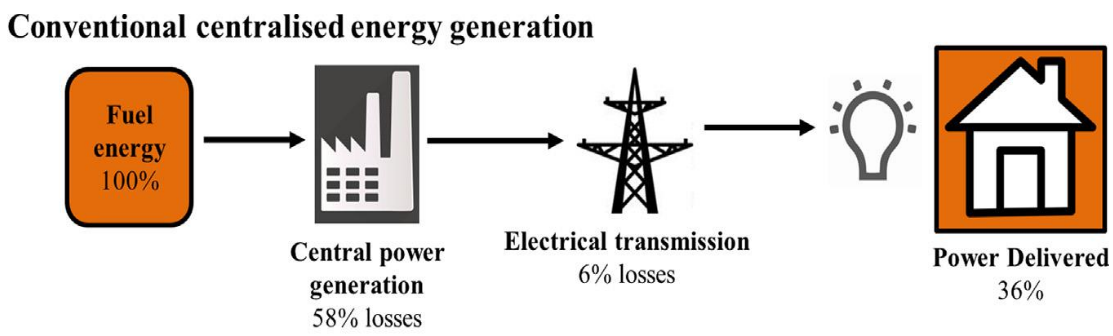

Figure 1-3: Scheme of the conventional centralized power generation system [9].

Due to the inefficient nature and environmental concerns associated with the conventional power generation and T&D system, development of newer concept knows as “on-site generation” has emerged. On site generation is also known as distributed generations (DGs) systems. DGs are mostly consists of renewable sources. However, most of the renewable sources are limited to only electricity generation.

Microgrid (MG), which includes on-site generation is a relatively small-scale localized energy network including, loads, control system and energy storage devices [10], [11]. Microgrid is widely recognized as a potential alternative to the conventional electricity generation and transmission infrastructure which utilizes DGs to increase system efficiency, minimize transmission loss and improve reliability [12], [13]. MG comprises of several renewable sources as DGs including; solar (photovoltaic) and wind. Although renewable sources like; wind and PV are receiving wide acceptance for non-polluting and inexhaustible nature but their intermittent characteristics, low power density and high capital cost involvement are limiting their mass application [14].

Because of the limitation of microgrid and distributed generation technologies, a new concept has been developed which is known as “Micro Energy Grid”. Micro energy grid (MEG) is an upgraded form of microgrid. MG mainly associates with the renewable sources (DGs) and deal with only electrical energy in the grid. Whereas, MEG includes both electricity and thermal generation in the same system. It is expected that, micro energy grid can be the best solution to maximize primary fuel utilization, ensure energy at low cost and enhanced reliability with minimum carbon footprint [7], [15]–[22].

One of the key elements of a micro energy grid is distribution energy generation (DEG) systems. DEGs are the energy generation systems located near the load sites and allows for onsite electricity and heat generation simultaneously. Cogeneration or combined heat and power (CHP) generation is the most promising DEG.

However, having a well-planned CHP system based on the load demand characteristics is a must to ensure profitability. Studies indicate that, having an unplanned CHP system might not prove economically and environmentally beneficial. So, having an optimal size and type of CHP prime mover for certain load type can lead to economic operation and reduce the emission at the same time.

The study is mainly focused on maximizing the economic and environmental benefits of CHP systems. To achieve the goal, a complete planning tool is developed to assist CHP capacity sizing and load following operation.

1.2 Motivation

Cogeneration or CHP has been identified as potential DEG as they can reduce fuel consumption and lessen GHG emission while meeting the growing energy demand. Like other distribution technologies, CHP prime movers require proper planning to ensure maximum economy and environmental benefits.

Studies indicate that, having an unplanned CHP system can become unprofitable rather being beneficial. Having a planned CHP system is essential to maximize the environmental and economic effectiveness of a prime movers [14], [23]–[25].

For example, having a Stirling engine based CHP prime mover for a system with higher electrical load can result in excessive heat energy dump and increases system cost and emission. However, in practical system, energy demand is always changing based on the time of operation. Moreover, energy demand during one season could be completely different than the other.

Beside these, many external factors influences the planning of the CHP system. Factor affecting the planning of CHP prime mover in MEG are;

- Load demand variation
- Ambient condition (like; temperature)
- Resource availability
- Fuel purchase cost
- Energy sell/purchase cost
- Prime mover characteristics
- Government policies (like; emission tax, subsidies, etc.)

So, it's evident that, having proper type of prime mover and having an optimal capacity is not an easy task as they depends on many factors. Moreover, the planning of CHP systems involves two stages;

- Sizing or capacity planning
- Operational planning

Sizing or capacity planning is also referred as optimal deployment of prime movers in some studies. This planning is involved in the primary level or before CHP installation. Capacity planning mainly involves finding the right type and size of prime mover for a certain load. A multi-objective optimization tools can be used to solve the planning problem.

Several studies has been carried out in this field to assist the CHP sizing planning problem. However, the studies lack some key aspects of the study. For instance; reference [26] and [27] discussed CHP planning issue in their study. However, possibilities of potential prime movers like fuel cell and sterling engine were not mentioned. Similarly, the study in [24] did not consider NOx emission. Cost and emission minimization objectives were not discussed in [28].

Most interesting thing is that, almost all the studies carried out in this field of study did not consider the load dependence (part-load) of prime mover performance. In, practical situation the operation of prime movers greatly depend on the load.

Second part, is the operation planning which comes in to consideration after the installation of CHP prime mover. Operational planning mainly involves the control of prime movers based on the specific load. For instance, prime movers can be controlled in such a way that it follows the electrical load of the system. This mode of operation is referred as electrical load tracking (ET) mode. Similarly, prime movers can be operated at heat load tracking (HT) mode.

However, having a prime mover set at specific mode of operation (HT or ET) often results in an increase operational cost and high energy dump. Having an intelligent control algorithm to switch between the prime mover's load tracking modes (HT and ET) can improve the system fuel utilization and minimize the operational cost.

1.3 Problem Definition

Application of distribution energy generation systems like CHP can bring down the GHS emission while improving primary fuel utilization. However, proper planning of prime movers in a CHP system is a key requirement to enhance system profitability. This study intends to develop a complete CHP planning and operation tool.

CHP system considered in this study mainly involves prime movers, different loads (electrical and heat), auxiliary heating unit and electricity grid. Candidate prime mover technologies being considered for the study involves; internal combustion engine, Stirling engine, gas turbine and fuel cell. All the prime movers and auxiliary heating units used natural gas as primary fuel.

System load involves both heat and electrical energy demand, where heat can be used for space heating, hot water supply and cooking, etc. System is so considered that, any surplus electricity generated from the PMs can be sold to grid while shortcoming of electricity is met by purchasing electricity from grid. Similarly, during operation any shortfall of heat demand is met from the auxiliary heating unit if heat generation from PMs is less than required.

The goal is to develop a planning tool to determine the optimal size and operation of CHP prime movers. A multi objective genetic algorithm has been developed for the study to assist prime mover capacity planning for the intended system. The objective is to minimize the total net present cost and emission (carbon dioxide (CO_2) and mono-nitrogen oxides (NO_x)) for a certain load (electrical or heat) condition. Moreover, a hybrid load tracking mode of operation has been proposed to achieve; maximum prime mover efficiency and minimum system running cost.

1.4 Objectives

Main objective of the study is to assist the end user to identify the optimal size and type of the CHP prime movers and to help the operational planning of the CHP unit. To attain the goal, following tasks are intended to be carried out in the study:

- Develop CHP prime mover model library based on their part-load performance.
- Develop an optimization algorithm to find the optimum size and type of CHP prime movers for distinct load conditions.
- Introduce hybrid load following operation mode for the CHP prime mover while focusing on two main aims;
  I. Maximize the primary resource utilization (maximum efficiency mode)
  II. Minimize the running cost
- Verify the proposed strategies by evaluating different scenarios/cases and investigate the impact of CHP over conventional energy infrastructure.

To achieve the goals, first the study is focused on developing system model library on Simulink. Next step is to develop a genetic algorithm based multi-objective optimization tool to identify the optimum size and type of CHP prime mover at certain load (heat or electrical) condition. The objective of the optimizer is to simultaneously minimize the total net present cost, carbon dioxide (CO_2) emission, and mono-nitrogen oxides (NO_x) emission for a specific load (electrical or heat) condition.

Moreover, the study is carried out to apply the optimization approach at different load ranging from residential load to a medium scale micro energy grid load as case study. Different scenarios with the intended optimization algorithm will be evaluated to verify the proposed tool and investigate the economic and environmental effectiveness of CHP over the existing energy infrastructure.

Second part of the study involves the development of a hybrid load following strategy over the conventional heat load and thermal load following strategies. The hybrid load following mode is intended to have two different objectives which are: achieving maximum system efficiency and minimizing the total running cost.

Finally, proposed hybrid load following mode is intended to be investigated for certain load types as case studies. Furthermore, environmental and economic benefits of the proposed hybrid mode of operation over conventional heat load and thermal load following strategies are to be evaluated to validate the proposed method.

1.5 Thesis Outline

The thesis consists of eight chapters where each chapter includes several sub-sections. Current chapter holds the introduction section of the study.

A brief review of the literature on the intended study is presented in Chapter 2. The chapter holds the basic idea and state of art of the following; micro energy grid, cogeneration, CHP prime movers, optimization algorithm and the system performance indicators.

Chapter 3, contains the research framework and methodologies. Prime mover modeling considerations along with the optimization objective functions and intended system performance indicators are discussed briefly in the chapter.

Detail system modeling is discussed in chapter 4. Detail of intended prime movers and other system components modeling has been discussed in this chapter. System mathematical problem formulation has also been developed and mentioned in chapter 4.

Next chapter depicts the formulation of CHP prime mover planning problem. System optimization constraints along with the proposed algorithms are discussed in detail in chapter 5.

Chapter 6, holds the information regarding the intended energy profiles used in the case studies. Moreover, detail of case studies being carried out regarding the prime mover capacity planning and operational planning are discussed in this chapter. Moreover, system performance indicators of individual case studies are also presented in this chapter.

Chapter 7 hold the results and detailed discussion of the findings from the case studies. Both sizing and operational planning related case studies are further investigated in this chapter. Moreover, this chapter analyzes the findings of the case studies and discusses their economic and environmental effectiveness over the conventional system.

Finally, Chapter 8 concludes with a summary of the research carried out in this thesis. Moreover, this chapter discussed the main contribution of the study and provides direction to future research.

Chapter 2 Literature Review

The literature review is presented in four main sections. Section 2.1 provides an overview of micro energy grid and its advantages over conventional energy infrastructure. Section 2.2 provides a brief detail about the cogeneration which also known as CHP. Details about the CHP prime movers are discussed in section 2.3. Finally, section 2.4 provides the detail about the system performance indicators considered for the study.

2.1 Micro Energy Grid (MEG)

Micro energy grid is an updated form of microgrid. Microgrid associates with the renewable sources an onsite distributed energy resources and deal with only electrical energy in the grid. Whereas, micro energy grid includes various sources of energy (i.e. electricity, heating, natural gas etc.). The main goal of micro energy grid with gas grid infrastructure shown in Figure 2-1 is to improve the efficiency and sustainability of current energy infrastructure [29].

It is expected that, micro energy grid can be the best solution to ensure energy at low cost, enhanced reliability with minimum carbon footprint [30]. In this study we have considered MEG with electricity supply from grid and CHP prime movers has been used as distributed generation system which operates on natural gas supplied from the gas grid.

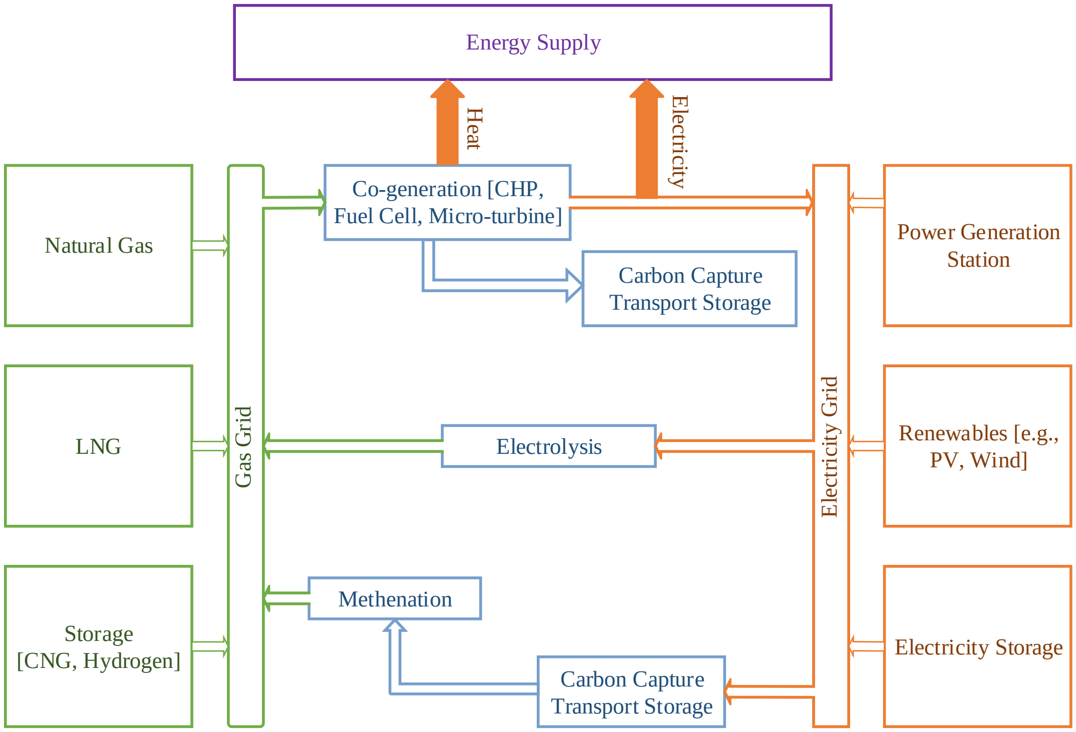

Figure 2-1: Typical micro energy grid infrastructure.

2.2 MEG Planning

Micro energy grid consists of different DGs including renewable sources (PV, wind, etc.) and CHP prime movers. Planning of MEG has received a great deal of attention [10], [14], [26], [27], [31]–[33] as an optimal planning is a must to ensure efficient and reliable operation of micro energy grid. By the term planning of MEG actually refers to the planning associated with distribution generation sources in it. The planning problem of MEG can be classified into two main categories; optimal capacity planning of DG/DEGs and operational planning of DG/DEGs in MEG.

Figure 2-2 shows the most commonly discussed issued regarding of MEG planning.

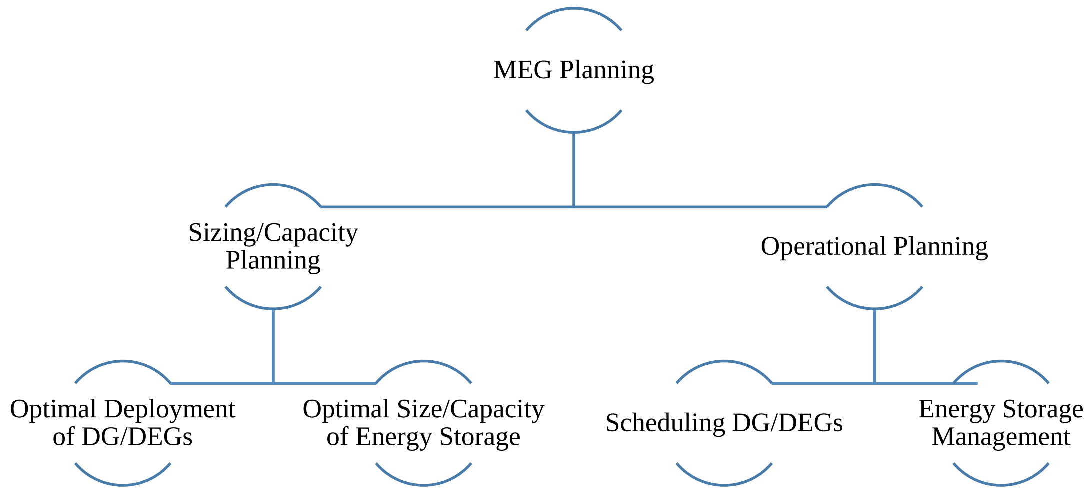

Figure 2-2: Figure depicting the typical MEG planning issues.

Sizing/capacity planning also referred as optimal deployment of DG/DEGs in MEG. This study is associated at the very primary level of MEG planning. This section involves the identification of optimal location, size and type of DEGs in the MEG. Optimal deployment of certain DEG depends on several facts like; the load characteristics, availably of resources, energy purchase/sell cost etc. For example; for a region with inadequate solar irradiation will result in less share from solar PV in MEG. Similarly, having a load type which requires electricity and heat energy at the same time, may require higher capacity of CHP installation.

In practical many external condition dominates the selection of optimal DER for a MEG. Many studies has been carried out in this specific planning field. Reference [26] and [27], discussed about the optimal deployment of DEGs in microgrid. However, the models of DEGs discussed in this studies do not include fuel cell and sterling engine. Besides, the part load performance of the DEGs were not taken into consideration. Optimal design and life cycle assessment was discussed in [24]. However, load dependency of the CHP prime movers were not taken into consideration. Besides, NOx emission from the prime movers were not discussed in the study.

Ref. [28], mentioned an optimization algorithm to find the optimal deployment DGs in a microgrid aiming to minimize the fuel consumption. However, the objective functions of the study do not include operational cost and system emission.

It has been seen that, most of the study used the DEG models based in rated performance only. Thus the performance (efficiency, emission etc.) of the DEGs are considered to be consistent at any load condition. However in practical, the performance of DEGs depends on the variation of the system load. Thus to achieve higher accuracy part-load characteristics of DEGs must be taken into consideration.

Operational planning of DEGs in MEG comes into consideration after the optimal deployment of DEGs. Operational planning mainly refer to optimal scheduling of DGs, energy storage management and control of CHP prime mover operations. Many factors affect the operational planning of DEG/DGs in MEG. For instance; during day time when sufficient solar radiance is available, DEGs like diesel generators are turned off to minimize the cost. However, at evening during peak hours diesel generators are put online to meet the peak demand. Similarly, CHP prime movers load tracking mode is controlled based in the electricity demand or heat demand. Electrical load following mode helps to control system economy while better emission performance is achievable with heat tracking mode of operation.

In this study, MEG with only CHP prime movers has been considered. Integration of renewable sources and energy storage technologies has been omitted to clearly picture the performance of CHP in MEG. Moreover, detail planning of CHP in MEG is carried out which involve; sizing planning of CHP prime mover and operational planning of PM.

2.3 Cogeneration System (CHP)

CHP or Combined heat and power system is a type of distribution energy system (DEG). Cogeneration units symmetrically generates electricity and heat at the same time from the same power generation unit known as prime mover [8],[24],[25]. CHP systems has normally five main components; prime mover, power generation unit, heat recovery unit, energy management and control system, and thermally activated equipment [7], [36].

Typically, CHP systems are strategically located near or at the location of the load. Due to on site energy generation, transmission and distribution (T&D) losses are avoided while need for new T&D is also minimized. Moreover, CHP is an effective way to utilize the waste heat energy while generating electricity from the prime mover. Thus, CHP inherent higher efficiency and results in efficient primary fuel utilization and reduces GHG emission. Figure 2-3 depicts the basic schematic showing the efficiency comparison between CHP and conventional energy infrastructure.

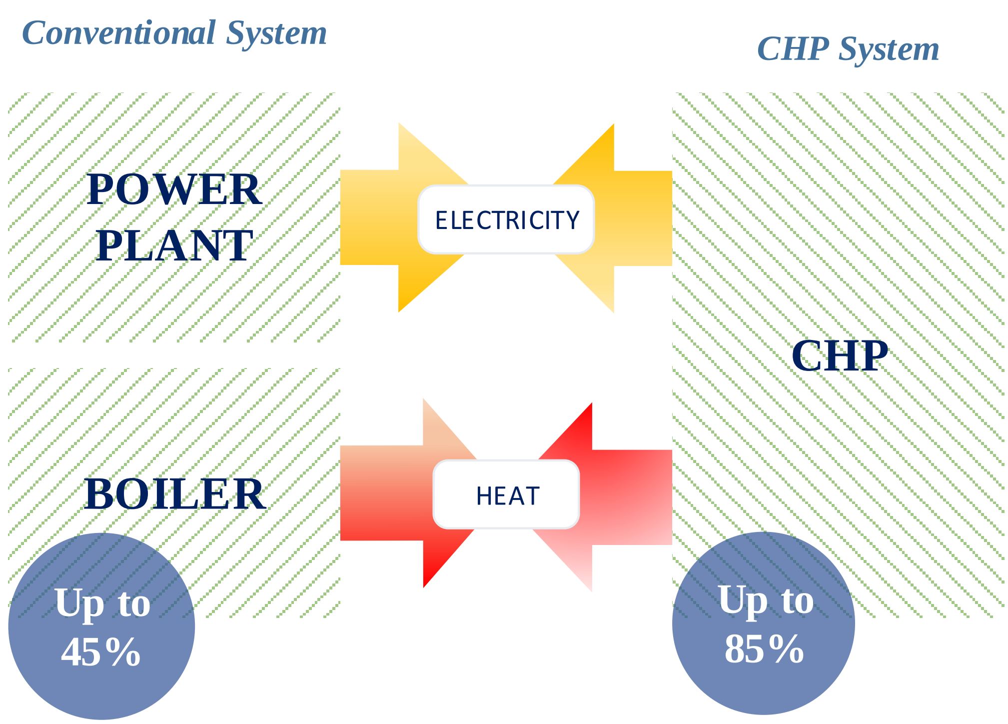

Figure 2-3: Efficiency comparison between CHP and conventional energy infrastructure. [37]

Like other distributed generation technologies, CHP systems can significantly reduce dependency on the electricity grid and come with less operational cost at the same time [38], [39]. Because of their environmental and economic benefits, CHP has gained intense global attention. Figure 2-4 shows the share of CHP in total national power production.

CHP contributes more than 50% of Denmark's total power generation while the share of CHP is almost 40% in Finland. Other countries like Russia, Netherland and Hungary also gets a large contribution from the CHP units in their total national power production.

North American countries, i.e. Canada and United States of America (USA) are now looking forward in more CHP installation. During year 2012, total installed CHP capacity in USA was estimated to be 82GWe [9]. According to the estimation provided by International Energy Agency (IEA), G8+5 countries alone has the potential to raise their CHP capacity over 830GW by the year 2030 [40].

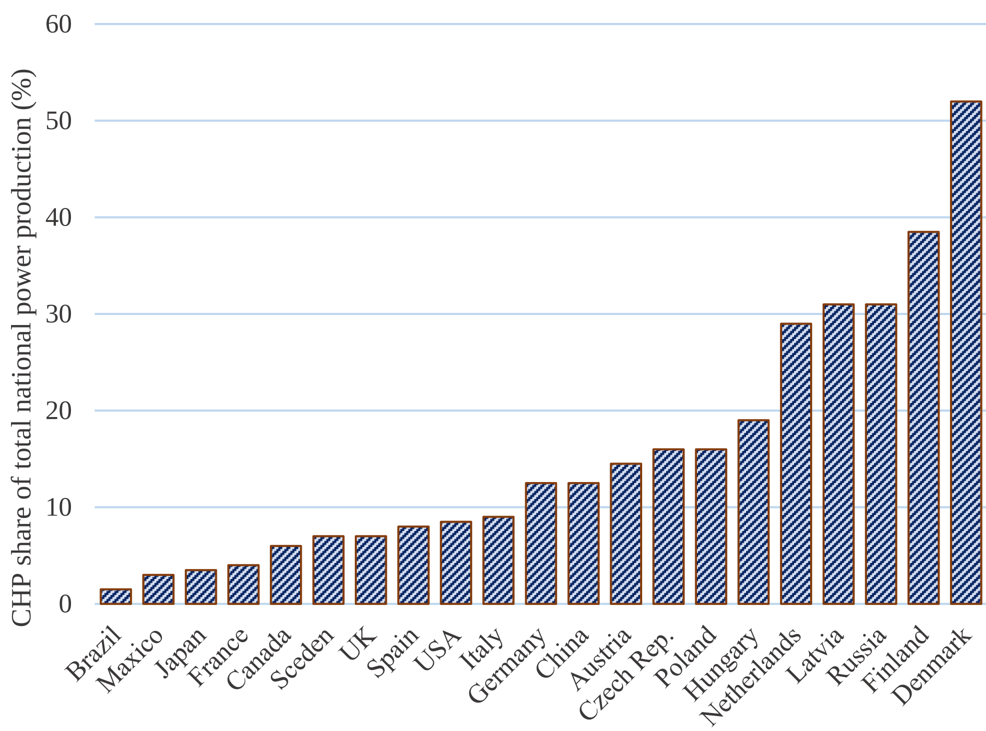

Figure 2-4: Share of CHP in national power production [41].

Currently, most of the CHP systems installed in USA are fueled by natural gas as shown in Figure 2-5.

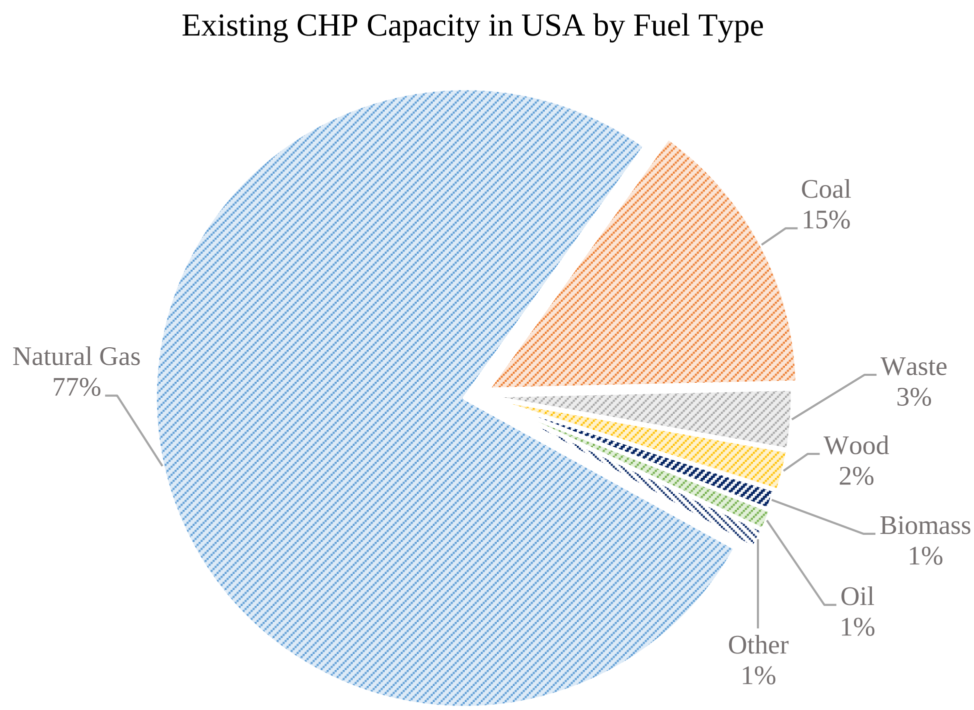

Figure 2-5: Existing CHP Capacity in USA by Fuel Type. [42]

Natural gas is the most commonly used fuel, 77% of the total installed CHP systems use natural gas as primary fuel. Low carbon content, cheat price (compared to oil) and easy transportation feature, makes natural gas the most popular CHP fuel compared to others. However, rest of the cogeneration system in USA uses coal (15%) and others sources like; waste, wood, biomass, oil etc. as primary fuel.

To clearly picture the economic and environmental benefits of CHP systems over conventional power plant and utility scale renewable sources, a study has been carried out by US department of energy [37]. They compared the net yearly emission and energy savings from a NG fired 10MW CHP system with NG combined cycle (NGCC) power plant (generating power only) and utility scale renewable systems (PV and Wind).

Table 2-1 depicts the comparison showing the energy and emission savings from the CHP system over others.

Table 2-1: CHP energy and emission saving potential over conventional power plant and utility scale renewable systems [37]

Category	**10 MW CHP**	**10 MW PV**	**10 MW Wind**	**Combined Cycle (10 MV Portion)**
Annual Capacity Factor	85%	22%	34%	70%
Annual Electricity (MWh)	74,446	19,272	29,784	61,320
Annual Useful Heat (MWht)	103,417	None	None	None
Footprint Required (sq ft)	6,000	1,740,000	76,000	N/A
Capital Cost (million)	$20	$60.5	$24.4	$10
Annual Energy Savings (MMBtu)	308,100	196,462	303,623	154,649
Annual CO2 Savings (Tons)	42,751	17,887	27,644	28,172
Annual NOx Savings (Tons)	59.4	16.2	24.9	39.3

Because of the efficient utilization of primary resource (NG) and use of low carbon fuels (like; natural gas), CHP results in a significant cost saving as well as reduces the GHG emission. The table depicts that, the CHP system has the highest capacity factor while PV and wind has lower capacity factor due to their intermittent nature. Besides, CHP system results in significant energy savings compared to renewable sources and NGCC power plant. Similarly, CO_2 and NOx emission is also noticeably low compared to other systems in consideration.

A similar study on the CHP systems located in New Jersey showed that, medium and large scale CHP systems can provide electricity at a lower price than the retail electricity rates for medium and large consumers respectively. Thus indicates that, CHP can generate cost savings for the end users. On the other hand, per unit electricity cost from large and medium CHP is also below or equal to the cost of electricity from coal and NG based power plants as well as from the renewable sources.

The comparison between CHP and other systems in terms of net electricity generation cost is shown in Figure 2-6. The comparison clearly indicate that, CHP holds the potential as cost effective energy generation source.

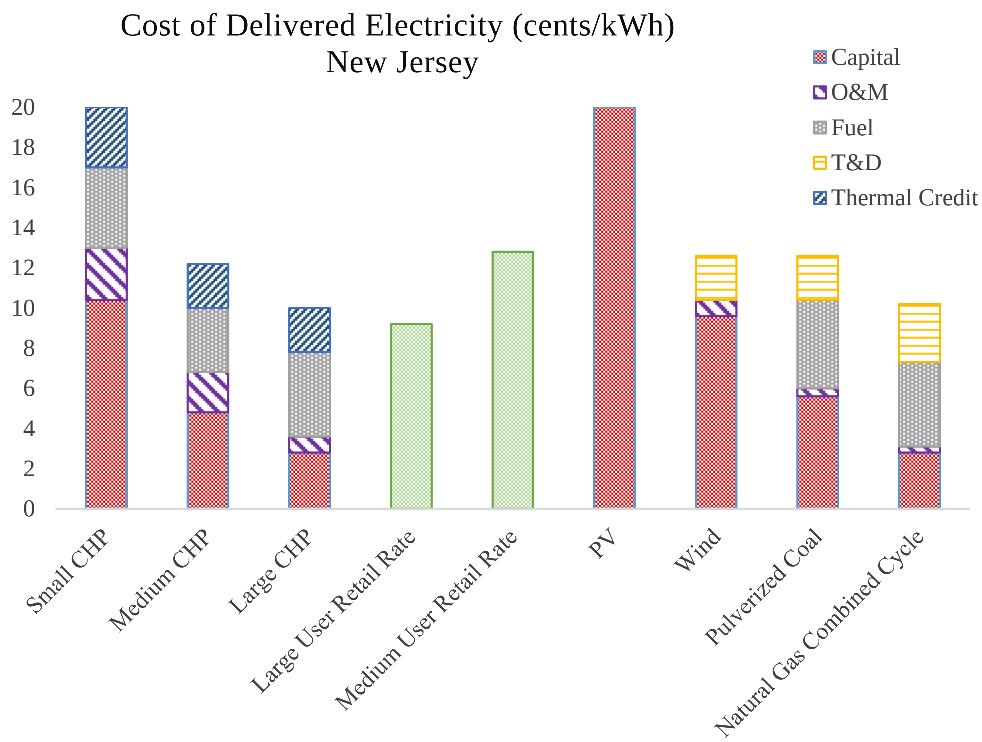

Figure 2-6: Cost of delivered electricity from different energy generation systems in New Jersey. [37]

Due to the cost and emission benefits, CHP system potentials are expected to increase significantly in near future. As a distribution generation system, CHP shows large potential in various commercial, industrial and even in residential sectors. Figure 2-7 shows various sectors which holds CHP potential.

Industrial sector has the highest CHP potential while huge opportunity for CHP unit is estimated in commercial and institutional facilities. Besides, according to Oak Ridge Laboratory (ORNL), increasing the current CHP capacity of USA to 240GW by 2030 would lower the CO_2 emission by 600 million metric tons along with significant energy savings.

Overall statistics clearly depict that, CHP can be the ultimate solution for efficient and environmental friendly generation.

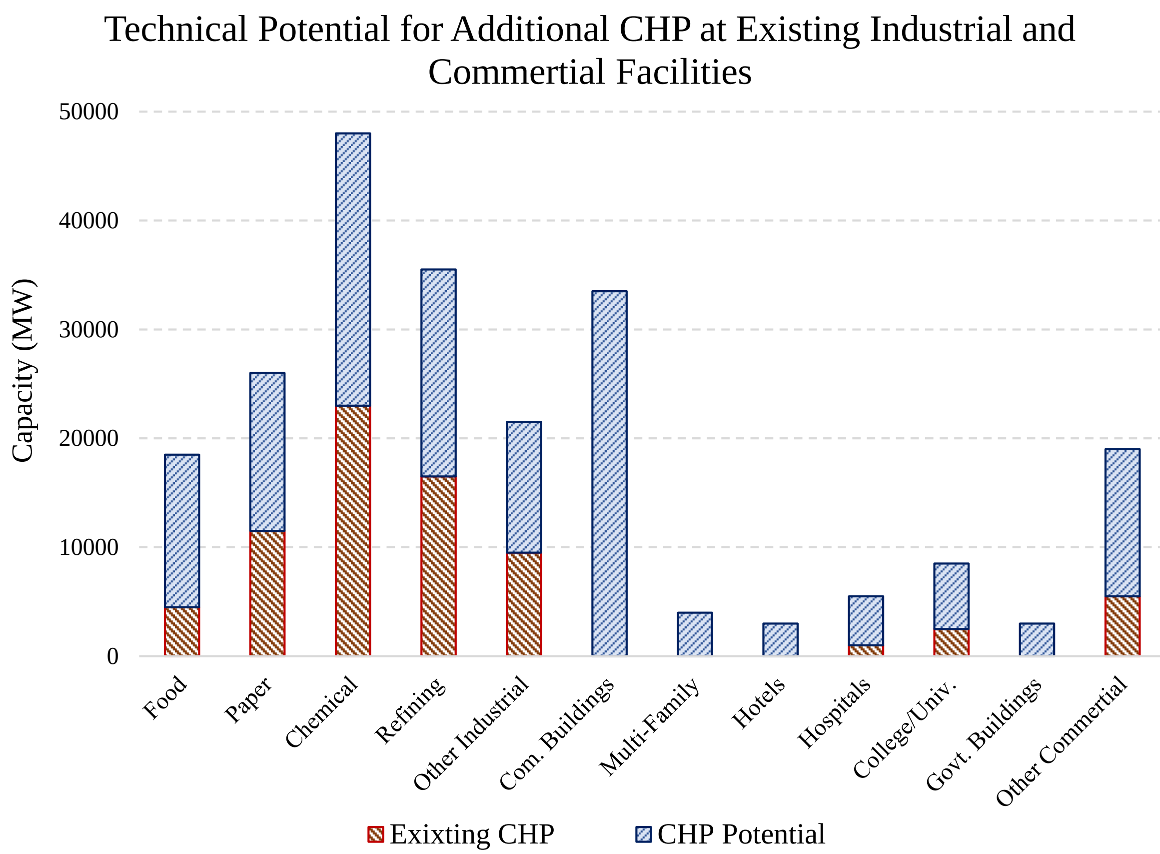

Figure 2-7: Technical potential for additional CHP at existing facilities [37], [42].

2.4 CHP Prime Movers

A prime mover is a core component in a CHP system which generates electricity and heat simultaneously [38]. Some literatures refer prime mover as power generating unit, while the waste heat is extracted from the system during operation.

Prime movers can be classified in several different ways; they can be classified based on the capacity range, fuel type, technical maturity, heat to power ratio etc. However, steam turbines, reciprocating internal combustion engine (ICE) and gas turbines are considered to be conventional prime movers. These three types of conventional prime mover make up most of the gross capacity of CHP being installed in USA [16]. Figure 2-8 shows the existing cogeneration capacity in USA by prime mover type.

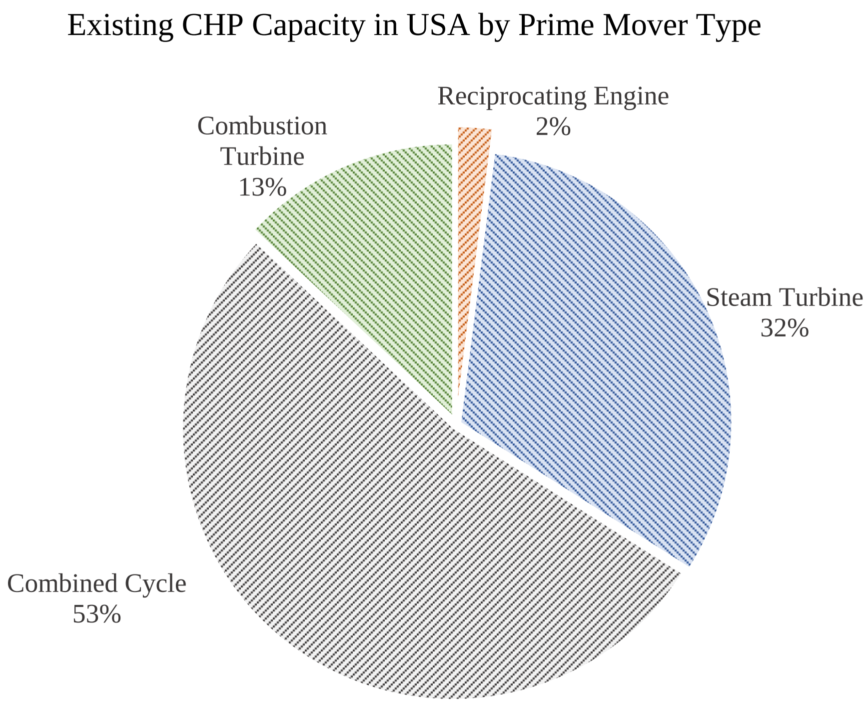

Figure 2-8: Existing CHP Capacity in USA by Prime Mover Type [42].

Although, total capacity of ICE based CHP systems is only 2% of the whole installed capacity, but they occupy the largest number of CHP sites in USA. Figure 2-9 depicts the existing CHP sites in USA by prime mover type. This represents that, IC engine CHP units are smaller while the combined cycle, steam and gas turbines have reasonably high capacity.

Besides, these technologically mature conventional prime movers, there are few newly emerging technology that seems to be promising. Comparatively new and promising prime mover technology mainly includes; Fuel cell (FC) and Stirling engine (SE) [16]. Fuel cell and Stirling engine based prime movers are currently under development and has less market share compared to the conventional technologies.

Most interesting thing about the prime movers is that, they have distinct characteristics and have certain advantages and disadvantages. Comparison between available prime mover technologies are discussed in Table 2-2.

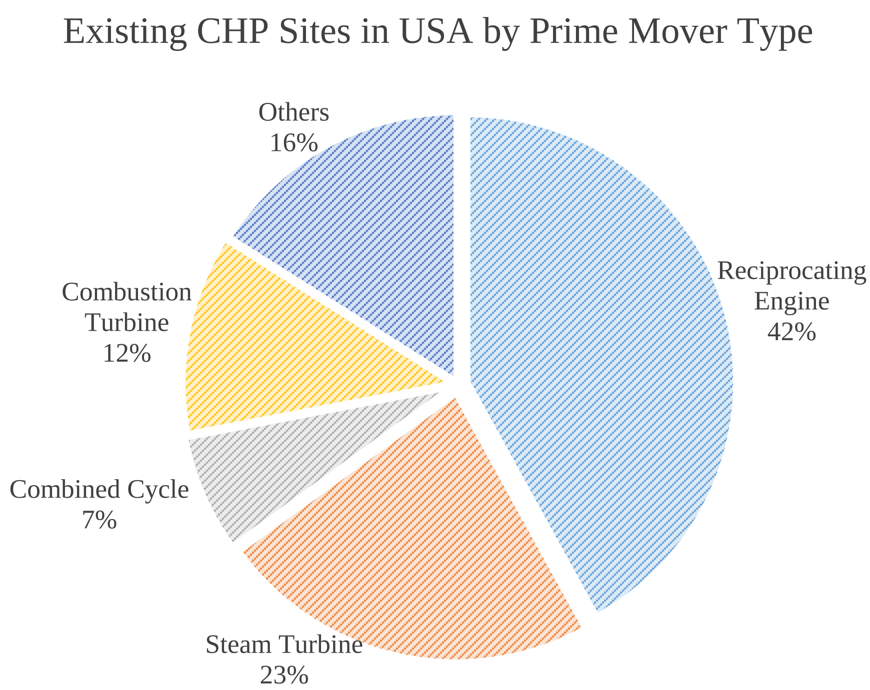

Figure 2-9: Existing CHP Sites in USA by Prime Mover Type [42].

The table depicts that, different PM technology has different strength and weakness. Because of their distinct characteristics, certain prime mover is appropriate for certain application. For example; because of the high temperature steam availability from steam turbine PM, they are more suited in industrial load environment. Similarly, IC engine and FC is more suitable in commercial and residential application.

Table 2-2: Comparison between different prime mover technologies [43]

Prime Mover	Pros.	Cons.	Available Size
Spark ignition reciprocating engine	• Low investment cost • Fast start-up • Better load following response • High part-load efficiency • High reliability	• Regular maintenance is required • High maintenance cost • Relatively high emission, especially NOx • High level of low frequency noise	• Small to medium scale • 1kW to 10MW in DG applications
Steam turbines	• High overall CHP efficiency-stem to power • Flexible fuel • Longer lifetime • High reliability • Variable power to heat ratio	• Slow start up • Low electrical efficiency • Requires steam source like boiler	• Usually medium to large scale • 50kW to several hundred MW's

Gas turbine and Micro-turbine	• High reliability • Reasonable capital investment • High grade exhaust heat • No extra cooling required • Low emission • Compact and light weight (micro-turbine)	• Poor part-load performance • Output falls with rise in ambient temperature • High pressure gas supply is needed • Micro-turbine is limited to low temperature CHP application	• Medium to large scale • 0.5 to 300MW • Micro-turbine capacity range is; 30kW to 1000kW
Stirling engine	• Less moving parts • More safe and silent • Longer life • Flexible fuel • Fast start up time • Low emission • High overall efficiency	• High capital investment required • Poor electrical efficiency • Hard to tune output power	• Small to medium scale • Up to 1000kW with multi-unit package
Fuel cell	• Extremely low emission and noise • High electrical and overall efficiency • Compact/modular design • Increases reliability	• Capital investment is highest • Fuel processing required if pure hydrogen is not used • Sensitive to fuel impurities • Moderate lifetime • High maintenance	• Micro to medium scale • 0.5kW to 2MW

In this study, four prime mover technologies has been selected. Candidate technologies involve;

- Internal combustion engine (spark ignition)
- Gas Turbine
- Fuel cell
- Stirling engine

More detail about individual prime mover in consideration has been discussed in the following sections.

2.4.1 Reciprocating Internal Combustion Engine (ICE)

Currently reciprocating internal combustion engines are the most commonly used CHP prime mover under 1MW [44]. A reciprocating engine also known as internal combustion engine or piston engine uses one or more reciprocating pistons to convert pressure into rotary motion [45]. There are mainly two types of IC engine used now a days;

— Spark Ignition Engine; runs mainly on natural gas, but propane or biogas could also be used.
— Compression Ignition Engines; runs mainly on diesel and other petroleum fuels.

Compression ignition engines results in much higher emission (especially NOx) compared to the spark ignition engines. So, the use of diesel fueled IC engine is mostly restricted. Consequently, most of the current IC engine based CHP system are spark ignition engine which is fueled by natural gas. In this study, spark ignition based IC engine has been considered and compression ignition engines are omitted from the consideration.

As a CHP prime mover, IC engine has distinct strength and weakness. Figure 2-10 shows the strength and weakness of IC engine in a scale 1-5.

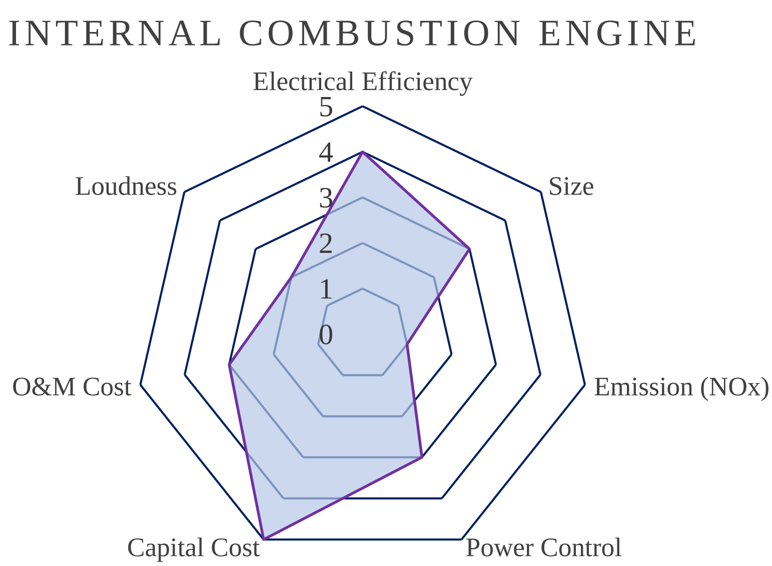

Figure 2-10: Strength and weakness of IC engine in a scale 1-5 (higher better).

Although reciprocating engine is considered as a mature technology, it has certain advantages and disadvantages. Main strength of IC engine is its lowest capital cost requirement. Compared to other CHP prime mover technologies, IC engine is the cheapest in terms of capital cost requirement [36]. Besides, IC engines has better efficiency and part-load performance compared to gas turbine and steam turbines.

Despite all the advantages, IC engine has some drawbacks as they need regular maintenance to ensure availability. This increases the system operation and maintenance (O&M) cost [46]. Moreover, having large number of moving parts involves low frequency (acoustic) noise and vibration in the system [35]. Shock absorbers and shielding measures are needed to reduce the vibration and noise. However, the largest drawback of IC engine is its emission characteristics, particularly NOx emission. Emission of nitrogen oxides are much higher compared to other technologies which is an obvious drawback of IC engine [47]. Natural gas fired IC engines has much less NOx emission compared to diesel fueled engines which limits the application of compression ignition engines. However, major manufacturers are putting continuous effort on developing new engines with improving emission characteristics. Currently, emission control options like; selective catalyst reduction (SCR) are mostly used to reduce system emission.

Typical reciprocating IC engines are coupled with generator and heat exchangers. The heat exchanger is used to extract the waste heat from the system. Figure 2-11 shows the CHP system layout with IC engine based prime mover.

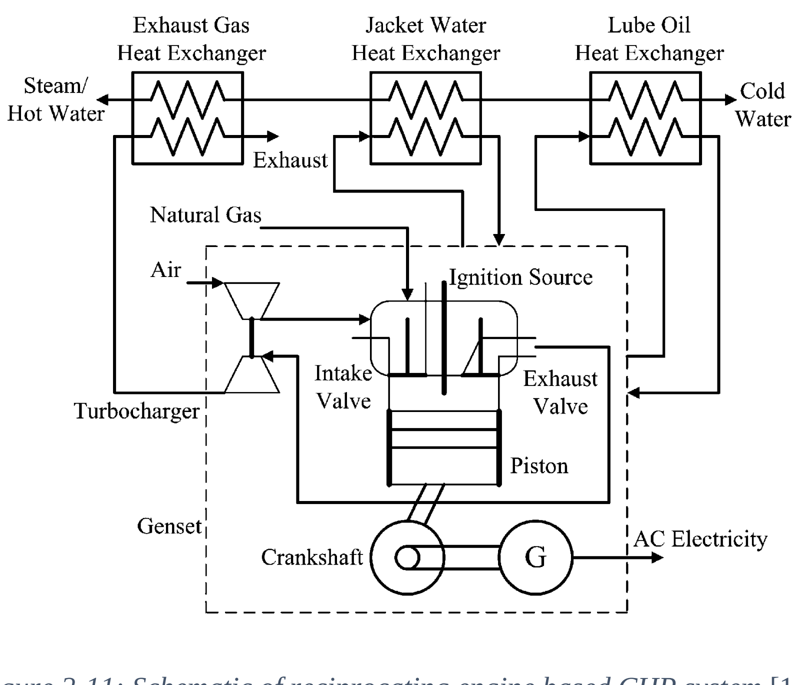

Figure 2-11: Schematic of reciprocating engine based CHP system [16].

Because of their low start up time, IC engine based CHP systems are mostly used as backup system or for peak saving operation. Moreover, moderate temperature of exhaust heat output from the system limits their application in large industries where high temperature is required. However, IC engine based CHP system are perfectly suitable for commercial, residential and small industrial application. IC engine can also be used in combined cooling heating power (CCHP) system to ensure better energy utilization.

2.4.2 Stirling Engine (SE)

Basic difference between the IC engine and Stirling engine (SE) is that, SE is an external combustion engine while the combustion is internal in case of IC engine. Usually the cycle medium used in SE are helium or hydrogen. During each cycle of operation, cycle medium is not exchanged but stays inside the device. However, the energy which is driving the cycles operates externally. Technically, Stirling engine can use any kind of fuel; natural gas, biogas, propane, wood etc. However in this study, the SE being considered is fueled by natural gas only. Currently, two main types of Stirling engines shows CHP potential;

- Kinematic Stirling Engine
- Free-piston Stirling Engine

Although Stirling engine has more than 100 year old history but as a CHP prime mover it is still under development. Stirling engine has its distinct strength and weakness as a CHP prime mover. Figure 2-12 shows the performance characteristics of SE in a scale of 1-5 where higher number represent better characteristics.

The external nature of heat source comes with combustion control flexibility which leads to reduced emission [16]. Because of external combustion characteristics, SE emits much less NOx compared to IC engines.

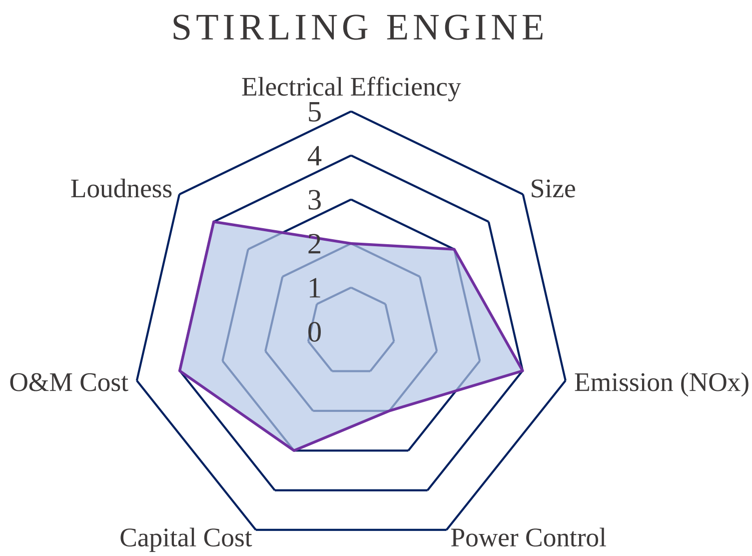

Figure 2-12: Strength and weakness of Stirling engine in a scale 1-5 (higher better).

Stirling engines requires less moving parts which not only reduce the vibration and noise but also results in longer device life. Besides, due to reduced moving parts, maintenance cost of SE based CHP systems are much less compared to IC engine and fuel cell.

Currently, the major disadvantages associated with SE are, high capital cost, small capacity and low electrical efficiency [48]. Stirling engine based prime movers are available in small size ranging from 1 to 500kW. However, multiple units can be mounted together to increase the maximum capacity of the system. Besides, as an emerging technology, SE requires much higher capital cost compared to IC engine which is a large barrier behind the popularization of this technology.

Electrical efficiency of commercially available SE based CHP units are less than 20%. Thus, most of the useable energy from the SE is heat energy which limits their application in certain cases. Because of their high heat to power ratio, SE is mostly suitable where heat load is much higher than the electrical load. However, CCHP application of SE can potentially improve the system energy utilization factor.

Despite all the drawbacks, SE has been considered as a potential CHP technology because of the longer service life, low level of emission, higher overall efficiency and reliability [44], [45].

Figure 2-13 shows the simple schematic of Stirling engine based CHP system.

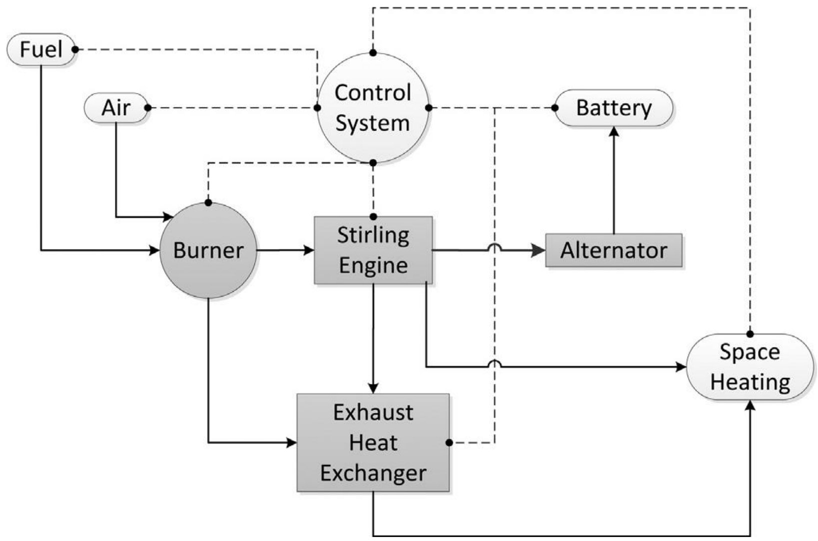

Figure 2-13: Schematic of Stirling engine based CHP system [49].

2.4.3 Gas Turbine (GT)

Gas turbines are well established prime movers for CHP application. Gas turbines also known as combustion turbines are mostly used in large-CHP systems due to their increased reliability and large power range. Conventional gas turbines below 1MW is not considered to be economically beneficial [16]. However, a new emerging technology known as micro-gas turbine which is based on the same operational principal can be used instead at lower capacity. In this study both conventional and micro-gas turbines has been considered as gas turbines as they depict almost similar performance during operation. Gas turbine being considered for this study used natural gas as primary fuel.

Figure 2-14 shows the operational performance of gas turbine based CHP prime movers in a scale of 1 to 5. Higher number in the scale represent better performance while lower number represent poor operation. The figure clearly depicts that gas turbines has certain strength and weakness as a CHP prime mover.

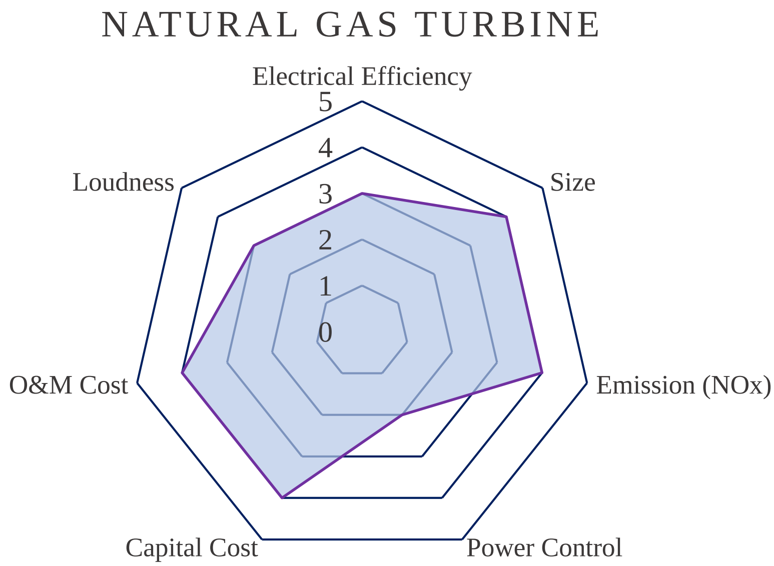

Figure 2-14: Strength and weakness of gas turbine in a scale 1-5 (higher better).

Typically the electrical efficiency of GT is less than the IC engines. However, GT with larger capacity has slightly improved electrical efficiency. Vibration and noise from the GT is less compared to IC engine based system but is comparatively higher than SE and FC. Although the capital cost for large scale GT is almost close to that of IC but the small capacity micro-GT has relatively higher cost. One other major drawback of GT is their longer start up time. However, the main disadvantage of GT is their poor part-load performance. At 50% rated capacity, gas turbine efficiency drops 25-35% of the rated efficiency [43], [45].

Despite all the drawbacks, GT has several advantages. It offers wide capacity range while micro-GT can be used in small scale application [40] and conventional GT can be used in large industrial applications. Another benefit of GT is that, it has less maintenance cost compared to fuel cell and internal combustion engine. Besides, gas turbines has much better emission characteristics over IC engine. Because of the advantages, gas turbines covers almost 15% of the total CHP capacity in USA.

Figure 2-15 shows typical schematic of gas turbine base CHP system.

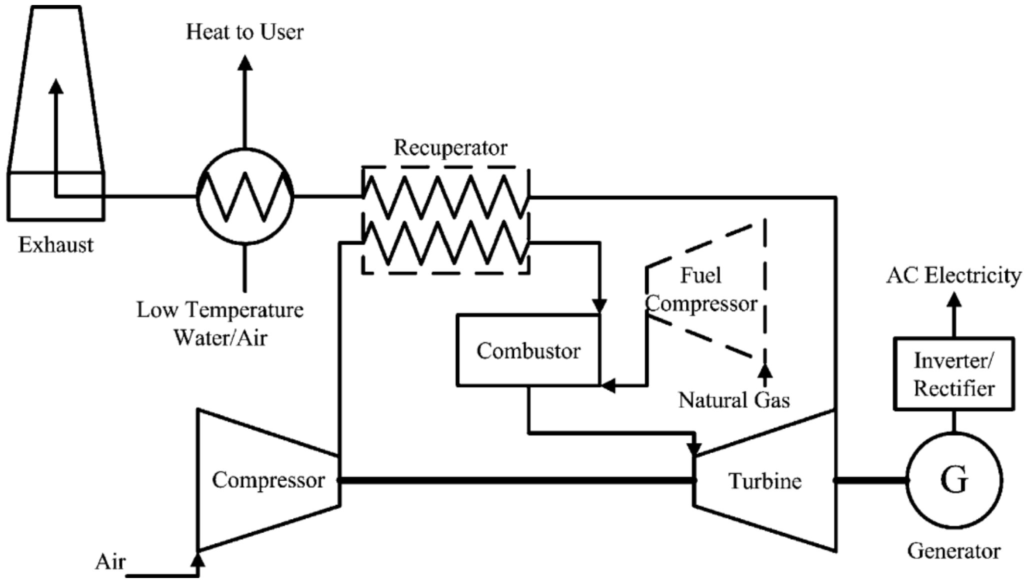

Figure 2-15: Schematic of gas turbine based CHP system [16].

2.4.4 Fuel Cell (FC)

Unlike regular prime movers, fuel cell does not involve any moving parts. Fuel cells are electro chemical devices which combines oxygen and hydrogen to produce electricity (with by-products of water and heat) [50]. Fuel cells are considered to be the most promising CHP prime mover technology. Typically, fuel cell uses hydrogen as fuel. However, natural gas can also be used with an added expense of NG reformer in the system.

Currently, small scale fuel cell based CHP systems involve either proton exchange membrane fuel cell (PMFC) or solid oxide fuel cell (SOFC). PMFC is a low temperature (80˚C) fuel cell while SOFC has a high temperature (800-1000 ˚C) output. However, in large scale, most commercially viable fuel cell technology is Phosphoric acid fuel cells (PAFC). Currently, a total capacity more than 40MW of PAFC have been installed worldwide [16].

Similar to other prime mover technologies, fuel cell also hold several operational benefits as well as drawbacks. Figure 2-16 depicts the strength and weakness of fuel cell based CHP system performance indicators.

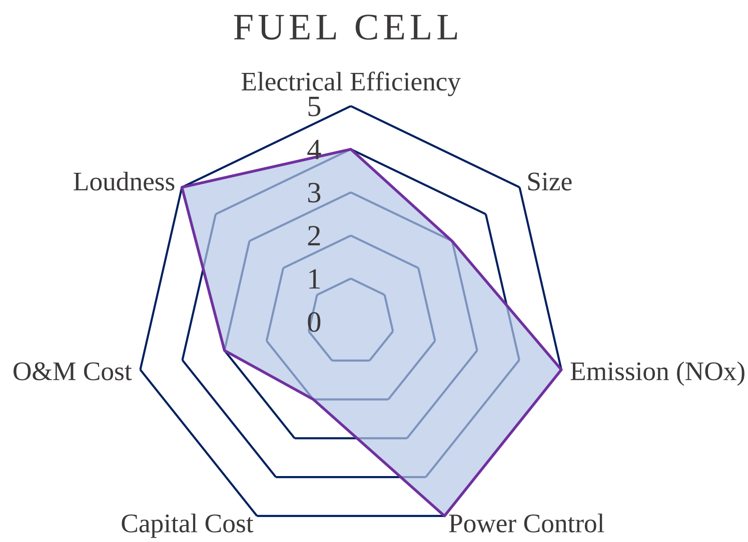

Figure 2-16: Strength and weakness of fuel cell in a scale 1-5 (higher better).

The main drawback of fuel cell is its high capital cost [43], [50]. Being a technology still at R&D level leaves fuel cell to be the most expensive prime mover compared to other technologies. Another drawback of FC is their size, currently most of the available CHP system are in micro to small range. Only few large scale fuel cell based CHP prime movers are currently available in the market [41]. Operation and maintenance cost of fuel cell based CHP systems are relatively high as periodic replacement of fuel processor is essential while using hydrocarbon fuels [51].

Fuel cell comes with several operational advantages. Most interesting feature of FC is its emission characteristics. While using hydrogen as fuel, FC emits almost no GHG. However, using natural gas as fuel results in emission of greenhouse gases but the emission is much less compared to other technologies. Moreover, NOx emission from fuel cell based systems are least compared to any other type of CHP prime mover. Another major advantage of fuel cell is its high electrical efficiency which makes it more suitable in residential and commercial application. Beside these, fuel cell comes will almost no noise or vibration while operation.

Because of the benefits, fuel cell based CHP system has caught attention in many countries. Japan initiated their fuel cell based “EneFarm” project in 1990s, which is considered to be most successful project of its kind [50]. Market share of fuel cell in European market is growing rapidly. Germany has also taken similar projects like EneFarm known as 'Callux' to promote fuel cell application. Ene.field is also a similar project initiated in European countries with a target to deploy up to 1,000 residential fuel cell CHP systems, across 11 key European countries.

Figure 2-17 below depicts the schematic of typical fuel cell based CHP system.

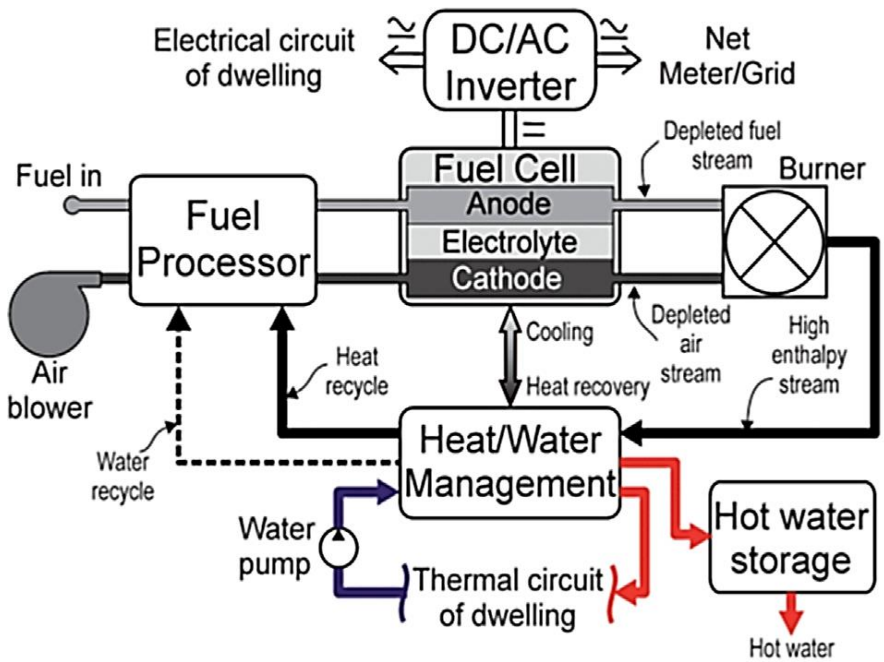

Figure 2-17: Schematic of fuel cell based CHP system [50], [51].

2.5 Optimization Algorithms

Many researchers has focused their research in the field of microgrid planning. The planning section involves the optimal allocation and selecting the proper size of the distributed generations (DGs) including the CHP in the micro energy grid [10], [24]–[28], [31]–[33], [52].

To solve the sizing problem of the DGs including in a micro energy grid, distinct algorithms has caught attention in different research work. For example, Hong Cui et al. [53] proposed a multi-objective optimization model to find the optimal allocation of DG in smart grid.

The objectives were to minimize the system loss and operational cost while maximizing the environmental benefits. In this literature, author applied fuzzy optimization theory to convert multi-objective planning into single-objective planning to solve the DG sizing problem.

An analytical method has been proposed in the study of Acharya et al. [54] to sought the optimal capacity of DGs. The optimization problem was formulated using direct equation using sensitivity factor equation.

AlHajri et al. [55] proposed a new approach based on Fast SQP approach to determine the optimal size and location of DG in a MG. Boundary restrictions were imposed along with nonlinear equality and inequality system constraints to solve the sizing problem which was defined using constrained nonlinear programming.

Genetic algorithm (GA) was proposed to solve the sizing problem by Celli and Pilo [56] focusing minimum cost and power loss in a distribution network. Later, Alinejad-Beromi et al. [57] used GA to sought the optimal allocation problem regarding DG in a network.

Particle swarm optimization (PSO) was used in the study of Alinejad-Beromi et al. [58] and Sedighi et al. [59] to identify the optimal size and location of single/multiple DGs to achieve minimum cost, minimum loss etc. Moradi and Abedinie [60], I theirs study introduced a noble algorithm which is the combination of both PSO and GA to solve the optimization problem.

In almost all the studies, the final objectives and expected outcomes were very much similar although they have used different optimization technique. However, in our study we chose genetic algorithm (GA) to optimize the CHP sizing planning problem.

2.6 System Performance Indicators

System performance indicators (SPIs) also referred as key performance indicators (KPIs) are used to assess the quality of a system or technology. SPIs mainly represent the qualities that defines the strength and weakness of the system. For instance, system performance indicators can clearly depicts the benefits or drawbacks of the system in terms of economy, emission, reliability, etc. Usually system performance indicators are focused to help the user to plan a system or help decision making.

Different literatures defines KPIs/SPIs is various ways depending on the type, use and characteristics of their intended system [61]–[64]. Figure 2-18 shows the classification of performance indicators used in different literatures.

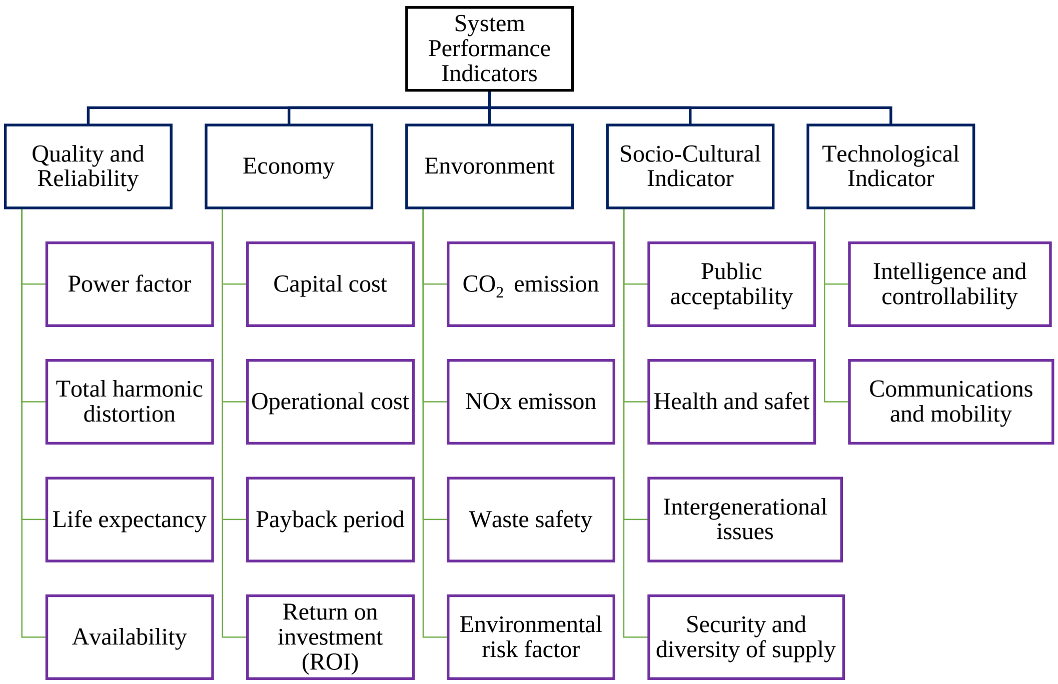

Figure 2-18: Classification of system performance indicators.

Most of the performance indicators stated in the above picture are system oriented. Certain performance indicators are applicable in certain system. For example, power quality, total harmonic distortion is related to dynamic behavior of a system containing electricity generation, distribution, transmission etc. Similarly, environmental indicator-waste safety and environmental risk factor is much related with nuclear related systems like nuclear power plant or nuclear waste repository. Technical indicator- communication and mobility is mainly related to communication based systems.

In this study, main performance indicators being considered are; economy and environmental indicators. Planning of energy based systems mainly depend on their economic and environmental performance. Sever case studies has been carried out in the study and corresponding performance indicators has also been evaluated to assess the proposed system over the conventional.

2.6.1 Economy Indicators

As shown in Figure 2-18, there are several performance indicators classifies under the economic indicator section. Capital cost requirement is one of the mostly used performance indicator of a system. In this study, system capital costs has been evaluated for individual case studies. Where;

$$System\ capital\ cost = \sum Prime\ movers\ capital\ cost + AHU\ capital\ cost$$

Total system capital cost is mainly composed prime movers cost and auxiliary heating unit's (AHU) capital cost. It to be noted that, electricity grid infrastructure does not have any involvement on system capital cost requirement. Thus to purchase or sell electricity from/to the grid, used does not need any initial investment or capital.

Another, economic performance indicator used in the study is the running cost of the system. Where,

$$\begin{aligned} &System\ running\ cost \\ &\qquad = Fuel\ cost + maintainace\ cost + energy\ purchase\ or\ sell\ cost \\ &\qquad - sold\ energy\ price \end{aligned}$$

Total cost of the fuel consume by the prime mover and the auxiliary heating unit is a key element of system running cost. Besides, operation and maintenance costs of system elements (mainly PM and AHU) also are included inside the running cost. Surplus energy (electricity) produces during operation can be sold to grid to reduce the running cost. However, if the generation of energy is less than the required, deficient energy is needed to be purchased from utility which will increase the cost.

Operational cost of the proposed systems has been compared with the conventional case. Operational saving has been estimated using the following relation;

$$Running\ cost\ saving$$
$$= Running\ cost\ of\ conventional\ sys. - Running\ cost\ of\ the\ poposed\ sys.$$

Running cost saving is the amount, which is being retained while proposed system is implemented over the conventional system. Based on the saving and the capital investment required, two new performance indicators; return on investment (ROI) and payback period has been introduced. Where,

$$ROI = Return\ on\ investment = \frac{Running\ cost\ savings}{Capital\ cost} * 100)$$

$$Pyback\ period = (\frac{Capital\ cost}{System\ running\ cost\ saving} * 100) = \frac{1}{ROI}$$

Return on investment is defined as a percentage, which represents the yearly revenue made over the capital invested. System with higher ROI is economically more appreciated. On the other hand, simple payback period is required number of years to recoup the capital invested in the system. A system with lower payback period is highly acceptable from economical point of view.

2.6.2 Environmental Indicators

Second set of performance indicators being considered are related with the emission characteristics of the system. Because of the global warming, climate change and health hazard related issues, environmental performance indicators are vastly analyzed in many studies.

Primary, emission indicator being considered is related to the CO_2 emission of the system.

Where,

$$System\ CO_2\ emission$$
$$= \sum CO_2\ emission\ from\ PMs + CO_2\ emision\ from\ AHU$$
$$+ CO_2\ emision\ from\ utility\ grid$$

Net CO_2 emission from the system is composed of the emission for prime movers, AHU and equivalent amount of CO_2 related to the purchased of electricity from the grid.

Another important environmental performance indicator being considered is the system NOx emission. Wide variety of health and environmental impact caused by the nitrogen oxides are the main reason behind choosing NOx emission as a performance indicator. Adverse effect caused by the family of NOx compound are;

- Human health hazard
- Ground level ozone formation
- Acid rain
- Water quality deterioration

Where, the NOx emission from the system is expressed as;

$$\begin{aligned} &System\ NOx\ emission \\ &\qquad = \sum NOx\ emission\ from\ PMs + NOx\ emision\ from\ AHU \\ &\qquad + NOx\ emision\ from\ utility\ grid \end{aligned}$$

Depending on the prime mover technology, NOx emission of the system could vary significantly. For instance, a system with large capacity of IC engine will result in higher emission of NOx than a system with fuel cell. However, system with lower NOx emission is highly acceptable from environmental perspective.

Chapter 3 Methodology

A genetic algorithm based optimization technique has been used to find the optimum CHP type and capacity for certain loads. Besides, an improved load following strategy has been proposed to manage the CHP operation with an intention to maximize system efficiency or minimize the system operation cost. The system intended for the study has been modeled in the Simulink interface and the optimization algorithm has been developed in the MATLAB environment.

In this chapter, the methods that has been followed to solve the intended research problem are discussed. Research framework is discussed in section 3.1. Section 3.2 and 3.3 discusses the idea behind modeling the prime movers and chosen objective function respectively. System performance indicates being considered are discussed in section 3.4.

3.1 Research Framework

This section gives the briefs idea about the problems that are considered in the study regarding the implementation and operation of CHP systems. Moreover, the methods to solve the respective problems are also summarized in this section. Figure 3-1 shows the whole research framework regarding the study.

According to the literatures[13], [14], [24], [27] it is found that, co-generation can be a good solution to cope with the growing energy demand while minimizing the CO_2 and NOx footprint. However, one of the major problem associated with the CHP system implication is to have the proper/optimal size and right type of prime mover. Authors [14], [23]–[25] agree that, without having a right prime mover with proper capacity, actual benefits of CHP systems cannot be realized. Moreover, an unplanned CHP system can become a burden rather than being beneficial.

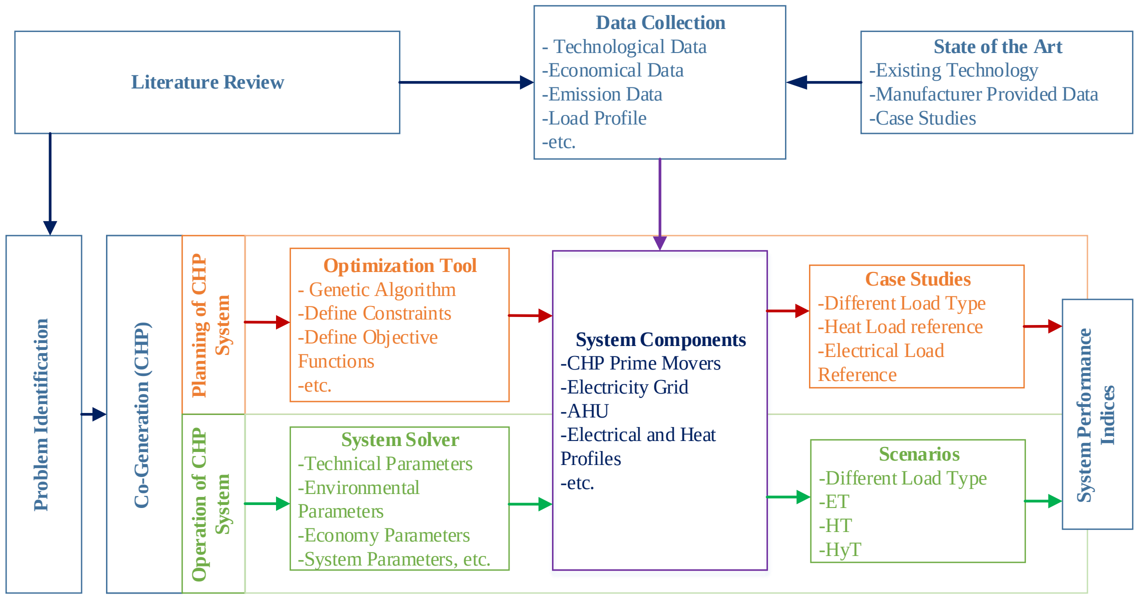

Figure 3-1: Research framework.

So, the first problem that we have identified for the study is the CHP planning problem. The CHP planning problem is mainly associated with the selection of proper prime mover type and optimal capacity. An optimization algorithm has been proposed to solve the problem and find optimal size and type of CHP prime mover for a given load. Detail of the optimization algorithm has been discussed in chapter 5.

Second problem that we have come through is regarding the CHP operation after the installation of the prime mover. Generally, the prime mover is operated at heat load tracking (HT) mode or electrical load tracking (ET) mode. However, they might not be able to ensure the maximum efficiency and could also cause increased system operational cost. So, an improved hybrid load tracking (HyT) mode has been proposed to ensure the minimum CHP running cost and maximize the primary resource utilization. More detail about the proposed solution has also been discussed in chapter 5.

The components (prime movers, AHU, grid, etc.) of the CHP system in consideration, are modeled in Simulink interface. Prime movers are modeled based on their part-load performance characteristics to get more accurate results. Technical, economic and environmental data were collected from various literatures, state of art technology reviews and from manufacturer provided information. CHP system model library created in Simulink are discussed in more detail in chapter 4.

Finally, we have carried out different case studies to investigate the feasibility of the proposed methods to solve the CHP sizing and operational planning problem. Various load conditions with distinct energy (heat and electricity) profiles has been used to evaluate the economic and environmental performance of the system. The energy profiles used for the case study are discussed in chapter 6.

3.2 Prime Mover Modeling

Prime movers of a CHP system is dependent on the load on which its operation. Based on the load supplied by the prime mover, energy generation efficiency can vary significantly. For instance; fuel cell shows maximum electrical efficiency at a load around 30~40% o of the rated. In most of the prime moves, having a load less than 30% results in a significant efficiency drop.

As we have discussed earlier, most of the studies carried out in this field of study used the constant performance model of the prime movers. The model is based on the rated prime mover performance only. The problem with the constant performance model is that, it does not take part-load performance of the PM and assumed to work at constant efficiency at any load condition. However, to have an accuracy while doing the CHP planning, part-load performance of prime mover must be taken into consideration.

In this study, the prime mover models are developed considering their part-load performance. Part-load performance data of respective prime mover is collected from different literatures, field performance data and from the manufacturers. Based on the collected information, curve fitting tool has been used to find the corresponding equation representing the part-load performance of the PMs. Detail modeling description is discussed in chapter 4.

3.3 Optimization Objective Functions

CHP systems are intended mainly to maximize fuel efficiency and minimize emission while improving system operational cost. Keeping that in mind, the planning objective functions of the studies are considered accordingly.

Multi-objection optimization intended for the capacity planning of prime movers has three objective functions. The objective is to simultaneously minimize the cost of operation and system emission. Intended objective functions for the capacity planning problems are focused on;

- System operational cost
- System CO_2 emission
- System NOx emission

Moreover, operation planning of the prime movers are also focused on two main objectives. The objectives mainly consider system running cost during operation and maximum fuel utilization of the PM. The goal of the operational planning is to control the prime mover load following mode to achieve;

- Maximum prime mover efficiency
- Minimum system running cost

More detail about the planning problems are discussed in chapter 5.

3.4 System Performance Indicators

Systems performance indicators are used to evaluate the performance of a system. In this study, specific sets of performance indicators are taken into consideration. Usually planning of a system is mainly associated with the system performance in terms of economy and emission. In other words, system operational cost and emission performance are the two main facts affecting planning decision making.

Performance indicators considered for the study are also economy and system emission oriented. Detail of the performance indicators are discussed in section 2.6. Performance indicators taken into account for the study involves;

I. Economy indicators
   a. System operational cost
   b. Return on investment of the system
   c. System payback period
II. Environmental indicators
   a. CO_2 emission from the system
   b. NOx emission from the system

Chapter 4 System Modeling

One of the objectives of the study was to build a CHP system components model library. The best feature of the model library is that, the components are generic. So, user has full flexibility to add custom data or even change the component characteristics with less effort. Detail about the modeling of each system component has been discussed in this section.

4.1 CHP Prime Movers Modeling

CHP prime movers are one of the core components of the system. In this study, the prime-movers are modeled based on their part-load performance. Detail about prime mover modeling is discussed in the following sections.

4.1.1 Internal Combustion Engine (ICE)

Wilbur L.C. has provided the typical energy balance breakdown in an internal combustion engine over the load range of 0~100%, shown in Figure 4-1. It depicts that the mechanical output of the engine falls rapidly below approximately 40~50% load and hence the system efficiency degrades as well.

The figure depicts that, the engine has a reasonable efficiency at load ranging from 50~100%. Moreover, over the whole load range, there exists a non-recoverable loss of 5~10% of the total fuel input. At no load condition, there is no mechanical output but to keep the engine running, the fuel is supplied to overcome the internal frictions during this condition.

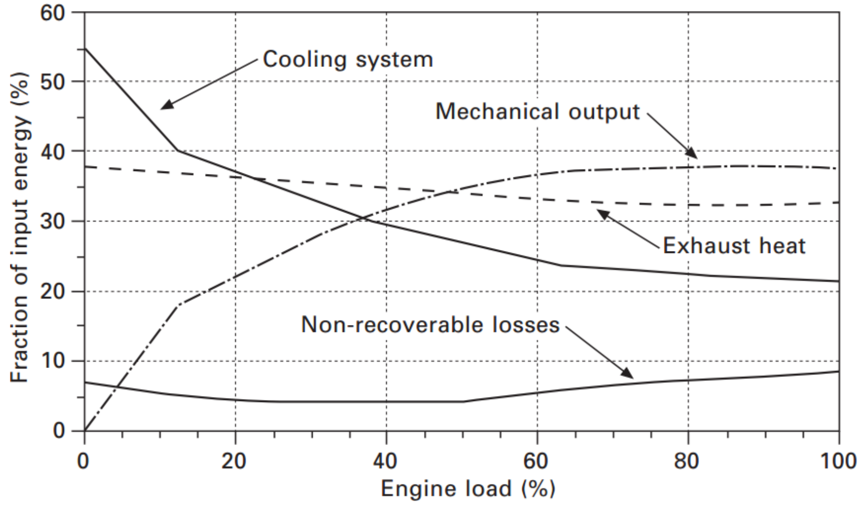

Figure 4-1: Typical energy balance in an internal combustion engine based CHP system [65].

In an IC engine, the cooling system carries away most of the dissipated heat resulted mostly due to the friction work. However, overall engine efficiency improves with increasing load while losses associated with the cooling system and exhaust decreases. In a typical spark-ignition IC engine, the energy associated with the mechanical work, exhaust heat and cooling system is distributed as a 37%, 33% and 21% respectively. [66]

Considering the above circumstances, we have designed the IC engine CHP based on their part-load efficiency characteristics. Both the heat and electrical the efficiency of an IC engine depends on the load and the maximum efficiency is possible at the rated condition. The part-load efficiency (heat and electrical) of IC engine has been represented using the following equation:

$$IC = \begin{cases} \eta_{PL,IC} = \eta_{IC,Rated}\{(0.9121)exp(0.08331)P_{ELR}) - (0.7543)exp(-6.529P_{ELR})\} \\ \bar{\eta}_{PL,IC} = \bar{\eta}_{IC,Rated}\{(0.9121)exp(0.08331P_{HLR}) - (0.7543)exp(-6.529P_{HLR})\} \end{cases} \quad (1)$$

Graphical representation of internal combustion engine part-load heat and electrical performance has been shown in Figure 4-2 and Figure 4-3 respectively.

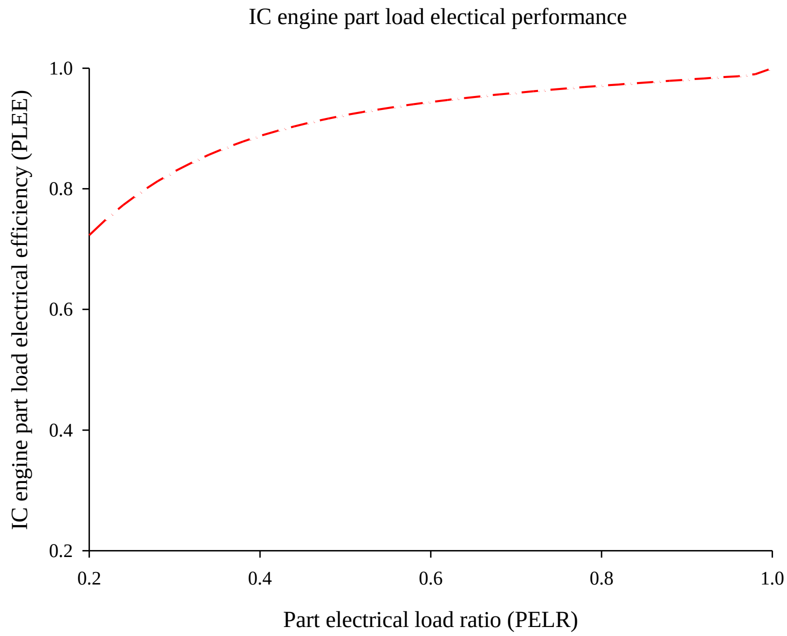

Figure 4-2: Part load electrical performance of IC engine.

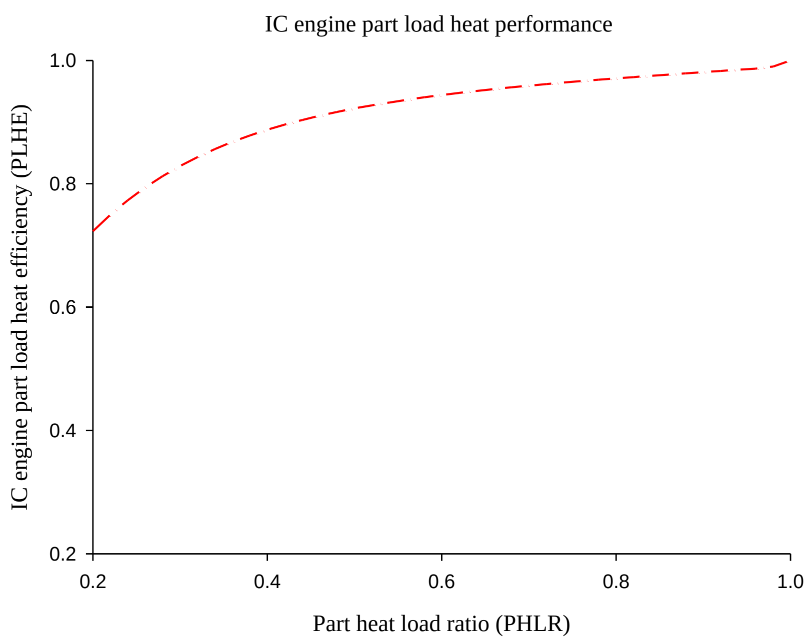

Figure 4-3: Part load heat performance of IC engine.

Figure 4-2 and Figure 4-3 depicts that both heat and electrical efficiency of spark ignition engines increases as the load increases and maximum (rated efficiency) occurs at the rated condition. Typically, efficiencies at 50% load is 10~15% less than the rated efficiency.

Further decrease in the load sharply decreases the efficiency of the IC engine. To improve the part load efficiency where significant load change are expected on a frequent basis, multiple engines are used instead of single unit. Compared to natural gas based Spark ignition engine Diesel engines has better part-load performance as the efficiency remains flat in the load range of 50~100%. However, because of their emission and reliability issue accompanied with the high cost of diesel we have ignored Diesel engines and considered natural gas based spark ignition engine for the study.

The design we have used is completely generic as the user has the complete freedom to design change the characteristics. As the characteristics could vary slightly depending on the manufacturer and the technology. The model we have built in Simulink interface has been shown in Figure 4-4. As shown in the figure, the user primarily has the flexibility to insert the intended information regarding IC engine. IC engine parameters could vary depending on the technology and different manufacturers. This feature is intended to provide the user with higher degree of freedom to define his own IC engine. However, in our study we have used the following IC engine parameters which are enlisted in Table 4-1.

Table 4-1: IC engine parameters used in the study

IC Engine Parameters	Values	References
Rated Electrical Capacity (kW)	TBD	-
Rated Heat Capacity (kW)	TBD	-
Rated Electrical Efficiency (%)	27	[43]
Rated Heat Efficiency (%)	53	[43]
Natural Gas Price ($/m3)	0.09823	[67]
Capital Cost ($/kW-Electrical)	2837	[43], [68]
Operations and Maintenance Cost ($/kWh-Electrical)	0.021	[23], [43], [44]
CO_2 Emission (kg/m3-NG)	1.879	[23]
NOx Emission (gm/kW-Electrical)	0.835	[43], [44], [69], [70]

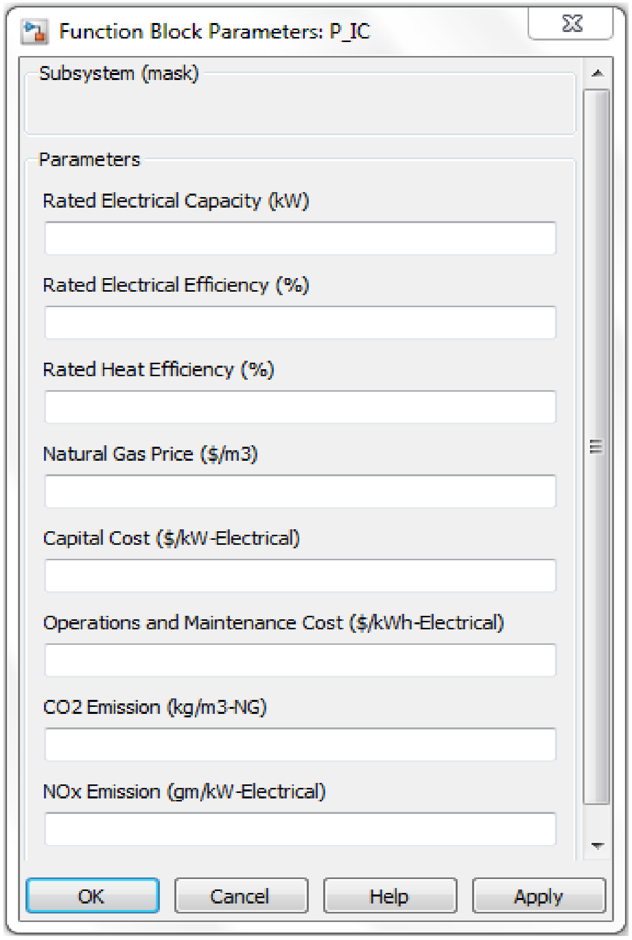

Figure 4-4: Simulink model of IC engine used for the study.

4.1.2 Gas Turbine (GT)

The main disadvantage of gas turbine (GT) over the IC engine is that, they have lower efficiency. Besides, gas turbines shows poor part load performance than IC engine from a load ranging from 40~100% of the rated.

While operating at part-load, the electrical power generated by the GT is reduced by decreasing both mass flow (by reducing the compressor speed) and turbine inlet temperature. In such condition, more heat is extracted from the turbine which causes better heat performance of the turbine. However, this changes reduce the power generation as well as the electrical efficiency of the turbine. Usually at 50% power output, electrical efficiency decreases 15~25% of the rated efficiency at standard condition[43]. However, due to the improved heat performance at part-load condition (at 50% load), the overall CHP performance decreases 10~15% than the rated.

The gas turbine efficiencies significantly decreases while the load is less than 40% of the rated [71]. So it is recommended to operate a gas turbine at more than 30~40% load. In larger systems, the part load efficiency is improved by installing multiple units. The efficiency of the GT also get affected by the ambient conditions, but for simplicity we have only considered the load dependence of the gas turbine. The overall part-load performance has been represented by the following equation:

$$GT = \begin{cases} \eta_{PL,GT} = \eta_{GT,Rated}\,\{(1.683P_{ELR}^{3}) - (4.202P_{ELR}^{2}) + 3.515P_{ELR} + 0.001129\} \\ \bar{\eta}_{PL,GT} = \bar{\eta}_{GT,Rated}\,\{(1.957P_{HLR}^{3}) - (4.963P_{HLR}^{2}) + 3.907P_{HLR} + 0.01651\} \end{cases} \qquad (2)$$

Graphical representation of gas turbine part-load heat and electrical efficiencies are shown in Figure 4-5 and Figure 4-6 respectively. It should be noted that, depending on the manufacturer and technological development, the above mentioned performance could vary slightly. However, the design being generic provides the used full flexibility to define own system.

The model of gas turbine built in Simulink interface has been shown in Figure 4-7. Same as IC engine model, the GT model gives the user extended option to select custom values for the required system.

Table 4-2 represents the parameters of GT that has been considered for the intended study.

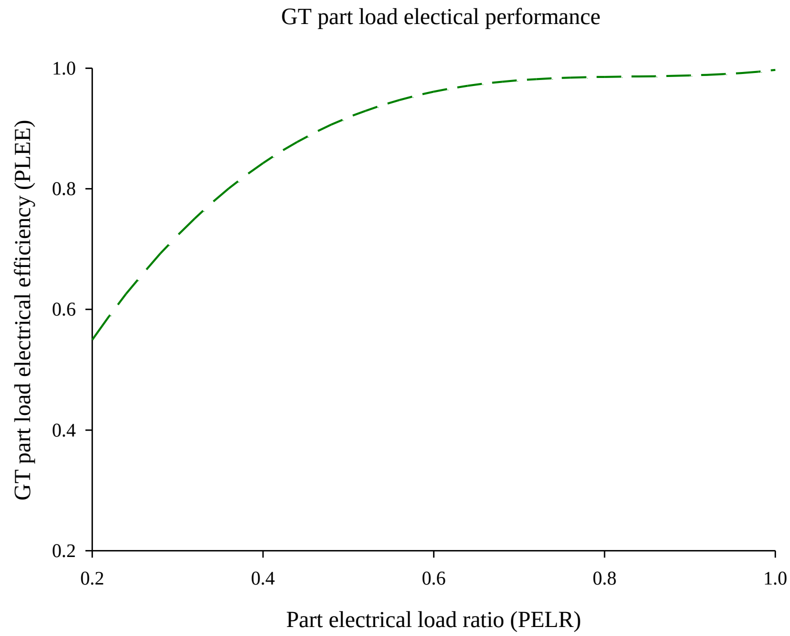

Figure 4-5: Part load electrical performance of GT.

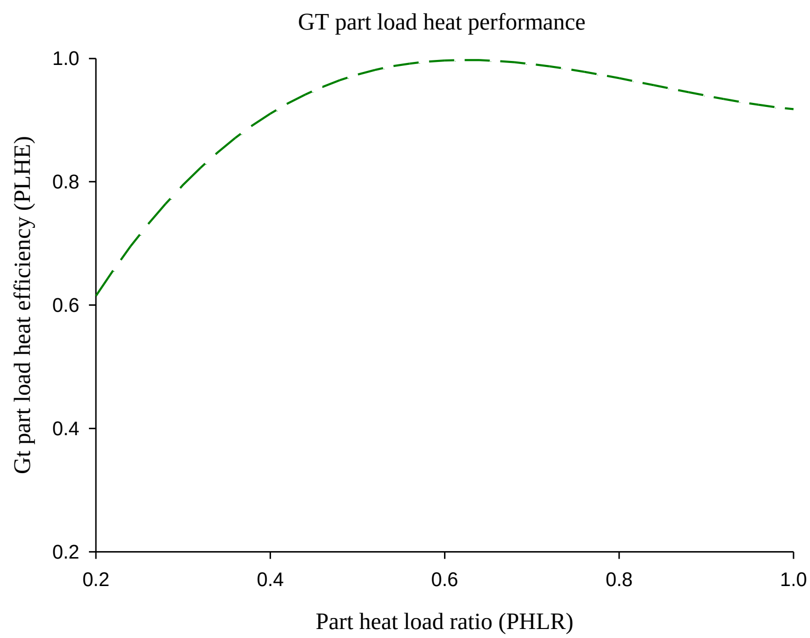

Figure 4-6: Part load heat performance of GT.

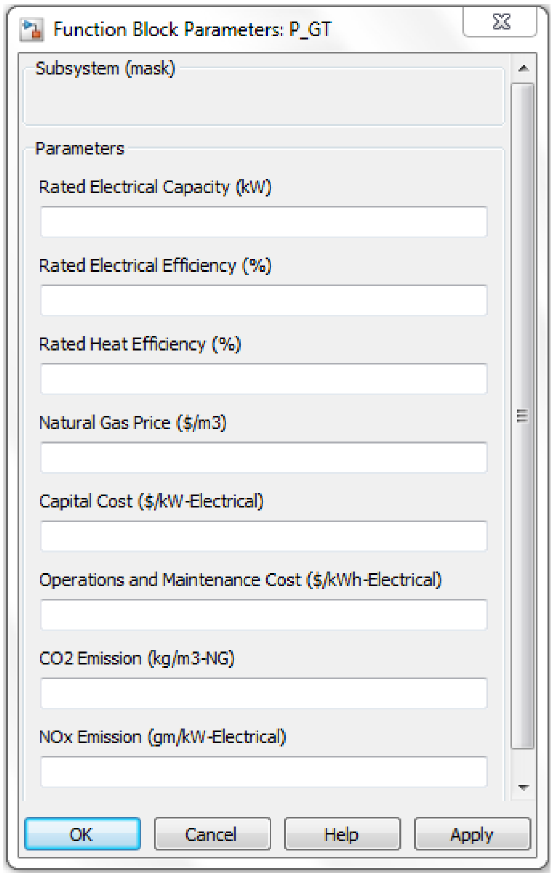

Figure 4-7: Simulink model of GT used for the study.

Table 4-2: GT parameters used in the study

Gas Turbine Parameters	Values	References
Rated Electrical Capacity (kW)	TBD	-
Rated Heat Capacity (kW)	TBD	-
Rated Electrical Efficiency (%)	26.3	[43]
Rated Heat Efficiency (%)	51.5	[43]
Natural Gas Price ($/m3)	0.09823	[67]
Capital Cost ($/kW-Electrical)	3220	[72]
Operations and Maintenance Cost ($/kWh-Electrical)	0.012	[23], [43]
CO_2 Emission (kg/m3-NG)	1.879	[23]
NOx Emission (gm/kW-Electrical)	0.077	[44], [69][70], [72]

4.1.3 Fuel Cell (FC)

In contrast to other prime movers, fuel cell shows slightly different characteristics. Unlike others, fuel cell electrical efficiency decreases approximately 5~10% from the load range of 40~100%. Therefore, decreasing the fuel cell electrical load slightly increases its efficiency compared to full load efficiency. The maximum electrical efficiency is achieved at a load around 30% of the rated capacity. This is due to the fact that, at low load the resistive losses in the cell decreases causing slight increase in the electrical efficiency [73]. However, at a very low load (less than 30%), the electrical efficiency decreases steeply due to increased electricity consumption by the system auxiliary aggregates. Thus fuel cell exhibits decreasing electrical efficiency at higher load condition where the maximum happens around 30% of the nominal load [74].

In case of the heat efficiency, there is a slight increase in the efficient at higher electrical load. However, maximum heat efficiency is achieved at full load/nominal load condition. Moreover, with a decrease in the load, the thermal efficiency decreases. At 50% load, heat efficiency is about 10~15% of the nominal. The efficiency decreases dramatically with a load less than 40%.

Overall, the whole system efficiency decreases about 5~10% at a load around 40~50%, but drastically deteriorates at load condition less than 30% due to increase heat loss in the component [75]. However, fuel cell shows better overall part load performance than the IC engine[43].

The overcall part load performance of the fuel cell has been shown in Figure 4-8 and Figure 4-9. The part load behavior is also being characterized with the equation 3.

$$FC = \begin{cases} \eta_{PL,FC} = \eta_{FC,Rated}\{\dfrac{(0.2695P_{ELR}^3 + 0.3662P_{ELR}^2 + 0.3778P_{ELR} + 0.0001462)}{(P_{ELR}^2 - 0.00234P_{ELR} + 0.06783)}\} \\ \bar{\eta}_{PL,FC} = \bar{\eta}_{FC,Rated}\{\dfrac{(-1.345P_{HLR}^4 + 3.877P_{HLR}^3 - 2.975P_{HLR}^2 + 1.12P_{HLR} - 0.006025)}{(P_{HLR}^2 - 0.6205P_{HLR} + 0.2909)}\} \end{cases} \quad (3)$$

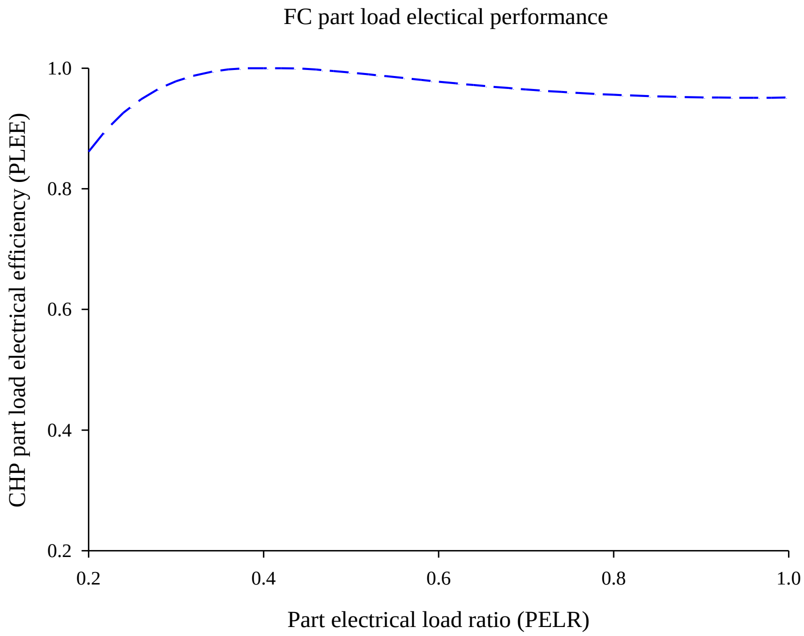

Figure 4-8: Part load electrical performance of FC.

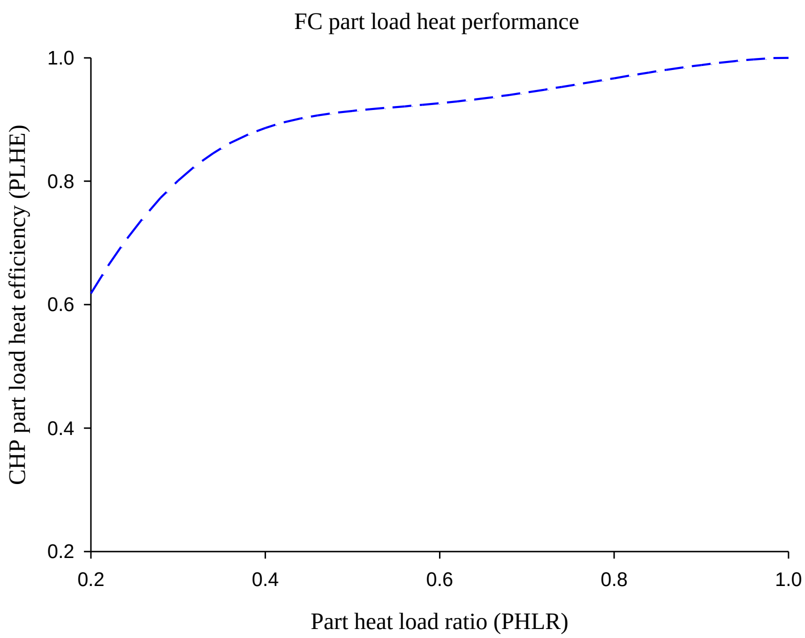

Figure 4-9: Part load heat performance of FC.

Simulink model representing the fuel cell has been shown in the Figure 4-10. As shown in the figure, the user has the flexibility to insert the custom information regarding fuel cell. This feature is intended to provide the user with higher degree of freedom to define his own FC as the parameters can vary depending on different circumstances.

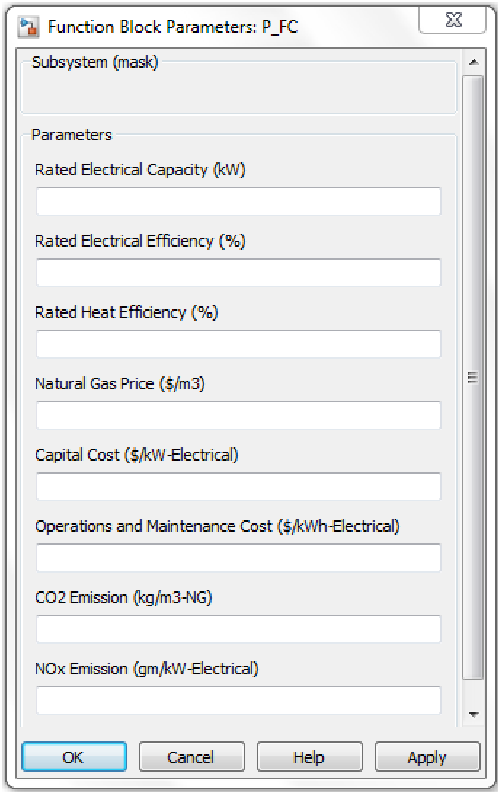

Figure 4-10: Simulink model of FC used for the study.

In our study we have used the following fuel cell parameters which are shown in Table 4-3.

Table 4-3: FC parameters used in the study

Fuel cell Parameters	Values	References
Rated Electrical Capacity (kW)	TBD	-
Rated Heat Capacity (kW)	TBD	-
Rated Electrical Efficiency (%)	34.3	[43], [76]
Rated Heat Efficiency (%)	46.7	[43], [76]
Natural Gas Price ($/m3)	0.09823	[67]
Capital Cost ($/kW-Electrical)	5500	[23]
Operations and Maintenance Cost ($/kWh-Electrical)	0.020	[69]
CO_2 Emission (kg/m3-NG)	1.879	[23]
NOx Emission (gm/kW-Electrical)	0.01	[69], [77]–[79]

4.1.4 Sterling Engine (SE)

Starling engine shows superior part-load performance. Theoretically, starling engine overall efficiency can be more than 90% with an electrical efficiency of as high as 40% [69]. However, in practical sterling engine CHP unit the electrical efficiency is limited to maximum of 20% but the overall CHP efficiency could be as high as 91% [49].

The part-load electrical efficiency of sterling engine is only decreases 5~10% at 50% load [49]. The efficiency remains reasonable with in a load range of 40~100%. However, the manufactures suggest not to operate the Stirling engine at load below 30% as the efficiency sharply decreases at such load condition.

Similarly, the part-load heat efficiency is also quite similar to the electrical performance. The heat efficiency stays within 95% of the rated efficiency at load ranging from 40~100%. But the efficiency sharply decreases at load less than 30% [80].

The part-load behavior of sterling engine has been represented with the following equation.

$$SE = \begin{cases} \eta_{PL,SE} = \eta_{SE,Rated}\,\{2.561P_{ELR}^3 - 5.843P_{ELR}^2 + 4.252P_{ELR} + 0.005927\} \\ \bar{\eta}_{PL,SE} = \bar{\eta}_{SE,Rated}\,\{-4.568P_{HLR}^4 + 12.72P_{HLR}^3 - 13.14P_{HLR}^2 + 5.951P_{HLR} - 0.0000207\} \end{cases} \quad (4)$$

The Figure 4-12 and Figure 4-12 also depicts the part-load behavior of the SE. From the figure it is also evident that, the minimum load of SE should be always more than 30% of the rated to maintain reasonable efficiency which is in good agreement with the literature [49], [80] and manufacturer provided specifications.

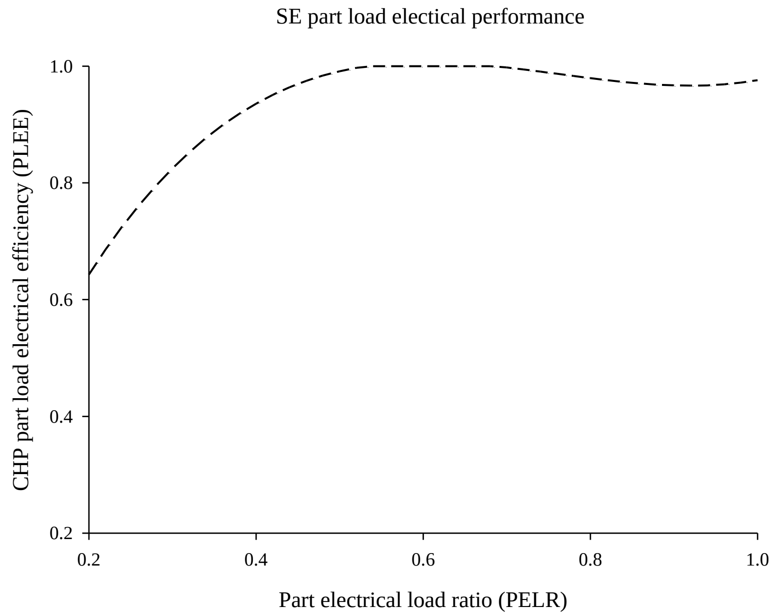

Figure 4-11: Part load electrical performance of SE.

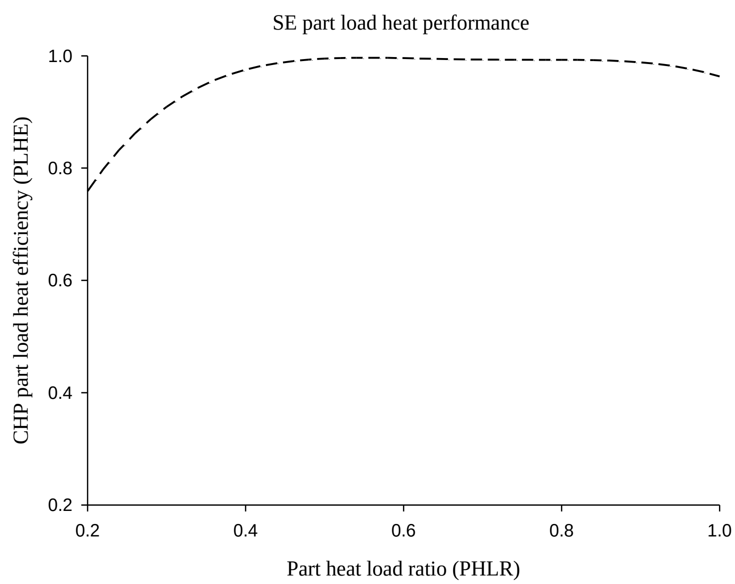

Figure 4-12:: Part load heat performance of SE.

Figure 4-13 represent the Simulink model of the SE which has been considered for the current study. The model shows that the user has option to specify his own system parameters as they can vary depending on different circumstance.

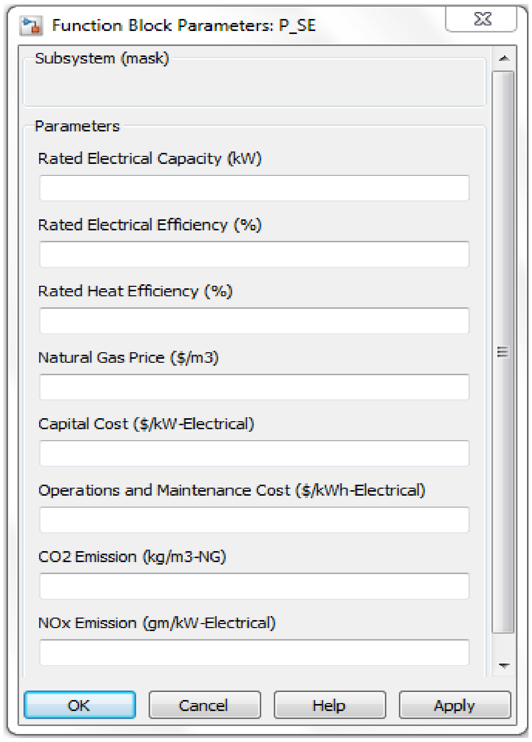

Figure 4-13: Simulink model of SE used for the study.

Table 4-4 depicts the technical specifications that has been considered for the intended study.

Table 4-4: SE parameters used in the study

Stirling Engine Parameters	Values	References
Rated Electrical Capacity (kW)	TBD	-
Rated Heat Capacity (kW)	TBD	-
Rated Electrical Efficiency (%)	14	[49], [81]
Rated Heat Efficiency (%)	77	[49], [81]
Natural Gas Price ($/m^3)	0.09823	[67]
Capital Cost ($/kW-Electrical)	4474	[81]
Operations and Maintenance Cost ($/kWh-Electrical)	0.013	[79], [81]
CO_2 Emission (kg/m3-NG)	1.879	[23]
NOx Emission (gm/kW-Electrical)	0.030	[69], [77]–[79]

4.2 Other Components Modeling

Except the prime movers, other two major component of the system are; electricity grid and the auxiliary heating unit (AHU).

The capacity of the grid has been considered to be much higher than the CHP system capacity. This will allow the intended CHP system to sell surplus electricity or purchase deficient amount of electricity from the grid without affecting the grid quality. This will also allow uninterrupted operation. Figure 4-14 shows the Simulink library model developed to represent the electricity grid. It's to be noted that the model is completely static and dynamic behavior of the grid has been ignored to avoid complexity.

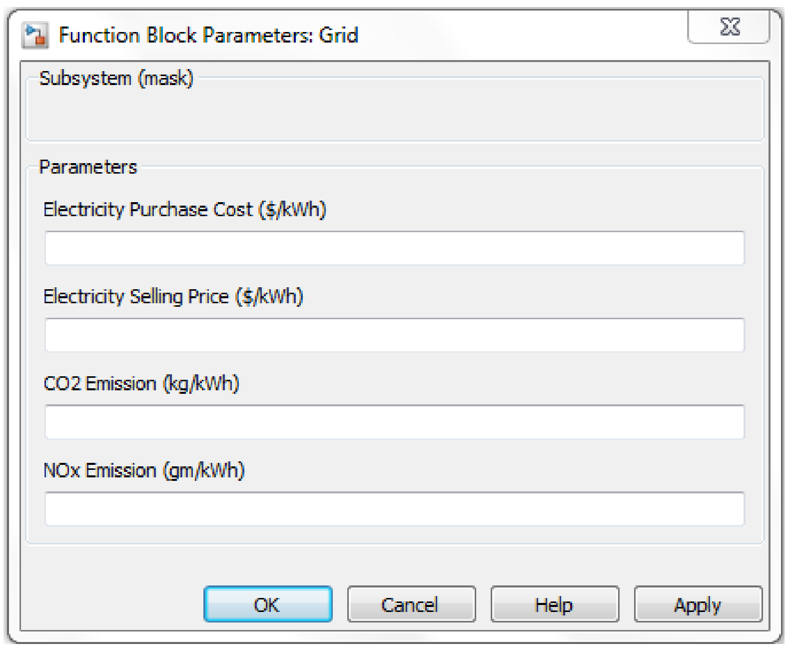

Figure 4-14: Simulink functional block representing the Electric Power Grid intended for the study.

As shown in the above figure, the model of the intended electrical power grid is generic which provides the used further degree of freedom choose different parameters. Based on the operation region, the emission regarding the grid electricity generation could vary. In such situation, used has the flexibility to choose and input emission information accordingly. Besides, the model gives the freedom to provide customer defined electricity purchase/sell price. However, in the study, both selling and purchase price of electricity are considered to be the same. Most interesting fact is that, the used does not need to pay any capital cost or O&M cost for the grid connectivity. User only pays the price for purchased electricity or earns revenue by selling the surplus electricity to the grid.

Another important system component is the auxiliary heating unit (AHU). The purpose of AHU in the system is to provide the required amount of heat energy when the heat generation from the PM is not sufficient to meet the load. Typical heating unit could be a natural gas fires boiler or furnace.

Similar to grid, the AHU being considered in the study is developed based on their static behavior. AHU model developed in Simulink has been show in Figure 4-15.

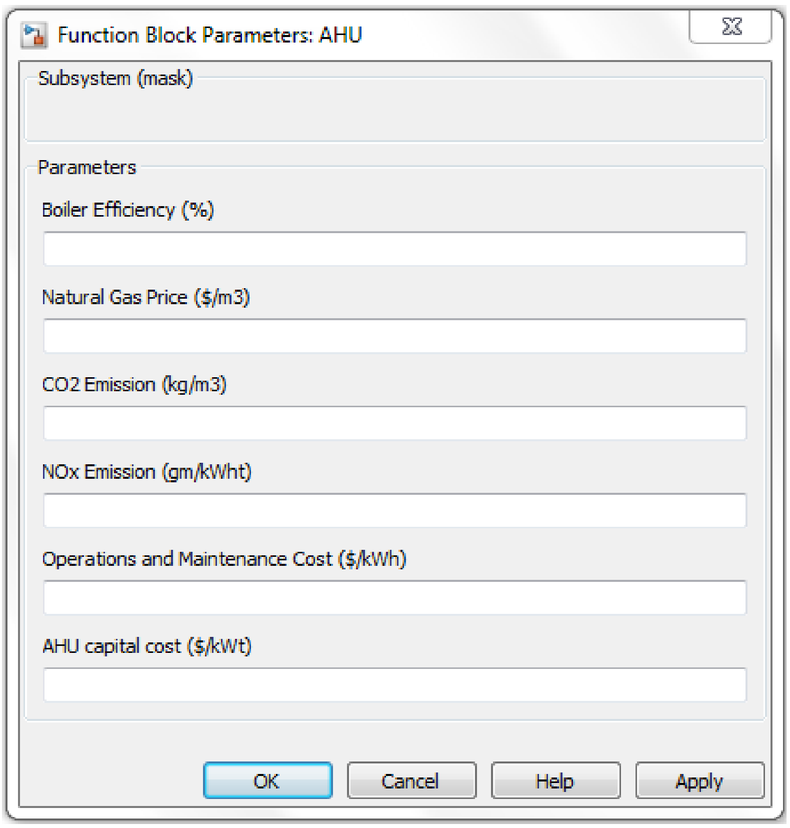

Figure 4-15: Simulink functional block representing the Auxiliary Heating Unit intended for the study.

As shown in the figure, user has the flexibility to define the AHU parameters. AHU efficiency represents the rated efficiency of the heating unit. Besides, used has the flexibility to provide the emission information as well as the operational and maintenance cost the heating unit. This feature gives the user to explore the possibilities with different heating unit available. However, unlike grid, user has to pay the capital required to install auxiliary heating unit in the system.

Table 4-5 shows the corresponding grid and AHU data used for the study. Information presented in the table are kept unchanged throughout the study. However, the user has the freedom to customize the data if required.

Table 4-5: Electricity grid and AHU parameters used in the study

System Component	Parameter	Value	References
Grid	Electricity Purchase Cost ($/kWh)*	0.1	[82]
	Electricity Selling price ($/kWh)*	0.1	[82]
	CO_2 Footprint (kg/kWh)	0.5967	[83]–[85]
	NOx Footprint (gm/kWh)	0.96	[83]–[85]
AHU	Capital Cost ($/kW-thermal)	1745	[81]
	Rated Thermal Efficiency (%)	87	-
	O&M Cost ($/kWh-thermal)	0.01	[81]
	CO_2 Emission (kg/m3-NG)	1.879	[23]
	NOx Emission (gm/kWh-thermal)	0.04	[86]–[88]

$^{*}daily\ average\ price = \frac{(off-peak\ price*hours)+(mid-peak\ price*hours)+(on-peak\ price*hours)}{24}$

4.3 Problem Formulation

According to different authors in their recent publications [14], [23], [24], [26] has mentioned that, CHP within micro energy grid can potentially improve primary fuel utilization and reduce the system operational cost and emission (CO_2 and NOx) at the same time. However, planning of CHP system, which involves selection of prime mover capacity and type for a specific MEG, is still a matter of concern to maximize the potential benefits.

The study presents a planning tool to identify the optimal deployment of CHP prime movers in a MEG with respect to type and capacity of the PM. The planning problem is resolved by evaluating the CHP performance from both environmental (NOx and CO_2)

emission and economical (operational cost) point of view. User can provide his point of interest focusing system economy or emission and the optimization algorithm will determine the best possible capacity of prime movers for the specific MEG.

Figure 4-16 shows the whole MEG system considered for the intended study. The system consists both electrical and heat load, where the heat load represents space heating, hot water supply, cooking etc. [11], [14]. CHP prime movers considered for the study involves; internal combustion engine (ICE), gas turbine (GT), Fuel cell (FC) and, Sterling engine (SE). The candidate technologies are designed based on their part-load performance to find the optimal deployment more accurately. Prime mover characteristics has been discussed in section 4.1.

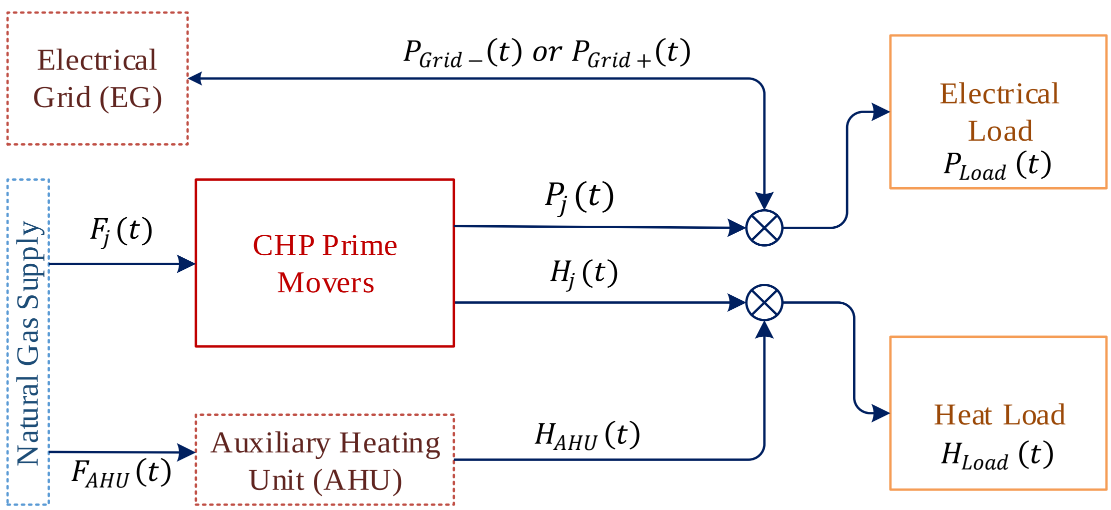

Figure 4-16: MEG system considered for the intended study

The energy flow schematic shown in Figure 4-16 depicts that, the CHP prime movers simultaneously provide electrical and heat energy while consuming natural gas as primary fuel. Electrical load is primarily met by the CHP unit while the deficient/surplus amount of electricity is purchased from/sold to the electricity grid. System heat load is met by the heat generated from the CHP prime mover while the heat energy shortcoming is met by the auxiliary heating unit (AHU). All the energy generation units, including the CHP prime movers and the AHU consumes only natural gas as the primary fuel. General equations defining the intended system are stated below.

$$F_j(t) = \frac{P_j(t)}{u\,\eta_{PL,j}(t)}\ ;\ \ \forall t \in T \text{ and } j \in G \tag{5}$$

In the above equation, $P_j(t)$represents the electrical power generated by the CHP prime mover at hour, t; where G is the set of CHP prime movers and T is the set of hourly periods over a year (i.e., 8760 hours over a year).

$$G = \{IC, GT, FC, SE\} \tag{6}$$

$$T = \{1,2,3, \dots \dots \dots 8760\}\ , \textit{over a year;}$$

u, represents the energy density of naturel gas (primary fuel) consumed by the energy generating unit in kWh/m^3. $\eta_{PL,j}(t)$, is the part load electrical efficiency of the prime mover j at hour, t; which can be achieved from the equation (1-4).

$$H_j(t) = P_j(t)\,\frac{\bar{\eta}_{PL,j}(t)}{\eta_{PL,j}(t)}\ ;\ \ \forall t \in T \text{ and } j \in G \tag{7}$$

$H_j(t)$, represents the generated heat by the prime mover prime mover j at hour, t. $\bar{\eta}_{PL,j}(t)$, is the part load heat efficiency of the prime mover j at hour, t; which can be achieved from the equation (1-4).

$$\Delta H(t) = H_{Load}(t) - \sum H_j(t) \tag{8}$$

$$= \begin{cases} -ve\ ; Dump\ or\ waste\ of\ surplus\ heat \\ 0\ ; No\ surplus\ or\ shortfall\ of\ heat \\ +ve\ ; Additional\ heat\ from\ AHU \end{cases}$$

$\Delta H(t)$, in the above equation represents the difference between the heat demand and generation at time, t. A positive $\Delta H(t)$ resembles the situation when the total heat generation is less than the total demand at t , where the shortcoming in the heat energy supply must be met using the auxiliary heating unit (boiler, furnace, etc.). If the difference is zero, thus represents that the total generation is equal to the total demand and there is no surplus or shortcoming in the energy supply. However, a negative value of, $\Delta H(t)$, signifies that, there is more heat generation in the network than the load requirement.

Excess heat generated during operation is dumped as waste heat in the atmosphere. Some studies [14] suggested thermal energy storage (TES) to store the surplus heat to maximize the system heat usage. However, in this study, the use of thermal energy storage in the CHP system has been avoided as TES involves more capital investment.

$$H_{AHU}(t) = \begin{cases} \Delta H(t), if\ \Delta H(t) > 0 \\ 0, otherwise \end{cases} \tag{9}$$

In the above equation, $H_{AHU}(t)$ represents the heat energy supplied by the auxiliary heating unit during time, t.

$$F_{AHU}(t) = \frac{H_{AHU}(t)}{u\,\bar{\eta}_{AHU}}\ ; \quad \forall t \in T \tag{10}$$

$F_{AHU}(t)$, in equation 10 represents the fuel input required at the AHU during, t. $\bar{\eta}_{AHU}$, depicts the thermal efficiency of the auxiliary heating unit while u, represents the energy density of naturel gas (primary fuel) in kWh/m^3.

$$\Delta P(t) = P_{Load}(t) - \sum P_j(t) \begin{cases} -ve\ ; Surplus\ electricity\ sold\ to\ grid = P_{Grid-}(t) \\ 0\ ; No\ surplus/shortfall\ of\ electricity \\ +Ve\ ; Electricity\ purchased\ from\ the\ grid = P_{Grid+}(t) \end{cases} \tag{11}$$

Equation above, simply represent the system equation regarding the purchased/sold electricity from/to the grid. $\Delta P(t)$, is the difference between the total electrical load demand ($P_{Load}(t)$) and total power generation ($\sum P_j(t)$) by the prime movers at, t. A negative value of $\Delta P(t)$ represents surplus electricity generation which is sold to the grid. $P_{Grid-}(t)$, represents the amount of electricity sold to the grid at, t. However, positive value of $\Delta P(t)$ depicts that the demand is higher than the generation, and the shortfall of electricity is met by purchasing electricity from the grid. Amount of electricity purchased from the grid is represented using, $P_{Grid+}(t)$.

$E_{C,j}(t)$, in the following equation 12, indicates the amount of CO_2 emission by the PM, j at hour, t. Amount of CO_2 emission is directly proportional to the amount of fuel burnt to produce the energy, so manufacturers often specify the CO_2 emission as a function of the fuel consumption. Thus in the equation, $k_{C,j}$ represents the CO_2 footprint of j in (kg/m^3-NG).

$$E_{C,j}(t) = F_j(t)\ k_{C,j} \quad ; \qquad \forall t \in T \ and \ j \in G \tag{12}$$

$$E_{N,j}(t) = P_j(t)\ k_{N,j}; \qquad \forall t \in T \ and \ j \in G \tag{13}$$

$E_{N,j}(t)$, indicates the amount of NOx emission by the PM, j at hour, t; where, $k_{N,j}$ is the NOx footprint of j in (g/m^3). Usually, NOx emission from the prime movers are related to electricity generation and the manufacturers specify the NOx foot print with respect to the electricity generation. Besides, NOx emission are relatively smaller in amount compared to CO_2 emission, so in our study we have used the milligram (mg) as unit of NOx emission rather than kilo-gram (kg).

$$E_{C,Grid}(t) = P_{Grid+}(t)\ k_{C,Grid} \quad ; \qquad \forall t \in T \tag{14}$$

$$E_{N,Grid}(t) = P_{Grid+}(t)\ k_{N,Grid} \quad ; \qquad \forall t \in T \tag{15}$$

$E_{C,Grid}(t)$, and $E_{N,Grid}(t)$ represent the amount of CO_2 and NOx emission by the main grid at, t; where, $k_{C,Grid}$ represent the CO_2 footprint of grid in (kg/kWh) . $k_{N,Grid}$, is the NOx footprint of the grid in mg/kWh.

$$E_{C,AHU}(t) = F_{AHU}(t)\ k_{C,AHU} \quad ; \qquad \forall t \in T \tag{16}$$

$E_{C,AHU}(t)$, indicates the amount of CO_2 emission by the auxiliary heating unit at hour, t; where, $k_{C,AHU}$ is the CO_2 footprint of AHU in (kg/m^3).

$$E_{N,AHU}(t) = H_{AHU}(t)\ k_{N,AHU}; \qquad \forall t \in T \tag{17}$$

$E_{N,AHU}(t)$, indicates the amount of NOx emission by the AHU at, t; where, $k_{N,AHU}$ is the NOx footprint of auxiliary heating unit in (mg/kWh).

Chapter 5 CHP Planning Problem Formulation

This section discussed the prime mover capacity planning and operation planning problems. Optimization technique that has been used to find optimal size and type of the CHP prime mover has been described in section 5.2. This chapter also talks about the boundary conditions, assumption and system constraints that has been considered for the intended study. Section 5.3 contains the detail about the conventional (HT and ET) load tracking mode and proposed hybrid load tracking (HyT) mode. HyT mode has been intended to maximize CHP operational efficiency and also minimize the system running cost.

5.1 Optimization Problem Formulation

The multi-objective MEG planning problem discussed in the study emphasizes on minimizing the total running cost and total system emission of both CO_2 and NOx. The goal of the planning problem is to find the optimal CHP prime mover combination (type and capacity) with an objective to minimize the objective functions. The multi-objective planning problem can be formulated as;

$$Minimize\ (O_{F1}, O_{F2}, O_{F3})$$

Where,

$$O_{F1} = System\ running\ cost = \sum_{t \in T} \{C_{Op}(t) + C_{Pur}(t)\} \tag{18}$$

$$O_{F2} = System\ CO_2\ emission \tag{19}$$

$$= \sum_{t \in T} \left\{ \sum_{j \in G} E_{C,j}(t) + E_{C,AHU}(t) + E_{C,Grid}(t) \right\}$$

$$O_{F3} = System\ NOx\ emission \tag{20}$$

$$= \sum_{t \in T} \left\{ \sum_{j \in G} E_{N,j}(t) + E_{N,AHU}(t) + E_{N,Grid}(t) \right\}$$

First objective function (O_{F1}), is the function of total running cost of the system. The study intend to find the optimal size and type of prime mover while minimizing, O_{F1}. Prime mover selection is independent of both system NOx and CO_2 emission while minimizing, O_{F1}. Equation 18 shows the basic equation defining, O_{F1}. The equation consists of both system operational cost ($C_{Op}(t)$) and energy purchase ($C_{Pur}(t)$) which are represented in equation 21 and 22 respectively.

Further, the study also intend to minimize second objective function (O_{F2}) which is a function of systems total CO_2 emission. O_{F2}, is independent of both system running cost and NOx emission. O_{F2}, is depicted in equation 19 which consists the CO_2 emission of all system components (i.e. prime movers, AHU and grid).

Final objective function (O_{F3}) is a direct function of system NOx emission. O_{F3}, is completely independent of system CO_2 emission and running cost. One on the goal of the study is to find the optimal PM size and type while minimizing the, O_{F3}. The equation regarding O_{F3},consists of the total NOx emission from each system components (prime movers, Grid and AHU). Equation 20 represent O_{F3} which is to be minimized.

$$C_{Op}(t) = \sum_{j \in G} \left\{ C_{NG}\, F_j(t) + C_{O\&M.j}\, P_j(t) \right\} \quad ; \forall t \in T \tag{21}$$

$$\begin{aligned} C_{Pur}(t) = \big\{ & C_{Grid}(t) P_{Grid+}(t) + \left(C_{NG} F_{AHU}(t) + C_{O\&M,AHU} H_{AHU} \right) \\ & + C_{Grid}(t) P_{Grid-}(t) \big\} \quad ; \forall t \in T \end{aligned} \tag{22}$$

Optimization and system constraints are also an important part of the study. The results of CHP planning can significantly change depending on the constraints. However, system constraints used in the study are kept unchanged. Equations defining system constraints are listed below.

$$\sum_{j \in G} P_j(t) + P_{Grid-}(t) + P_{Grid+}(t) = P_{Load}(t) + P_{Loss}(t);\ \forall t \in T \tag{23}$$

Constraints shown in equation 23 depicts that, sum of total electricity generation, amount of electricity sold and purchased to/from the grid is equal to system electrical load and system loss at hour, t.

$$0 \leq P_{Grid+}(t);\ \forall t \in T \tag{24}$$

Another consideration made for the study is that, power purchased from the grid at specific hour is always greater or equal to zero.

$$|P_{Grid-}(t)| < P_{Grid,max};\ \forall t \in T \tag{25}$$

Maximum capacity of the grid ($P_{Grid,max}$), is considered to have much higher capacity than the amount of electricity to be purchased or sold. This allows the system to get required electricity from grid as well as to sell surplus electricity to grid without interruption.

$$0.3P_{j,Rated} \leq P_j(t) \leq P_{j,Rated} \tag{26}$$

As most of the prime movers efficiency falls significantly at load less than 30% of the rated, so it is assumed that, all PMs operate at least at a minimum load of 30% to have a reasonable system efficiency.

$$\sum_{j \in G} H_j(t) + H_{AHU}(t) = H_{Load}(t) + H_{Dump}(t);\ \forall t \in T \tag{27}$$

According to the above constraint, total heat generation and heat from AHU is equal to total system heat load and heat dump during specific hour. Thus represents that, any heat energy shortcoming after generation is met from AHU. However, if the generated heat is higher than the required, excess heat is then dumped in the atmosphere.

$$P_{j,Rated} \leq P_{Load,max} \tag{28}$$

During the sizing selection optimization problem, it is assumed that the maximum allowable electrical capacity of individual prime mover cannot exceed the maximum electrical load of the system. Thus the boundary condition limits the capacity of the individual PM.

$$\sum_{j \in G} P_{j,Rated}(t) \leq P_{Load,max} \tag{29}$$

Above constrain depict that, the total CHP capacity (sum of the available PM capacity) must not exceed the maximum load of the system. Thus the sum of all PM electrical capacity must stay equal or below the maximum electrical load of the system.

User has freedom to restrict the capacity constraints as per requirement. For example, the sum of Prime movers electrical capacity could be set not to exceed 75% of the maximum electrical load of the system. User could further restrict the capacity limit of the individual prime mover as per interest.

Based on the system constraints, selection of optimal prime movers for an intended system could vary significantly. However, system constraints defined by equation 23-29 are kept unchanged throughout the study.

5.2 Implementation of Genetic Algorithm

Genetic algorithm is a probabilistic search algorithm inspired from the concepts of biological evolution[89]. GA is a well-established optimization tool to find the solution of a problem. GA explores the problem search space and tries to find the solution in a finite time based on predefined constraints and fitness function.

Genetic algorithm continuously refines a set of solutions to a problem through iteration by introducing best features from the existing solutions[90]. The solutions are known as individuals or chromosomes and the set of the solutions/individuals are called the population. Each and every individual has a genome that holds its unique features. In general, the genome itself consists of certain bit-string or arrays of real values.

The fittest individual/chromosomes survives generation after generation while reproduce and create offspring’s that might be stronger or weaker than their parents. However the weakest individuals are removed from the solution space and only the strongest ones are considered for the further evolution. The cycle of evolution continues repeatedly until it reaches the solution or meets the termination criterion. User has the freedom to set a fitness function, or the total number of evolution cycle to define the termination criterion.

General procedure of GA has the following steps [91], [92];

I. A population of chromosomes are randomly generated.

II. Fitness of each chromosome in the population is calculated.

III. Genetic operators are used to create offspring.

IV. Remove the unfitted individuals/chromosomes from the solution space and only consider the best fitted individual for further mutation.

V. Stop the search if the termination criterion is meet. Otherwise go back to step II.

In this study, similar approach has been used to implement GA to find the optimal solution of the problem. The detail of GA applied to solve the CHP planning problem based on the proposed formulation has been shown in Figure 5-1.

Proposed algorithm used the traditional GA which is a simple yet effective mechanism to optimize the MEG planning problem. In this method, user has the freedom to define system input (like; rated efficiency of components, part-load performance, etc.) as well as the cost and emission (CO_2 and NOx) data for each component of the system. The GA uses all the available information and solve the optimization problem based on the user defined objective functions.

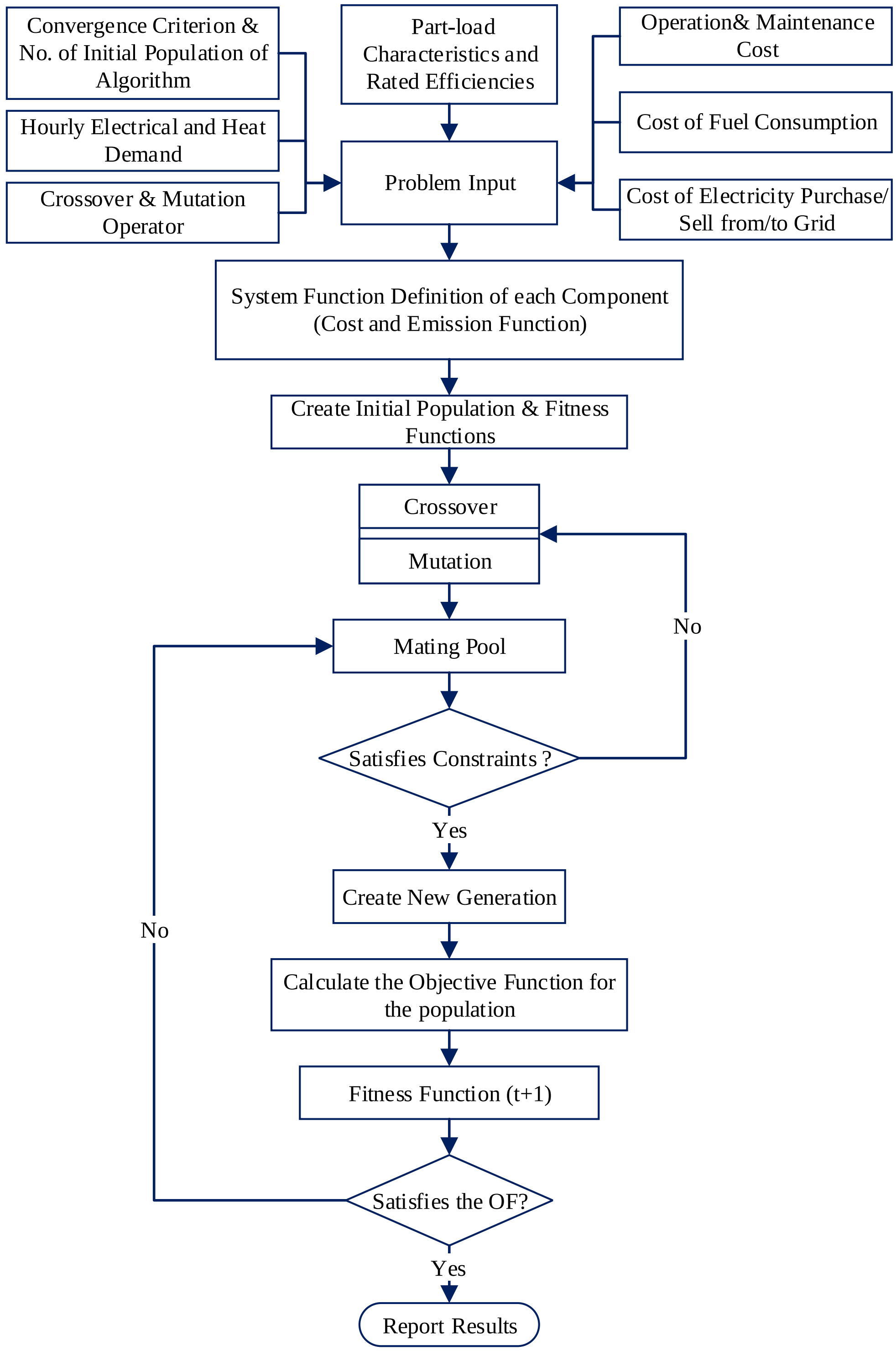

Figure 5-1: Implementation of GA to solve the CHP prime mover sizing selection problem.

Genetic algorithm based optimization algorithm follows certain steps to find the optimal solution. Where,

Step 1:	Read the following input data regarding the MEG planning problem: I. Part-load characteristics and rated efficiencies of the prime movers. II. Hourly electrical and heat demand of the MEG over the whole year. III. Operation & maintenance cost of the system components. IV. Cost of Fuel Consumption, Natural gas price ($/m^3). V. Cost of Electricity Purchase/Sell, from/to Grid. VI. Initials information regarding the GA (i.e; population size, chromosome length, and maximum number of iterations, constraints, etc.)
Step 2:	Generate an initial population (P_0). As shown in equation 30, the length of the chromosome equals the total number of decision variables (optimal rating for each CHP prime mover). $P_0 = [\, P_1 \;\; P_2 \; \ldots \; P_j \ldots \; P_G \,] \quad where, \forall\, j \in G$ (30)
Step 3:	For the individuals in the initial population, P_0, check the constraints defined by the user. If the solution/individual does not satisfy constrains then the infeasible solution is ignored from the solution space by assigning a very large penalty cost against it.
Step 4:	Evaluate the fitness function for the best individuals in P_0 that satisfies the constraints by using the objective functions defined by the user (equation18, 19, and 20). The new population is then represented using iteration number k, (i.e; the population is denoted as, P_k).

Step 5:	New population (P_{k+1}) is created through the application of mutation and crossover operators to (P_k). The process has the following traits; — Some parents are chosen to participate in the next generation based on the values of their fitness function. This is done to maintain elitism, by which the presence of best individuals of the current generation (parents) are carried over to the next generation. — Further crossover between the parents are introduced to produce offspring that has some behaviors from their parents. This is done in order to find better individuals. — Mutation, which introduces random change to a single chromosome with a purpose to create a child for the new population.
Step 6:	The constraints are verified for the new population, P_{k+1}, and only the best individuals which satisfies the constrains are carried out further.
***Step 7*:**	The fitness function for the individuals in the new population $P_{k+1}$is evaluated.
Step 8:	Check the termination conditions for the population. Where, the termination conditions are; — The objective function is satisfied, if the optimal pattern remains constant even after a certain number of iterations. — Maximum number of iterations (defined by the user) has been reached. If either of the termination condition is met, the algorithm continues to step 9, else it goes back to step 5.
Step 9:	Report the results.

The genetic algorithm based optimization method manipulates a string of numbers in a manner similar to how chromosomes are changed in biological evolution. An initial population made up of strings of numbers is chosen at random or is specified by the user. Each string of numbers is called a "chromosome" or an "individual," and each number slot is called a "gene." A set of chromosomes forms a population. Each chromosome represents a given number of traits which are the actual parameters that are being varied to optimize the "fitness function/objective function". The fitness function is a performance index that we seek to minimize.

A Gene is a digit position that can take on certain values. A Chromosome is a string of genes. A Trait is a decimal number which is decoded from a chromosome. Normally, a chromosome is a concatenation of several Traits. An Individual is the object that the GA is attempting to optimize. An individual is described by its chromosome. The individual's traits determine its fitness. A Population is a set of individuals (set of chromosomes). Fitness function is the objective function to be optimized which provides the mechanism for evaluating each string (we maximize the fitness function). Selection: a fitter string receives a higher number of offspring and thus has a higher chance of surviving in the subsequent generation. Crossover is an operation which swaps genes between two chromosomes. Mutation is flipping a digit in the chromosome after crossover.

The operation of the GA proceeds in steps. Beginning with the initial population, "selection" is used to choose which chromosomes should survive to form a "mating pool." Chromosomes are chosen based on how fit they are (as computed by the fitness function) relative to the other members of the population. More fit individuals end up with more copies of themselves in the mating pool so that they will more significantly affect the formation of the next generation. Next, several operations are taken on the mating pool. First, "crossover" (which represents mating, the exchange of genetic material) occurs between parents. To perform crossover, a random spot is picked in the chromosome, and the genes after this spot are switched with the corresponding genes of the other parent. Following this, "mutation" occurs. This is where some genes are randomly changed to other values. After the crossover and mutation operations occur, the resulting strings form the next generation and the process is repeated. A termination criterion is used to specify when the GA should end (e.g., the maximum number of generations or until the fitness stops increasing).

Genetic algorithm parameters used in this study are:

Parameter	:	Values
Number of traits	:	4
High Trait	:	Maximum Load of the system (kW)
Low Trait	:	0
No of genes in each trait	:	4
Mutation Probability	:	0.05
Crossover Probability	:	0.8
Population Size	:	1000
Epsilon and Delta	:	0.001 and 5 (Program is terminated if the fitness changes less than Epsilon over Delta generations)
Maximum Generation	:	100

5.3 Operational Planning of CHP Prime Movers

CHP operation in an MG is influenced by various factors. However most dominating factors are heat and electrical demand and weather conditions. Typically the CHP operation is controlled by running the CHP prime mover in accordance to either heat or electrical load of the system [93]–[95]. Most common load following strategies are discussed in literature [95]–[98] ;

I. Heat demand following or Heat load tracking
II. Electrical load tracking or Electricity demand following
III. Continuous mode of operation
IV. Base load operation
V. Peak saving

In this study, only heat and electrical load tracking mode along with a proposed hybrid load tracking mode has been discussed, shown in Figure 5-2. Following sections have more details about the intended modes of operation.

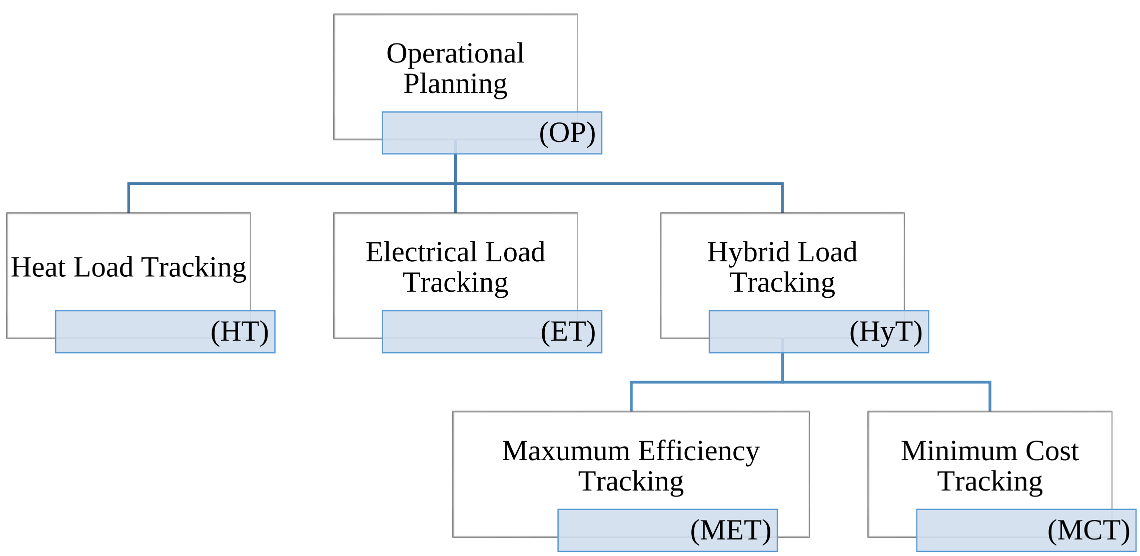

Figure 5-2: CHP operational modes considered in the study.

5.3.1 Heat Load Tracking (HT)

While in heat load tracking (HT) mode (also called heat load following or thermal tracking mode), CHP prime mover follows the heat load of the system and produces electricity accordingly. Electricity generation at that time depends on the type of the prime mover and on its part load performance characteristics. However, electricity generation during HT mode is completely independent of the system electricity demand. HT is known as the 'classical' strategy of CHP operation, which is intended to ensure no/less heat west and to minimize the emissions[99].

During HT mode of operation, surplus/deficient electricity are sold to/bought from the main electrical grid. Moreover, if the CHP prime mover has the capacity less than the maximum demand, required heat energy demand is met from a natural gas fueled auxiliary heating unit (e.g., boiler, furnace).

From the heat energy outlook, HT is considered as controlled generation mode. However, from an electricity generation point of view, HT mode can be considered as an unrolled mode of operation.

Equations (eq. 1-17) discussed in chapter 4 are used to define the operational planning system too. Where, equation 31 defines the total cost during the HT operation, equation 32 depicts total system CO_2 during HT mode of operation and equation 33 is used to evaluate total NOx emission during operation.

It's to be mentioned that during HT mode, the reference load is the heat load. Whole system performance indicators are evaluated taking heat load as reference. Electrical load at this time of operation has no direct influence on the energy generation of the CHP prime mover.

$$System\ running\ cost = C_{NG}\ F_j(t) + C_{O\&M.j}\ P_j(t) + C_{Grid}(t)P_{Grid+}(t) + \left(C_{NG}F_{AHU}(t) + C_{O\&M,AHU}H_{AHU}\right) + C_{Grid}(t)P_{Grid-}(t)\ ;\ \forall t \in T\ and\ j \in G \tag{31}$$

$$System\ CO_2\ emission = E_{C,j}(t) + E_{C,AHU}(t) + E_{C,Grid}(t)\ ;\ \forall t \in T \tag{32}$$

$$System\ NOx\ emission = E_{N,j}(t) + E_{N,AHU}(t) + E_{N,Grid}(t)\ ;\ \forall t \in T \tag{33}$$

All three equations stated above, usually are for a specific hour, t. So, the total cost, emission (CO_2 and NOx) can be evaluated by integrating the individual hourly results over the whole period of operation.

5.3.2 Electrical Load Tracking (ET)

Another very common of CHP operation is electrical load tracking mode (ET) also referred as electrical load following mode. In ET mode, CHP prime mover solely tracks electrical load of the system, while heat energy is generated accordingly. During this mode of operation, heat generation depends mainly on the type of prime mover and their part load performance characteristics but are not subjected to the system heat load demand.

ET strategy mainly focuses on system economy as it is intended to control (maximize or minimize) the amount of electricity to be sold to grid or purchased from the grid. Typically, if it is not economical to sell surplus electricity to grid then the ET strategy focuses on minimizing the net electrical energy sell. In the study, both the electricity selling/purchase price has been considered to be same regardless of the time of operation. As a result, ET mode in consideration in the study always focuses on higher electricity generation to earn more revenue by selling the surplus electricity to the grid. However, depending on the prime mover capacity and load requirements, any electrical energy shortcoming is met by the electricity purchased from the grid.

There is a higher probability of excess heat energy generation during this mode depending on the nature of prime mover and the load condition. The excess heat could either be dumped or be stored using a thermal storage. However, the study does not consider thermal storage in the system to limit the system cost, so the surplus heat is considered to be dumped in the surrounding environment. Moreover, if the CHP prime mover has the capacity less than the maximum demand, required heat energy demand is met from a natural gas fueled auxiliary heating unit (e.g., boiler, furnace).

During this strategy, it is more likely to have a smaller auxiliary heating unit but to have increased heat waste in the system. So, this strategy is supposed to result in more economic benefit but less environmental effectiveness [99]. Overall, from the heat energy point of view, ET is an uncontrolled mode of generation.

Similarly like HT mode, ET mode utilizes the same system defined by equation (1-17). Moreover, the equations used to find the running cost, CO_2 emission and NOx emission are also same as equation 31, 32 and 33 respectively. The only difference with HT mode is the operational point of view.

During, ET mode, the reference load to be followed by the PM is electrical load. Heat load at this time of operation has no direct influence on the energy generation of the CHP prime mover.

5.3.3 Hybrid Load Tracking (HyT)

Optimizing the running mode of CHP prime mover to match the electrical and heat load is a major challenge. Besides, convention methods (HT and ET) has their own limitations as they cannot ensure maximum efficiency or minimum cost while operation.

Maximum efficiency of the system is achievable when the system electrical and heat loads are perfectly matched. With HT and ET mode of operation, there is a huge possibility of operating the system with increased energy dump or even with high operational cost. So, having a hybrid load following mode to operate the prime mover on the optimal mode could increase system effectiveness. The hybrid mode should be able to switch between the conventional HT and ET mode depending on the load (heat and electrical) requirements to follow the user defined objectives.

Besides two conventional strategies (HT and ET), the study also discusses another approach of load following referred as hybrid load tracking (HyT) mode.

The HyT mode has two distinct objectives;

- maximize system efficiency or maximum efficiency tracking (MET)
- minimize operational cost or minimum cost tracking (MCT)

User can choose either of the objectives to operate the CHP prime mover. Based on the chosen objective, the operation of CHP prime mover switches between HT and ET mode of operation to pursue given objective. So, the HyT mode is a modified method composed of both HT and ET mode of operation. Simple block diagram of hybrid load tracking mode has been shown in Figure 5-3 .

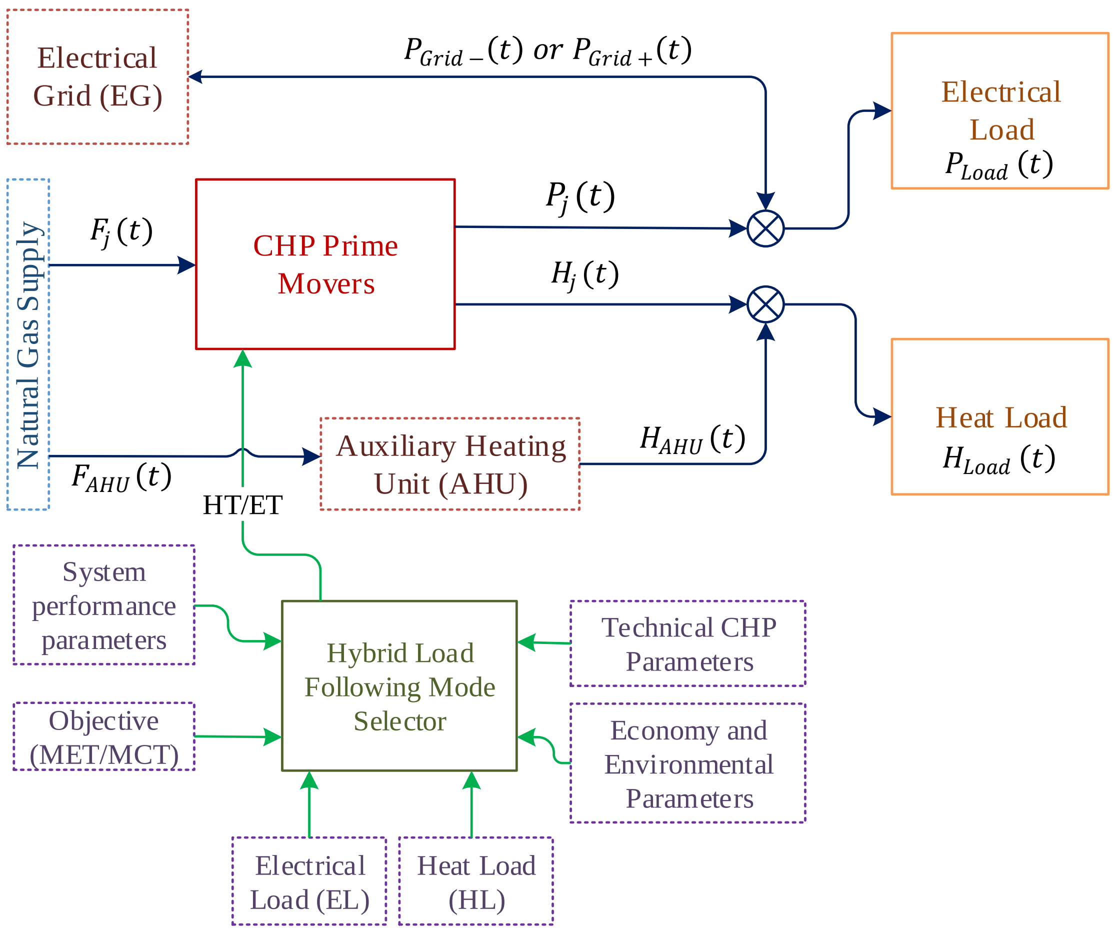

Figure 5-3: Hybrid load tracking mode system block diagram.

Hybrid load following mode selector utilizes the system design parameters to find the optimal mode of operation (HT or ET). User has the full degree of freedom to choose intended design parameter values.

Design parameters used to model HyT are classified as;

I. System technical data
   - Prime mover capacity (electrical and heat)
   - Prime Mover part load performance characteristics
   - Prime mover rated efficiencies (heat and electrical)
   - AHU efficiency and technical specifications
   - Etc.

II. System economic and environmental data
   - Operational and maintenance (O&M) cost of the prime mover
   - O&M cost of AHU
   - Prime mover emission (CO_2 and NOx) data
   - AHU and electrical grid emission (CO_2 and NOx) data
   - Etc.

III. Energy Profile
   - Electrical load profile
   - Heat load profile

IV. Energy tariff
   - Natural gas purchase cost
   - Electricity buying cost from the grid
   - Electricity selling cost to the grid

V. Operational objective
   - Maximum primary resource utilization (maximum efficiency)
   - Minimum operating cost

All the necessary information considered for the study are mentioned elsewhere in this chapter.

Figure 5-4 shows the logic diagram regarding HyT. The logic depicted in the figure is the core of the "Hybrid Load Following Mode Selector" shown in Figure 5-3. In Figure 5-4, system performance indices solver utilizes the set of system equations (equation 1-17). Afterward, based on the user provided system parameters, the economic, and the environmental parameters, system indices solver evaluates the performance indices (cost, emission, efficiency, etc.) of the MEG under study. Then, based on the evaluated performance indices, a decision making algorithm tool decides which mode of operation (HT/ET) is better to meet a certain objective (i.e., minimize cost and/or maximize efficiency). Hence a control signal is sent to the CHP prime mover to operate on the selected mode and the system continue over the whole running period.

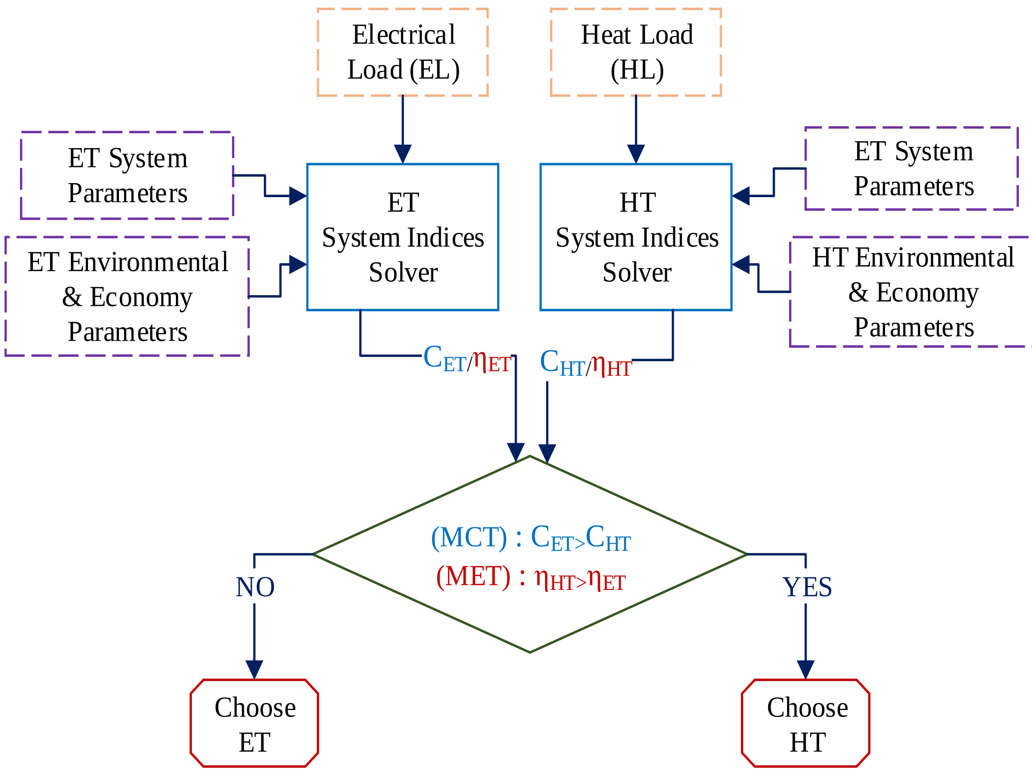

Figure 5-4: Logic diagram for the hybrid load tracking mode.

Chapter 6 Scenario Synthesis

The study is divided into two main parts; CHP prime mover capacity planning and prime mover operational planning. Two different methods has been proposed to find solution to the intended problem. To investigate the impact of both proposed methods and evaluate their effect, several case studies has been carried out in this section.

Section 6.1, depicts the energy profiles being considered for the scenario simulation. Moreover, CHP prime mover planning scenarios and operational planning scenarios are discussed in section 6.2 and 6.3 respectively.

6.1 Energy Profiles Considered for Case Studies

Distinct weather condition due to the seasonal change affects the energy consumption. In order to have an accurate and precise design, both daily variation and seasonal variation of energy demand is needed to be considered.

In this study, based on ambient temperature variation, the entire year is divided into three periods/seasons having; 92 summer days, 153 mid-season days and 120 winter days. All three seasons sum up to 365 days representing the whole year. Each season has been represented by a single day having 24 hour. Each 24 hour segment represents the average load (electrical and heat) trend during specific season [14], [100]. Hence, to simulate the load scenario over a year, the emission (OF2 and OF3) and cost (OF1) functions are multiplied by the weighting factor of the sample day. For example; the weighting factor of the summer day is 92, while the waiting factor of winter and mid-season day is 120 and 153 respectively [14], [100].

6.1.1 Load Type 1: Hospital

Hospitals are considered to be the most suitable for CHP application as they have long operating hours and are more energy intensive. Hospital energy demand is more predictable than any other type of building considered for the study. These reasons make them ideal for CHP application and are extensively discussed in various literatures [101],[102], [103] as CHP case study.

So, type 1 load considered for the study has the load characteristics of a hospital. The intended hospital load profiles were discussed in the report by [85] Caneta Research Inc. The hospital being considered, is a five story building with an area of 14,000m^2 (150,000ft^2). The building has a basement, emergency rooms, patient's rooms, administration, kitchen, lobby, laundry, nursing station, etc. Figure 6-1 depicts the energy demand profile of the intended hospital.

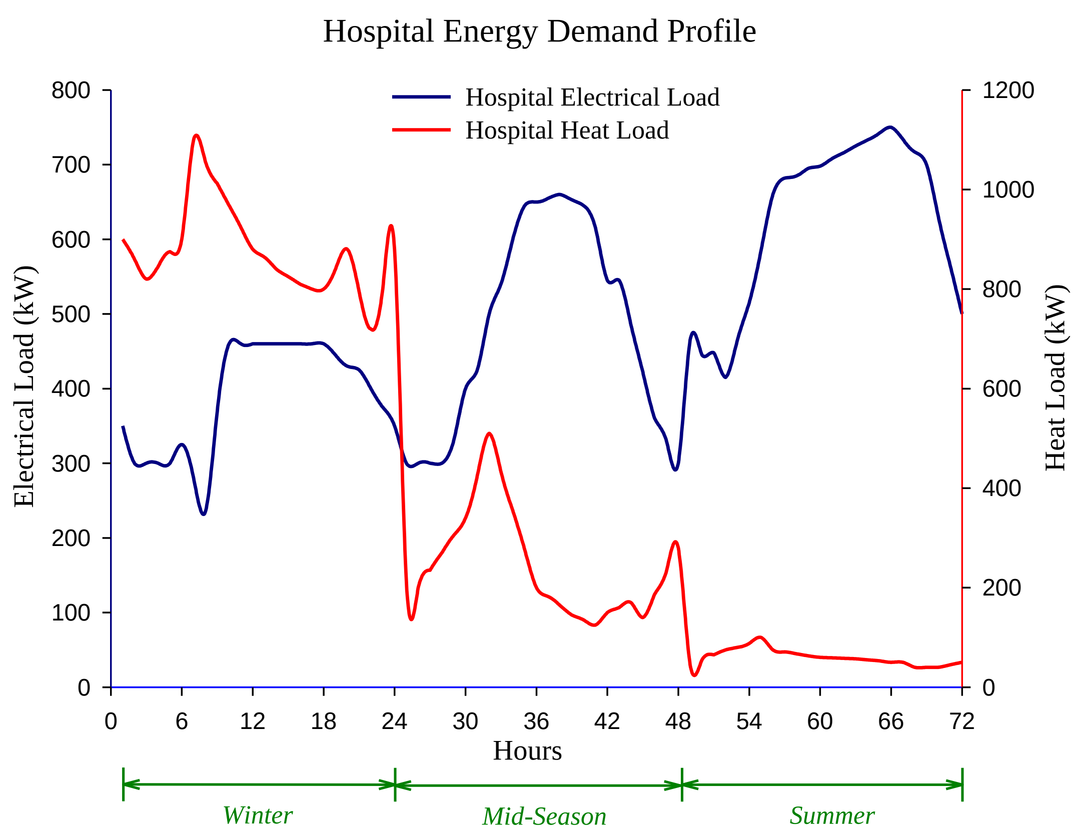

Figure 6-1: Hospital (load type 1) energy demand profile.

The figure shows hospital's heat and electricity load profiles of the three sample days, representing three seasons over the entire year. Hour 1-24 represent a day in winter, hour 25-48 represents a day during mid-season and hour 49-72 represent a sample summer day. Hospital load characteristics are summarized in Table 6-1.

Table 6-1: Summery of load type 1 (Hospital)

Hospital					
Load Type	Peak Load (kW)	Base Load (kW)	Intermediate Load (kW)	Average Load (kW)	Total Load (kWh)-per year
Electrical	750	300	420	486	4257241
Heat	1100	45	530	405	3543995

Above figure and table depict that, the hospital load profile has the most attractive load characteristics. Unlike multi-unit residential building (MURB) and office load profile, the building has high off-peak electrical demand. Moreover, hospital has a continuous heat demand during summer, which is very insignificant compared to the heat demand during winter. During mid-season, it has moderate electrical and heat demand.

6.1.2 Load Type 2: Office

Load type 2 considered in this study has the load characteristics of a commercial office building. The building details were given in the report [85]. The 18 story office building has a total area of 24,200m^2 (260,000ft^2). During unoccupied period, the cooling temperature is set to 27˚C and has no temperature setback for heating. Building service water heating is supplied by electrical storage water heater. Energy demand profile of the intended office building is shown in Figure 6-2.

The figure shows respective heat and electricity load profiles, where three sample days representing three seasons over the entire year. Hour 1-24 represent a day in winter, hour 25-48 represents a day during mid-season and hour 49-72 represent a sample summer day. Office load characteristics are summarized in Table 6-2

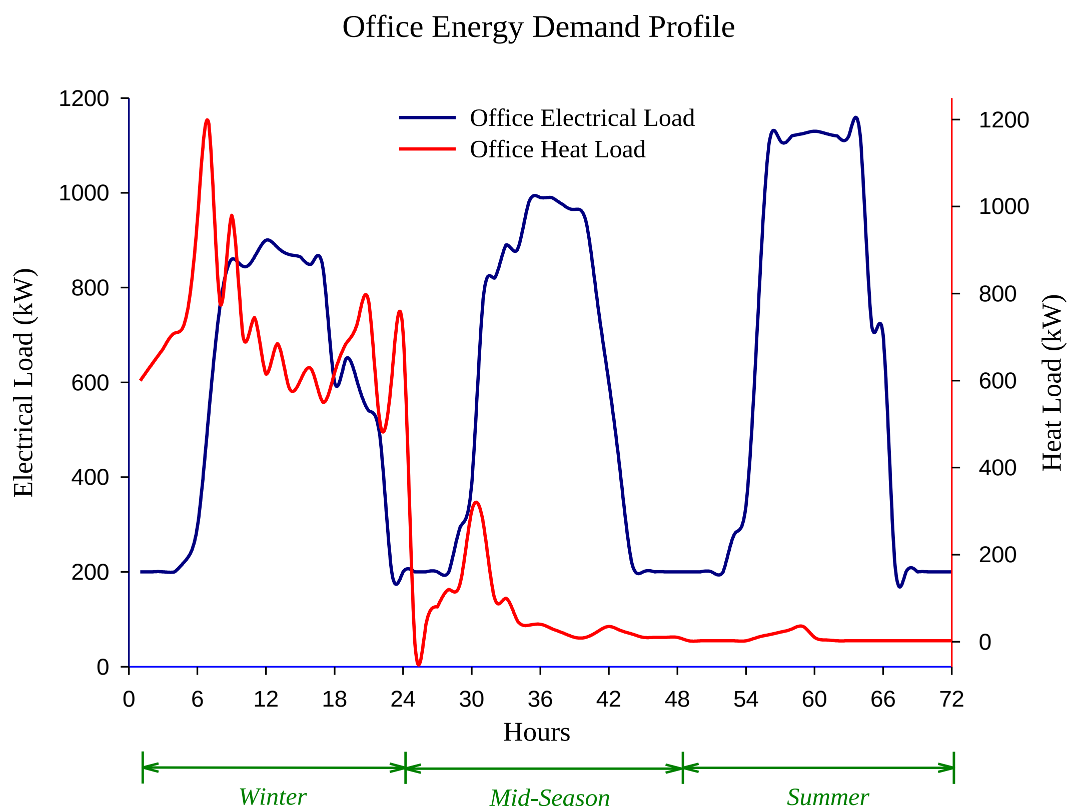

Figure 6-2: Office (load type 2) energy demand profile.

Table 6-2: Summery of load type 2 (Office)

Office					
Load Type	Peak Load (kW)	Base Load (kW)	Intermediate Load (kW)	Average Load (kW)	Total Load (kWh)-per year
Electrical	1130	200	400	579	5070265
Heat	1190	40	250	261	2285354

From the above information, it is evident that the office is a less attractive building from heat load point of view. It has almost no heat load demand during summer and have a small heat demand during mid-season. Electrical equipment and lighting involves almost 30% of the installed load and are needed to be supplied with electricity even during unoccupied periods. This results in a higher base load of approximately 200 kW. However, electrical energy demand trend remains almost same throughout the year. While, more electrical energy is consumed during summer than mid-season and winter.

6.1.3 Load Type 3: Multi-unit Residential Building (MURB)

Multi-unit residential building considered for the study is a twelve story building has an area of 24,000m^2 (260,000 ft^2). Total number of apartments in the building complex is 260. The MURB also has floors of unconditioned underground perking which are located below the ground floor. The idea of the MURB is replicated from the multi-unit residential building in Toronto mentioned in [85]. The energy (electrical and heat) demand profile is shown in Figure 6-3.

The figure shows MERB heat and electricity load profiles of the three sample days representing three seasons over the entire year. Hour 1-24 represent a day in winter, hour 25-48 represents a day during mid-season and hour 49-72 represent a sample summer day.

Table 6-3 depicts the basic characteristics of the MURB electrical and heat load profile.

Table 6-3: Summery of load type 3 (MURB)

Multi-unit Residential Building					
Load Type	Peak Load (kW)	Base Load (kW)	Intermediate Load (kW)	Average Load (kW)	Total Load (kWh)-per year
Electrical	580	95	150	224	1959430
Heat	1150	45	210	238	2087708

Both the figure and table represent that electrical load trend during winter and mid-season is quite similar. However, electrical load demand increases during summer and are more “peaky” during this period. Thermal demand on the other hand increases during the winter season. However, thermal load demand is insignificant during summer and mid-season.

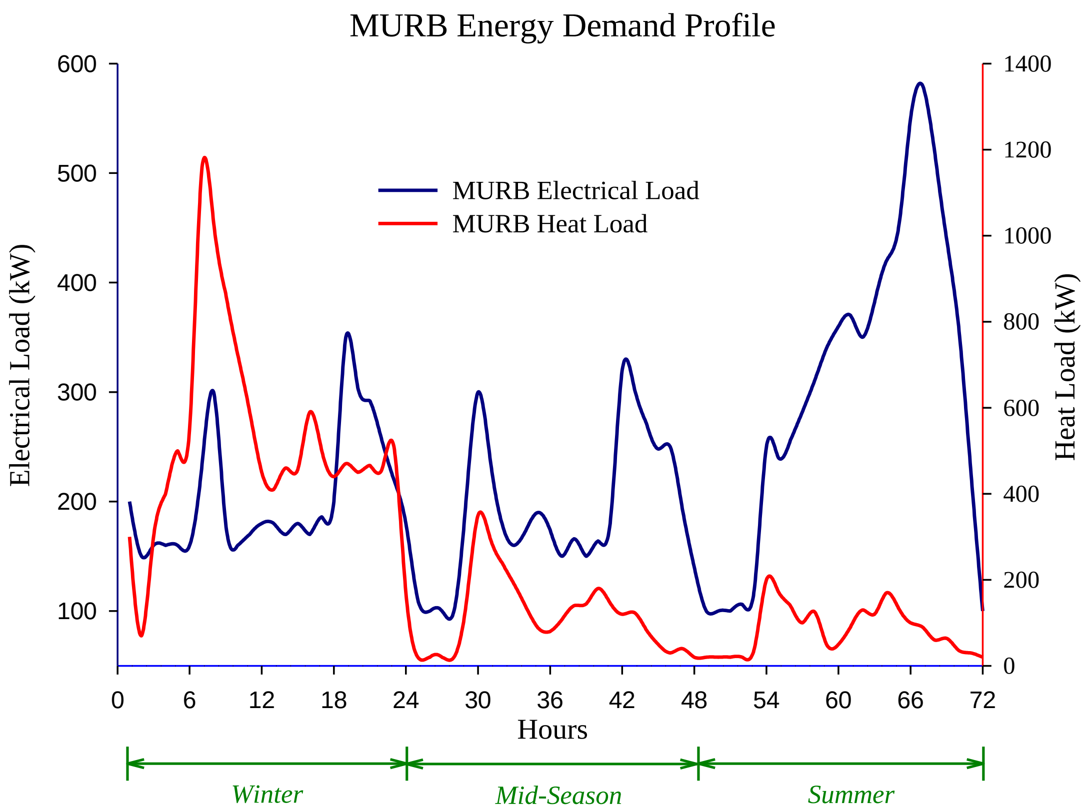

Figure 6-3: MURB (load type 3) energy demand profile.

6.1.4 Load Type 4: Micro Energy Grid (MEG)

Load type 4 consists the load behavior of a typical micro energy grid. The microgrid being considered in this study was used in the literature by A. Zidan et al. [14]. As per the description provided, the proposed microgrid is consists of buildings with distinct load characteristics. Buildings under the microgrid are; a school, residential hotel, numbers of residential buildings/houses, restaurants and commercial office space. All these building type has distinct energy demand pattern as their functions are different than each other. Residential load demands has their specific peaking time, where school energy demand is significant mainly during the day time. Moreover, restaurant consumes more energy during lunch or dinner hours. Being commercial building, both hotel and office has relatively flat energy demand during working hours. The energy demand profile for the intended microgrid is shown in Figure 6-4

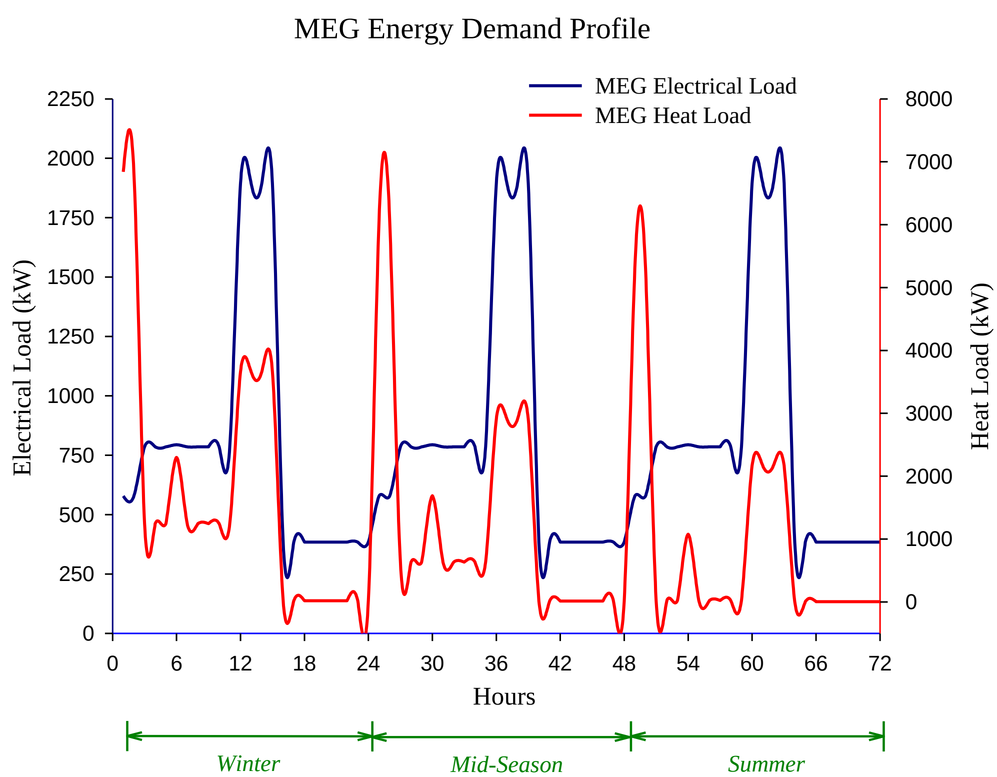

Figure 6-4: MEG (load type 4) energy demand profile.

The figure depicts three sample day representing three seasons. Where, hour 1-24 represent a day in winter, hour 25-48 represents a day during mid-season and hour 49-72 represent a sample summer day. Hospital load characteristics are summarized in Table 6-4.

Table 6-4: Summery of load type 4 (MEG)

Micro Energy Grid					
Load Type	Peak Load (kW)	Base Load (kW)	Intermediate Load (kW)	Average Load (kW)	Total Load (kWh)-per year
Electrical	1895	385	750	803	7032893
Heat	6840	20	550	1310	11474695

From the above information, it is seen that the micro energy grid being considered has relatively higher heat energy demand. However, the electrical energy demand remains almost similar throughout the year. Peak heat load of the system is 6840kW while electrical peak demand is only 1895kW. Although maximum heat demand rises during winter but energy demand trend throughout the seasons stays almost constant.

6.2 CHP Prime Mover Capacity Planning: Case Studies

This section holds the information about four different case studies regarding the sizing problem. Proposed genetic algorithm based optimization algorithm (chapter 5) along with the system equation and parameters (section 4.1-4.3) has been used to synthesize the scenarios. In each case studies, energy profiles discussed in section 6.1 are used to see the impact on different load types. Finally, each case studies were investigated to evaluate the system performance indicators (cost and emission). Intended case studies are outlined in Figure 6-5.

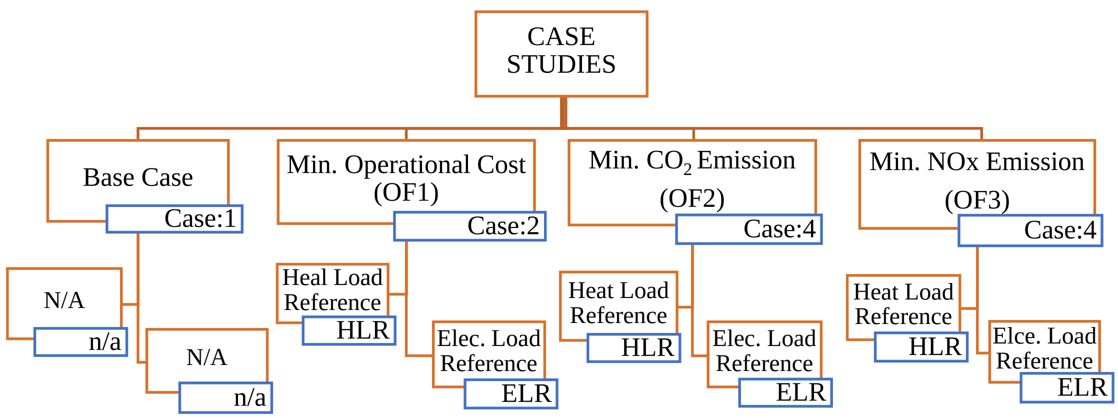

Figure 6-5: CHP prime mover sizing planning scenarios.

As shown in the figure, there are four case studies. Each case studies has been carried out for four different load conditions (described in section 6.1). Besides, each cases has also been investigated for two modes; heat load reference mode (HLR) and electrical load reference mode (ELR).

Energy demand characteristics is a key concern while selecting the right size and type of prime mover. Prime mover can be selected based on either heat load characteristics as well as for electrical load too. Depending on the energy (electrical or heat) demand characteristics, the optimal size of prime mover can be different. So, in this study each case has been investigated considering both heat load and electrical load reference to find the optimal sizing.

HLR, takes heat load as reference and carries out the optimization algorithm to find the optimal size and type based on the heat energy requirement. In this mode of operation, electrical load has no direct influence on the selection of the prime mover. Similarly, ELR mode has electrical load as reference to find the optimal CHP type and size for selected case. Heat load has no direct influence on PM selection while electrical load is taken as reference.

Finally, each cases are evaluated to find the system performance indicators. System performance indicators considered in this study are; economy indicators and emission indicators. Economy indicator refers to system running cost which includes both fuel cost and operational and maintenance cost of all the system components. Besides, emission indicators include total CO_2 emission and NOx emission from the system.

6.2.1 Case 1: Base Case

This is the typical household condition mostly see in Canada. Normally the electricity demand is fulfilled by the grid supply whereas the heat demand is supplied by the natural gas boilers. In such case, user only has to install heating unit in their building to meet the heat demand. Typically the heating unit (furnace, boiler, etc.) is supplied by natural gas. Any electrical energy need is met from the centralized electricity grid which does not requires capital investment by the end user. CHP prime mover are not considered in this case which replicate the conventional energy infrastructure.

The base case, has been carried out for four different load types (Hospital, Office, MURB and MEG). Moreover, each load has been separately investigated taking their heat demand and electrical demand as reference. Finally, the summarized results with optimal size of PM and system performance indicates are listed in Table 6-5.

6.2.2 Case 2: Minimize Running Cost Objective ($\boldsymbol{O_{F1}}$)

The system considered in this case, has CHP prime movers installed in it. However, the objective of the case is to have a minimum system running cost and identify the optimal size and type of PM to achieve the goal. CHP prime movers generate electricity and heat energy at the same time. If the electricity generated during the operation is higher than the demand, excess energy is sold to the grid for revenue. On the other hand, if the generation is not sufficient enough to meet the load, required amount of electricity is purchased from the grid. Similarly, any short fall in heat energy is met by a natural gas supplied AHU installed in the system.

This case study intend to find the optimal size and type of prime mover with an objective to minimize system running cost (O_{F1}). While minimizing O_{F1}, other two objective function O_{F2} and O_{F3} has no effect on the selection of the prime mover. Four different load types (Hospital, Office, MURB and MEG) has been considered to synthesize the case study. Each load type has been further investigated taking both their heat load (HLR) and electrical load (ELR) as reference.

Finally, the system performance indicators has been determined and are summarized in Table 6-6.

6.2.3 Case 3: Minimize CO_2 Emission Objective ($\boldsymbol{O_{F2}}$)

Same system described in section 6.2.2 (for case 2) has been considered for this study. Only different between case 2 and case 3 is the objective function. Objective of case 3 is to evaluate the optimal sizing of prime mover while minimizing the system total CO_2 emission (minimize O_{F2}). Neither running cost nor NOx emission has any influence in the selection of PM during this case. System CO_2 emission is the sole dominating factor while selecting the right size and type of PM.

Four different load types (Hospital, Office, MURB and MEG), has been considered while taking their heat load and electrical load as reference to select the prime movers. The whole system has been designed and investigated in MATLAB-Simulink interface. Moreover, for each load type, optimal CHP size and type is identified separately taking both heat and electrical load as reference. Moreover, system performance indicators are investigated for the optimal sizing of the prime movers in the system. The results of case study 3 are summarized in Table 6-7.

6.2.4 Case 4: Minimize NOx Emission Objective ($\boldsymbol{O_{F3}}$)

Similar system with CHP prime mover has been considered for this case. However, the goal is to find the optimal capacity of CHP prime movers to have minimum NOx emission (minimize O_{F3}). While minimizing O_{F3}, system running cost and CO_2 emission has no influence on prime mover selection.

Each load type considered in the study has two modes; heat load reference (HLR) mode and electrical load reference (ELR) mode. Load types considered in this case of operation are; office load, hospital load, MURB and MEG loads.

The proposed GA based optimization tool, identifies the optimal size and type of the prime mover to achieve the objective of having minimum NOx emission. Different load types also plays a vital role during selection of PM. However, prime mover selection in this case is completely independent of cost and CO_2 emission.

Finally, with the optimal size of PM for a certain load, system performance indicators (running cost and emissions) are evaluated. The results of case studies 4 are summarized in Table 6-8.

Table 6-5: Summarized results of case studies 1

Load Type		Total Electrical (kWh/year)	Total Heat (kWh/year)	Capital Cost ($)	Electricity Purchase Cost/year	Heating Unit Running Cost ($)	Total Running Cost	Revenue	ROI	Payback Period	CO_2 (kg/year)	NOx (mg/year)
Load1:	Hospital	4257241	3543995	1919500	425724.1	73453.77	499177.87	0	n/a	n/a	3267446.08	532734961
Load2:	Office	5070265	2285354	2076550	507026.5	47366.85	554393.35	0	n/a	n/a	3494331.85	566732830
Load3:	MURB	1959430	2087708	2006750	195943	43270.38	239213.38	0	n/a	n/a	1597543.96	261175060
Load4:	MEG	7032893	11474695	11935800	703289.3	237827.56	941116.86	0	n/a	n/a	6550884.07	1076772053

Table 6-6: Summarized results of CHP sizing planning case studies 2

Load Type		**Optimal PM Capacity (kW-electrical)**				**Energy generated by PM (kWh)**		**Elec. from/to Grid (kWh)**		**Heat from AHU (kWh)**	**Cost ($)**		**CO_2 Emission (kg)**	**NOx Emission (mg)**
		IC	GT	SE	FC	Elec.	Heat	Purchased	Sold		Capital	Operational		
1	HLR	19.25	62.15	5.33	635.45	4.03×10^6	5.89×10^6	1.18×10^6	9.55×10^5	2466	3855444.44	2.24×10^5	3.02×10^6	4.19×10^8
	ELR	167.49	297.41	101.35	180.79	6.55×10^6	1.47×10^7	270.8	2.29×10^6	0	2880683.88	1.31×10^5	4.78×10^6	1.47×10^9
2	HLR	67.53	74.793	16.87	702.13	3.57×10^6	5.63×10^6	2.22×10^6	7.13×10^5	2788	4369639.03	3.35×10^5	3.50×10^6	7.61×10^8
	ELR	395.57	380.43	105.48	242.05	8.49×10^6	1.85×10^7	859.7	3.42×10^6	0	4150485.68	1.28×10^5	6.12×10^6	2.61×10^9
3	HLR	48.13	230.17	28.41	278.12	2.54×10^6	5.27×10^6	4.07×10^5	9.76×10^5	1.7×10^4	2656672.83	8.22×10^4	2.08×10^6	1.93×10^8
	ELR	251.72	206.32	33.39	70.42	4.19×10^6	8.77×10^6	1668	2.22×10^6	5358	1915244.26	7325	2.97×10^6	1.57×10^9
4	HLR	143.33	41.88	280.83	2578.37	1.46×10^7	2.57×10^7	0	7.63×10^6	5.79×10^5	18467020.57	2.83×10^4	9.41×10^6	1.43×10^9
	ELR	525.55	602.34	387.50	377.02	1.545×10^7	3.99×10^7	3163	8.38×10^6	1.27×10^6	10702196.14	8.12×10^4	1.24×10^7	4.01×10^9

Table 6-7: Summarized results of CHP sizing planning case studies 3

Load Type		**Optimal PM Capacity (kW-electrical)**				**Energy generated by PM (kWh)**		**Elec. from/to Grid (kWh)**		**Heat from AHU (kWh)**	**Cost ($)**		**CO_2 Emission (kg)**	**NOx Emission (mg)**
		IC	GT	SE	FC	Elec.	Heat	Purchased	Sold		Capital	Operational		
1	HLR	5.74	32.10	0.96	466.72	2.00x10^{6}	3.60x10^{6}	2.26x10^{6}	6469	1.09x10^{6}	3364121.45	3.49x10^{5}	2.78x10^{6}	4.46x10^{8}
	ELR	30.76	35.72	85.50	232.16	3.37x10^{6}	8.09x10^{6}	1.05x10^{6}	1.73x10^{5}	5.66x10^{4}	2182266.24	2.83x10^{5}	3.13x10^{6}	3.96x10^{8}
2	HLR	12.45	29.45	10.73	347.77	2.13x10^{6}	3.23x10^{6}	3.13x10^{6}	1.95x10^{5}	2.69x10^{5}	3095834.86	4.07x10^{5}	3.17x10^{6}	4.55x10^{8}
	ELR	48.42	90.25	22.00	648.89	5.40x10^{6}	8.77x10^{6}	4.90x10^{5}	8.14x10^{5}	8.72x10^{4}	4095381.83	2.48x10^{5}	3.44x10^{6}	5.12x10^{8}
3	HLR	14.44	12.57	41.67	71.35	1.05x10^{6}	2.62x10^{6}	9.22x10^{5}	0	4.33x10^{5}	2005393.93	1.60x10^{5}	1.42x10^{6}	2.91x10^{8}
	ELR	380.64	79.17	21.82	38.00	3.15x10^{6}	6.56x10^{6}	8375	1.18x10^{6}	9.59x10^{4}	1775910.67	6.23x10^{4}	1.55x10^{6}	1.68x10^{9}
4	HLR	89.32	77.78	257.61	441.05	5.40x10^{6}	1.37x10^{7}	2.08x10^{6}	4.13x10^{5}	4.04x10^{6}	11927309.58	5.53x10^{5}	6.10x10^{6}	1.22x10^{9}
	ELR	48.42	90.25	22.00	648.89	4.56x10^{6}	9.33x10^{6}	2.93x10^{6}	4.32x10^{5}	7.59x10^{6}	13805689.22	6.31x10^{5}	6.07x10^{6}	3.40x10^{9}

Table 6-8: Summarized results of CHP sizing planning case studies 4

Load Type		**Optimal PM Capacity (kW-electrical)**				**Energy generated by PM (kWh)**		**Elec. from/to Grid (kWh)**		**Heat from AHU (kWh)**	**Cost ($)**		**CO_2 Emission (kg)**	**NOx Emission (mg)**
		IC	GT	SE	FC	Elec.	Heat	Purchased	Sold		Capital	Operational		
1	HLR	8.09	165.72	9.54	271.43	2.89x10^{6}	4.88x10^{6}	1.63x10^{6}	2.61x10^{5}	3.28x10^{5}	2681427.61	2.89x10^{5}	2.84x10^{6}	3.70x10^{8}
	ELR	20.38	234.51	9.64	287.97	4.85x10^{6}	8.13x10^{6}	3.22x10^{5}	9.11x10^{5}	6.46 x10^{4}	2711675.49	1.86x10^{5}	3.21x10^{6}	3.69x10^{8}
2	HLR	0.21	168.10	98.92	225.12	2.47x10^{6}	5.75x10^{6}	2.91x10^{6}	3.11x10^{5}	1583	2239821.15	4.01x10^{5}	3.64x10^{6}	3.75x10^{8}
	ELR	14.81	73.81	280.61	725.61	7.34x10^{6}	1.94x10^{7}	1.99 x10^{4}	2.28x10^{6}	0	5526039.34	2.08x10^{5}	5.78x10^{6}	2.70x10^{8}
3	HLR	6.92	2.68	110.81	90.49	1.18x10^{6}	3.61x10^{6}	8.25x10^{5}	3.21x10^{4}	5.15x10^{4}	1717401.74	1.55x10^{5}	1.54x10^{6}	1.91x10^{8}
	ELR	15.82	3.54	415.56	84.00	2.86x10^{6}	1.23x10^{7}	8571	8.96x10^{5}	0	2377597.03	1.17x10^{5}	3.12x10^{6}	1.85x10^{8}
4	HLR	42.79	16.57	685.05	559.45	6.50x10^{6}	2.07x10^{7}	1.4 x10^{6}	8.38x10^{5}	1.29x10^{6}	10146931.72	4.98x10^{5}	6.93x10^{6}	6.83x10^{8}
	ELR	10.05	3.42	740.84	608.84	9.95x10^{6}	3.52x10^{7}	7.76x10^{5}	3.66x10^{6}	1.84x10^{6}	10037303.03	3.98x10^{5}	1.01x10^{7}	4.18x10^{8}

6.3 CHP prime movers operational planning: Scenarios

6.3.1 Scenario 1: Load Type 1

In this scenario, load type 1 (discussed in 6.1.1) has been considered. Load type 1, which represents a typical hospital has its unique demand characteristics. Because of long operating hours of hospital, this load type has continuous electricity and heat demand throughout the day. Moreover, this load type has high off-peak electrical demand compared to MURB and office load types.

During summer, hospital heat load is continuous but is significantly less compared to the electrical energy demand. However, heat demand increases during the mid-season and reaches to maximum during the winter. Maximum electricity demand of load type 1 is 750kW during the summer. Besides maximum heat demand occurs during the winter and peaks at 1100kW. Prime mover operational planning scenario 1 outline is shown in Figure 6-6.

Load type 1 has been analyzed considering that, all four types of prime movers (ICE, GT, SE and FC) are supplying energy separately. However, electrical capacity of individual prime mover is kept constant which equal to 75% of systems maximum electrical load.

This analysis could be carried out for the optimal prime mover size found in the planning section. However, having same capacity is a must to compare different prime movers at different load tracking modes of operation. Thus the electrical capacity of each prime mover is kept (75% of the maximum load) unchanged throughout the scenario. Although the electrical capacity of prime movers is kept constant but depending on the heat to power generation ratio of individual PM, heat generation can vary significantly.

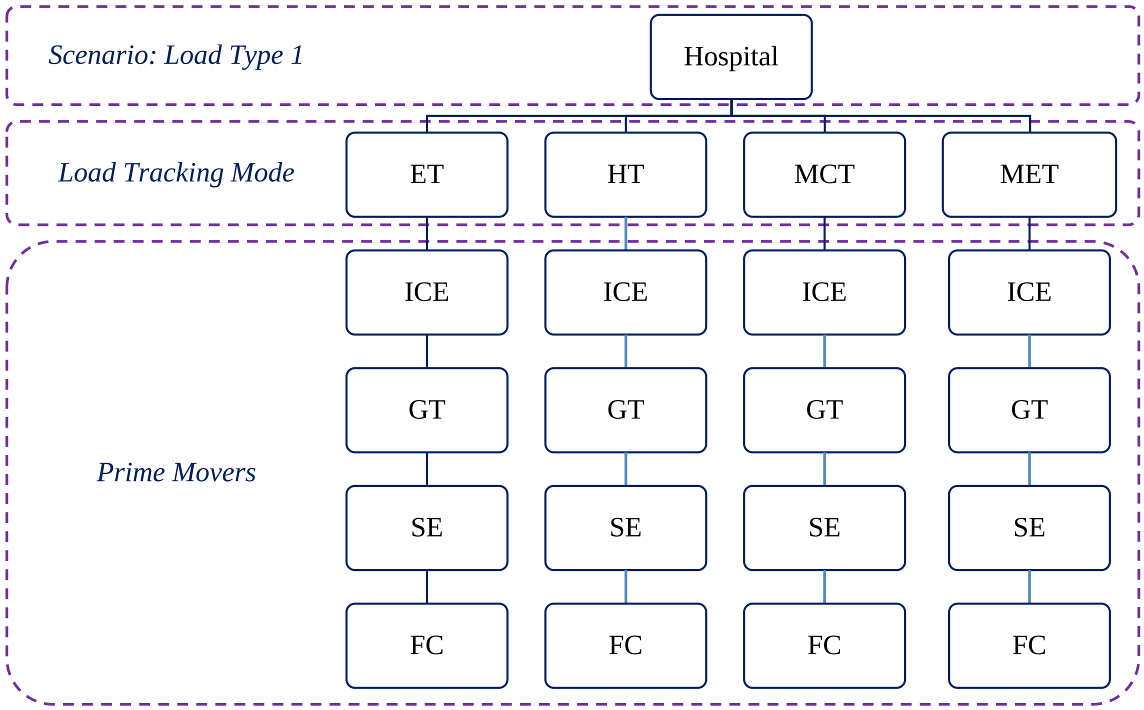

Figure 6-6: Outline of CHP prime mover operational planning - Scenario 1.

Load type 1, with individual PM has also been analyzed with four different load tracking mode of operation. Load tracking modes, being considered for the scenario are;

- Electrical Load Tracking Mode (ET)
- Heat Load Tracking Mode (HT)
- Minimum Cost Tracking Mode (MCT)
- Maximum Efficiency Tracking Mode (MET)

Moreover, each case with different PM and load tracking mode has been further analyzed to evaluate the system performance indicators. System performance indicators, considered for the scenario evaluation are;

- System Operational Cost
- CO_2 Emission from the CHP Prime Mover
- NO_x Emission from the CHP Prime Mover
- CHP Prime Mover Overall Efficiency

Performance indicators of each case for scenario 1 has been summarized in Table 6-9.

Table 6-9: Performance indicators of each case for scenario 1

Load Following Mode	PM Type	Electrical Capacity (kW)*	Heat Capacity	Electricity Generated (kWh)	Heat Generated (kWh)	Electricity From Grid (kWh)	Electricity Sold To Grid (kWh)	Heat From AUH (kWh)	System Running Cost ($)	CO_2 Emission Form PM (kg)	NOx Emission From PM (mg)	CHP Effi. (%)
ET	**IC**	585	1148.3	4025862	7902618	233379	0	418066.67	258373.25	2744202.77	3361594770	77.28
	GT		1145.5	4025862	7655316.67	233379	0	382822.81	227949.27	2789646.05	309991374	74.84
	SE		3217	4025862	22100966.59	233379	0	0	344781.15	5224643.49	120775860	89.44
	FC		796.5	4025862	5540535.25	233379	0	1081106.45	126063.81	2181636.13	40258620	78.06
HT	**IC**	585	1148.3	2383529.05	4678779.24	2088689.31	212977.36	0	328730	1742703.02	1990246754	70.32
	GT		1145.5	2309580.82	4674431.4	2182939	233278.82	0	319965	1816726.90	177837723.42	65.92
	SE		3217	1405616.64	8514370.8	2853624.36	0	0	415595.61	2168525.88	42168499.22	81.65
	FC		796.5	3005641.02	3922983.45	1749001.74	495401.77	251940	277471.39	1621254.40	30056410.28	74.45
HyT (MCT)	**IC**	585	1148.3	4238839.36	8320684.67	233379	212977.36	0	241423.66	2876323.10	3539430864	77.80
	GT		1145.5	4259140.82	8038139.47	233379	233278.82	0	208792.39	2934582.56	327953843.45	74.92
	SE		3217	4025862	22100966.59	233379	0	0	344781.15	5224643.49	120775860	89.44
	FC		796.5	4360399.55	6092147.19	233379	334537.55	529494.50	113257.49	2372772.60	43603995.53	78.51
HyT (MET)	**IC**	585	1148.3	4238839.36	8320684.67	233379	212977	0	241423.66	2876323.10	3539430864	77.80
	GT		1145.5	4150474.51	7866319.73	269318.70	160552.21	116037.35	216477.62	2863417.71	319586537.20	75.10
	SE		3217	4025862	22100966.59	233379	0	0	344781.15	5224643.49	120775860	89.44
	FC		796.5	4521263.77	6369701.70	233379	495401.77	251940	120522.95	2463513.15	45212637.77	78.81

*Prime Mover Electrical Capacity = 75% of the maximum electrical load

6.3.2 Scenario 2: Load Type 2

Scenario 2 regarding the operation planning of prime movers only considers load type 2. Typical energy demand characteristics of an office building has been represented in load type 2.

This load type (office) has almost no heat load demand during summer and have a small heat demand during mid-season. Electrical equipment and lighting involves almost 30% of the installed load and are needed to be supplied with electricity even during unoccupied periods. This results in a higher base load of approximately 200 kW. However, electrical energy demand trend remains almost same throughout the year. While, more electrical energy is consumed during summer than mid-season and winter.

Maximum electricity demand of load type 2 is 1130kW during the summer. Besides maximum heat demand occurs during the winter and peaks at 1190kW. Prime mover operational planning scenario 2 outline is shown in Figure 6-7.

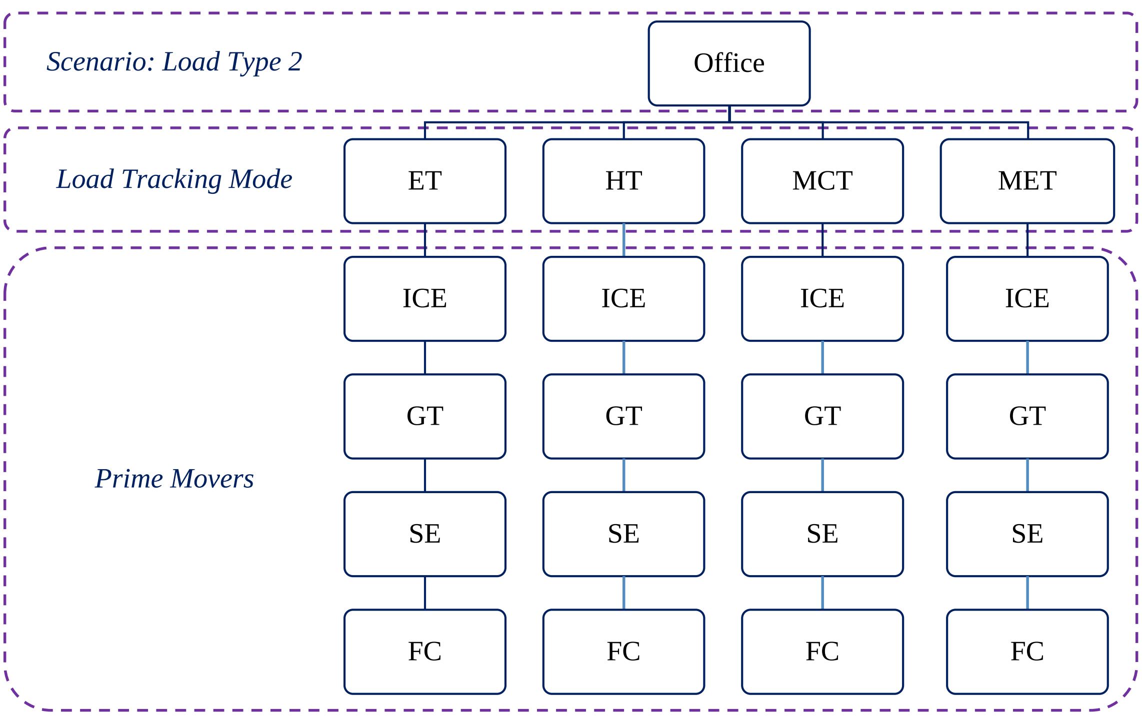

Figure 6-7: Outline of CHP prime mover operational planning - Scenario 2.

Load type 2 has been analyzed considering that, all four types of prime movers (ICE, GT, SE and FC) are supplying energy separately. However, electrical capacity of individual prime mover is kept constant which equal to 75% of systems maximum electrical load.

This analysis could be carried out for the optimal prime mover size found in the planning section. However, having same capacity is a must to compare different prime movers at different load tracking modes of operation. Thus the electrical capacity of each prime mover is kept (75% of the maximum load) unchanged throughout the scenario. Although the electrical capacity of prime movers is kept constant but depending on the heat to power generation ratio of individual PM, heat generation can vary accordingly.

Load type 2, with individual PM has also been analyzed with four different load tracking mode of operation. Load tracking modes, being considered for the scenario are;

- Electrical Load Tracking Mode (ET)
- Heat Load Tracking Mode (HT)
- Minimum Cost Tracking Mode (MCT)
- Maximum Efficiency Tracking Mode (MET)

Moreover, each case with different PM and load tracking mode has been further analyzed to evaluate the system performance indicators. System performance indicators, considered for the scenario evaluation are;

- System Operational Cost
- CO_2 Emission from the CHP Prime Mover
- NO_x Emission from the CHP Prime Mover
- CHP Prime Mover Overall Efficiency

Performance indicators of each case for scenario 2 has been summarized in Table 6-10.

Table 6-10: Performance indicators of each case for scenario 2

Load Following Mode	PM Type	Electrical Capacity (kW) *	Heat Capacity	Electrical Generation (kWh)	Heat Generation (kWh)	Electricity From Grid (kWh)	Electricity Sold To Grid (kWh)	Heat From AUH (kWh)	System Running Cost ($)	CO_2 Emission Form PM (kg)	NOx Emission From PM (mg)	CHP Effi. (%)
ET	**IC**	847	1662.6	4866085.50	9551945.60	372646	162866.5	213651.56	303966.63	3389727.93	4063181392.50	73.42
	GT		1658.5	4866085.50	9263474.92	372646	162866.5	157836	273237.75	3564535.31	374688583.50	68.54
	SE		4658	4866085.50	27137296.88	372646	162866.5	0	422217	6558156.09	145982565	85.95
	FC		1153.2	4866085.50	6589022.41	372646	162866.5	500168.27	269524.96	2638730.28	48660855	75.68
HT	**IC**	847	1662.6	2545100.81	4995938.64	2802462.05	271697.87	0	409324.58	1966437.58	2125159181.86	68.02
	GT		1658.5	2343844.59	4988819.40	2927312.67	195292.26	0	410925.05	2051597.64	180476033.12	63.20
	SE		4658	2025715.08	12280351.2	3138351.62	88201.70	0	493030.60	3131482.23	60771452.33	81.55
	FC		1153.2	3412058.70	4107000.48	2289537.27	625730.96	4416	333080.63	1816688.67	34120586.92	73.06
HyT (MCT)	**IC**	847	1662.6	4974926.86	9765597.17	372646	271707.86	0	295155.09	3454387.60	4154063926.84	74.06
	GT		1658.5	4949213.19	9421310.91	372646	245994.19	0	264767.07	3591621.85	381089415.75	69.65
	SE		4658	4866085.50	27137296.88	372646	162866.5	0	422217	6558156.09	145982565	85.95
	FC		1153.2	5328949.96	7225536.87	372646	625730.96	4416	237631.50	2887607.23	53289499.62	76.36
HyT (MET)	**IC**	847	1662.6	4974926.86	9765597.17	372646	271707.86	0	295155.09	3454387.60	4154063926.84	74.06
	GT		1658.5	4846369.67	9233219.11	416511.27	187015.94	13398.38	269704.72	3510610.81	373170464.78	69.70
	SE		4658	4866085.50	27137296.88	372646	162866.50	0	422217	6558156.09	145982565	85.95
	FC		1153.2	5323816.81	7222975	372646	620597.81	4416	237862.83	2884275.26	53238168.16	76.43

*Prime Mover Electrical Capacity = 75% of the maximum electrical load

6.3.3 Scenario 3: Load Type 3

In this scenario, only load type 3 (discussed in 6.1.3) has been considered and analyzed for the prime mover operational planning. Load type 3, represents the loads of a multi-unit residential building (MURB).

Electrical load trend of MURB during winter and mid-season is quite similar. However, electrical load demand increases during summer and are more “peaky” during this period. Thermal demand on the other hand increases during the winter season. However, thermal load demand is insignificant during summer and mid-season.

Maximum electricity demand of load type 3 is 580kW during the summer. Besides maximum heat demand occurs during the winter and peaks at 1150kW. Prime mover operational planning scenario 3 outline is shown in Figure 6-8.

Load type 3 has been analyzed considering that, all four types of prime movers (ICE, GT, SE and FC) supplying energy separately. However, electrical capacity of individual prime mover is kept constant which equal to 75% of systems maximum electrical load.

This analysis could be carried out for the optimal prime mover size found in the planning section. However, having same capacity is a must to compare different prime movers at different load tracking modes of operation. Thus the electrical capacity of each prime mover is kept (75% of the maximum load) unchanged throughout the scenario. Although the electrical capacity of prime movers is kept constant but depending on the heat to power generation ratio of individual PM, heat generation can vary accordingly.

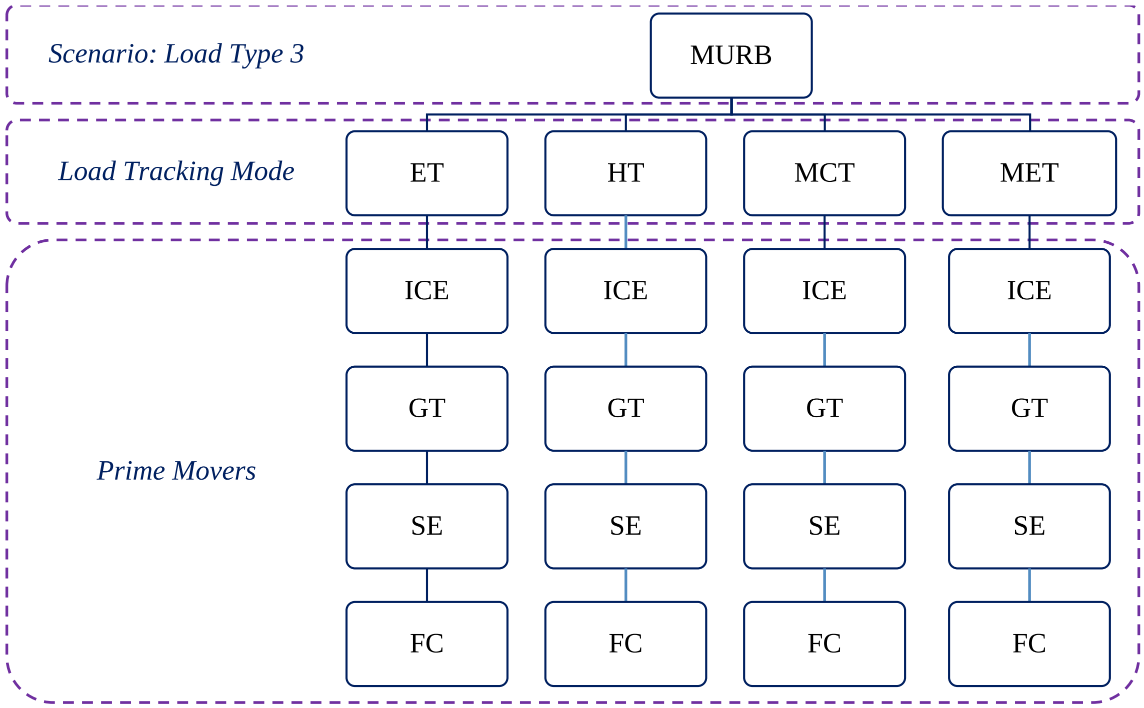

Figure 6-8: Outline of CHP prime mover operational planning - Scenario 3.

Load type 3, with individual PM has also been analyzed with four different load tracking mode of operation. Load tracking modes, being considered for the scenario are;

— Electrical Load Tracking Mode (ET)

— Heat Load Tracking Mode (HT)

— Minimum Cost Tracking Mode (MCT)

— Maximum Efficiency Tracking Mode (MET)

Moreover, each case with different PM and load tracking mode has been further analyzed to evaluate the system performance indicators. System performance indicators, considered for the scenario evaluation are;

— System Operational Cost

— CO_2 and NOx Emission from the CHP Prime Mover

— CHP Prime Mover Overall Efficiency

Performance indicators of each case for scenario 3 has been summarized in Table 6-11.

Table 6-11: Performance indicators of each case for scenario 3

Load Following Mode	PM Type	Electrical Capacity (kW) *	Heat Capacity (kW)	Electrical Generation (kWh)	Heat Generation (kWh)	Electricity From Grid (kWh)	Electricity Sold To Grid (kWh)	Heat From AUH (kWh)	System Running Cost ($)	CO_2 Emission Form PM (kg)	NOx Emission From PM (mg)	CHP Effi. (%)
ET	**IC**	435	853.9	1975424	3877684.12	33580	28774	451751.11	123540.25	1415091.43	1649479040	72.90
	GT		851.8	1975424	3995243.66	33580	28774	401474.93	110766.42	1489217.29	152107648	70.70
	SE		2392	1975424	11098016.13	33580	28774	0	162069.57	2637522.26	59262720	88.00
	FC		592.3	1975424	2528211.50	33580	28774	791675.24	110244.60	1051404.86	19754240	75.90
HT	**IC**	435	853.9	1537773.66	3018592.74	671763.26	229306.91	58116	137695.61	1151144.21	1284041006	69.20
	GT		851.8	1459462.16	3014231.88	738742.70	217974.86	58872	134726.65	1199107.46	112378586	64.80
	SE		2392	1062298.94	6414220.80	933853.89	15922.83	0	189692	1628823.17	31868968.22	81.80
	FC		592.3	1968631.24	2473373	475066.66	463467.90	168096	100621.76	1057685.38	19686312.39	73.50
HyT (MCT)	**IC**	435	853.9	2175956.91	4271322.83	33580	229306.92	58116	107515.05	1538228.40	1816924023	73.90
	GT		851.8	2177159.54	4337846.59	33580	23509.54	58872	93306.59	1601182.69	167641284.34	71.80
	SE		2392	1975424	11098016.13	33580	28774	0	162069.57	2637522.26	59262720	88.00
	FC		592.3	2410117.90	3190505.70	33580	463467.90	168096	78284.95	1297569.95	24101178.95	76.30
HyT (MET)	**IC**	435	853.9	2175956.91	4271322.83	33580	229306.92	58116	107515.05	1538228.40	1816924023	73.90
	GT		851.8	2100109.71	4210365.30	48236.41	168116.12	134863.40	98503.75	1547923.95	161708447.54	71.90
	SE		2392	1962423.08	11019201.57	33729.75	15922.83	0	162163	2617424.60	58872692.45	88.10
	FC		592.3	2368301.04	3148385.45	33580	421651.04	171501.30	80441.55	1274535.10	23683010.40	76.60

*Prime Mover Electrical Capacity = 75% of the maximum electrical load

6.3.4 Scenario 4: Load Type 4

This scenario uses load type 4 to investigate the proposed CHP prime mover operational planning algorithm. Load type 4 depicts the load characteristics of a micro energy grid which has been discussed in section 6.1.4.

Considered micro energy grid has relatively higher heat energy demand compared to other load profiles. However, the electrical energy demand remains almost similar throughout the year. Peak heat load of the system is 6840kW while electrical peak demand is only 1895kW. Although maximum heat demand rises during winter but energy demand trend throughout the seasons stays almost constant.

Maximum electricity demand of load type 4 is 1895kW with a base load of 385kW. Besides maximum heat demand occurs during the winter and peaks at 6840kW. Prime mover operational planning scenario 4 outline is shown in Figure 6-9.

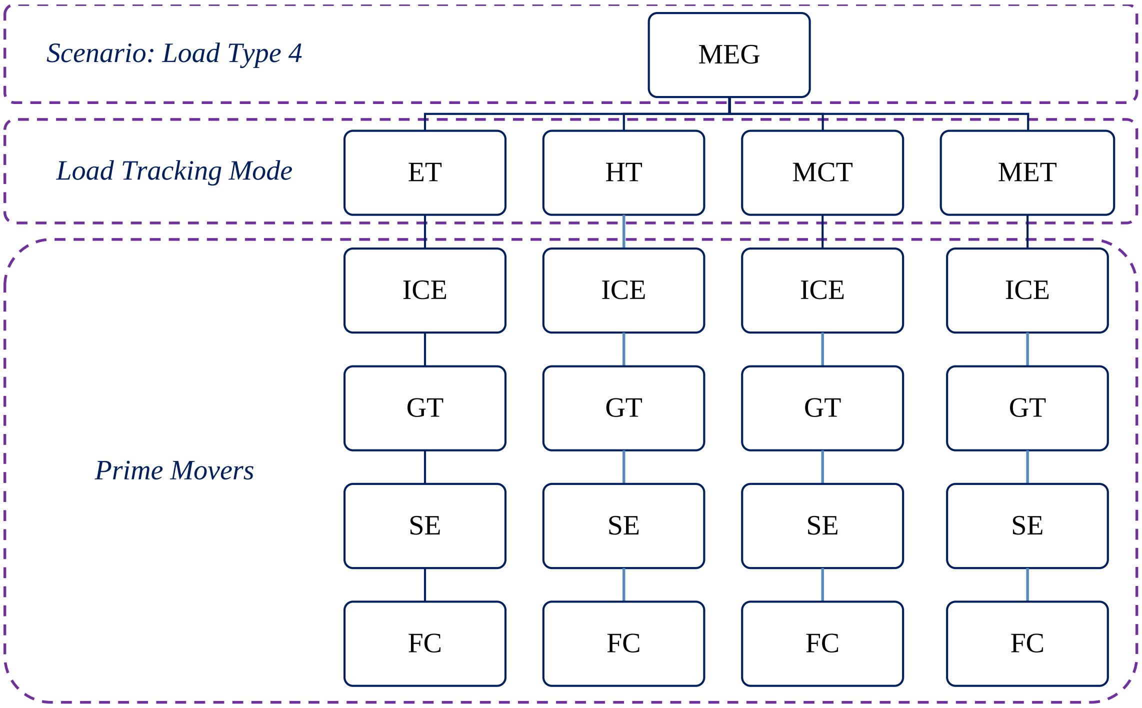

Figure 6-9: Outline of CHP prime mover operational planning - Scenario 4.

Load type 4 has been analyzed separately for individual prime movers (ICE, GT, SE and FC). While evaluating the scenario, electrical capacity of individual prime mover is considered to be set at 75% of systems maximum electrical load.

This analysis could be carried out for the optimal prime mover size found in the planning section. However, having same capacity is a must to compare different prime movers at different load tracking modes of operation. Thus the electrical capacity of each prime mover is kept (75% of the maximum load) unchanged throughout the scenario. Although the electrical capacity of prime movers is kept constant but depending on the heat to power generation ratio of individual PM, heat generation can vary accordingly.

Load type 4, with individual PM has also been analyzed with four different load tracking mode of operation. Load tracking modes, being considered for the scenario are;

- Electrical Load Tracking Mode (ET)
- Heat Load Tracking Mode (HT)
- Minimum Cost Tracking Mode (MCT)
- Maximum Efficiency Tracking Mode (MET)

Moreover, each case with different PM and load tracking mode has been further analyzed to evaluate the system performance indicators. System performance indicators, considered for the scenario evaluation are;

- System Operational Cost
- CO_2 Emission from the CHP Prime Mover
- NOx Emission from the CHP Prime Mover
- CHP Prime Mover Overall Efficiency

Performance indicators of each case for scenario 4 has been summarized in Table 6-12.

Table 6-12: Performance indicators of each case for scenario 4

Load Following Mode	**PM Type**	**Electrical Capacity (kW)***	**Heat Capacity (kW)**	**Electrical Generation (kWh)**	**Heat Generation (kWh)**	**Electricity From Grid (kWh)**	**Electricity Sold To Grid (kWh)**	**Heat From AUH (kWh)**	**System Running Cost ($)**	**CO_2 Emission Form PM (kg)**	**NOx Emission From PM (mg)**	**CHP Effi. (%)**
ET	**IC**	1421	2789.4	6510228.40	12779337.23	691456	134744.60	4933896.70	519116.85	4662573.90	5436040714	72.10
	GT		2782.6	6510228.40	13009899.10	691456	134744.60	5091004.80	484121.60	4938870.80	501287586	69.10
	SE		7815	6510228.40	36424044.00	691456	134744.60	2489518.15	633727.10	8762088.10	195306852	86.70
	FC		1935	6510228.40	8371848.30	691456	134744.60	6565820.70	484729.50	3479773.20	65102284	75
HT	**IC**	1421	2789.4	6293779.35	12354455.76	1679688.70	906528.25	3418910	504422.45	4541801	5255305756	70.65
	GT		2782.6	6297360.70	12330738.04	1657706.50	888127.45	3432115.60	470958.10	4866515.90	484896776	65.50
	SE		7815	4220784.60	24886371.80	3314412.50	468257.30	0	657846.40	6170523.80	126623538	83.10
	FC		1935	7180791.35	9310310.90	1272638.30	1386489.80	5207247.60	429351.70	3870878.20	71807913	74.30
HyT (MCT)	**IC**	1421	2789.4	7282028.50	14294352.30	691439.50	906528.25	3418910	457550.30	5138603.90	6080493819	73
	GT		2782.6	7521392.20	14668788.35	556780.65	1011233.05	3432115.60	400991.15	5565163.15	579147196	69.50
	SE		7815	6970059.85	38913562.15	691456	594576.05	0	581307.35	9334336	209101795	86.90
	FC		1935	7761973.65	10213047.35	691456	1386489.85	5060647.30	397164.20	4180599.83	77619736	75.40
HyT (MET)	**IC**	1421	2789.4	7282028.50	14294352.30	691439.50	906528.25	3418910	457550.30	5138603.90	6080493819	73
	GT		2782.6	7238058.60	14178533.70	667646.25	838765.04	3512606.80	415554.10	5346316	557330510	69.70
	SE		7815	6477124.45	36204119.60	1058072.65	468257.30	0	589371.40	8658825.05	194313733	87
	FC		1935	7353429.80	9724360.60	793803.40	1080293.40	5213308.40	420565.85	3961752.10	73534298	75.50

*Prime Mover Electrical Capacity = 75% of the maximum electrical load

Chapter 7 Results and Discussion

7.1 CHP Sizing Planning

Summarized results of the sizing planning case studies are discussed in section 6.2. In this section, comparison between the base case (case 1) and other cases (case 2-4) are discussed.

Economic and environmental impact of the base case has been considered as a reference case to compare with. Table 6-5 holds the emission data as well as the system economical detail regarding base case (case 1). The table depicts that, the case only allows the purchase of energy. Hence, the system does not provide any revenue. Grid connectivity does not require any capital investment for the user. However, the only capital cost involved in this case is associated with the installation of auxiliary heating unit to supply required heat energy. Due to these reasons this case is the least capital intensive case compared to the other scenarios. However, the operational cost is relatively higher due to the high price of electricity purchase cost from the grid.

Although the base case has least capital involvement but the system investment payback period is infinite. Which means the system never pays back its investment as the system does not allow any revenue generation.

The emission of both CO_2 and NOx are dependent only on the emission characteristics of grid and auxiliary heating unit.

Environmental (emission) and economic comparison between the base case and case 2 are shown in Table 7-1.

As user now can sell the excess electrical energy to the grid, case 2 has return on investment which base case lacks. Besides, base 2 is focused on achieving minimum running cost which is achieved by;

- Efficient utilization of primary fuel
- Selling surplus electricity to grid to gain revenue

During this scenario, the prime movers normally generate more electricity than required and sell the surplus to the grid. As depicted in Table 7-1, optimal allocation of prime movers require an increased capital investment for most of the load types. However, MEG and MURB load with electrical load reference mode actually requires less capital investment compared to the base case.

The table also shows that, in each and every load condition, the proposed system has less running cost compared to the base case. Depending on the revenue generated, the proposed system with optimal prime movers can have return on investment (ROI) from 4.95% to 12.78%. Depending on the return on investment, the system payback period could be as low as 7.83 years (Load type 1-FEL) where maximum payback period is 20.23 years (load type 1-HLR).

Although, the system economy is better compared to the base case but the emissions from the system is mostly increased. Load type 1 with heat load reference mode has a CO_2 emission savings of around 7.3%. However, other load types has increased CO_2 emission compared to the base case. Depending on the load type and load reference mode, the carbon dioxide emission could increase op to 89.3% over the base case. This is because, the system generates more energy to make more revenue by selling surplus electricity. More energy generation requires to burn more primary fuel (natural gas) which results in an increase over CO_2 emission. However, due to high system efficiency, CO_2 emission per kWh energy generated is still significantly low compared to the conventional energy generation technologies.

Similarly, NOx emission saving only occurs during heat load reference mode for both load type 1 (21.18%) and load type 3 (26%). All other load type at different load reference mode results in an increased emission of NOx. The highest emission is almost five times more than the base case emission occurs during electrical loads reference mode for load type 3. The highest emission mainly occurs due to the high involvement of IC engine based prime mover which has minimum O&M cost but comes with maximum NOx emission. Besides, total energy generation is much higher than the required which is also a key reason behind the excessive NOx emission.

Table 7-2 shows the comparison of case 3 system economy and emission over the base case. The objective of case 3 was to minimize the CO_2 of the system with and optimal allocation of CHP prime movers. While trying to minimize CO_2 emission, system running cost and NOx emission has no influence on the selection of emission. Moreover, user also has no control over system running cost and NOx emission while finding the optimal size for minimum CO_2 emission.

CO_2 emission savings mainly depends on the following;

- Load (electrical and heat) profile
- Efficiency of the system
- Proper selection of PM

Results shown is the table depicts that, all load types having either heat load or electrical load reference has potential CO_2 savings. This clearly indicates that, the proposed algorithm is able to find optimal combination of prime movers to minimize net CO_2 emission.

The table also depicts that the maximum achievable CO_2 savings per year is about 15%. Optimal prime mover allocation for load type 1 with heat load reference results in the maximum CO2 savings. However, the minimum saving is around 1.5% per year for load type 2 (ELR).

Different load with optimal PM, not only provides CO_2 savings but also generates revenue. Unlike the base case, each load type has reasonable return on investment (ROI). Based on the capital cost and ROI associated with the load type, system payback period could be as low as 10.10 years. Minimum payback period occurs for the load type 1 with electricity as reference load. However, system payback period could be as high as 44 years. Load type 4 with electrical load reference, requires more contribution from the fuel cell to achieve minimum CO_2 emission. Fuel cell has the highest capital cost involvement with moderate running cost which results in a significantly high system payback period. However, the system generates revenue and saves CO_2 emission at the same time which is very significant compared to the base case.

NOx emission of the intended system with minimum CO_2 emission objective is also interesting compared to the base case. Load type 1 and 2 actually has reasonable NOx emission saving at the same time while minimizing CO_2 emission. The maximum NOx emission savings could be as high as 25.6% (for load type 1-ELR) while the minimum saving is almost 10%. However, because of the electrical reference load profile for load type 3, optimal allocation of PM involves higher contribution from the IC engine. As IC engine results in the highest NOx emission, load type 3 with ELR has five times more NOx emission compared to the base case.

It is evident that, the proposed algorithm is able to find the optimal size and type of PM to minimize the CO_2 emission with reasonable ROI of the system. Although NOx emission saving is also possible in most of the cases but in some cases, minimum CO_2 emission is achieved with an expense of higher NOx emission.

Table 7-3 shows the comparison between case 4 and base case scenario in terms of system economy and emission. The objective of case study 4 was to find the optimal size of CHP prime movers while minimizing NOx emission. System total NOx emission is a function of the total energy generation (mainly electricity). Issues that directly influences NOx emission are listed below;

- Electricity generation of prime movers
- Energy (heat) generation of AHU
- Prime mover types

The comparison table depicts that, capital cost increases in most of the cases to attain minimum NOx emission. However, load type 4 and load type 3 (HLR) actually requires less capital involvement than the base case due to the optimal selection of PM.

The table also shoes that, due to the optimal selection of prime movers, all the load types has significant amount of NOx savings over the base case. Maximum achievable NOx emission savings is around 61.2% for load type 4 on electrical load reference mode. Other load types has savings around 30% while the minimum savings is 26.8% (load type 3-HLR). This results clearly indicate that the optimization technique is capable of finding optimal PM and minimize system NOx emission.

Moreover, unlike the base case, all the load types with optimal size of prime mover generated profit by selling surplus electricity to grid. Due to this, each load type has reasonable amount of ROI depending on their respective revenue and capital cost. System payback period with the proposed algorithm is also noteworthy. Depending on the load type and ROI, system payback period could be as load as 8.68 years. However, the maximum payback period in this case is 22.9 years which is for heat load reference mode of load type 4. Interesting thing to notice that, the proposed PM selection algorithm not only saves NOx emission but also helps to payback systems initial investment gradually.

However, in some cases the minimum NOx emission goal is achieved with a of increased CO_2 emission. CO_2 emission could increase up to 95% as shown in Table 7-3. However, depending on the selection of the prime mover and load type, both CO_2 and NOx emission is possible at the same time. Maximum CO2 saving achiever for load type 1 during heat load reference mode is around 13%.

Table 7-4: Comparison of the findings regarding MEG load between the intended study and reference [14], shows the comparison between the study and similar study carried out in reference [14] in terms of MEG load. Results indicate that the proposed strategy is able to achieve intended objectives like the reference [14]. Results found in both of the studies are similar. However, the amount of cost saving and emission reduction are slightly different as the components designed in this study are based on their part-load performance. Because of the consideration of part-load performance, the proposed strategy is able to provide much better planning estimation compared to the reference work. Moreover, for the sake of verification, several load types has been used for case studies.

Overall, the proposed algorithm is able to find optimal prime movers for different load while minimizing system NOx emission and improving system economy. Besides, in some load types, the goal is achiever by having an increase on the system total CO_2 emission. However, CO_2 saving is also possible depending on the load type and selected reference load.

Table 7-1: Comparison between base case and case 2

Load Type	Reference Load	Optimal PM Capacity (kW-electrical)				Capital Cost increase ($)	Running Cost Saving ($)	ROI	Payback Period (year)	CO_2 Saving (%)	NOx Saving (%)
		IC	GT	SE	FC						
1	FHL	19.258	62.159	5.334	635.458	1935944.44	274777.87	7.12	14.03	7.29	21.18
	FEL	167.494	297.410	101.357	180.794	961183.88	368077.87	12.77	7.82	-46.56	-176.12
2	FHL	67.536	74.793	16.871	702.130	2293089.03	218793.35	5.00	19.97	-0.36	-34.43
	FEL	395.575	380.439	105.485	242.050	2073935.68	426293.35	10.27	9.73	-75.14	-361.41
3	FHL	48.138	230.172	28.410	278.124	649922.83	157013.38	5.91	16.92	-30.19	26.02
	FEL	251.724	206.324	33.395	70.422	-91505.73	231888.38	12.10	8.25	-86.16	-501.89
4	FHL	143.336	41.888	280.836	2578.375	6531220.56	912746.86	4.94	20.23	-43.73	-33.64
	FEL	525.557	602.346	387.505	377.023	-1233603.86	859846.86	8.03	12.44	-89.28	-272.59

Capital cost increase = $(System\ capital\ cost - Base\ case\ capital\ cost$

Running cost savings = $(System\ running\ cost - Base\ case\ running\ cost)$

CO_2 savings = $\left(\frac{System\ CO_2\ emission - Base\ case\ CO_2\ emission}{ase\ case\ CO_2\ emission} * 100\right)$

NOx savings = $\left(\frac{System\ NOx\ emission - Base\ case\ NOx\ emission}{Base\ case\ NOx\ emission} * 100\right)$

ROI =Return on Investment = $\left(\frac{Running\ cost\ savings}{Capital\ cost} * 100\right)$

Payback period = $\left(\frac{Capital\ cost}{System\ running\ cost\ saving}\right)$

Table 7-2: Comparison between base case and case 3

Load Type	Reference Load	Optimal PM Capacity (kW-electrical)				Capital Cost increase ($)	Running Cost Saving ($)	ROI	Payback Period (year)	CO_2 Saving (%)	NOx Saving (%)
		IC	GT	SE	FC						
1	FHL	5.743	32.105	0.969	466.728	1444621.45	150277.87	4.46	22.38	14.76	16.18
	FEL	30.766	35.726	85.502	232.165	262766.24	215977.87	9.89	10.10	4.17	25.61
2	FHL	12.453	29.459	10.731	347.775	1019284.86	147193.35	4.75	21.03	9.28	19.57
	FEL	48.428	90.259	22.006	648.890	2018831.83	306593.35	7.48	13.35	1.35	9.60
3	FHL	14.449	12.579	41.673	71.351	-1356.06	78513.38	3.91	25.54	10.92	-11.07
	FEL	380.642	79.176	21.828	38.007	-230839.32	176913.38	9.96	10.03	2.97	-542.48
4	FHL	89.324	77.785	257.618	441.052	-8490.41	387316.86	3.24	30.79	6.79	-13.39
	FEL	48.428	90.259	22.006	648.890	1869889.22	310216.86	2.24	44.50	7.34	-216.03

Table 7-3: Comparison between base case and case 4

Load Type	Reference Load	Optimal PM Capacity (kW-electrical)				Capital Cost increase ($)	Running Cost Saving ($)	ROI	Payback Period (year)	CO2 Saving (%)	NOx Saving (%)
		IC	GT	SE	FC						
1	FHL	8.089	165.719	9.541	271.430	761927.61	209877.87	7.82	12.77	12.83	30.54
	FEL	20.388	234.513	9.646	287.975	792175.49	312377.87	11.51	8.68	1.57	30.67
2	FHL	0.215	168.107	98.927	225.121	163271.15	153293.35	6.84	14.61	-4.36	33.79
	FEL	14.813	73.815	280.616	725.609	3449489.34	345793.35	6.25	15.98	-65.43	52.27
3	FHL	6.923	2.683	110.810	90.495	-289348.25	83513.38	4.86	20.56	3.53	26.83
	FEL	15.827	3.542	415.566	84.007	370847.03	121713.38	5.11	19.53	-95.73	28.97
4	FHL	42.798	16.579	685.054	559.449	-1788868.28	442816.86	4.36	22.91	-5.90	36.56
	FEL	10.051	3.421	740.840	608.847	-1898496.97	542316.86	5.40	18.50	-54.63	61.16

Table 7-4: Comparison of the findings regarding MEG load between the intended study and reference [14]

Ref. Load	**Objective Function**	**Optimal PM Capacity (kW-electrical)**					**Electricity trade with main grid (MWh)**		**Generated heat (MWh)**		**Total operational cost**	**Total CO_2 Emission (kg)**
		ICE	GT	SE	FC	H_2FC	Purchased	Sold	NG AHU	Elec. Heater		
					A. Zidan et al. / Energy 93 (2015) [14]							
ELR	Base Case	N/A	N/A	N/A	N/A	N/A	7032.90	0	11474.70	N/A	7.74x10^{5}	6.63x10^{5}
	Operational Cost	N/A	1830.80	N/A	18	0.07	66.78	0	5320.32	0	4.13x10^{5}	3.29x10^{5}
	CO_2 Emission	N/A	46.70	N/A		1728.24	5758.4	0	0	5583.70	2.44x10^{6}	9.36x10^{5}
HLR	Base Case	N/A	N/A	N/A	N/A	N/A	7032.90	0	11474.70	N/A	7.74x10^{5}	6.63x10^{5}
	Operational Cost	N/A	3922.5	N/A	158.88	34.73	2172.40	4040.83	0	0	4.81x10^{5}	6.93x10^{6}
	CO_2 Emission	N/A	6.28	N/A	0	4366.05	2982.00	4338.05	648.10	859.10	4.44x10^{6}	3.05x10^{5}
					Intended study							
ELR	Base Case	N/A	N/A	N/A	N/A	N/A	7032.90	0	11474.70	N/A	9.41x10^{5}	6.55x10^{6}
	Operational Cost	525.55	602.34	387.50	377.02	N/A	3.163	8380	1270	N/A	8.12x10^{4}	1.24x10^{7}
	CO_2 Emission	48.42	90.25	22.00	648.89	N/A	2930	432	7590	N/A	6.31x10^{5}	6.07x10^{6}
HLR	Base Case	N/A	N/A	N/A	N/A	N/A	7032.90	0	11474.70	N/A	9.41x10^{5}	6.55x10^{6}
	Operational Cost	143.33	41.88	280.83	2578.37	N/A	0	7630	579	N/A	2.83x10^{4}	9.41x10^{6}
	CO_2 Emission	89.32	77.78	257.61	441.05	N/A	2080	413	4040	N/A	5.53x10^{5}	6.10x10^{6}

7.2 CHP Operational Planning

In this section, best and worst load tracking mode regarding different PM for distinct scenarios has been discussed. Depending on the load characteristics and prime mover type, different load tracking mode may have distinctive impact on the system performance indicator.

Table 7-5, shows the best and worst possible load tracking modes for different prime movers considered in operational planning scenario 1.

For the intended scenario, minimum system operational cost with an IC engine is possible while having it operated at either minimum cost tracking mode (MCT) or maximum efficiency tracking mode (MET). This modes also has the added advantage of having maximum prime mover (ICE) efficiency. However, having the IC engine set at heat load tracking (HT) mode will result in maximum system running cost as well as minimum PM efficiency. Due to the emission characteristics of IC engine, NOx emission from the prime mover (ICE) is the highest compared to any other prime mover. Among the modes of operation, HT mode results in minimum emission (CO_2 and NOx) from the IC engine as in this mode less energy (electricity and heat) is generated. However, during this mode of operation more energy is purchased from grid and AHU. This phenomenon could result in a higher overall system emission.

Results depicted in Table 6-9 shows that, gas turbine based CHP prime mover efficiency is the least compared to the other cases. This is due to the poor part-load performance of gas turbine based prime movers. However, highest gas turbine efficiency is achievable while operating at MET mode while MCT mode results in minimum operational cost. On the other hand, having the GT set at HT mode will cause the maximum operation cost and minimum PM efficiency. However, HT mode comes with the minimum PM emission (CO_2 and NOx) advantage.

Stirling engine (SE), having a higher heat to power ration is not perfectly suitable for the load type considered in scenario 1.Because, the heat energy demand for the load type is much less compared to the electricity demand in most of the days in the year. Despite of having maximum prime mover efficiency, system operational cost and CO_2 emission from

SE is higher than the other cases with different prime movers. While running at ET mode, SE produces more surplus heat energy while meeting the electricity demand. This surplus heat resulted due to higher heat to power ration is further dumped as waste resulting in inefficient utilization of energy. Similarly at HT mode, less electricity is produced while supplying the heat demand. This leads to higher electricity purchase from the grid and increases system operational cost. However, minimum system operational and maximum PM efficiency is possible with any other mode except HT.

For fuel cell based prime mover in scenario 1, minimum operational cost is achievable while running at MCT mode. Moreover, MET more results in highest prime mover (FC) efficiency. Although, HT mode of operation in case of fuel cell results in minimum (NOx and CO_2) emission from PM but also comes with highest system operational cost and minimum PM efficiency.

Table 7-5: Best and worst load tracking modes of CHP operational planning scenario 1

Scenario 1: Load Type 1 (Hospital)								
Performance Indicator	**Best Load Tracking Mode**				**Worst Load Tracking Mode**			
	ICE	**GT**	**SE**	**FC**	**ICE**	**GT**	**SE**	**FC**
System Cost	MCT MET	MCT	ET MCT/MET	MCT	HT	HT	HT	HT
PM CO_2 Emission	HT	HT	HT	HT	MCT MET	MET	ET MCT/MET	MET
PM NOx Emission	HT	HT	HT	HT	MCT MET	MET	ET MCT/MET	MET
PM Efficiency	MCT MET	MET	ET MCT/MET	MET	HT	HT	HT	HT

Table 7-6, shows the best and worst possible load tracking modes for different prime movers considered in operational planning scenario 2.

Best and worst load tracking mode for IC engine, Stirling engine and Gas turbine based prime mover are similar as scenario 1. This similarities exists because of the similar load characteristics of hospital and office building considered in scenario 1 and scenario 2 respectively. In both load types, heat energy demand in significantly less compared to electricity demand during most of the seasons (summer and mid-season). This results in a similar trend on the operation of prime movers. However, fuel cell based PM has maximum efficiency at MET mode and has minimum cost during minimum cost tracking mode. Minimum emission of fuel cell happens at HT mode of operation which is similar to scenario 1. However, unlike scenario 1, maximum emission from fuel cell happens while operating at MCT mode.

Table 7-6: Best and worst load tracking modes of CHP operational planning scenario 2

Scenario 2: Load Type 2 (Office)								
Performance Indicator	**Best Load Tracking Mode**				**Worst Load Tracking Mode**			
	ICE	**GT**	**SE**	**FC**	**ICE**	**GT**	**SE**	**FC**
System Cost	MCT MET	MCT	ET MCT/MET	MCT	HT	HT	HT	HT
PM CO_2 Emission	HT	HT	HT	HT	MCT MET	MCT	ET MCT/MET	MCT
PM NOx Emission	HT	HT	HT	HT	MCT MET	MCT	ET MCT/MET	MCT
PM Efficiency	MCT MET	MET	ET MCT/MET	MET	HT	HT	HT	HT

Best and worst possible load tracking modes for different prime movers considered in operational planning scenario 3 are shown in Table 7-7.

Similar as scenario 1 and 2, having an IC engine running at either MET or MCT mode will result in minimum operational cost and maximum PM efficiency. However in maximum emission from IC engine is evident as more energy (electricity and heat) is generated during these modes of operations. Running an IC engine in HT mode will have the minimum PM efficiency with maximum cost. However, HT mode of operation for IC engine will result in minimum emission compared to load tracking modes.

Best possible load following modes for gas turbine based prime mover on scenario 3 is similar to that of scenario 1 and 2. Similarly, worst load following modes also matches accordingly with scenario 1 and scenario 2. Same as usual, gas turbine has the least prime mover efficiency due to its inferior part-load performance.

For scenario 3, minimum operational cost with SE is possible while operating at either ET or MCT mode. However, these modes of operations results in maximum emission from the SE as more energy is generated during operation. Although running the SE at heat tracking mode causes least emission from the system but comes with the price of maximum operational cost and minimum PM efficiency. Efficiency of SE based prime movers are significantly higher over any other prime mover. Excess heat is generated during operation due to higher heat to power ratio of SE. This excess energy is mostly dumped as waste which results in higher energy loss in the system.

Fuel cell based prime mover in scenario 3, results in minimum operational cost during MCT mode and highest efficiency is achieved during MET mode of operation. On the other hand, MCT mode comes with the maximum emission (CO_2 and NOx) from the system. While, ET mode and HT modes are well suited for minimum CO_2 and NOx emission respectively. However, HT and ET modes of FC operation are least preferred for highest PM efficiency and lowest operational cost.

Table 7-7: Best and worst load tracking modes of CHP operational planning scenario 3

Scenario 3: Load Type 3 (MURB)								
Performance Indicator	**Best Load Tracking Mode**				**Worst Load Tracking Mode**			
	ICE	**GT**	**SE**	**FC**	**ICE**	**GT**	**SE**	**FC**
System Cost	MCT MET	MCT	ET MCT	MCT	HT	HT	HT	ET
PM CO_2 Emission	HT	HT	HT	ET	MCT MET	MCT	ET MCT	MCT
PM NOx Emission	HT	HT	HT	HT	MCT MET	MCT	ET MCT	MCT
PM Efficiency	MCT MET	MET	MET	MET	HT	HT	HT	HT

Table 7-8, shows the best and worst possible load tracking modes for different prime movers considered in operational planning scenario 4. Load type 4 (MEG) being considered for this scenario has higher heat to power energy demand ratio compared to the other load types.

Best economy and efficiency for the IC engine is possible for either MCT or MRT but with an expense of highest emission. However, ET mode of IC operation results in maximum operational cost while HT mode will have the least prime mover efficiency. In general, IC engine has the maximum NOx emission due to its emission characteristics compared to any other PM.

For both GT, SE and FC, MCT and MET mode of operation will result in minimum system operational cost and maximum prime mover efficiency respectively. However for GT and SE, running at HT mode leads to minimum emission from the prime mover. On the other hand, having the fuel cell set at ET mode will result in minimum emission from the prime mover. In both cases, due to increased energy penetration from grid and AHU, system overall emission could increase significantly. On the other hand, running SE, GT or FC on MCT mode increases prime mover emission to max. This is because, the prime mover generates higher amount of energy during MCT mode which requires more fuel burn and increases emission.

For the gas turbine, ET mode of operation leads to maximum operational cost while HT mode results in minimum gas turbine efficiency. Similarly, HT mode of fuel cell operation leads to minimum PM efficiency and maximum operational cost is evident with ET mode of FC operation. However, setting the SE in HT mode will not only minimize the prime mover efficiency but also will maximize system operational cost.

Table 7-8: Best and worst load tracking modes of CHP operational planning scenario 4

Scenario 4: Load Type 4 (MEG)								
Performance Indicator	**Best Load Tracking Mode**				**Worst Load Tracking Mode**			
	ICE	**GT**	**SE**	**FC**	**ICE**	**GT**	**SE**	**FC**
System Cost	MCT MET	MCT	MCT	MCT	ET	ET	HT	ET
PM CO_2 Emission	HT	HT	HT	ET	MCT MET	MCT	MCT	MCT
PM NOx Emission	HT	HT	HT	ET	MCT MET	MCT	MCT	MCT
PM Efficiency	MCT MET	MET	MET	MET	HT	HT	HT	HT

Chapter 8 Conclusion and Recommendation

One of the objectives of the study is to develop an optimization tool to find the optimal size and type of CHP prime mover for specific load. Another aim is to develop an improved load following strategy to enhance system operational efficiency and reduce emission form the PM. Having an unplanned CHP system can increase system operation cost and emission rather being beneficial. Intended study is focused on developing a complete planning tool to enhance environmental and economical effectiveness of CHP systems.

8.1 Conclusion

As part of the objectives, system components has been modeled in Simulink. Developed system components includes; CHP prime movers (ICE, GT, FC and SE), electrical grid and auxiliary heating unit. CHP prime movers has been designed based on their part-load performance to achieve higher accuracy. Most importantly, developed component models are made generic. This allows the user to define and select his own system based requirement, availability of resources, region, etc. Thus, the component model library is capable of replicating any scenario and assist the planning as per user's interest.

A genetic algorithm based multi-objective optimization tool has been developed to find the optimal type and capacity of prime movers for a given load. Although, optimization and system constraints are defined but the user has the freedom to define constraints as per requirement.

Proposed GA based optimization tool has been applied to investigate case studies. For each case studies with specific objective functions, four different energy demand profiles has been applied to find the optimal size and type of prime movers. Investigation of the case studies clearly depicts that, the proposed optimization tool is able to find the optimal prime mover capacity according to the defined objective functions. It is also found that, with optimal sizing, return on investment of the system could be as high as 13% which leads to a payback period of only 7.8 years. Similarly, maximum possible CO_2 and NOx emission saving achieved were 15% and 61% respectively. From the results, it's evident that, the optimization tool is capable of assisting the user to find the optimal CHP prime mover capacity in order to minimize system emission and maximize profitability.

A hybrid load tracking algorithm has been proposed in this study to assist the operational planning of CHP prime movers. Hybrid load following mode has been developed focusing two main objectives; to maximize PM efficiency and minimize system operational cost.

Case studies with the proposed hybrid load following strategy has been investigated in the study. Studies indicate that, having the PM set at conventional load tracking modes (HT and ET) does not ensure maximum efficiency and minimum operational cost all the time. Besides, in some cases, conventional modes can result in efficiency reduction and increase system operational cost. However, unlike conventional modes, proposed hybrid load tracking strategies (MCT and MET) were able to ensure maximum efficiency and minimum cost for each and every scenario being considered.

This the results of the study clearly depict that, hybrid load tracking modes are able to ensure maximum fuel utilization and minimize system operational cost for any type of prime mover at any load condition.

8.2 Contribution of the Thesis

The main goal of the study is to develop an effective planning tool to maximize CHP benefits in terms of system economy and emission. In order to attain such objective, CHP system components were modeled in MATLAB/Simulink interface. Data from different literatures, manufacturer’s specification and real life case studies are used to develop the system component model library as accurately as possible. However, main contributions of the study are summarized as follows;

- Required information regarding the modeling of the system has been collected from different literatures, case studies, and manufacturers to ensure accurate modeling..
- One of the major contribution of the author is the development of the CHP system model library on Simulink. Unlike most of the study carried out in this field, CHP prime movers are modeled based on their part-load performance. Prime movers

modeled using part-load characteristics are developed to increase the accuracy of the results.

- A genetic algorithm based optimization tool has been developed and system constrains were defined to find the optimal size and type of prime mover. The optimization tool is intended to find the optimal CHP capacity while minimizing system operational cost and emission.
- Further, a hybrid load following technique has been proposed to ensure maximum fuel utilization and minimize operation cost during the CHP operation.
- Finally, the developed methods regarding both sizing and operational planning of CHP has been demonstrated by investigating several case studies. Four different load types were used and corresponding system performance indicators are investigated to verify the effectiveness of the proposed methods.

8.3 Future Work

The study is focused on developing an accurate planning tool to assist the sizing and operation. As future research framework, following has been proposed;

- In current study, CHP prime moves are developed based on their part-load performance. However, the performance of the prime mover dependent of system load and on ambient temperature. In future, both part-load performance and ambient temperature dependency of prime mover can be taken into consideration while modeling the component. This will result in higher accuracy and more precision while finding the optimal size and type of prime mover for a certain load.
- Current study only discusses the planning of MEG with CHP prime movers only. However, renewable sources and energy storage device could be integrated in the system and similar study can be carried out as future research.
- Currently, genetic algorithm based optimization tool has been used to identify the right capacity of PM. It is intended to develop optimization tools based on other algorithms like PSO, fuzzy optimization theory, Mixed Integer Nonlinear Programming (MINLP) and others.

— For the operational planning section, current study only depicts the algorithm regarding hybrid load following mode. However in future, it is intended to implement the complete control mechanism based on the proposed hybrid load following strategy. Implementation of the developed hybrid load tracking mode will help to validate the effectiveness of the proposed strategy.

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