Simulation of a Cogeneration System in Developing the Concept of Smart Energy Networks

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.
I understand that my thesis may be made electronically available to the public.

Abstract

In recent years, there has been significant pressure to reduce greenhouse gas emissions, to achieve higher efficiency and to integrate greater amounts of renewable energy resources in energy system. Governments at all levels have recognized the environmental impacts of the energy sector, as well as the ways in which this sector is closely-linked to a range of economic issues (e.g., industrial development, inflationary prices and local economic development). In general, every effort has been made to cope with the challenges in providing a sustainable energy solution for achieving the following goals: for example, to decrease the greenhouse gas (GHG) emission, to satisfy the increasing demand of energy, to achieve cleaner use of fossil fuels, to develop renewable energy technologies, and to integrate emerging renewables with low-carbon resources into grid and pipelines.

The concept of "Smart Grid" has recently been highlighted in the electricity sector to improve efficiency of energy use and to reduce greenhouse gases to achieve business goals. Several countries have increased their efforts to deploy the concept of Smart Electricity Grid and to implement a number of demonstration projects. While the driving initiatives for generating a Smart Grid are straightforward, its scope and functions differ from a Smart Energy Network (SEN) which has a broader boundary and more components. A comprehensive concept is presented to effectively integrate energy systems which can not only cover available energy resources but also address sustainability issues.

The availability of new technologies for utilizing the renewable energy such as solar, wind and biomass, and reducing the carbon footprint of fossil fuels by including natural gas within an integrated energy network provides a base for better conservation of energy usage and providing a cleaner environment. Moreover, the new energy carriers such as hydrogen and sustainable natural gas should be taken into account when such a network is developed. In addition, cogeneration systems, which combine heat and power and are different from the electricity dominant approach, can provide greater energy conversion efficiency.

A cogeneration system is a promising solution for effectively supplying energy to district consumers for high density urban environment. However, the existing district cogeneration systems, which have been developed under old energy supply structure, needs to be modified and remodeled in order to comply with the environment of Smart Energy Networks. In this thesis, a new community-scale cogeneration system is modeled using TRNSYS (Transient System Simulation Software), which enables analysis of transient characteristics of cogeneration and to investigate critical factors which should be considered for successful integration into a Smart Energy Network environment. This study has identified the elements that must be considered: 1) Transient characteristics such as hourly, daily and seasonal load variations, and its patterns should be investigated, which cannot be analyzed using a steady state model, 2) Heat-to-Power ratio of load and energy generations, which should be considered to select proper types of facilities in order to cope with the transient characteristics, 3) Excessive and unmet energies, which should be analyzed to investigate a feasible system configuration, 4) Capacity factors and renewable contribution to energy capacity at peak times, which should be provided for system design, 5) Transient system efficiency, which is requited for effective combination of operation of PV arrays, fuel cell system, gas turbine combined system, and auxiliary boiler, 6) Emission levels should be confirmed for environmental monitoring and compliance, and 7) Communications and control methodologies, which is required to deploy the proper function of the cogeneration system.

This thesis focuses on defining what a Smart Energy Network is, its functions and the critical criteria of demonstrating and validating this concept, and developing a model for cogeneration system according to the concept of Smart Energy Network.

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Table of Contents

List of Figures

List of Tables

Chapter 1

INTRODUCTION

1.1 Background

In recent years, the ‘smarter’ use of energy resources, together with developing renewable ones, has drawn much attention in order to address the challenges in global energy security, climate change and economic growth. The availability of new technologies for utilizing the renewable energy such as solar, wind and biomass, and reducing the carbon footprint of fossil fuels by including natural gas within an integrated energy network provides a base for better conservation of energy usage and providing a cleaner environment. In addition, the combined heat and power concept, which is different from the electricity dominant approach, can provide greater energy conversion efficiency. Moreover, the new energy carriers such as hydrogen and sustainable natural gas should be taken into account when such a network is developed. In addition, cogeneration systems, which combine heat and power and are different from the electricity dominant approach, can provide greater energy conversion efficiency for achieving the following goals:

- To decrease the greenhouse gas (GHG) emission
- To satisfy the increasing demand of energy
- To achieve a cleaner use of fossil fuels
- To develop renewable energy technologies
- To integrate emerging renewables with low-carbon resources to grid and pipelines

It is worthwhile to mention the smart energy management; the term of “Smart Grid” has recently been exemplified and highlighted not only in the energy sector but also in business. Several countries have increased their efforts to deploy the concept of Smart Electricity Grid and to implement a number of demonstration projects. Energy carriers, which are being delivered to the end users and consumed by them, include electricity, heat, liquid fuels and natural gas. While the driving initiatives for generating a Smart Grid are straightforward, its scope and functions differ from a Smart Energy Network (SEN) which has a broader boundary and more components. A comprehensive concept is presented to effectively integrate energy systems which can not only cover available energy resources but also address sustainability issues.

1.2 Objectives

This research focuses on defining the smart energy network (SEN) concept, its functions and the critical criteria for demonstrating and validating the concept, rationale and feasibility, and simulating of a cogeneration system as followings:

- Investigate building a SEN in Ontario
- Review the concept of the Smart Grid
- Define the concept of the SEN and its functionalities
- Simulate a cogeneration system in SNE environment in Ontario to verify cogeneration operating modes (winter, summer, and seasonal operation), energy savings, existing utility capacity savings at variable load points, energy unmet and excessive, and storage in hourly operation, influences of energy load pattern and variations on component capacity, and influences of weather variations on components capacity.

1.3 Methodology

The methods used in this research include archive, interactive and direct analytic approaches. The archive methods consist of reviewing pertinent literature data including journal article, reports, publications and websites. The interactive methods cover doing interviews with key informants and seeking advice from experts in academia and industry. The direct analytic method includes modeling, calculations and analysis of the reference data by means of engineering theories, thermodynamic laws and computational software such as HOMER[1], TRNSYS[2], and Matlab.

The research tasks are categorized into several groups and each group is subdivided into detailed research activities. The first step is to collect and search necessary energy data showing the current status and outlook of the energy supply, demand and resources in Ontario. The next step is to review the concept of the Smart Grid and to study its link to the Smart Energy Grid. Then the concept of the Smart Energy Network is proposed and a cogeneration system is simulated and proposed for implementing the Smart Energy Grid in Ontario. Finally, based on a proposed demonstration project,

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[1] HOMER is the micropower optimization model analysis software, which has been developed by NREL (National Renewable Energy Laboratory) U.S. HOMER simulates the alternatives of energy systems to evaluate design options for both grid connected and off grid power systems for all types of applications including Distributed Generation. [1]

[2] "TRNSYS (pronounced 'tran–sis') is an extremely flexible software tool used to simulate the performance of transient systems. Although most often the systems that we investigate are focused on energy, TRNSYS can equally well be used to model other dynamic systems such as traffic flow, or biological processes." [2]

key factors for validation and other recommendations are put forward, including further Research, Development, and Demonstration (RD&D) task.

Chapter 2

LITERATURE REVIEW

2.1 Smart Grid

Recently aiming at the development of renewables with the low-carbon energy technology, a few countries (e.g., U.S.A, EU, Japan, and Korea) and international organizations (IEA and IEEE, etc.) have led the implementation, standardization and demonstration of Smart Grids in the world.

2.1.1 Definitions

Even though the basic scope and functionalities of the Smart Gird are similar for many developers, there are a variety of distinct definitions of Smart Grids. The definitions set by U.S.A, EU and Japan are as follows:

- U.S.A.:

"The Smart Grid uses the digital technologies to improve reliability, security, and efficiency of the electrical system: from large generation through the delivery systems to electricity Consumers and a growing number of Distributed Generation and storage resources." [3] Or

"Smart Grid refers to a distribution system that allows for the flow information from a customer's meter in two directions: both inside the house to thermostats, appliances, other devices, and from the houses back to the utility. Smart Grid is defined to include a variety of operational and energy measures-including smart meters, smart appliances, renewable energy resources and energy efficiency resources." [4]

- European Nations:

"An electricity network that can intelligently integrate the actions of all the users connected to it-Generation, Customers and those that do both, in order to efficiently deliver sustainable economic and secure electricity supply." [5]

- Japan:

"Smart Grid is an electricity transmission and distribution grid to promote the stability of electric power supply by using information and communication technology while introducing huge amount of renewable energy." [6]

2.1.2 Characteristics of the Smart Grid

The Smart Gird has been defined as having a key theme in its concept, implementation, and demonstration projects which emphasizes

- Energy Systems: Electricity Grid covering generation, transmission & distribution (or utilization)
- Integration, two-way communications, and automations
- Sustainable reliability, security, and efficiency of the system
- Growing renewables, energy storage, and smart appliances

The characteristics of a Smart Grid can be described as [7]

- Enabling and motivating active participations by Consumers
- Accommodating all power generation and energy storage options
- Enabling new businesses ranging from products, services to markets
- Providing the quality of electrical power for the digital economy: information, communication & control
- Optimizing asset utilization and operates efficiently the entire system
- Anticipating and responding to system disturbances using the self-recovery system
- Operating resiliently against attacks and natural disasters

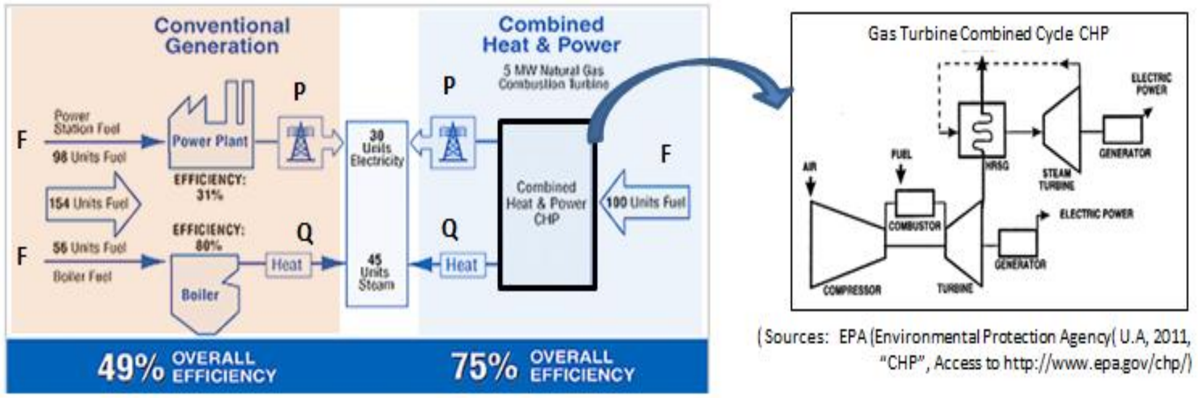
2.1.3 Its Scope as a Typical Conceptual Model

The development of Smart Grids has shown a higher level of being a typical conceptual model which serves as a tool for identifying actors and possible communication paths in an electrical grid. [12] The actors can be equipment, components, devices and computer systems. These actors have the capacity to generate, store and transfer energy, or to make decisions and exchange information with other actors through interfaces. A Smart Grid normally covers seven domains, which are the groups of actors and paths serving the same or similar functionalities or objectives, consisting of customers, markets, service providers, operators, bulk generation, transmission and distribution. Many countries have tried to deploy the concept of Smart Grids and these initiatives and demonstration projects.

2.2 Cogeneration System

2.2.1 Concept

The definition of cogeneration is an integrated system that can generate sequentially or simultaneously two or three useful energies in the forms of electricity, heating and cooling with a single energy source, thereby increasing overall efficiency. Cogeneration systems may consist of a number of variety individual components such as prime mover, generator, heat recovery unit, absorption chiller unit, and electrical/control interconnections. cogeneration is one of specific forms of distributed generation (DG), which can deploy energy generation unit at or near consumers to supply electricity, heating and cooling energy needed.[8] Figure-1 illustrates the general concept of cogeneration system (or called CHP: combined heat and power) compared to conventional generation.



(Sources: EPA (Environmental Protection Agency(U.A, 2011, "CHP", Access to http://www.epa.gov/chp/)

(Sources: EPA, 2011, “CHP”, accessed to http://www.eps.gov/chp/)

Figure-1 General Concept of Cogeneration

2.2.2 System Efficiency

One of main parameters used to define the characteristics of cogeneration system is system efficiency. In order to investigate cogeneration system efficiency compared to separate power and thermal generation, several efficiencies are defined; thermal efficiency of separate generation, electricity efficiency of separate generation, effective efficiency of separate thermal and power generation, total cogeneration system efficiency, effective electrical efficiency of cogeneration, and effective thermal efficiency of cogeneration.

For separate generation: [38]

Thermal Efficiency is defined as ratio of net thermal output to energy input.

$$EFF_Q = \frac{Net\ Useful\ Thermal\ Output}{Energy\ Input} \tag{2.1}$$

Electricity efficiency of separate generation is defined as ratio of net power output to energy input.

$$EFF_P = \frac{Net\ Power\ Output}{Energy\ Input} \tag{2.2}$$

Effective efficiency of separate heat and power (SHP) is defined as sum of net useful thermal output and net power over sum of fuel consumed to produce the energy.

$$EFF_{SHP} = \frac{P + Q}{\frac{P}{EFF_{Power}} + \frac{Q}{EFF_{Thermal}}} \tag{2.3}$$

For cogeneration system: [38]

Total cogeneration system efficiency is defined as sum of net power and useful thermal energy to total fuel consumed.

$$EFF_{Cogen} = \frac{P + Q}{F} \tag{2.4}$$

Effective electrical efficiency of cogeneration, $EEFF_P$, is defined as ration of net power output to net fuel input, excluding net fuel used for producing useful thermal energy. $EEFF_P$ means maximum possible power efficiency of cogeneration assuming that effective thermal efficiency of cogeneration is equivalent to that of separate generation. $EEFF_P$ can be compared with electricity efficiency of separate generation.

$$EEFF_P = \frac{P}{F - Q/EFF_{Thermal}} \tag{2.5}$$

Effective thermal efficiency of cogeneration, $EEFF_Q$, is defined as ration of useful thermal energy to net fuel input, excluding net fuel used for producing net power. $EEFF_Q$ means maximum possible thermal efficiency of cogeneration assuming that effective power efficiency of cogeneration is equivalent to that of separate generation. $EEFF_Q$ can be compared with thermal efficiency of separate generation.

$$EEFF_Q = \frac{Q}{F - P/EFF_{Power}} \tag{2.6}$$

Where,

P = Net power output from cogeneration system,

Q = Net useful thermal energy from cogeneration system,

F = Total fuel input to cogeneration system,

EFF_{Power} = Efficiency of displaced electric generation,

$EFF_{Thermal}$ = Efficiency of displaced thermal generation

Figure 2 represents efficiency matrix for separate generations and cogeneration system.

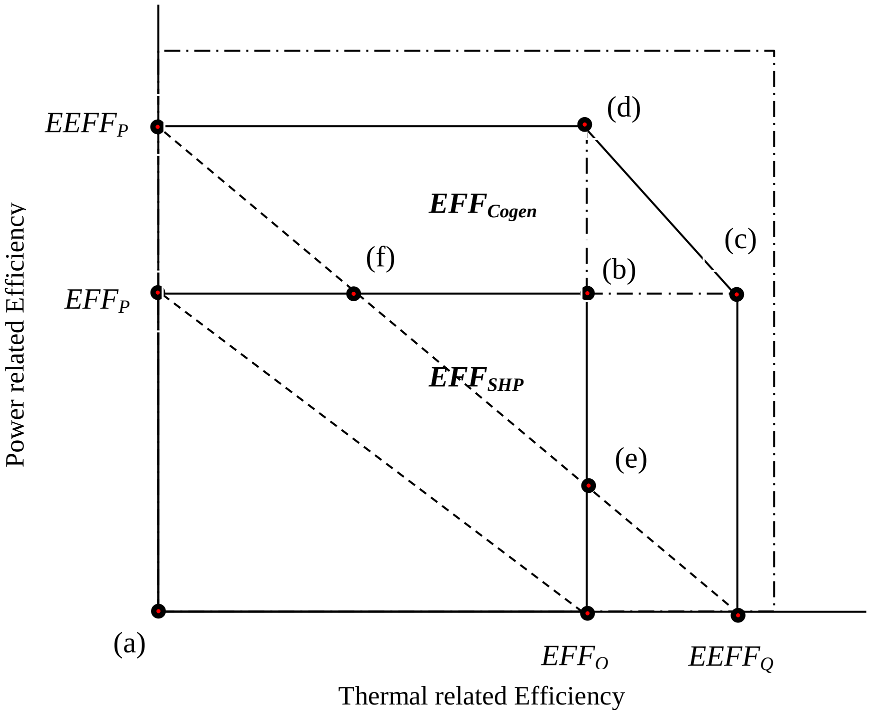


Figure-2 Efficiency matrix for separate generations and cogeneration system

Efficiency relationship:

In figure 2, the area [EFF_Q - *(b)* - EFF_P - EFF_Q] is a separate generation efficiency zone, in which effective efficiency of separate heat and power, EFF_{SHP} , can be located, while the area [$EEFF_Q$ - (c) - (d) - $EEFF_P$ - $EEFF_Q$] is a cogeneration system efficiency zone, in which total cogeneration system efficiency , EFF_{Cogen} ,can be located. The area [(e) – (b) – (f) – (e)] is a common zone, in which EFF_{SHP} and EFF_{Cogen} could be concurrently existed. It means EFF_{Cogen} could be lower than EFF_{SHP}

in the zone depending on the efficiency matrix created by several factors such as cogeneration system configuration, its operating characteristics, and load consumption and patterns.

Cogeneration Efficiency Index (CEI):

In order to clarify if total cogeneration system is higher than effective efficiency of separate heat and power, cogeneration efficiency index (CEI) is defined in this study. When cogeneration system is implemented, EFF_{Cogen} should be higher than EFF_{SHP} for keeping qualification. From equation (2.3) and (2.4), the condition is as follows.

$$EFF_{Coge} > EFF_{SHP} \tag{2.7}$$

$$\frac{P + Q}{F} > \frac{P + Q}{\frac{P}{EFF_{Power}} + \frac{Q}{EFF_{Thermal}}} \tag{2.8}$$

Rearranging equation (2.8) yields.

$$\frac{\frac{P}{EFF_{Power}} + \frac{Q}{EFF_{Thermal}}}{F} > 1 \tag{2.9}$$

Therefore, the left side of equation (2.9) is defined as Cogeneration Efficiency Index (CEI) in this study, which means cogeneration system becomes more efficient than separate heat and power generations when CEI > 1.

$$\frac{\frac{P}{EFF_{Power}} + \frac{Q}{EFF_{Thermal}}}{F} = \text{CEI} > 1 \tag{2.10}$$

2.2.3 Technology state-of-the-Art

There are several types of cogeneration technologies. Generally, cogeneration technologies are categorized based on prime mover in the system: Combustion Gas Turbines cogeneration, Microturbines cogeneration, Reciprocating engines cogeneration, Backpressure steam turbines cogeneration, Fuel cells cogeneration, and its companions. [8]

(1) Combustion Gas Turbines cogeneration: This technology use combustion gas turbine as a prime mover. Typically, the gas turbines are available in sizes ranging from 500 kW to 250 MW per unit and can operate with some gaseous fuels such as natural gas, biogases, and landfill gas. Combustion Gas Turbines cogeneration system have a variety operation modes including (a) simple cycle

operation with a single gas turbine, producing electricity only, (b) cogeneration operation with a single gas turbine coupled and a heat recovery boilers or (c) combined cycle operation with a steam turbine. There are many cogeneration plants in industrial and institutional, which have successful operation experiences. The prime mover of gas turbines are well suited for cogeneration because of high thermal ratio to electricity.

(2) Microturbines cogeneration: This technology use small combustion gas turbine as a prime mover that was developed and commercialized in 2000. Currently, the available microturbines size ranges from 30 kW to 250 kW per unit. Several units of microturbines may be connected in parallel to serve larger loads and provide power reliability. Microturbines can burn a wide variety of fuels including natural gas, biogases, and liquid fuels such as gasoline, kerosene, and diesel fuel. This system have several configurations together with heat exchangers to generate different energy for different applications including potable water heating, absorption chillers and desiccant dehumidification equipment, space heating, and process heating.

(3) Reciprocating engines cogeneration: This technology use reciprocating engines such as spark ignition (SI) and compression ignition (CI). SI engines are available in sizes up to 5 MW per unit. Normally, natural gas is used for SI engines, but propane, gasoline and landfill gas can also be used. CI engines (so called Diesel engines) are available in sizes up to 7 MW per unit, operating with mainly on diesel fuel or heavy oil. However, natural gas with a small amount of diesel pilot fuel can be also used in dual fuel engine case. Multiple units of reciprocating engines can be connected in parallel to enhance plant capacity and availability. The reciprocation engines start quickly, follow load well, have good part-load efficiencies, and generally have high reliabilities.

(4) Backpressure steam turbines cogeneration: This technology use steam turbines as a prime mover. This technology consists of steam turbine, generator, steam boiler, heat exchangers. The high pressure steam generated in steam boiler is delivered to the steam turbine/generator in which the energy turns into electricity. The steam boiler can use a variety of fuels including natural gas, biofuels, solid waste, coal, and wood waste. The steam turbines are typically available in size ranges between 50 kW to over 250 MW. Because of complex configurations, these systems are generally applied to medium or large scale facilities for industrial or institutional facilities with high thermal loads, and variety available fuels such as solid wastes.

(5) Fuel cells cogeneration: This technology is one of emerging technologies that has been developed and commercialized for serving power and thermal needs cleanly and efficiently in commercial and

residential sectors. Fuel cells use an electrochemical process to convert the chemical energy of hydrogen into electricity and thermal energy. Fuel cells use hydrogen, which can be obtained from natural gas, coal gas, methanol, and other hydrocarbon fuels. Typically, there are five types of fuel cells that are under development: Direct Methanol Fuel Cell (DMFC), Proton Exchange Membrane (PEMFC), Alkaline Fuel Cell (AFC), Phosphoric Acid Fuel Cell (PAFC), Molten Carbon Fuel Cell (MCFC), and Solid Oxide Fuel Cell (SOFC). PEMFC system is commercially available in range between 1kW to 100kW. AFC system is available in range between 10kW to 100kW. PAFC are available two sizes, 100 kW and 400 kW. MCFC systems are available, 300 kW and 3000 kW. And SOFC systems are available, 300 kW and 2200 kW. Figure 3 illustrates the capacity and power density of cogeneration.

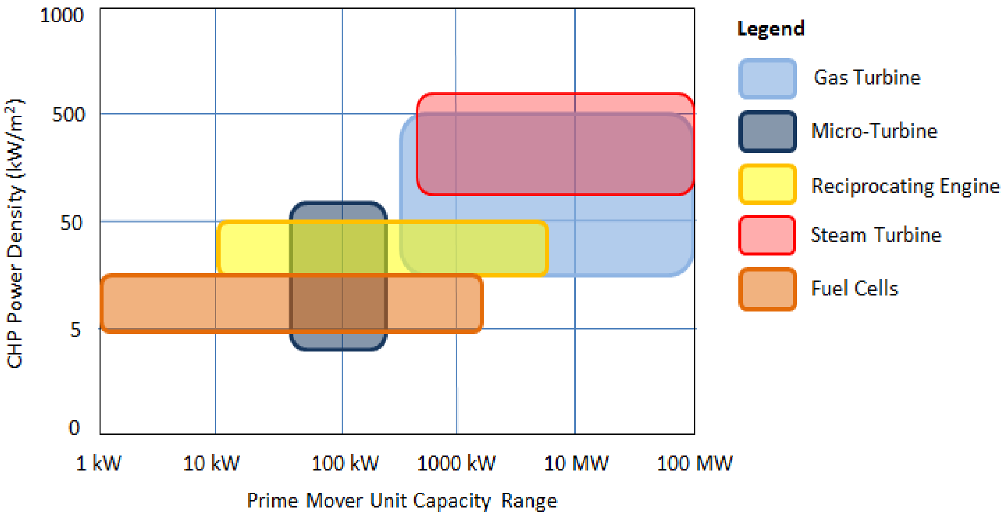
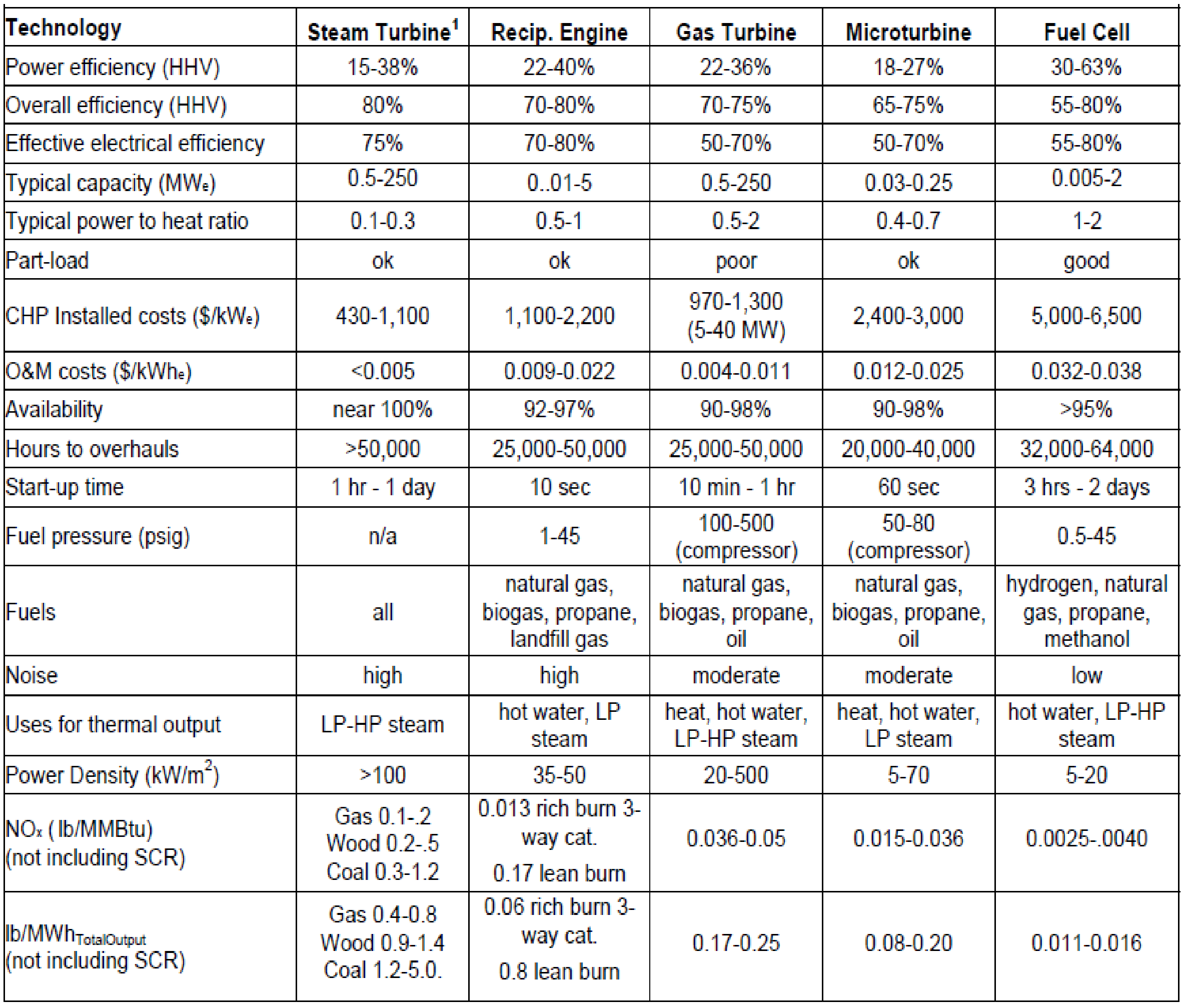


Figure-3 Prime Mover Capacity vs. Cogeneration Power Density

Table 1 shows the characteristic of cogeneration.

Table-1 Characteristic of Cogeneration



Technology	Steam Turbine[1]	Recip. Engine	Gas Turbine	Microturbine	Fuel Cell
Power efficiency (HHV)	15-38%	22-40%	22-36%	18-27%	30-63%
Overall efficiency (HHV)	80%	70-80%	70-75%	65-75%	55-80%
Effective electrical efficiency	75%	70-80%	50-70%	50-70%	55-80%
Typical capacity (MW$_e$)	0.5-250	0..01-5	0.5-250	0.03-0.25	0.005-2
Typical power to heat ratio	0.1-0.3	0.5-1	0.5-2	0.4-0.7	1-2
Part-load	ok	ok	poor	ok	good
CHP Installed costs ($/kW$_e$)	430-1,100	1,100-2,200	970-1,300 (5-40 MW)	2,400-3,000	5,000-6,500
O&M costs ($/kWh$_e$)	<0.005	0.009-0.022	0.004-0.011	0.012-0.025	0.032-0.038
Availability	near 100%	92-97%	90-98%	90-98%	>95%
Hours to overhauls	>50,000	25,000-50,000	25,000-50,000	20,000-40,000	32,000-64,000
Start-up time	1 hr - 1 day	10 sec	10 min - 1 hr	60 sec	3 hrs - 2 days
Fuel pressure (psig)	n/a	1-45	100-500 (compressor)	50-80 (compressor)	0.5-45
Fuels	all	natural gas, biogas, propane, landfill gas	natural gas, biogas, propane, oil	natural gas, biogas, propane, oil	hydrogen, natural gas, propane, methanol
Noise	high	high	moderate	moderate	low
Uses for thermal output	LP-HP steam	hot water, LP steam	heat, hot water, LP-HP steam	heat, hot water, LP steam	hot water, LP-HP steam
Power Density (kW/m^2)	>100	35-50	20-500	5-70	5-20
NO$_x$ (lb/MMBtu) (not including SCR)	Gas 0.1-.2 Wood 0.2-.5 Coal 0.3-1.2	0.013 rich burn 3-way cat. 0.17 lean burn	0.036-0.05	0.015-0.036	0.0025-.0040
lb/MWh$_{TotalOutput}$ (not including SCR)	Gas 0.4-0.8 Wood 0.9-1.4 Coal 1.2-5.0.	0.06 rich burn 3-way cat. 0.8 lean burn	0.17-0.25	0.08-0.20	0.011-0.016

(EPA (Environmental Protection Agency (U.A, 2011, “COGENERATION”, Access to http://www.epa.gov/cogeneration/) * Data are illustrative values for typically available systems; All costs are in 2007$)

2.2.4 Cogeneration Applications

Generally, cogeneration applications are classified with reference to three energy sectors: utility, industrial, and residential and commercial sectors. Thermal power plants can be planned and constructed to a cogeneration system supplying their wasted heat to nearby neighbors where the energy for process, heating, and cooling purpose are needed. In this utility application, the distance between thermal power plant and end-user and their dispersion would be of critical issues for technical and economical points of view. In addition, the thermal ratio to power will be an important factor to be considered because this ratio can impact on the operation of thermal power plant. Two possible application of cogeneration in utility sector are gas turbine combined power plant and landfills plant which are located nearby cities. Various kinds of energy are needed in many industrial sectors depending on their purposes of process, heating and cooling. The main industrial are food and beverage, textile, pulp and paper, aluminum product, chemicals, petroleum refineries, and cement. A cogeneration application is important to the industrial sectors because of high energy consumption users. In residential and commercial sectors, a cogeneration system is important because this sector can utilize both electricity and thermal energy for long period of time. The main buildings are hotels, hospitals, office, schools, shopping centers, restaurants, and households and apartment.

Table 2 represents Canadian cogeneration capacity in industrial by region, 2011 year. [10]

Table-2 Canadian Cogeneration by Region and Type

Region	Industrial		Commercial		Resident/Utility		Total	
	kW	%	kW	%	kW	%	kW	%
Alberta	748,900	27.8	31,100	40.8	955,238	51.4	1,735,238	37.5
British Columbia	806,500	30.0	40,889	53.7	94,013	5.1	941,402	20.3
Manitoba	22,000	0.8		0.0	22,900	1.2	44,900	1.0
New Brunswick	124,500	4.6		0.0	52,745	2.8	177,245	3.8
Newfoundland	17,500	0.7		0.0	-	0.0	17,500	0.4
Nova Scotia	64,031	2.4		0.0	1,820	0.1	65,851	1.4
Ontario	632,517	23.5	3,400	4.5	221,990	11.9	857,907	18.5
Unspecified	28,600	1.1		0.0	39,822	2.1	68,422	1.5
Quebec	192,000	7.1		0.0	100,000	5.4	292,000	6.3
Saskatchewan	55,225	2.1	800	1.1	370,620	19.9	426,645	9.2
Canada	2,691,773	100.0	76,189	100.0	1,859,148	100.0	4,627,110	100.0

In 2011, the total cogeneration capacity in Canada is about 4,627 MW. The capacity in Ontario is about 857 MW,18.5% of the total which is lower ratio than that in Alberta, 37.5% and that in British Columbia, 20.3%.

Ontario government has a target to install a total of 1,000 MW up to 2030. Ontario Power Authority (OPA) will precede individual negotiations for large projects and a new standard offer program for smaller projects under 20 MW in specific locations. [11]

2.3 TRNSYS Simulation Software

2.3.1 Introduction

For modeling cogeneration system in Smart Energy Networks and system simulation, TRNSYS (**Tr**ansient-**Sy**stem-**S**imulation) software is used broadly in this thesis. TRNSYS is a transient simulation software which is developed based on component based architecture by the University of Wisconsin's Solar Energy Lab in 1970s and many components have been further developed by several research contributors such as DLR (German Aerospace Centre), Sun Lab/SANDIA (USA) and IVTAN (Institute for High Temperatures of the Russian Academy of Science, Russia). The language used in this program is basically FORTRAN, which calls subroutines to implement each modeled component. TRNSYS is iterative process which runs until the convergence tolerance is met with set value. [18]

TRNSYS has several internal and external libraries of components for extensively applications. The components include controllers, electrical, ground heat pump (TESS: Thermal Energy System Specialist), green building library (TESS), heat exchangers, HVAC, hydrogen systems, hydronics, loads and structures, optimization library, physical phenomena, solar library (TESS), solar thermal collectors, STEC library, thermal storage, utility, cogeneration system, and weather data. The user can also develop new components with FOTRAN or C languages, which calls without interrupting the source code of any native component. In addition, TRNSYS can use various external simulation packages such as Excel, Matlab, Fluent, and EES by liking them to components.

For simulating the developed model, weather data components in TRNSYS is used, which can read a TMY2 file (Typical Meteorological Year). TMY2 data, which is derived from data collected from 1961 to 1990, in 2,238 locations, U.S is provided by the National Renewable Energy Lab (NREL) and that in 12 locations, Canada [1] is prepared by CWEC (Canadian Weather for Energy Calculations) with WYEC2 format.

This TRNSYS simulation package has been used for more than 30 years for HVAC system analysis and sizing, multi-zone airflow analyses, electric power simulation, solar design, building thermal performance, analysis of control schemes, etc. [12] TRNSYS is flexible tools for modeling a variety of energy systems in differing levels of complexity because of its modular approach. TRNSYS 17 was released in July 2010 and current release is 17.01.0019.

2.3.2 Structures

The TRNSYS program has a graphical interface to drag and drop components for creating input files in main program of Simulation Studio. It can connect several tools such as TRNBuild that is a tool for easily creating a building input file, IISiBat that is a graphical front-end for TRNSYS, PREBID that is a graphic tool for entering building information, TRNSED that is a utility to share simulations with non-user, SimCad that is a CAD tool for building simulation. Figure 4 shows the TRNSYS and its utilities.

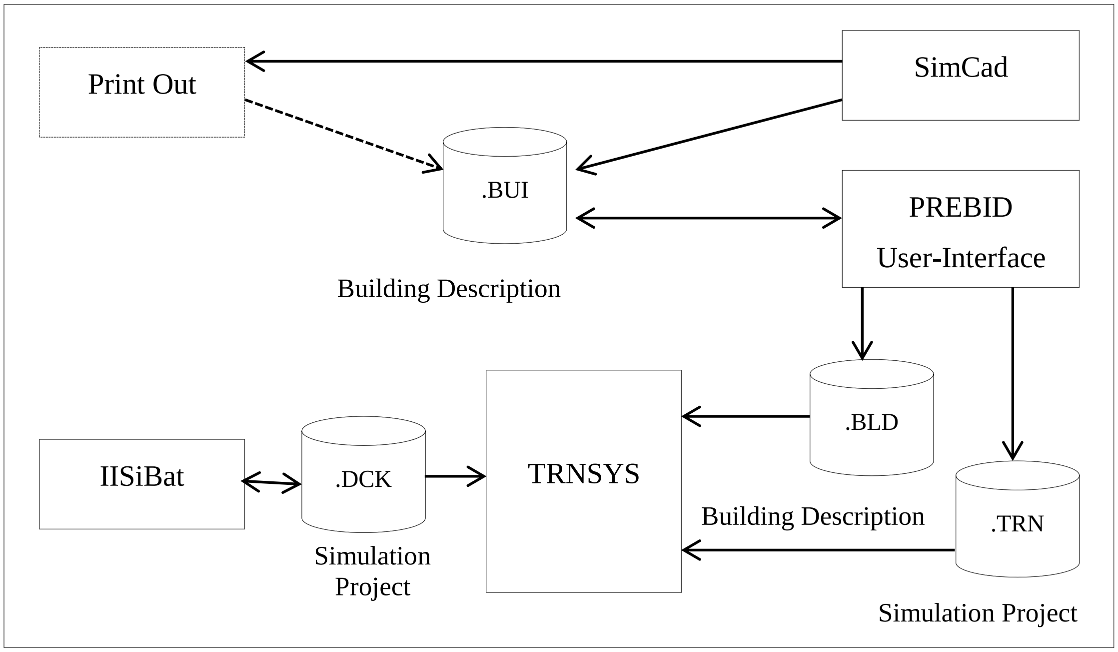


Figure-4 TRNSYS Program and Its Utilities

2.3.3 Solvers

The TRNSYS use a successive substitution as a solver. The algorithm is that the outputs for each unit in the first step are calculated for the given inputs and the outputs are passed as inputs to other units. In the next step, the first is repeated as long as the system does not converge to the set value. Powell's method is also used in TRNSYS. It generates a matrix using input and output connections and solves the input and output matrix of simultaneous equation.

Chapter 3

SMART ENERGY NETWORKS CONCEPT

3.1 Motivations behind Smarter Energy Solutions

As mentioned earlier, using energy resources ‘smarter’, together with developing renewable ones, has drawn much effort from the following stakeholders for addressing the challenges in global energy security, climate change and economic growth:

- Energy Consumers including residential, commercial, and industrial
- Vendors including equipment, technology, service, and construction companies
- Utilities including power generation plants, power marketers, natural gas suppliers, natural gas distributors, natural gas marketers, and independent power providers (IPP)
- Governments including federal, provincial and municipal levels
- Advocacies including RD&D, environmental and associations

Through implementing Smart Energy Networks (SEN), basically, a two-way real-time communication network can be constructed between the energy suppliers and Consumers. The Smart Grid and distributed renewable energy supply can be integrated and a new business platform will be created. Under this new network the stakeholders can have a variety of benefits from providing a more sustainable energy supply and generating new revenues. The following sections list three major technical goals in order to develop clean, affordable, sustainable and economical energy supply.

3.1.1 Government

Government’s goals regarding environment protection and energy supply as follows:

Greenhouse Gas Emissions Reduction Goals:

The Government of Canada has committed to reduce greenhouse gas (GHG) by providing business programs and policies, conducting RD&D and co-operating with provinces, territories and international organizations. Canada signed the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol in 1992 and 1998, respectively. When the amount of GHG emitted in 1990 (592 megatonnes of CO2 equivalent or Mt CO2 eq. [13]) is used as the base line, in 2008 Canadians emitted GHG of about 734 Mt CO2 eq. [13] to the atmosphere, which is 24.1% above the 1990 level and 31.5% above the Kyoto Protocol target [13].

Increasing Energy Demands:

According to National Energy Board Canada data [16] , the total energy demand is expected to increase by 11% (1,159 Peta-Joules1) in 2020 compared to 2010 level. In the case of Ontario, the total energy demand in 2020 is expected to increase by 12.6 % (391Peta-Joules) compared to 2010 level. This level is about 30% of Canada's overall level. In the estimation of mid-term energy demand in 2020, it is clear that energy demand increased by 11% and 12.6% in Canada and Ontario, respectively. The Ontario government has plans for the development of energy policy to meet mid-term and long-term the energy demands.

Emerging Renewable Energy Resources and Integrating into the Grid:

The Ontario Power Authority (OPA) developed an Integrated Power System Plan (IPSP) in 2008, It is designed to support capacity and demand of energy, transmission, and the energy policy goals of Ontario government. According to IPSP [16] , in 2010, the goals of renewable energy resources were 10,402 MW in Ontario. In 2025, the goal of renewables will be 15,700 MW, an increase of approximately 51% (or 5298 MW) from 2010 level. In mid-term and long-term energy planning, the Ontario government has plans for the development of renewable energy resources of 15,700 MW, an increase of approximately 51% (or 5298 MW) from 2010 levels.

Replacing Coal Power Plants:

Coal and Nuclear Power plants are the key electricity generations covering base load of electricity. In 2010, two generators supplied about 27% of total electricity demand in Canada. In Ontario, coal power plant covered 8.3% of total electricity [17] . According to IPSP [16] , coal power plants in Ontario will be replaced by cleaner generation beyond 2014.

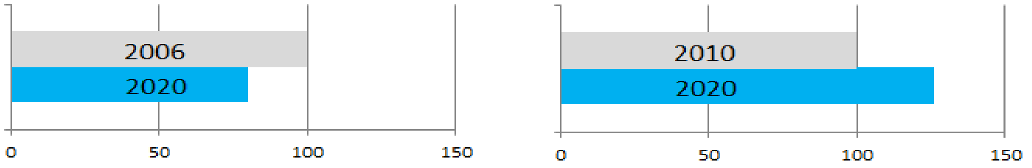
Figure 5 shows Government's goals regarding environment protection and energy supply.

3.1.2 Consumers

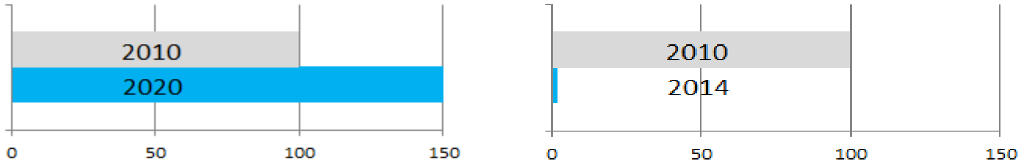
The government's motivation and the ambitious goals regarding environment protection and energy supply require a smarter energy system and active consumers' participation, which help motivate consumers to participate in SEN's implementation.

Increasing Energy Saving Cost:

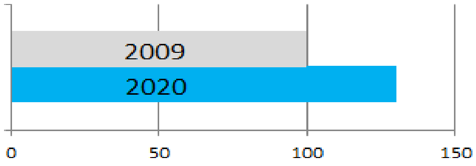
Consumers receive real-time energy price and time-of-use (TOU) tariffs information through two-way communication networks including advanced metering infrastructure (AMI). Consumers will save energy costs by using energy price information, and by using smarter appliances which can shift usage to off- peak times.



(a) GHG Emissions Reduction Goals (b) Increasing Energy Demands



(c) Emerging Renewable Energy Resources (d) Replacing Coal Power Plants



(e) Increasing natural gas demands

Figure-5 Government's goals regarding environment protection and energy supply

Increasing Reliability Energy Supply:

Consumers can install an individual high efficiency combined heat and power systems (CHP) such as photovoltaic system, fuel cell system, and micro-turbine system. Or, the energy will be supplied from Distributed Generation which locate near consumers' energy load. Consumers will secure high reliability energy supply by providing self CHP, by supplying energy from Distributed Generation, and by reducing the grid's vulnerability to unexpected hazards, power outages and the frequency of power quality disturbances.

3.1.3 Utilities

For the energy generation and distribution utilities, motivations include;

Improving System Reliability:

A new energy system which includes Distributed Generation, self-healing systems, and real time information on networks will reduce uncertainty and enable the system to secure high reliability.

Reducing Energy Production Cost:

New energy system networks, which provide real time information on consumers' demand and its pattern, enable utility operators to forecast the load and its pattern (i.e. off peak or on peak demand), which can produce energy with low cost and supply to consumers.

Participating New Energy Businesses:

Introducing Distributed Generation[3] and emerging renewable[4] energy into the energy sectors can provide opportunities for utilities to participate in the new businesses.

3.1.4 Gas Industry

A smart energy network provides an opportunity for the gas industry to expand its scope of services to customers by integrating with the electricity network and to enable great use of intermittent renewable energy resources within the system.

Increasing Electrification:

In Smart Grid systems, intelligent appliances, heat pumps and electric vehicles (EV) communicating with the grid can be charged over-night at the cheapest times depending on consumers' preferences while providing the same level of service. In addition, the gas for transportation is the main cause of greenhouse gas emissions in Ontario. And, electrification of transportation is a new development in Ontario and globally. The more Smart Grids are implemented, the more electrification is extended.

Replacing Coal Power Plants:

The contribution of capacity and energy production by coal power plants in Ontario, 4,400 MW, is planned to be replaced by gas fired generation (GFG) by 2014.

Increasing Distributed Generation:

According to the Ontario government energy plan, Distributed Generation connecting to the grid will be increased. Distributed Generation type will be dispatchable[5] generation or non-dispatchable renewable energy connecting electricity storage systems and/or dispatchable generations.

Increasing Renewable Energy:

Some renewables such as wind energy conversion systems and photovoltaic systems are producing intermittent or variable electricity. Renewables cannot produce consistent electricity and are not

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[3] "Distributed Generation is the use of small-scale power generation located close to the load being served, capable of lowering costs, improving reliability, reducing emissions and expanding energy options."

[4] "Energy resources that are naturally replenishing but flow-limited. They are virtually inexhaustible in duration but limited in the amount of energy that is available per unit of time. Renewable energy resources include: biomass, hydro, geothermal, solar, wind, ocean thermal, wave action, and tidal action."EIA (Energy information agency, DOE, U.S)

[5] Dispatchable, meaning it can generate more or less power on-demand or on a human-defined schedule.

dispatchable. When the intermittent renewable resources have a period of low production, dispatchable generation like gas turbine power plants are often operated simultaneously in order to ensure that demand is met.

Developing Natural Gas Fuel Cell Technology:

Hydrogen technology has been developing to produce hydrogen gas from renewable energy resources. Natural gas fuel cell systems will be the best bridge technology to a hydrogen-powered system. Meeting the diverse and complex challenges and the target to be reached requires a smarter energy system concept in the energy supply structure, platform, and policy. And, the wider systematic energy network concept integrating all motivation is particularly important as it can enables all stakeholders which comprise government, utilities, operators, Consumers, and energy markets to effectively co-ordinate demand/supply and generation of energy. The concept of smarter energy system aims at maximizing efficiency, reliability and energy security, and reducing cost, investment, and environmental impacts. Furthermore, the smarter energy system, which will be a new paradigm of energy supply structure, platform, and policy, which motivates stakeholders to positively participate in deploying the system.

3.2 Approaching Smart Energy Network Concept

3.2.1 Comprehensive Concept of Smarter Energy Solutions

Even though the definition of the Smart Grid, its characteristics, and its implementations have been extended to a variety energy sectors, a more comprehensive concept is required to actually cope with the challenges and to effectively reach the goals.

Need for Diverse Energy and its Infrastructure:

Smart Grid concept is focusing on electrical system and its components such as smart meters, in which the other energy resources could not be actually incorporated. Renewable energy with high technology and competitiveness has been emerging into the energy sectors. In addition, renewable energy research and development, and its communization have been sharply progressed. Diverse energy resources and networks must be targeted and included in a new smarter energy infrastructure networks as follows:

- Natural gas and its infrastructure
- District heating and cooling networks

- Hydrogen system and its infrastructure
- Biomass resources and Bioenergy system

Need for Consumers’ High Efficiency Energy Systems:

Distributed Generation is one of the key elements in the Smart Grid. However, the Distributed Generation have several limitations to grid connection. The Distributed Generation concept must be extended to Consumers’ field and Consumers’ high efficiency energy systems should be integrated into a smarter energy system in order to increase energy security and flexibility and to drive Consumers to positively participate in a smarter energy system. The main Distributed Generation include as follows:

- Cogeneration system (or called CHP: Combined Heat and Power)
- Micro-turbine CHP
- Fuel cell CHP
- Gas heat pump system

Need for All Stakeholders Active Perception:

Practically, each country’s initiative to implement Smart Grid differs because it has been aiming at national goals focusing on the grid and electrical system and the implementation has been led by national organizations in which no all stakeholders’ active participation could not be expected. Therefore, stakeholder’s active participation is a vital initiative in a smarter energy system as follows:

- Consumers: residential, commercial, and industrial
- Vendors: equipment, technology, service, construction
- Utilities: power generators, power marketers, natural gas (NG) suppliers, NG distributors, NG marketers, independent power providers (IPP)
- Governments: federal, provincial, and local
- Advocacy: R &D, environmental, associations

Need for Manageable Implementation with Full Functionality:

Generally, the demonstration projects of the Smart Grid are significantly huge in size, complex to handle, and partial deployment. Therefore, more effective manageable models with full functionality for all stakeholders must be identified and provided as follows:

- For Consumers: residential, commercial, and industrial Consumers
- For community
- For municipality or city

- For region or province

Table 3 illustrates comparison of basic concepts between the Smart Grid and a more comprehensive system.

Table-3 Comparison Smart Grid vs. a more Comprehensive System

Description	Smart Grid General Concept	A More Comprehensive Concept (Smart Energy Network)
Main Energy System Networks	Single network	Triple networks
	• Grid network	• Grid network + • Natural Gas network + • District Heat and Cooling network
Main Targets	Electricity	Electricity, Natural Gas, Heating, and Cooling
	• Grid and Electrical Components	• Grid and Electrical Components • Natural gas and its Infrastructure • District heating and cooling network • Hydrogen and its infrastructure • Biomass and Bioenergy system
Main Components	Electricity and DG	Electricity and High Efficiency Systems
	• Electrical System • Distributed Generation (DG) connecting to the grid • Communication and Information Technology	• Electrical System • Distributed Generation (DG) connecting to the grid • Communication and Information Technology • Cogeneration (or called CHP) • Micro-turbine CHP • Fuel cell CHP • Gas heat pump system
Stakeholder Participation	Government leading	All Stakeholders Active Participation
	• Governments: federal, provincial, and local • Advocacy: R &D, Environmental, Associations • Vendors: equipment, technology, service, construction	• Consumers: residential, commercial, and industrial Consumers • Vendors: equipment, technology, service, construction • Utilities: power generators, power marketers, natural gas (NG) suppliers, NG distributors, NG marketers, independent power providers (IPP) • Governments: federal, provincial, and local • Advocacy: R &D, environmental, Associations
Initiatives	Large scale Implementations	Effective Manageable Implementations
	• Modernizing grid • Electrical Components Application • Partial implementations	• Full functionality of Smart Energy Network • Models ranges from Consumers to Province

3.2.2 Approaching Smart Energy Networks Concept

A comprehensive concept for defining Smarter Energy Networks has been conducted beyond the scope of the Smart Grid concept. For this development available energy sources (renewables and nature gas) are integrated, stakeholders' active participations are included and effective management models are considered.

Distinct from the concept of Smart Grids, their initiatives, functionalities and demonstrations which have been focused on electricity and related components, a comprehensive concept is needed for identifying the integrated energy system (or network) which covers all available energy resources such as natural gas, possible renewables, higher efficiency systems such as CHP (Combined Heat and Power), novel technologies for residential use such as fuel cell systems, and so on. The following factors have been considered to construct the comprehensive concept, but not limited to:

- Available energy resources in Ontario
- Natural gas resource, its supply and distribution
- All Distributed Generation including renewable resources
- Higher efficiency systems such as CHP added as Distributed Generation
- Stakeholders' active participations from Consumers, utilities, vendors, advocacy, provincial government, federal government, and inter-provincial organizations.
- Effective management models considering the different levels from individual Consumers, community, municipality, regional, provincial, and federal.

The comprehensive concept of SEN enables energy generators, network operators, consumers, and energy markets to co-ordinate the demand/supply and generation of energy. This new concept aims at maximizing the efficiency, providing the reliability and energy security, and reducing costs and investment and addressing environmental impacts. Following the development of Smart Grids, the key themes for capturing the concept, implementation and demonstration of a SEN can be described as

- Energy: electricity*, natural gas, and thermal energy (i.e., district heating and cooling)
- Renewable resources and renewable energy utilization for residential usage
- Natural gas energy resources
- Natural supply and distribution

- Natural gas energy application systems
- High energy efficiency systems including the combined heat and power (CHP)
- Optimum combination of energy distribution and generation
- Stakeholders and their participation
- Effective management models
- Integration, two-way communications, and automation*
- Integration and interoperability
- Sustainable reliability, security, and efficiency of the energy systems*
- Growing renewables, energy storage, and smart appliances*
- Complete energy infrastructure
- Energy supply, demand, and its related business platforms

Note that the aforementioned items which are indicated with * are the same as ones defined in the Smart Grid. Based on these key themes, the characteristics of the comprehensive concept of the SEN can be stated as:

- Enabling the optimum integration of renewables, electricity and natural gas energy supply, distribution and utilization systems
- Providing a high efficient energy generation and distribution
- Enabling the highly secure and reliable energy systems
- Enabling stakeholders to participate in energy projects
- Enabling stakeholders to play an important role in implementing smarter energy system's concept
- Enabling and motivating the active participation by Consumers*
- Accommodating various energy generation and storage options *
- Enabling new businesses: Products, Services, and Markets*
- Providing the quality of power supply for the digital economy: Information, Communication & Control*
- Optimizing the asset utilization and efficiently operating the individual systems*
- Anticipating and responding to system disturbances by means of the self-healing system*
- Operating resiliently against attacks and natural disasters*

To address these key themes and the characteristics, the concept of SEN has been developed through identifying energy, environmental and economic targets and objectives of the project, and investigating the available models. Ultimately, the targeted energy generation resources include grid (electricity network), natural gas pipelines and natural gas firing/co-firing applications, distributed power generation and district heating/cooling networks. The overall objectives are to improve reliability, security, and efficiency of energy supply, distribution and utilization in a specified region. Consequently with the implementation of the SEN, greenhouse gas (GHG) can be reduced and energy can be conserved. The realization of those objectives is achieved by integrating all related components in the system and real-time monitoring and optimization of the energy supply and utilization by means of the communication and information technology (CIT). In addition, the interoperability of all components has been considered. Figure 6 illustrates approaches used for developing the SEN concept.

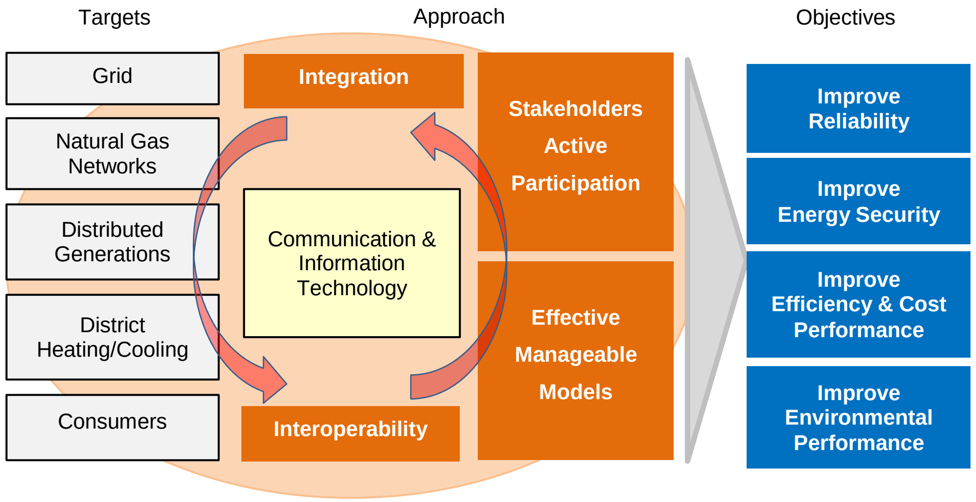


Figure-6 Approach to Smart Energy Networks Concept

3.2.3 Expectations

In developing the SEN concept, stakeholders have been classified as:

- Consumers including residential, commercial and industrial
- Vendors including equipment, technology, service and construction
- Utilities including power generators, power marketers, natural gas suppliers, natural gas distributors, natural gas marketers and independent power providers (IPP)

- Governments including federal, provincial and local government
- Advocacies including RD&D, environmental and associations

Through implementing SEN, basically a two-way real-time communication network is constructed between suppliers and Consumers. A distributed renewable energy supply structure is set up and a new business platform is created which combines the energy technology and new service. Under the new paradigm of energy and business, the stakeholders can have a variety of benefits from implementing the SEN.

Consumers:

- Energy cost saving: Consumers receive real-time energy pricing and time-of-use (TOU) pricing information through the two-way communication network including AMI (Advanced Metering Infrastructure). Consumers will save energy costs by using energy price information and by using smarter appliances which can shift usage to non-peak time.
- Low cost energy supplied: Distributed Generation can reduce cost of energy supply to consumers by providing renewable energy resources and combing with high efficiency system such as combined heat and power (CHP) and district heating and cooling systems, located near the consumers' load.
- Reliability and security: consumers can provide high efficiency self-CHP such as a photovoltaic system, fuel cell system, and micro-turbine system. Or, the energy can be supplied from Distributed Generation located near the Consumers' energy load. Therefore, supplying energy to customers can be secure and reliable by reducing the grid's vulnerability to unexpected hazards, power outages and the frequency of power quality disturbances.
- Revenues: Consumers can get earnings by reselling excess energy produced from self-CHP and the electricity charged in PEV to the grid.

Vendors:

- Business promotion and new business development: Vendors will provide equipment, technology, energy management services, repair and maintenance services and construction in new a SEN market.

Utilities:

- Direct cost savings: Real time information on networks and Consumers will save direct cost from lower field operators operation, lower meter readings and on-line billing service.

- Asset utilization improvement: Real time information on Consumers’ demand and its pattern will enable operators to provide efficient planning and maintenance of the system, which improves asset utilization.
- System reliability improvement: Distributed Generation, self-healing system, and real time information on networks will reduce uncertainty risks and enable the system to secure high reliability.
- Low energy production cost: Distributed Generation, high efficiency systems, and real time information on Consumers’ demand and its pattern enable operators to forecast the load and its pattern, which will produce energy with low cost and supply to Consumers.

Governments:

- Energy system reliability improvement: SEN will improve energy system reliability by reducing the grid’s vulnerability to unexpected hazards, power outages and the frequency of power quality disturbances through networks atomization and self-healing systems.
- Energy efficiency improvement: SEN will improve energy efficiency and economy by shifting peak load through the interaction of Consumers’ demand with the supply, and by reducing energy losses and leakages through real time information on networks.
- Energy security improvement: SEN will improve energy security by reducing foreign oil consumption and by providing energy resources’ flexibility including renewable energy.
- Economic improvement: Through new investment and job creations, economics will be improved.
- Greenhouse gas emissions reduction: Through integrating high efficiency system and renewable energy resources, and reducing energy losses, greenhouse gas emissions will be reduced.

Table 4 illustrates stakeholders and expectations by implementing SEN.

Table-4 Stakeholders and Smart Energy Network Expectations

Stakeholders	Expectations
• **Consumers**: Residential, Commercial, Industrial Consumers • **Vendors**: Equipment, Technology, Service, Construction • **Utilities**: Power generators, Power marketers, Natural gas suppliers, Natural gas distributors, Natural gas marketers, Independent power Providers (IPP) • **Governmen**ts: Federal, Provincial, Local • **Advocacy**: R &D, Environmental, Associations	• Energy cost savings • Low energy price supplied • Reliability securing • Earnings by reselling excess energy • Business improvement • New business development • Direct cost savings • Asset utilization improvement • System reliability improvement • Low energy production cost • Energy system reliability improvement • Energy efficiency improvement • Energy security improvement • Greenhouse gas emissions reduction

3.3 Modeling of Smart Energy Networks (SNE)

3.3.1 Identification of System Clusters

When developing the conceptual model of SEN, the concepts of Model, Cluster, and Elements are identified. A Model is a representation, generally in idea, concept or miniature, to show the construction or appearance of a SEN.

A Model normally contains several Clusters which are composed of elements such as equipment, components, devices and computer systems. Elements have the capacity to generate, store and transfer energy. For example, in the Cluster of power generation, the electrical power plant itself can be one of the Elements. Clusters are the groups of elements which serve the same or similar functions and are gathered together. Clusters have not a physical but only an imaginary boundary. Generally, Elements in the same Cluster have similar objectives. For example in the Cluster of power generation, the Element of the nuclear power plant and another Element of the hydro power plant are located in the same Cluster since they have the same objectives. The Interfaces are the points of access between

Clusters for exchanging information. Interfaces in this report represent not physical but communications or electronic connections. The physical power grid and natural gas pipelines, and electronic and telecommunication cables are connected among different Clusters. The SEN model represents an overall concept which identifies Clusters, Elements, and possible communication paths. Specifically speaking, Clusters are first identified to address the themes and characteristics of the SEN. Basically this step of processing Cluster identification is benchmarked with that of the Smart Grid and has been further developed to meet the requirements of the SEN.

The Clusters are eventually classified into ten modules; Bulk Power Generation, Power Transmission, Power Distribution, Distributed Generation, Customers, NG Transmission, NG Distribution, Markets, Operators, and Service Providers. The following figure shows the structure of the model containing Elements and Clusters. The following sections will introduce key Clusters used to the model.

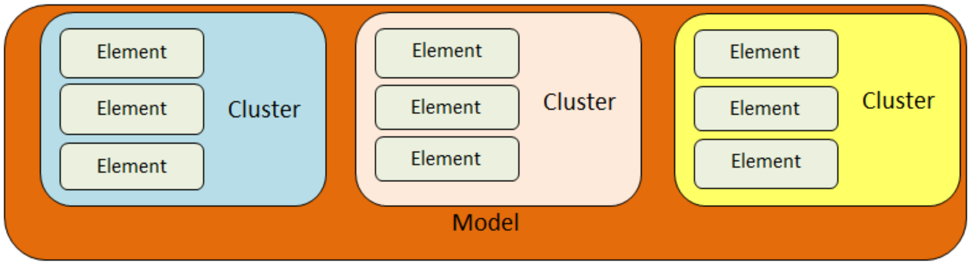
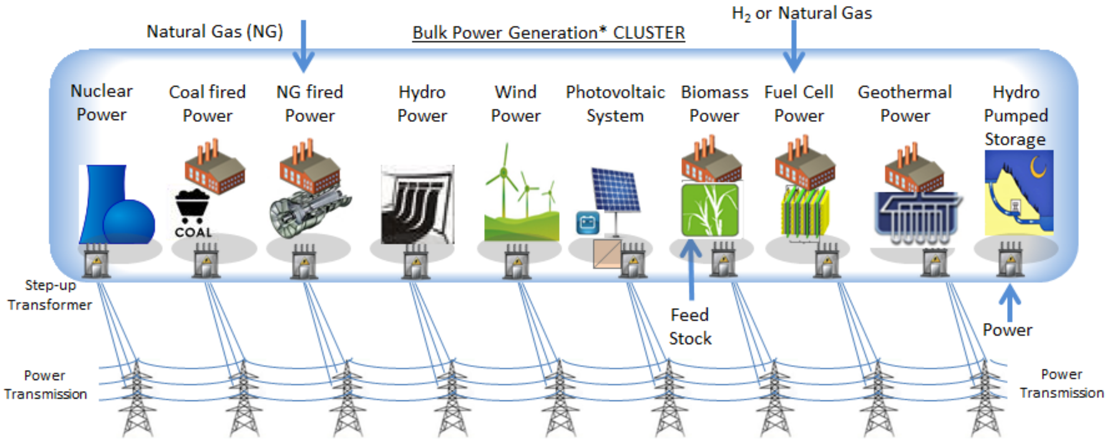


Figure-7 Elements, Clusters and Model

The Cluster of Bulk Power Generation:

This Cluster may consist of facilities designed to produce electric energy from other forms of energy (such as renewables, coal and nature gas). The actors in this Cluster are generators. Generally, the facilities are divided into two types. The first type is non-renewables consisting of fossil fuels and nuclear fission power generators and the other is renewables** consisting of hydro power, wind power, solar radiation, photovoltaic cell, biomass, geothermal, and fuel cells power generators, hydro pumped storage system. Normally, the facilities in this Cluster cover large-scale generations. [19][20] Figure 8 illustrates the elements for the Cluster of Bulk Power Generation.



* The starred domains are similar to Smart Grid, but include additional energy sources such as Natural Gas and Thermal.
**Renewable fuels defined as: Fuels that are substantially non-petroleum and yield energy security and environmental benefits. Energy Policy Act of 1992

Figure-8 Bulk Power Generation Cluster

The Cluster of Power Transmission:

This Cluster consists of facilities to transmit electrical power generated from the Cluster of Bulk Power Generation to the Cluster of Power Distribution through multiple substations (elements) in this Cluster. The actors may include remote terminal units, substation meters, protection relays, power quality monitors, phase measurement units, sag monitors, fault recorders, substation user interfaces, and electric storage system. This Cluster is electrically connected to the Clusters of Bulk Power Generation and Power Distribution and communicating with the Cluster of Markets and Operators as well. [19][20] Figure 9 illustrates the Cluster of Power Transmission.

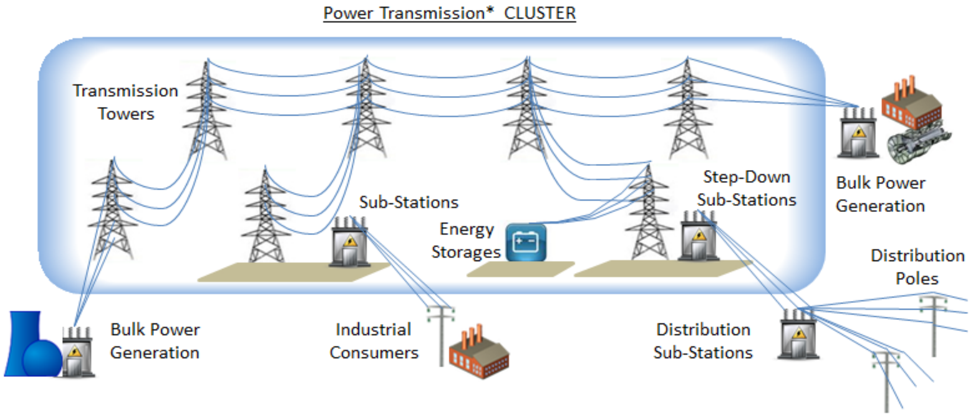


Figure-9 Power Transmission Cluster

The Cluster of Power Distribution:

This Cluster consists of facilities to distribute electrical power transmitted from the Cluster of Power Transmission to the Cluster of Consumers through multiple distribution substations (elements) in this Cluster. The actors may include substations, distribution feeder circuits, switches, protective equipment, primary circuits, distribution transformers, sectionalizes, and recloses. This Cluster is electrically connected to the Clusters of Power Transmission and Consumers at the metering points for monitoring energy consumption. It communicates with the Cluster of Markets and Operators as well. [19][20] Figure 10 illustrates the Cluster of Power Transmission.

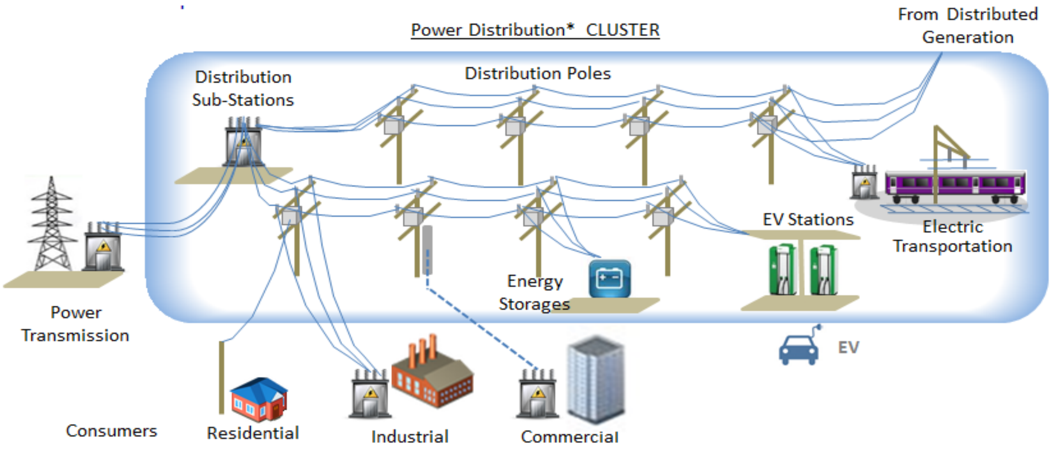


Figure-10 Power Distribution Cluster

The Cluster of Distributed Generation:

This Cluster consists of facilities to distribute electrical power transmitted from the Cluster of Power Transmission to the Cluster of Consumers through multiple distribution substations (elements) in this Cluster. The actors may include substations, distribution feeder circuits, switches, protective equipment, primary circuits, distribution transformers, sectionalizes, and recloses. This Cluster is electrically connected to the Clusters of Power Transmission and the Consumers at the metering points for monitoring energy consumption. It communicates with the Cluster of Markets and Operators as well. [19][20] Figure 11 illustrates the Cluster of Power Transmission.

The matrix of Distributed Generation technology and energy resources is in Appendix A.

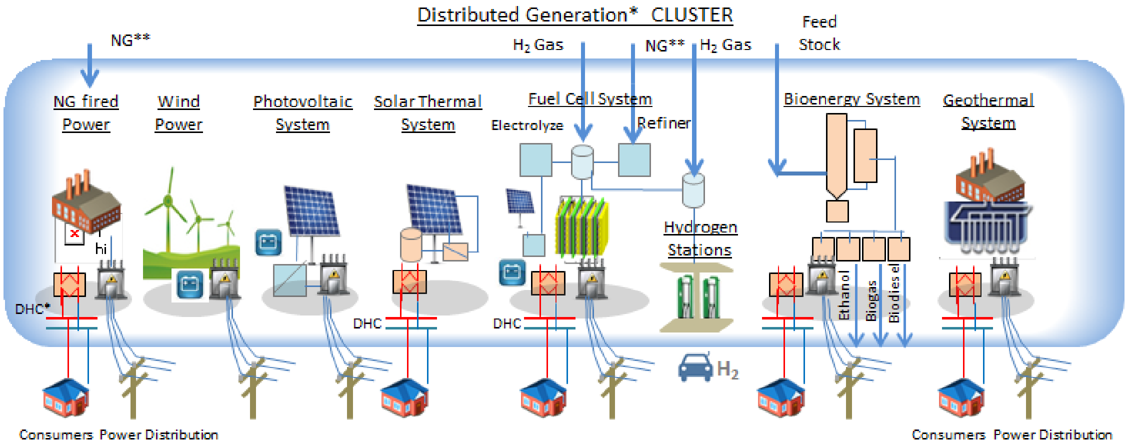


Figure-11 Distributed Generation Cluster

The Cluster of Consumers:

This Cluster is ultimately the end-users of various energy forms such as electricity, natural gas and heating/cooling energy. This Cluster consists of mainly three types of customers: Residential, Commercial, & Industrial. Typically, Consumers are classified by the amount of electricity demand. Residential is set at less than 20kW, commercial 20kW-200kW, and Industrial over 200kW. Consumers may have energy generation similar to the systems of Distributed Generation, but for residential usage. The actors in this Cluster enable Consumers to manage their energy generation, usage, and sales. Some actors provide monitoring, control, and information flows between the Consumers and other Clusters. This Cluster may electrically or thermally connect to the Clusters of Power Distributed and Distributed Generation. [19][20] Figure 12 illustrates the Cluster of Consumers.

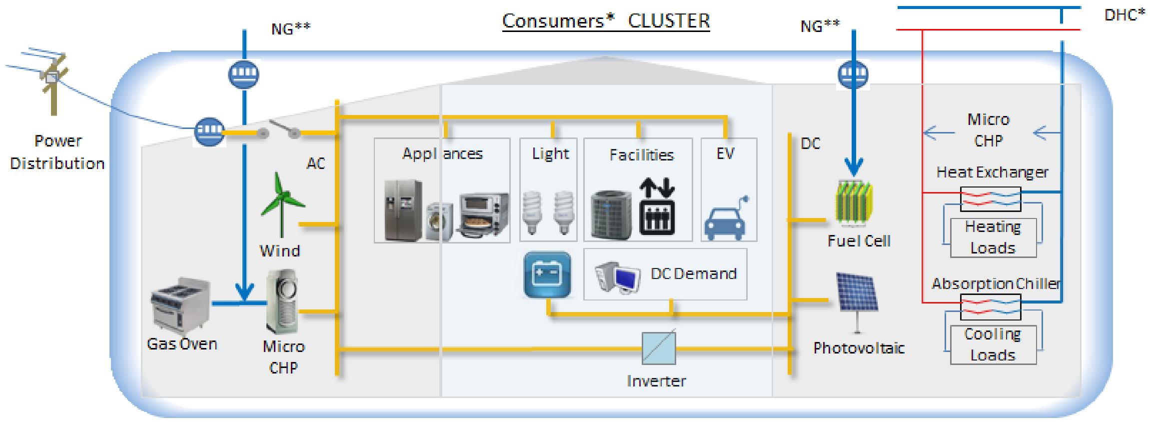
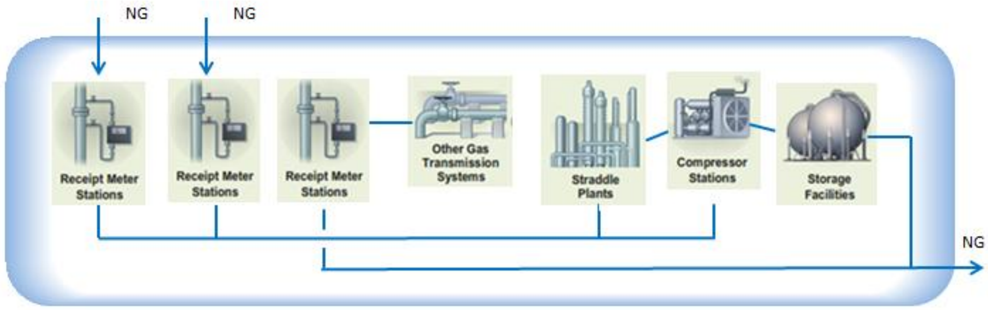


Figure-12 Consumers Cluster

The Cluster of Natural Gas Transmission:

According to literature, “Natural gas transmission is the transport (usually by pipelines) of natural gas at high pressure from producing areas to consuming areas. Natural gas storage is the accumulation of natural gas in caverns, spheres or in a liquefied state at facilities usually located close to consuming areas for use in servicing peak demands.” [21] This Cluster may include, receipt meter stations, sales meter stations, storage sites, transmission farm taps, transmission pipelines, transmission stations, booster stations, border meter stations, control valve stations and block valve stations. Figure 13 illustrates the Cluster of Natural Gas Transmission.

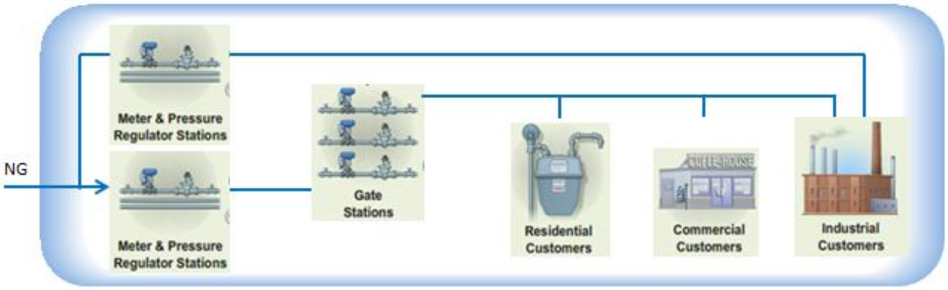


(Sources: Oil & Gas Industry Overview, http://www.ontime.methanetomarkets.org/m2mtool/index.html)

Figure-13 Natural Gas Transmission Cluster

Natural Gas Distribution Cluster:

The Natural Gas Distribution Cluster is a “cross-linked grid of medium pressure gas and low pressure customer service lines, grouped in customer supply sectors where the pressure of each sectors is individually controlled by at least two District Regulator Stations with every customer having supply from at least two directions and customer closest to the lowest pressure (Low Pressure Point) having sufficient gas pressure to meet demand.” [21] Figure 14 illustrates the Cluster of Natural Gas Distribution.



(Sources: Oil & Gas Industry Overview, http://www.ontime.methanetomarkets.org/m2mtool/index.html)

Figure-14 Natural Gas Distribution Cluster

The Cluster of Markets:

This Cluster typically performs pricing or balancing supply and demand within the power and natural. [18][20]

The Cluster of Operators:

This Cluster performs the ongoing management functions which are necessary for the smooth operation of the power and natural gas systems. It includes the network operation, network operation monitoring, network controlling, fault management, operation feedback analysis, operational statistics and reporting, real-time network simulation and dispatcher training. [19][20]

The Cluster of Service Providers:

This Cluster provides customers with services such as billing and customer account management. Service providers may create new and innovative services and products for the customers. [18][20]

3.3.2 The Conceptual Model of Smart Energy Networks

The aforementioned Clusters and their components are used for constructing the conceptual model of SEN. Note that the practical model can vary in its size, scale and functions. Table 5 shows the matrix of relationships between the model Clusters and the model scales.

Table-5 Conceptual Models and Applicable Clusters

Legend: ◎ Applicable ○ Partially Applicable

Applicable Clusters	Scenarios (Scale)	Individual Consumers	Community	Municipality	Region	Province
Clusters	Bulk Generation				○	◎
	Power Transmission				○	◎
	Power Distribution		◎	◎	◎	◎
	Consumers	◎	◎	◎	◎	◎
	Distributed Generation		◎	◎	◎	◎
	Natural gas Transmission			○	◎	◎
	Natural gas Distribution		◎	◎	◎	◎
	Markets				○	◎
	Operators		◎	◎	◎	◎
	Service Providers			○	○	◎
Communication and Information Technology		○	◎	◎	◎	◎

Figure 15 illustrates conceptual models at different scenarios (or scales) which are classified by the number of application Clusters.

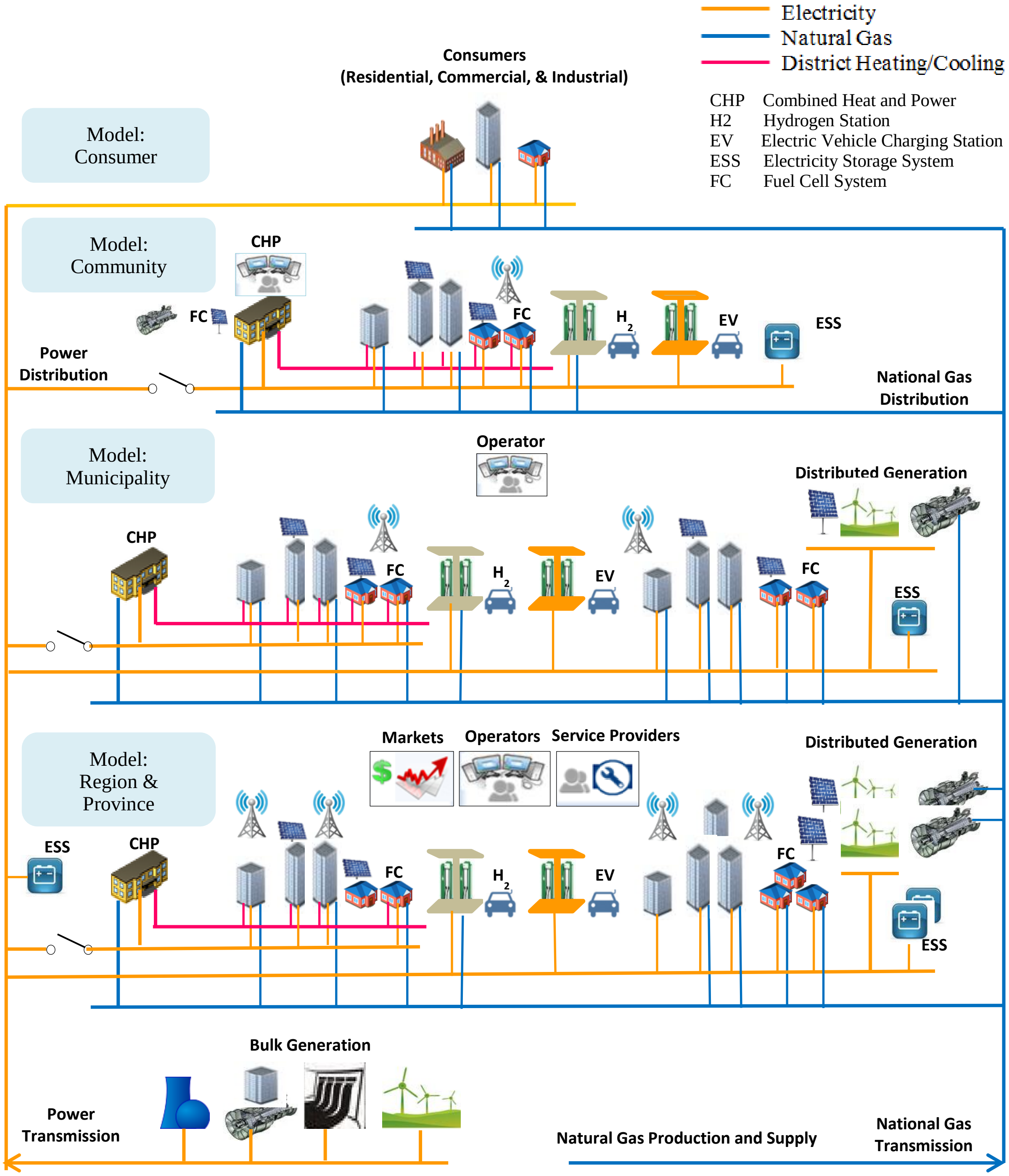


Figure-15 Conceptual Models of Smart Energy Network

In the conceptual model of SEN, energy required for Consumers and utilities are electricity, natural gas, heating, and cooling. Energy is supplied through its network system which is connected from generation to end-users.

The Clusters, which are groups of the same or similar functions or objectives gathered together, consist of bulk power generation, power transmission, power distribution, distributed generation, customers, natural gas transmission, natural gas distribution, markets, operators, and service providers. Each Cluster consists of several basic elements that are equipment, components, devices, or computer system.

A model or scenarios of SEN can be developed according to Consumers targeted, energy needed, Clusters configured, and elements selected. In this research, 5 models are configured as basic structures, which are based on scale of system from Consumers to province: models for Consumers, community, municipality, region, and province.

As a basic model, a Consumers model produces self-energy of electricity, heating, and cooling through various elements: for example, a natural gas fuel cell combined heat and power system (CHP). This model is the same as the Consumers Cluster.

The second is a community model. This model produces electricity, heating, and cooling energies in a CHP which is located near end-users. The produced energies are supplied to end-users through energy supply networks. This model can include a couple of Clusters with variety elements: for example, a Distributed Generator Cluster with a small capacity gas turbine and renewable energy hybrid CHP element. All stakeholders can actively participate in implementing this SEN model. This model includes a Consumers model.

The next is a municipality model. This model can be consisted of several Clusters with variety elements: Consumers, Distributed Generation, and Operators Clusters. The applied Clusters are interoperated and Distributed Generation are integrated into the grid. This model includes community models.

The last is regional and provincial models. This model can include all Clusters with variety elements. This model is a complete national-wide SEN system, which can be reached through gradually implementing lower level SEN models.

3.3.3 Conceptual Schematic of Communication

A two-way communication among Clusters in a SEN can be implemented by means of communication infrastructure shown in the conceptual schematics. Its scheme consists of Clusters, Control sensors, Communication infrastructure, Data integration, and Applications. Figure-16 shows the flows of information in the schematic of communication.

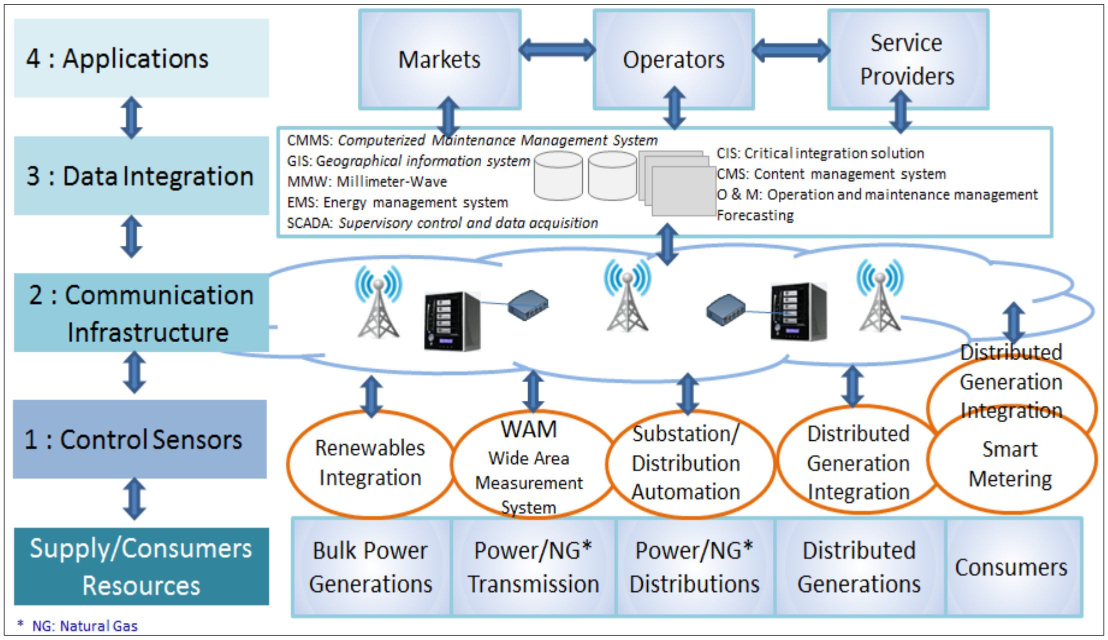


Figure 16 Conceptual Schematic of Communication

3.3.4 Definition of Smart Energy Networks

With SEN's operations, energy and the related business paradigm are shifted to a multi-integration network from the existing one-dimensional supply-to-utilization scheme. In summary, the infrastructure of energy generation and supply are expected to be two-way real-time communications while the current system is one-way. And the energy supply structure is to be a horizontal network frame while the current one is a hierarchy structure. Moreover, the energy marketing platform is changed to a combined energy supply and new business one from the current energy supply platform. Finally, evolution in both technology and business are expected.

Fully supported by its key themes, characteristics and expectations of smarter energy supply, distribution and utilization and through identifying its key elements, its communication schemes and conceptual structure, the SEN can be generally defined as follows:

A Smart Energy Network is a functional energy network system consisting of grid, natural gas and district heating pipelines, which improves reliability, security, and efficiency of the entire energy systems by enabling an optimum integration of renewables, energy storages, and effective natural gas *energy applications with bulk energy generations and through implementing the information and communication technologies for achieving online monitoring and real-time simulation.*

From the stakeholders' points of view, the definition of SEN can be simplified as

A Smart Energy Network is a general energy network system with integrated centralized and distributed energy generations and sustainable energy distribution and utilization which combines with new digital information technologies for improving the utility reliability, communicating in real-time with Consumers, and allowing applications of the home automation system (HAM) such as intelligent appliances and plug-in vehicles.

3.4 Considerations for SEN Implementation

To implement the SEN's concept, the following factors must be considered:

3.4.1 Technical Consideration

Demonstrated Technology Solutions:

The key technology required for SEN (SEN) should be developed in use, at scale, in common in the world, serving multiple applications. However, the application of the required technology can vary depending on different implementation of SEN.

Natural Gas Supply Affordability:

In the SEN environment, natural gas consumption will be increased because gas-fired high efficiency energy systems are extended to residential and commercial Consumers. In addition, coal power plant is replaced with gas-fired dipatchable generation. Shale gas and coal-bed-methane are an unconventional natural gas resource, which is contained in reservoir rock. Recently, the unconventional resource has been developed with the help of advanced drilling technologies. However, affordable natural gas supply must be considered.

Grid Reliability:

One of the main visions in SEN is distributed generation. The conventional break down boundary of reliability between supply and Consumers would be changed in SEN due to open networks. In addition, the integration of distributed generation to a grid could affect the quality and reliability of the grid. An assessment should be carried out identifying the reliability of bulk generation and distributed generation, investigating the expected impacts on a grid, and suggesting the solutions in planning, design, installation, operation, and maintenance stages.

Cyber Security:

SEN completes a fully integrated network without boundaries. The network should be absolutely secure with concrete cryptography and security across all boundaries and at every endpoint. Ensuring cyber security is critical in SEN. And, it should also be central to policy and strategy.

Standardization:

The function and performance of the product should be standardized for usage as a material of compatibility and interoperability in SEN. The definition of the standardization is: "It defines specifications for language, communication protocol, data formats, and linkages, within and across systems, interfaces between software applications and between hardware devices, and much more. The standards must be robust so that they can be extended to accommodate future applications and technologies." [22] The key players in this task are IEC (International Electrotechnical Commission), IEEE (Institute of Electrical and Electronics Engineers) and ISO.

Interoperability:

Interoperability is the ability to exchange information and serve between two or more networks in SEN. Interoperability is defined as follows:

"The capability of two or more networks, systems, devices, applications, or components to exchange and readily use information-securely, effectively, and with little or no inconvenience to the user….. The reliability, fidelity, and security of information exchange between and among the systems must achieve requisite performance levels." [22]

Optimal Combination of Distributed Generation:

In SEN, there are various Distributed Generation (DG) such as wind power, photovoltaic system, geothermal system, natural gas CHP, Fuel cell system, and micro-turbine CHP. The optimal combination between DG should be analyzed considering customer load pattern, the characteristics of each DG, and environmental conditions.

Multi-purpose Architecture:

The system and the component of SEN should be multi-purpose architecture, enabling rapidly deploy SEN applications such as AMI, DR, and DM. The definition of architecture is "the conceptual structure and overall organization of the SEN from the point of view of its use or design. This includes technical and business designs, demonstrations, and standards that, together convey a common understanding of the SEN." [22]

Scalability:

All hardware and software in SEN should have enough scale to support hundreds and thousands of input/out points.

Consumer-Side Platform:

The SEN system must provide Consumers with two-way communication and the information of real-time energy price rates. The information enables Consumers to automatically control their energy usage on their side based on the data provided by suppliers.

Energy Supply and Demand Outlook in Ontario:

The outlook for the supply and demand of energy in Ontario is not just a matter for an energy supply company but an issue for all of stakeholders in a SEN. It would also be one of the key informative projections which have to be considered for implementing the concept of a SEN. In the outlook of long-term and shot-term energy trends, all stakeholders' views on technology, economy, and energy policy should be incorporated.

3.4.2 Cogeneration in Smart Energy Networks Environment

Cogeneration system is one of important component which comprises energy supply system in Smart Energy Networks environment. However, traditional cogeneration system has been planned and developed based on mainly steady-state performance and stand-alone system configuration. In SEN environment, cogeneration system should be considered variety factors beyond only energy supplier's economic value.

Primary Considerations:

- System reliability
- Energy security
- Energy efficiency and economic
- Environmental impact

Cogeneration system can use a variety of new technologies in both utilizing the renewable energies and reducing carbon footprint of fossil fuels. In application and combination of the different technologies in SEN environment, firstly, reliability should be considered through feasible system configuration with adequate redundancy of energy generations. Secondly, energy security should be obtained through flexible energy resources contributed to the whole system. Thirdly, the system should be economical through optimal combination of cost-effective technologies and adequate heating-to-power ratio of the system. Lastly, environmental impact should be reduced through utilizing the renewable energies and energy saving.

In addition, the followings should be considered.
Value Added Considerations:

- Stakeholders Active Participation
- Incorporation of renewables and optimized system configuration
- Application of critical integration technologies and standards
- Incorporation of dynamic rates or incentives for consumers
- High-contribution to whole energy infrastructure as a distributed generation

Chapter 4

COGENERATIN SYSTEM MODELING AND VALIDATION

In order to implement an optimal cogeneration in Smart Energy Networks environment, a cogeneration system is to be modeled with consideration factors which mentioned previous chapter. The cogeneration is community-scaled energy supply system and located in Ontario.

4.1 Targeted Area and System Configuration

4.1.1 Proposed Site

The proposed area is the David Johnston Research and Technology Park (R+T Park) and neighborhood areas in Waterloo, Ontario, which consist of residential, commercial, and industrial Consumers. The R+T Park is located north of Columbia Street in the University of Waterloo's North Campus. At just under 120 acres of land and having 18 commercial buildings (about 174,000 m^2 total floor areas) [62] and about 50 households, the R+T Park site is bordered by an established residential neighborhood on the north (about 2,100 households) [63], a rail line on the east, University-related users on the south and an ongoing residential and community center development on the west. Figure-17 and Figure 18 illustrate the location of the proposed site.

Figure-17 Site Location

Figure-18 Proposed Site

Table 6 shows the office buildings in the proposed area.

Table-6 Office Building List in the Proposed Site

No.	Name of Building	Floor Area (sq.ft.)	Floor Area (m^2)	Note
1	Sybase, Anywyere Solutions	105,000	9,755	
2	Open Text	122,000	11,334	
3	Accelerator Building	97,000	9,012	
4	TechTown	69,000	6,410	
5	Research Advancement Center(RAC)	70,000	6,503	
6	InnoTECH	103,000	9,569	
7	AGFA	110,000	10,219	Under construction
8	RAC II	70,000	6,503	
9	Open Text II	110,000	10,219	
10	Multi-Tenant	140,000	13,006	Committed (Phase I)
11	Multi-Tenant-A 1	150,000	13,935	Committed (Phase I)
12	Multi-Tenant-A 2	150,000	13,935	Committed (Phase I)
13	Multi-Tenant-B 1	150,000	13,935	Committed (Phase II)
14	Multi-Tenant-B 2	150,000	13,935	Committed (Phase II)
15	Building-B 1	70,000	6,503	Phase II Planned
16	Building-B 2	70,000	6,503	Phase II Planned
17	Building-B 3	70,000	6,503	Phase II Planned
18	Building-B 4	70,000	6,503	Phase II Planned
Summary		1,876,000	174,285 ➔ 174,000	Application
Existing: 79,524 m2 (46%), Committed: 68,748 m2 (39%), Planned: 26,013m2 (16%)				

(Source: David Johnston Research and Technology Park)

4.1.2 System Configuration

Based on the objectives of this study and cogeneration considerations in SEN environment, the scope of the plant is next identified and specified. The energy supply plant provides a high efficiency system and alternative energy sources to reduce fossil fuel consumption and replaces fossil fuels with electricity. Several assets or functions can be provided for this purpose. There is variety of higher efficiencies and possible savings in SEN, which were described in the previous chapters. The plant consists of photovoltaic (PV) array, fuel cell system including electrolysis and hydrogen storage tank, heat exchanger for heat recovery from fuel cell system, gas turbine system including heat recovery unit, district heat and cooling supply system, thermal storage tank, and auxiliary boiler for peak thermal load.

There are AC load and thermal load for heating and cooling for the buildings in the complex area. The system consists of PV array, fuel cell system, and cogeneration unit. Electricity is generated by the PV array, fuel cell system, and cogeneration unit. Thermal energy is produced by both fuel cell system and cogeneration unit while generating electricity.

The component of the system has a parallel energy supply structure. For electricity supply, the PV array supplies a portion of the load demand directly through the inverter that will ultimately result in higher system efficiency. Then, the cogeneration unit and the fuel cell system supply the balanced demand. The inverter of PV array, cogeneration unit, and fuel cell system’s inverter can operate in either parallel or stand-alone mode that allows flexibility in matching the demand. For example, when peak load, all components can operate in parallel, which can share the demand, while in low load demand, the PV array inverter or fuel cell system or cogeneration unit can supply the energy.

A complex building has a unique thermal to power consumption ratio. In this system, energy conversion and storage system are considered in order to allow for more flexibility of matching thermal loads to electric loads. For the AC electric load, an inverter is included to change a DC outputs generated by PV array into an AC output compatible with the consumer’s electric load. Similarly, a electrolysis is included to convert excess DC output from the PV array into a hydrogen form of energy and storage it in the hydrogen storage tank.

For thermal energy production and supply of the system, waste heats from fuel cell system and cogeneration unit are collected by the heat exchangers and carried onto heating and domestic hot water loads. In addition, the collected heat is sent to the absorption chiller, which converts the waste heat into chilled water and supply to meet cooling demand.

This hybrid cogeneration system including renewable energy sources can allow system to reduce the cogeneration unit capacity, maximize cogeneration system efficiency, energy security, and supply–demand correlation. However, in order to successfully implement the hybrid cogeneration system, optimal combination of the components, overall conversion efficiency, and dispatch strategy should be considered.

A hybrid cogeneration system's schematic flow diagram is illustrated in Figure 19.

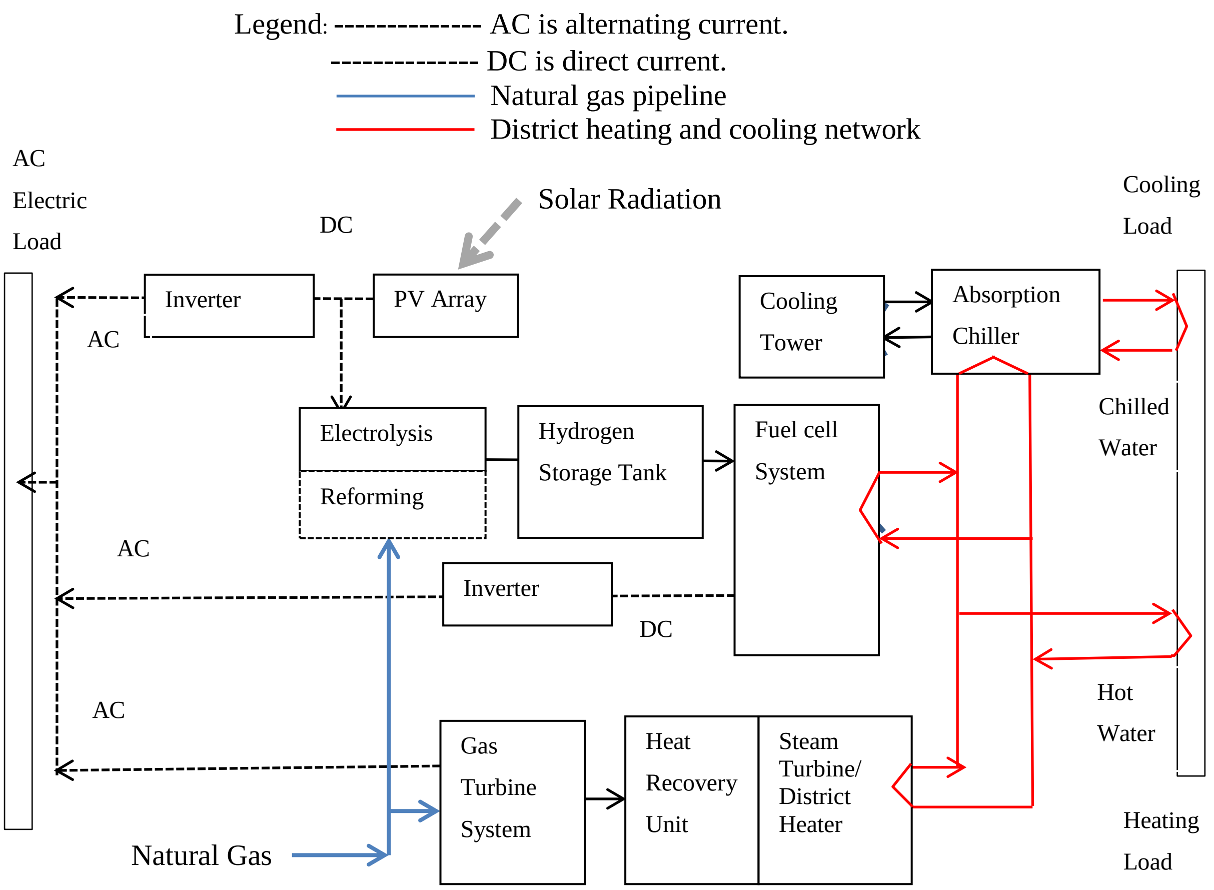


Figure-19 Schematic Flow Diagram of Cogeneration

4.2 Cogeneration System Modeling

Cogeneration system in SEN environment is modeled using TRNSYS according to the system configuration. Figure 20 illustrates the system model.

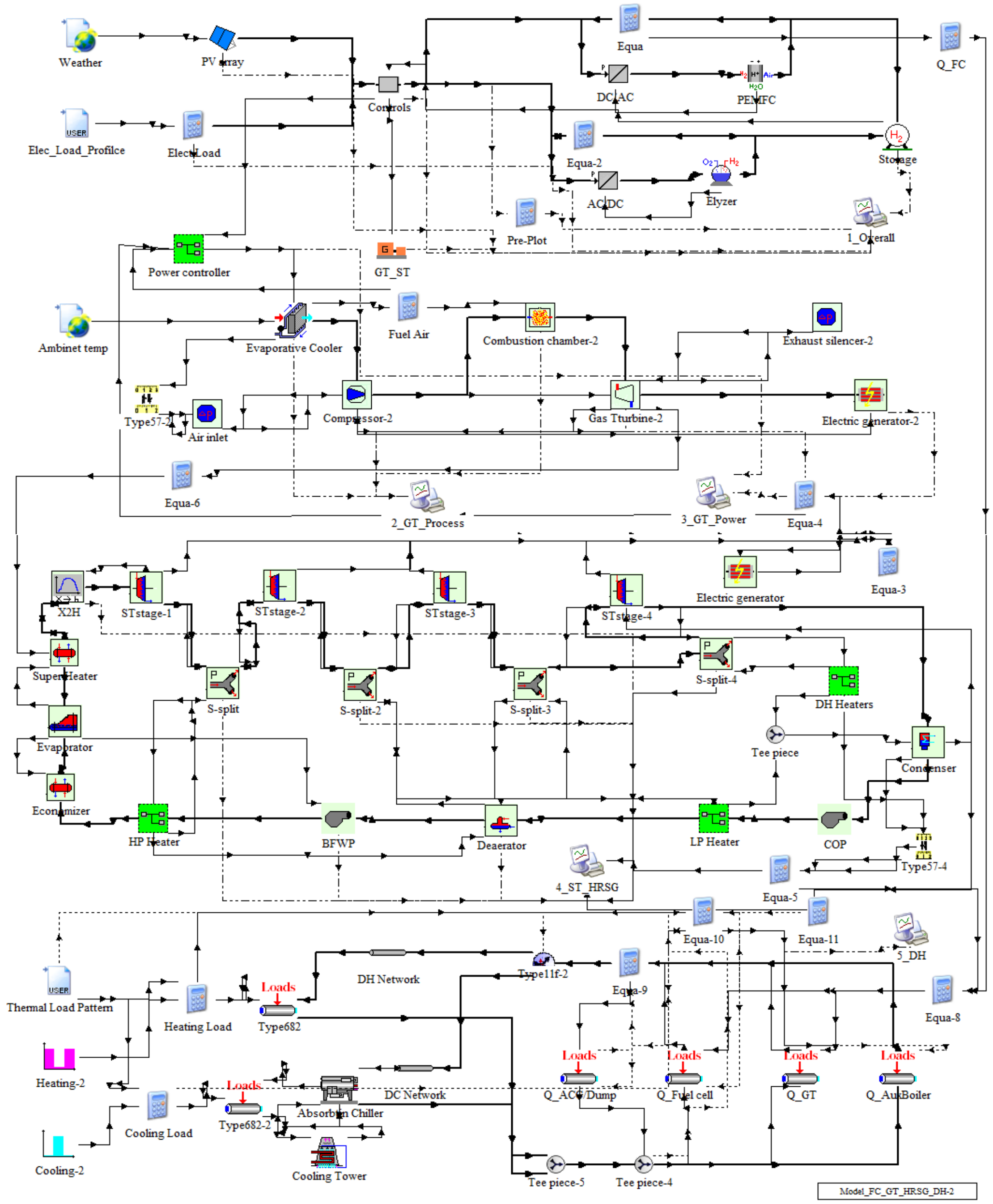


Figure-20 Cogeneration System Model using TRNSYS

This model uses about 78 components of TRNSYS; weather data, PV Array, fuel cell, inverter, power control, air compressor, combustor, gas turbine, hydrogen storage tank, heat recovery steam generator, steam extraction unit, condenser, heaters, deaerator, pump, flow converter and diverter, and so no. Table 7 lists main components used for this model.

Table-7 TRNSYS Main Component of the Cogeneration Model

Ser.No	Components	Type	Library
1	Annual Energy Consumption and Load Profile Model	-	Dong Sig Chai
2	Weather Data	TMY2	TRNSYS 16
3	Photovoltaic Array	Type 194	TRNSYS 16
4	Inverter	Type 175a	TRNSYS 16
5	Fuel cell System	Type 170e	TRNSYS 16
6	Power Controller (Electrolyzer Controller)	Type 105a	TRNSYS 16
7	Power Conditioning	Type 175	TRNSYS 16
8	Evaporative Cooler for Gas Turbine	Type 506	TRNSYS 16
9	Air Compressor	Type DLR	STEC
10	Combustion Chamber	Type DLR	STEC
11	Gas Turbine	Type DLR	STEC
12	Heat Exchanger (Shell and Tube)	Type 5g	TRNSYS 16
13	Heat Exchanger (Counter flow)	Type 5b-2	TRNSYS 16
14	Gas and Steam turbine Controller (Calculator)	-	Dong Sig Chai
15	Auxiliary Boiler System	Type 700	TESS
16	Absorption Chiller	Type 677-2	TESS
17	Cooling Tower	Type 510	TESS
18	Air Pressure Drop	Type DLR	STEC
19	Fluid Diverter	Type 11f	TRNSYS 16
20	Fluid Mixer	Tee piece	STEC
21	Heating load timer	Type 14k	TRNSYS 16
22	Cooling load timer	Type 14l	TRNSYS 16
23	Flow stream load	Type 682	TESS
24	Online Printer without file	Type 65d	TRNSYS 16
25	Online Printer with file	Type 65a	TRNSYS 16

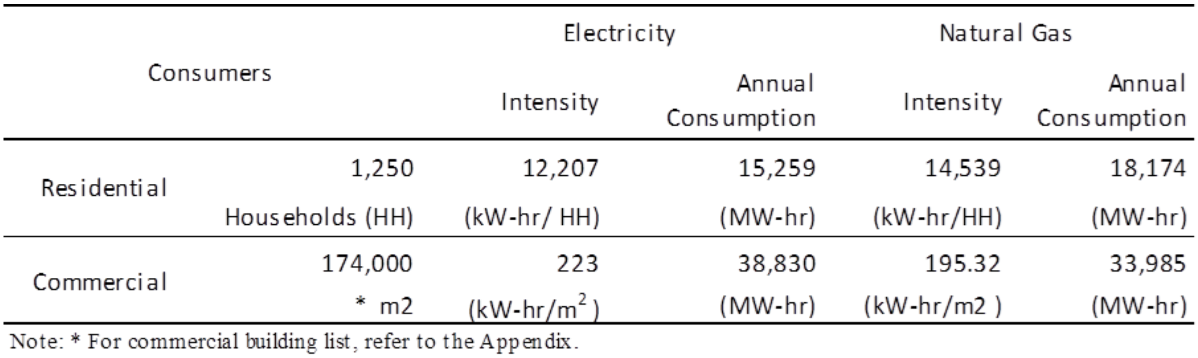
Detailed data for key components are attached in Appendix C in this thesis.

4.3 Components Modeling

4.3.1 Annual Energy Consumption and Load Profile Model

Target Consumers at the proposed site are about 1,250 householders and 18 commercial buildings having approximately 174,000 m^2 floor areas. The energy intensities for residential and commercial end-users are based on the data from Natural Resources Canada, Energy Use Data by End users, 2008. [24] The residential energy intensity is 12,207 kW-hr/ households for electricity and 14,539 kW-hr/households for natural gas. The commercial building's energy intensity is 223 kW-hr/m^2 for electricity and 195 kW-hr/m^2 for natural gas. [24] as shown in Table 8.

Table-8 Annual Energy Consumption



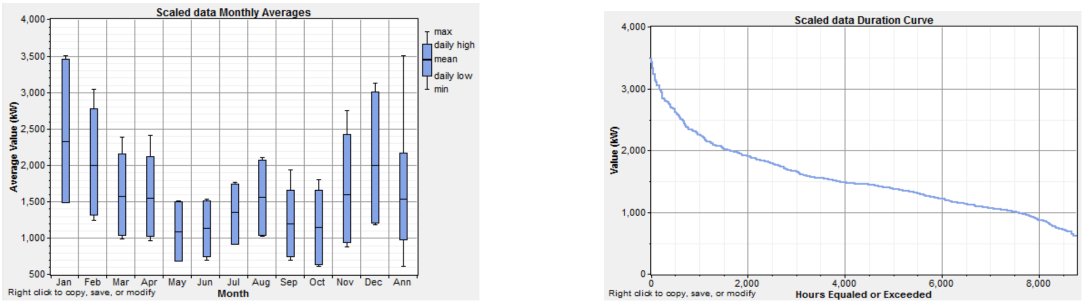
Consumers		Electricity		Natural Gas	
		Intensity	Annual Consumption	Intensity	Annual Consumption
Residential	1,250	12,207	15,259	14,539	18,174
	Households (HH)	(kW-hr/ HH)	(MW-hr)	(kW-hr/HH)	(MW-hr)
Commercial	174,000	223	38,830	195.32	33,985
	* m2	(kW-hr/m^2)	(MW-hr)	(kW-hr/m2)	(MW-hr)

Note: * For commercial building list, refer to the Appendix.

The hourly electricity consumption patterns for residential and office buildings are based on the load patterns data given by the Independent Electricity System Operator (IESO) in Ontario, and the heating energy consumption patterns are based on the assumptions that the pattern is mainly proportional to the outdoor air temperature which is available in Environmental Canada.

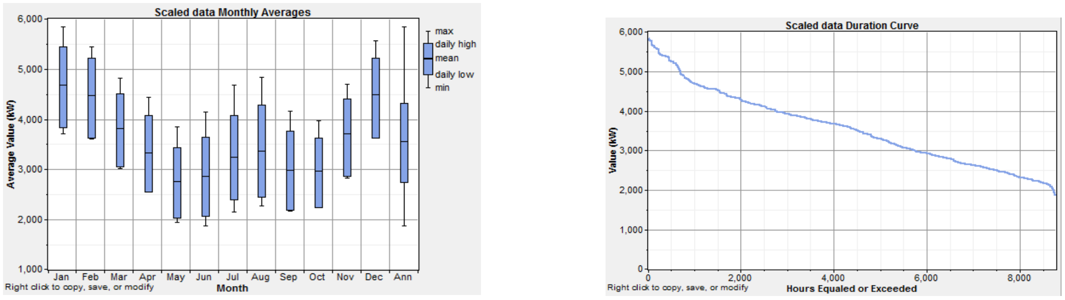
For the office buildings, the maximum electricity load, average load, and load factor are 6,008 kW, 3,240kW, and 0.54, respectively. For residential buildings, the maximum electricity load, average load and load factor are 4,005 kW, 1,280 kW, and 0.32, respectively. The electricity peak load combined the two loads is 9,507 kW and diversity factor of electricity load is analyzed about 0.95 according to load patterns. Diversity Factor is defined as "the ratio of the sum of the non-coincidental maximum demands of two or more loads to their coincidental maximum demands for the same period." [23] The capacity of cogeneration component can be reduced as a consequence of diversity factor of load.

For the office buildings, the maximum thermal load, average load, and load factor are 12,221 kW, 3,873 kW, and 0.32, respectively. For residential buildings, the maximum electricity load, average load and load factor are 6,546 kW, 2,090 kW, and 0.32, respectively. The thermal peak load combined the two loads is 18,767 kW and diversity factor of thermal load is assumed 1.0 for this study. Cooling load for residential use is not considered in this study. Figure 21 illustrates load profile model of electricity and thermal for residential and office building.



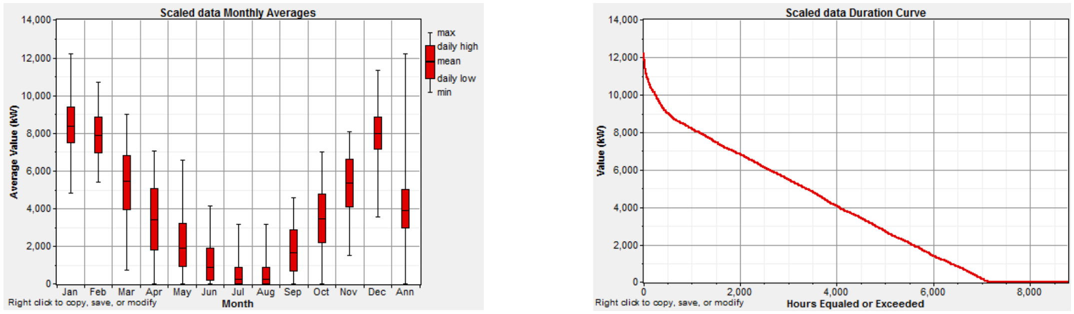
(a) Monthly electric load -Households

(b) Electric load duration -Households



(c)Monthly electric load –Office buildings

(d) Electric load duration –Office buildings



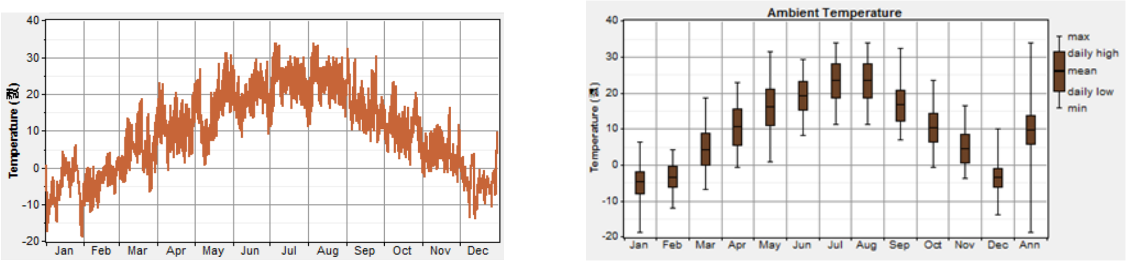
(e)Monthly heating load –Office buildings

(f) Heating load duration –Office buildings

Figure-21 Energy Load Profiles Model

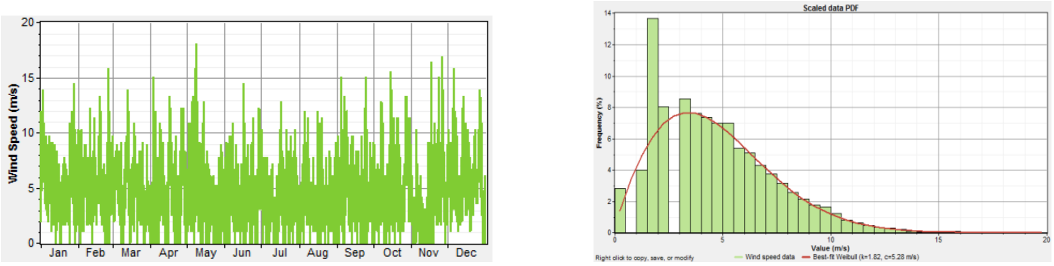
4.3.2 Weather Data

Recently, TMY3 (Typical Meteorological Year) data sets derived from 1991 to 2005 are used as a weather data. However, no TMY3 data is available in the proposed area. Therefore, this study uses TMY2 data set which was derived from 1961 to 1990 year for 8760 hourly data in Toronto airport area, which is provided in TRNSYS. Sensitivity analysis for the environmental data is conducted for checking. The maximum, minimum, and average temperature is 33.8◦C, -18.8oC and 9.8 ◦C, respectively. Annual average wind speed at 10m above ground is 4.66 m/s. The Weibull distributed factor, k, is 1.83. The autocorrelation factor is 0.841. The diurnal pattern strength is 0.236, and the peak wind speed is 15 hours. The average clearness index is 0.491, and average annual radiation is 3.68 kW-h/m2/d. Figure-20 shows the weather data model.



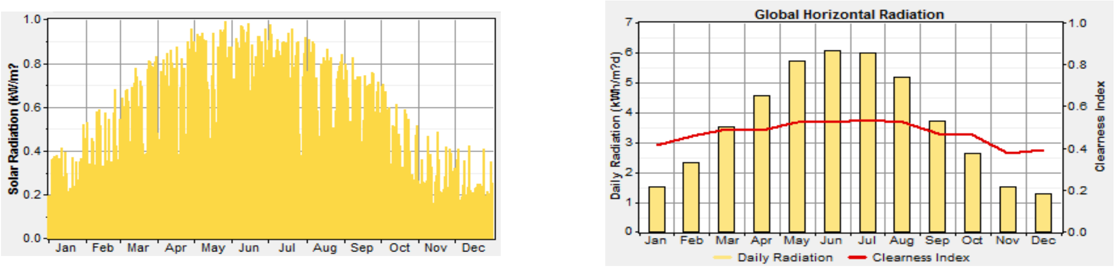
(a) Temperature Variations (°C)

(b) Monthly Average Temperature (°C)



(c) Wind Speed Variations (m/s) at 10m

(d) Wind Speed PDF



(e) Average Daily Radiation (kW/m^2)

(f) Monthly Average Radiation with Cleanness Index

Figure-22 Weather Data Model

4.3.3 Photovoltaic Array

Photovoltaic with DC/AC inverter model, 194, in TRNSYS is used. This model gives cell output that can be maximized by operating near or at the maximum power point. Maximum power tracking system are applied in order to keep the impedance of the circuit of the cells at levels corresponding to best operation.

The Canadian Solar PV array panel is used for this study. A sample PV array panel models of CS6X-290 P with manufacturer's parameters [27][28] is used for validation as shown in Table 9.

Table-9 PV Array Parameter (1 Module)

Parameter	Value	Unit	Parameter	Value	Unit
Mode	1	-	Module temperature at NOCT	320	K
Module short-circuit current at reference conditions	8.64	amperes	Ambient temperature at NOCT	293	K
Module open-circuit voltage at reference conditions	44.4	V	Insolation at NOTC	800	W/m^2
Reference temperature	298	K	Module area	1.91	M^2
Reference isolation	1000	W/m2	Tau-alpha product for normal incidence	0.99	-
Module voltage at max power point and reference conditions	35.9	V	Semiconductor band-gap	0.95	any
Module current at max power point and reference conditions	8.08	amperes	Value of parameter a at reference conditions	2.015	-
Temperature coefficient of isc at (reference condition)	0.07	any	Value of parameter I_L at reference conditions	5.7	amperes
Temperature coefficient of Voc at (reference condition)	-0.34	any	Value of parameter I_O at reference conditions	~0	amperes
Number of cells wired in series	72	ea	Module series resistance	0.21	-
Number of modules in series	1	ea	Shunt resistance at reference conditions	53.6	-
Number of modules in series	1	ea	Extinction coefficient-thickness product of cover	0.008	-

The current-voltage equation for the circuit of PV array in TRNSYS is based on the circuit diagram as follows: [26]

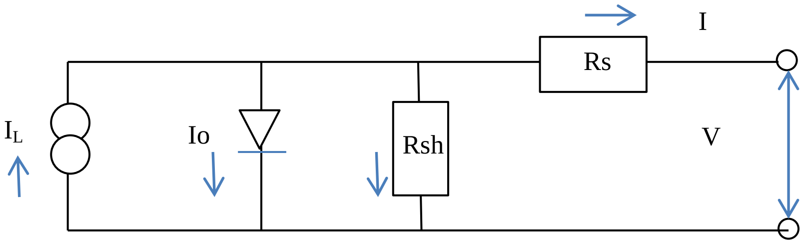


Figure-23 PV Array Circuit Diagram

$$I = I_L - \; I_0 \left[e^{\frac{V+I\,Rs}{a}} - 1 \right] - \frac{V+IRs}{R_{sh}} \tag{4.1}$$

Where,

$$a \;\equiv \frac{N_s\, n_I\, kT_c}{q} \tag{4.2}$$

Where,

N_S	Number of modules in series in array
k	Boltzmann constant [J/K]
Tc	Module temperature [K]

From equations (4.1) and (4.2), five parameters must be known in order to calculate the current and voltage: I_L light current, I_0 diode reverse saturation current, R_s series resistance, R_{sh} shunt resistance, and a modified ideal factor.

The light current, I_L is observed by:

$$I_L = \; \frac{S}{S_{ref}} \frac{M}{M_{ref}} \left[I_{L,ref} + \; \alpha_{Isc} \left(T_c - \; T_{c,ref} \right) \right] \tag{4.3}$$

The diode reverse saturation current, I_0 calculated by following relation:

$$\frac{I_0}{I_{o,ref}} = \left[\frac{T_c}{T_{c,ref}} \right]^3 \mathrm{exp}[\frac{1}{k} \; \left(\frac{E_g}{T} |_{T_{ref}} - \frac{E_g}{T} |_{T_c} \right)] \tag{4.4}$$

The series resistance, R_s is assumed constant at its reference value of $R_{s,ref}$.

The shunt resistance R_{sh} is observed empirically by following relation:

$$\frac{R_0}{R_{o,ref}} = \; \frac{S_{ref}}{S} \tag{4.5}$$

Where,

α_{Isc}	Temperature coefficient of short-circuit current [A/K]
E_g	Semiconductor band-gap [eV]

Figure 24 shows the IV curve obtained from TRNSYS model with the given parameters. The graph verifies that the TYPE194 component agrees very well with the experimental data taken on the Canadian Solar PV array panel.

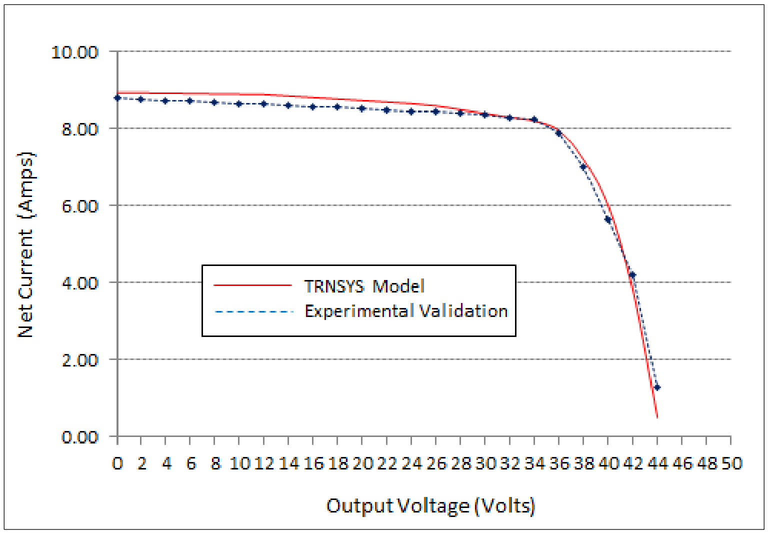


Figure-24 PV Array IV Curve compared with Experimental Data

Inverter model of 175a is used in this study. As an experimental data, Power-One Inverter model of PVI-400.0-TL which 400kW class [28] is used. Table 10 represents the parameter of the inverter.

Table-10 Parameter of Inverter

Parameter	Value	Unit
Mode	1	-
Nominal Power, Pn	400	kW
Idling Constant [ratio between constant power loss (P0) and nominal power (Pn)]	0.03	-
Set point voltage, Us	208	V
Ohmic constant [product of internal resitance (Ri) and nominal power (Pn)], RiPn	138	V^2
Number of units in parallel, MP	1	-
Auxiliary power requirement, Paux	12	kW

4.3.4 Fuel cell System

The PEM (Proton Exchange Membrane) fuel cell stack is modeled using the Type170e in TRNSYS. Table 11 represents the parameters of the model.

Table-11 Parameter of Fuel cell System

Parameter	Value	Unit	Parameter	Value	Unit
OXMODE (OXmode=1. Air is provided to the cathode. OXmode=2. Pure oxygen is provided to the cathode)	1	-	Minimum allowable cell voltage	0.7	V
TMODE (TMODE = 1: TSTACK is a constant. TSTACKout = TSTACKin)	1	-	Maximum allowable Current density	700	mA/m^2
Number of cells in series per stack (NCELLS gives the VOLTAGE RATING of the fuel cell)	35	-	RTCTMODE (Mode for calculating the overall thermal resistance (R_T) and capacitance (C_t) of a single FC stack: 1 = Simple: Few FC geometry and thermal parameters needed)	1	-
Number of stacks in parallel per FC unit (NSTACKS gives the CURRENT RATING of the fuel cell)	1		Heat transfer coefficient from FC stack to ambient air	40	W/m^2.K
Electrode area of PEM (A_PEM < A_CELL)	232	cm^2	Cross-sectional area of a single fuel cell (A single FC consists of an MEA sandwiched between two bipolar plates: A_CELL > A_PEM: MEA = Cathode + PEM + Anode = Membrane Electrode Assembly)	441	cm^2
Proton Exchange Membrane (PEM) thickness	0.0118	cm	Thickness of one single fuel cell (One single FC conists of an MEA sandwiched between 2 bipolar plates: T_CELL >> T_PEM)	1	cm
GAMMA (Transport number for water: 0.0 = Well hydrated PEM.	0,0	-	-		

A fuel cell is an electrochemical device that converts hydrogen (or hydrogen rich fuel) and oxygen to electricity by an electrochemical process. The fuel cell system configurations differ from the applications of type of fuel cell and integration devices. Generally, a fuel cell system consists of fuel processing, air processing, fuel cell stack, thermal management/water treatment, power conditioning, and control system. Figure 25 illustrates fuel cell and polarization curve, and Figure 26 shows the configuration of fuel cell system.

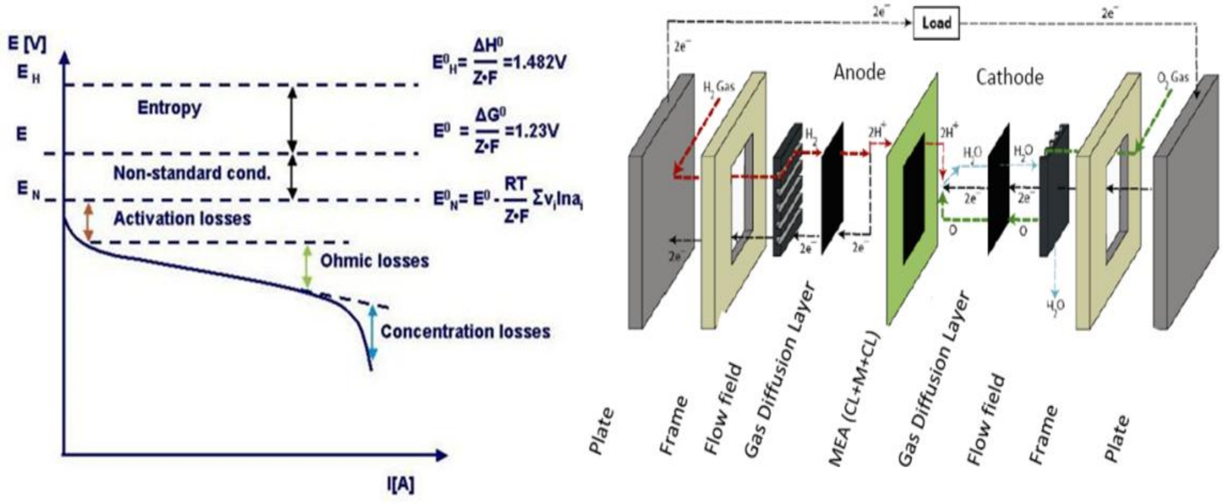


Figure-25 Fuel cell Polarization Curve

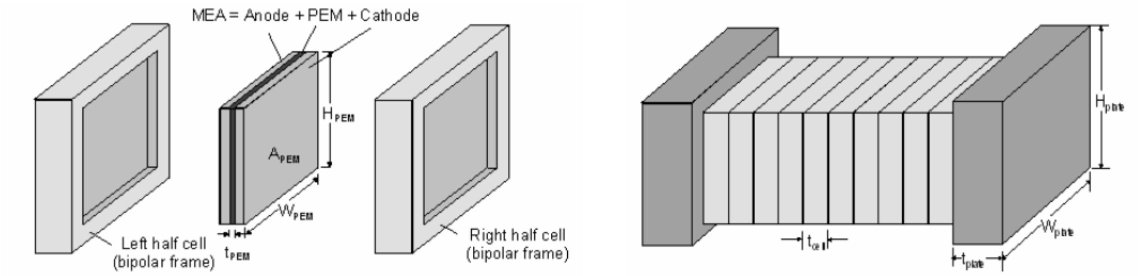


Figure-26 Configuration of Fuel cell System [26]

The anodic and cathodic reactions taking place in a PEM fuel cell, where its fed with hydrogen-containing anode gas and an oxygen-containing cathode gas.

In anode pole:

$$H_2(g) \Rightarrow 2\ H^+ (aq) + 2\ e^- \tag{4.6}$$

In cathode pole:

$$2\ H^+ (aq) + 2\ e^- + \tfrac{1}{2}\ O_2(g) \Rightarrow H_2O\ (l) \tag{4.7}$$

The total fuel cell reaction is:

$$H_2\ (g) + \tfrac{1}{2}\ O_2\ (g) \Rightarrow H_2O\ (l) \tag{4.8}$$

The products of this process are electricity, liquid water and heat. The basic expression for the voltage of the single cell is:

$$U_{cell} = E + \eta_{act} + \eta_{ohmic} \tag{4.9}$$

Where,

E Thermodynamic potential

$$E = 1.23 - 0.00085 \cdot (T_{stack} - 298) + 0.0000431 \cdot T_{stack} \cdot \mathbf{ln}\,(p_{H2} \cdot p_{O2}{}^{0.5}) \qquad (4.10)$$

η_{act} Anode and cathode activation over-voltage, a measure of the voltage loss associated with the anode and cathode

$$\eta_{act} = -0.95 + 0.00243 \cdot T_{stack} + 0.000192 \cdot T_{stack} \cdot \mathbf{ln}\,(A_{PEM}) - 0.000192 \cdot T_{stack} \cdot \mathbf{ln}\,(I_{FC}) + 0.000076 \cdot T_{stack} \cdot \mathbf{ln}\,(c_{O2}) \qquad (4.11)$$

η_{ohmic} Ohhmic over-voltage, a measure of the IR losses associated with the proton conductivity of the solid polymer electrolyte and electronic internal resistances

$$\eta_{ohmic} = \frac{-I_{FC}\, t_{PEM}}{A_{PEM}} \; \frac{8}{\exp[\,3.6\,\left(\frac{T_{stack}-353}{T_{stack}}\right)]} \; [\,1 + 1.64\,\frac{I_{FC}}{A_{PEM}} + \gamma\left(\frac{I_{FC}}{A_{PEM}}\right)^{3}] \qquad (4.12)$$

The output voltage with net current is generated with TRNSYS component model. The calculated dat is evaluated against experimental data on a Ballard 1.2kW NexaTM Power Module [29] . Figure 27 shows polarization curve and comparison with experimental data. The graph verifies that the TYPE170 component agrees very well with the experimental data taken on the Ballard 1.2kW NexaTM Power Module.

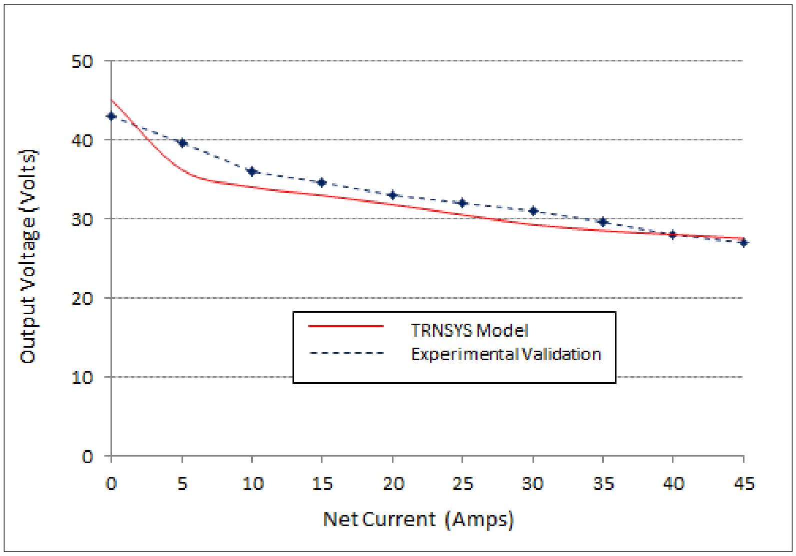


Figure-27 Fuel cell Polarization Curve compared with Experimental Data

4.3.5 Power Controller (Electrolyzer Controller)

For power control, TRNSYS component of Type 105a is used as a master level controller for this cogeneration system analysis, which consists of a photovoltaic system, an electrolyzer, a fuel cell, a hydrogen storage tank and a gas turbine system.

The controller makes decisions based on the mini-grid bus bar power balance, assuming that the minimum number of gas turbine system is operating and that the fuel cell and electrolyzer are idling:

Power balance, P_{busbar} on a grid bus bar is obtained by

$$P_{busbar} = P_{PV} + N_{GT},min\ P_{GT},max + P_{FC},min - P_{Load} - P_{Ely},min \qquad (4.13)$$

Table 12 represents the parameters of the model.

Table-12 Parameter of Power Controller

Parameter	Name	Unit	Parameter	Name	Unit
Minimum allowable number of gas turbine system in operation	NMIN	-	Rated electrolyzer power	PELYMAX	W
Maximum allowable number of gas turbine system in operation	NMAX	-	Upper SOC limit (H2-storage), i.e., ELY switched OFF (idle)	EL_UP	%
Rated power of each gas turbine system	DEGSMAX	W	Lower SOC limit (H2-storage), i.e., ELY switched ON after having been idling	EL_LOW	%
Fuel cell idling power	PFCMIN	W	Upper SOC limit (H2-storage), i.e., FC switched ON after having been idling	FC_UP	%
Rated fuel cell power	PFCMAX	W	Lower SOC limit (H2-storage), i.e., FC switched OFF (idle)	FC_LOW	%
Electrolyzer idling power	PELYMIN	W	-		

SOC: H2-storage 'state of charge' (normalized pressure level)

4.3.6 Power Conditioning

TRNSYS component of Type 175 is used as a power controlling. The power-conditioning units in TRNSYS are designed to convert or invert the DC/AC power into AC/DC power at the appropriate voltage. The PV array input power varies continuously with time. The output characteristics of a PV array have peak power points that depend on ambient conditions such as solar insolation and cell temperature. Therefore, it can be advantageous to use a maximum power point tracker (MPPT) to utilize the input power source to its fullest capability [26]. The power loss (P_{loss}) for a power conditioner is mainly dependent on the electrical current running through it. The power loss is defined by: [26]

$$P_{loss} = P_{in} - P_{out} \tag{4.14}$$

$$P_{in} - P_{out} = P_0 + (U_S / U_{out})\, P_{out} + (R_{ipn} / U_{out}{}^2)\, P_{out}{}^2 \tag{4.15}$$

Input power can be expressed with respect to the nominal (maximum) power P_{nom} of the power conditioner as follows:

$$\frac{P_{in}}{P_{nom}} = \frac{P_0}{P_{nom}} + \left[1 + \frac{U_s}{U_{out}}\right]\frac{P_{out}}{P_{nom}} + \frac{R_{ipn}}{U_{out}{}^2}\, P_{nom} \left[\frac{P_{out}}{P_{nom}}\right]^2 \tag{4.16}$$

Electric efficiency is defined by:

$$\eta = \frac{P_{out}}{P_{in}} \tag{4.17}$$

Current output is defined by:

$$I_{out} = \frac{P_{out}}{U_{out}} \tag{4.18}$$

Where,

P_0	Idling power, W
Us	Setpoint voltage, V
Uout	Output voltage, V
Ri	Internal resistance, Ω
Ripn	Internal resistance constant = Ri Pn, V^2

4.3.7 Evaporative Cooler for Gas Turbine System

TRNSYS component of Type 506 is used for modeling evaporative cooler, which provide optimum inlet air conditions for air compressor-gas turbine system. The cooling process is assumed to be a constant wet bulb temperature process. The controls that monitor the conditions of the outlet air is not applicable. When the device is ON by signal sent by user's signal value, the evaporative cooling device cools an inlet air stream by passing the air through or across a wetted surface, which evaporate the water from the surface and cooling the air stream in the process. The ideal exiting air state for an evaporative cooler is if the air exits with a dry-bulb temperature equal to its inlet wet-bulb temperature. The cooler effectiveness of this model is defined as:

$$\text{N} = \text{Cooler effectiveness} = \frac{(\text{Tair,db,in - Tair,db,out})}{(\text{Tair,db,in - Tair,wb,in})} \tag{4.19}$$

where,

"in" means inlet condition, "out" air outlet condition, "db" air dry-bulb temperature, and "wb" air wet bulb temperature. The power output is simply the parasitic power (power consumption of the evaporative cooler: fans, pumps, etc.) when operating if the machine is operating.

The dry-bulb temperature of the air leaving the evaporative cooler is calculated by:

$$T_{air,db,out} = T_{air,db,in} - \frac{N}{100\%} (T_{air,db,in} - T_{air,wb,in}) \tag{4.20}$$

4.3.8 Air Compressor

Compressor component in STEC (Solar Thermal Element Section) library which was developed by DLR (German Aerospace Centre) is used as a model. Table 13 shows the parameters of the component. As a validation model for the compressor, 2000kW class GE PGT2 compressor for gas turbine [30] is used for this study.

Table-13 Parameter of Air Compressor

Parameter	Value	Unit
Compressor ratio	12.9	-
Mechanical efficiency	0.98	-
ISO inlet mass flow design	38,050	Kg/h
Partial load by mass flow reduction if mode-2	0	-
Operating mode (mode-1: inlet mass flow as a function of the inlet condition, mode-2: inlet mass flow as an input	1	-

Using an isentropic efficiency given in the parameter, the compressor model calculates the outlet conditions from the inlet state. And model calculates the outlet- temperature, *tou at isentropic* and enthalpy, *hout* at isentropic using an isentropic compression. Then, the real outlet conditions are obtained by using the isentropic efficiency and a new call of the Gas routine (call Gas with the inputs *p2* and *h2*) as shown in Figure 28.

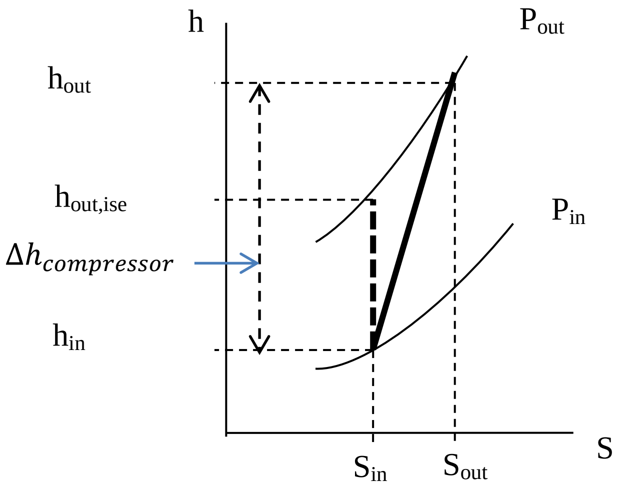


Figure-28 Process of Air Compressing

$$\Delta \boldsymbol{h}_{compressor} = \frac{\boldsymbol{h}_{out,isen} - \boldsymbol{h}_{in}}{\eta_{isentropic}} \tag{4.21}$$

$$\boldsymbol{h}_{out} = \boldsymbol{h}_{in} + \Delta \boldsymbol{h}_{compressor} \tag{4.22}$$

$$\boldsymbol{P}_{compressor} = \frac{\dot{\boldsymbol{m}}_{out} \ \Delta \boldsymbol{h}_{compressor}}{\eta_{mech}} \tag{4.23}$$

4.3.9 Combustion Chamber

Combustion Chamber component in STEC(Solar Thermal Element Section) library which was developed by DLR (German Aerospace Centre) is used as the combustion chamber model for this study. Table 14 shows the parameters of the component. As a validation model for the Combustion Chamber, 2000kW class GE PGT2 combustion chamber for gas turbine [30] is used for this study. Natural gas chemical composition of Union Gas [31] in Ontario is applied.

Table-14 Parameter of Combustion Chamber

Parameter	Value	Unit	Parameter	Value	Unit
Operating mode (mode-1: outlet temperature as a result of given fuel flow rate, mode-2: fuel flow rate as a result of given outlet temperature)	1	-	H_{2O} mass fraction	-	%
Lower calorific value	42630	kJ/kg	Ash mass ration	nil	%
C mass fraction	72.0	%	Relative pressure drop, design		
H_2 mass fraction	23.8	%	Design or off-design (mode-3 or moe-4)	3	-
S mass fraction	0.00002	%	Inlet temperature _design if mode-4	-	C
N_2 mass fraction	3.1	%	Inlet pressure _design if mode-4	-	Bar
O_2 mass fraction	1.1	%	Inlet mass flow _design if mode-4	-	Kg/hr

This model calculates chemical combustion process based on an adiabatic combustion chamber for different liquid or gaseous fuels. The combustion chamber receives air from compressor and natural gas from governing valve, then lets the mixture combust. This kind of process is known as internal combustion. The ideal reaction is then given by: [32]

$$C_xH_y + \in (X_{O_2} O_2 + X_{N_2} N_2 + X_{CO_2} CO_2 + X_{Ar} Ar) \rightarrow n_{CO_2} CO_2 + n_{H_2O} H_2O + n_{N_2} N_2 + n_{Ar} Ar \qquad (4.24)$$

Where, in air

$$X_{O_2} = 0.2095,\ X_{N_2} = 0.7808,\ X_{CO_2} = 0.0003,\ X_{Ar} = 0.0094$$

The term ∈ is the number of moles of air necessary for every mole of fuel.

$$\in = \frac{x + 0.25\,y}{X_{o2}} \qquad (4.25)$$

The reaction productions are calculated by:

$$n_{CO_2} = x + \in X_{CO_2} \qquad n_{H_2O} = 0.5\ y \qquad n_{N_2} = "X_{N_2} \qquad n_{Ar} = \in X_{Ar} \qquad (4.26)$$

The stoichiometric fuel to air ratio, FAR_{st}, is calculated by:

$$FAR_{st} = \left[\frac{\dot{m}_{fuel}}{\dot{m}_{air}}\right]_{st} = \frac{1}{\in}\frac{M_{CxHy}}{M_{air}} = \frac{X_{O2}}{x + 0.25y}\frac{M_{CxHy}}{M_{air}} \qquad (4.27)$$

Where, M_{CxHy} and M_{air} are the molar mass of the fuel and the air, respectively.
In real situation, FAR_{st} is smaller than 1. The ratio of actual FAR to FAR_{st} is defined by fuel to equivalent ratio, φ.

$$\varphi = \frac{FAR}{FAR_{st}} \tag{4.28}$$

The enthalpy of combustion meaning the heat leaving the chamber is calculated by:

$$\Delta h_c = h_{react} - h_{prod} \quad \text{(Jule per mole of mixture)} \tag{4.29}$$

Lower heating value, LHV is

$$LHV = \frac{\Delta h_c}{M_{mix}} \frac{\dot{m}_{mix}}{\dot{m}_{fuel}} \tag{4.30}$$

Heat balance around combustion chamber with a few simplifying assumptions becomes below.

$$\dot{m}_{fuel}\, \eta_c\, LHV = \dot{m}_{air}\, c_{p,gas}\, (T_{out} - T_{in}) \tag{4.31}$$

Where, η_c is the combustion efficiency. Finally, the temperature leaving the chamber is written by:

$$T_{out} = T_{in} + \frac{\varphi\, FAR_{st}}{c_{p,gas}}\, \eta_c\, LHV \tag{4.32}$$

4.3.10 Gas Turbine

Gas Turbine component in STEC(Solar Thermal Element Section) library which was developed by DLR ((German Aerospace Centre) is used as gas turbine model for this study. Table 15 shows the parameters of the component. As a validation model for the gas turbine, 2000kW class GE PGT2 combustion chamber for gas turbine [30] is used for this study.

Table-15 Parameter of Gas Turbine

Parameter	Value	Unit
Mechanical efficiency	0.981	-
Maximum inlet temperature without cooling	1038	C
Ambient pressure	1.01	bar
Maximum inlet temperature with cooling	-	C

Using an isentropic efficiency given in the parameter, the compressor model calculates the outlet conditions from the inlet state. And, the model calculates the outlet temperature, t_{out} using a given ambient pressure and turbine outlet pressure, and enthalpy, h_{out} at isentropic expansion by calling the Gas routine (call Gas with the mixture of the combustion air and the inputs p_{out} and $S_{out} = S_{in}$) as shown in Figure 29.

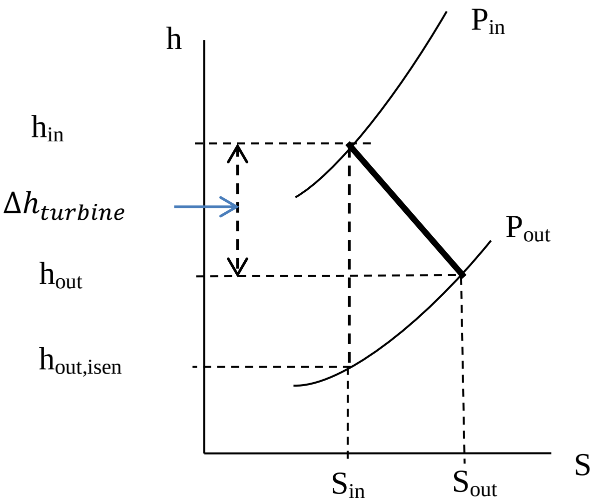


Figure-29 Process of Gas Turbine Expansion

$$\Delta h_{turbine} = \frac{h_{in} - h_{out,isen}}{\eta_{isentropic}} \tag{4.34}$$

$$h_{out} = h_{in} + \Delta h_{turbine} \tag{4.35}$$

$$P_{turbine} = \dot{m}_{in} \ \Delta h_{turbine} \quad \eta_{mech} \tag{4.36}$$

4.3.11 Heat Exchangers

TRNSYS component of Type 5g (Shell and Tube) is used for modeling gas-to-district heating water heat exchanger and Type 5b-2 is used for fuel cell system heat exchanger. Table 16 shows the parameters of heat exchanger.

Table-16 Parameter of Gas-to-DH water Heat Exchanger

Parameter	Type 5g		Type 5b-2	
	Value	Unit	Value	Unit
Flow mode	Shell and Tube	-	Counter flow	-
Specific heat of hot side fluid	simulated	kJ/kg.K	simulated	kJ/kg.K
Specific heat of cold side fluid	simulated	kJ/kg.K	simulated	kJ/kg.K
Number of Shell Passes	simulated	-	simulated	-

A zero capacitance sensible heat exchanger is modeled in the shell and tube modes. Given the hot and cold side inlet temperatures and flow rates, the effectiveness is calculated for a given fixed value of the overall heat transfer coefficient. The cross flow modes assume that neither the cold nor the hot side fluids are mixed. The shell and tube model and the situation in which both fluids are unmixed are covered in DeWitt and Incropera [26]. A schematic diagram of shall and tube heat exchanger is shown in Figure 30.

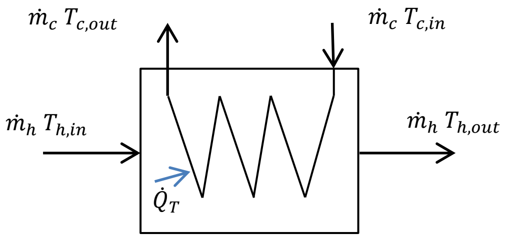


Figure-30 Heat Exchanger Schematic

The capacitance of each side of the heat exchanger is calculated according to the following four equations.

$$C_c = \dot{m}_c\, C_{p,c} \tag{4.27}$$

$$C_h = \dot{m}_h\, C_{p,h} \tag{4.28}$$

$$C_{max} = max\,\{\ C_{p,h} :\ C_{p,c}\,\} \tag{4.29}$$

$$C_{min} = min\,\{\ C_{p,h} :\ C_{p,c}\,\} \tag{4.30}$$

Heat exchanger effectiveness is defined by [26]

For shell and tube flow mode:

$$\varepsilon_1 = 2\left\{1+\frac{C_{\min}}{C_{\max}}+\left(1+\left(\frac{C_{\min}}{C_{\max}}\right)^2\right)^{0.5} * \frac{1+\exp\left[-\frac{UA}{C_{\min}}\left(1+\left(\frac{C_{\min}}{C_{\max}}\right)^2\right)^{0.5}\right]}{1-\exp\left[-\frac{UA}{C_{\min}}\left(1+\left(\frac{C_{\min}}{C_{\max}}\right)^2\right)^{0.5}\right]}\right\}^{-1} \tag{4.31}$$

$$\varepsilon = \left[\left(\frac{1-\varepsilon_1\frac{C_{\min}}{C_{\max}}}{1-\varepsilon_1}\right)^N - 1\right]\left[\left(\frac{1-\varepsilon_1\frac{C_{\min}}{C_{\max}}}{1-\varepsilon_1}\right)^N - \frac{C_{\min}}{C_{\max}}\right]^{-1} \tag{4.32}$$

For counter flow mode:

$$\varepsilon = \frac{1 - \exp\left(-\frac{\mathrm{UA}}{\mathrm{C_{min}}}\left(1-\frac{\mathrm{C_{min}}}{\mathrm{C_{max}}}\right)\right)}{1 - \left(\frac{\mathrm{C_{min}}}{\mathrm{C_{max}}}\right)\exp\left(-\frac{\mathrm{UA}}{\mathrm{C_{min}}}\left(1-\frac{\mathrm{C_{min}}}{\mathrm{C_{max}}}\right)\right)} \tag{4.33}$$

Heat transferred between two flows is calculated by

$$T_{h,out} = T_{h,in} - \in \left(\frac{C_{min}}{C_h}\right).\left(T_{h,in} - T_{c,in}\right) \tag{4.34}$$

$$\dot{Q}_T = \in C_{min}\left(T_{h,in} - T_{c,in}\right) \tag{4.35}$$

4.3.12 Thermal Storage Tank

TRNSYS component of "Type 60c NoHeat" can be used for modeling thermal storage tank, which is Vertical Cylinder - Uniform Losses and Node Heights - 2 Inlets, 2 Outlets. Table 17 shows the parameters of thermal storage tank for reference only. This component is not used to this study.

Table-17 Parameter of Thermal Storage Tank

Parameter	Value	Unit	Parameter	Value	Unit
User-specified inlet positions	2	-	Set point temperature for element 1 (N/A)	-	C
Tank volume	simulated	m^3	Deadband for heating element 1 (N/A)	-	delC
Tank height	simulated	m	Maximum heating rate of element 1 (N/A)	-	kJ/hr
Tank perimeter(1:vertival tank)	1	-	Height of 2nd aux. heater (N/A)	-	m
Height of flow inlet 1	simulated	m	Height of 2nd aux. heater (N/A)	-	m
Height of flow outlet 1	simulated	m	Height of 2nd thermostat (N/A)	-	m
Height of flow inlet 2	simulated	m	Set point temperature for element 2 (N/A)	-	C
Height of flow outlet 2	simulated	m	Deadband for heating element 2 (N/A)	-	delC
Fluid specific heat	4.19	kJ/kg.K	Maximum heating rate of element 2 (N/A)	-	kJ/hr
Fluid density	1000.0	kg/m^3	Overall loss coefficient for gas flue (N/A)	-	kJ/hr.K
Tank loss coefficient	3.0	kJ/hr.m^2.K	Flue temperature (N/A)	-	C
Fluid thermal conductivity	1.40	kJ/hr.m.K	Fraction of critical time step	6	-
Destratification conductivity	0.0	kJ/hr.m.K	Gas heater? (N/A)	1	-
Boiling temperature	100	C	Number of internal heat Exchangers(No heat exchanger in this case)	1	-
Auxiliary heater mode (N/A)	1	-	Equal sized nodes	0	-
Height of 1st aux. heater (N/A)	-	m	Uniform tank losses	0	-
Height of 1st thermostat (N/A)	-	m	-		

A typical thermal storage tank is filled with hot district heating (DH) water. Through top and bottom of the tank, the supply/return water is discharged/charged, respectively, in which thermal layer exists between the supply and return water. The stabilization of thermal layer is very important to discharge or charge the water. In this study, the effect of the thermal layer thickness is not take into account.

Figure 31 represent thermal storage tank, in which there are two basically hot and cool fluids with thermal stratification. It is assumed that the tank consists of number, N (<15) fully mixed equal volume segments, meaning the degree of stratification is determined by the value of N. If value of M is 1, the fluids inside tank are fully mixed and no stratification effects are possible.

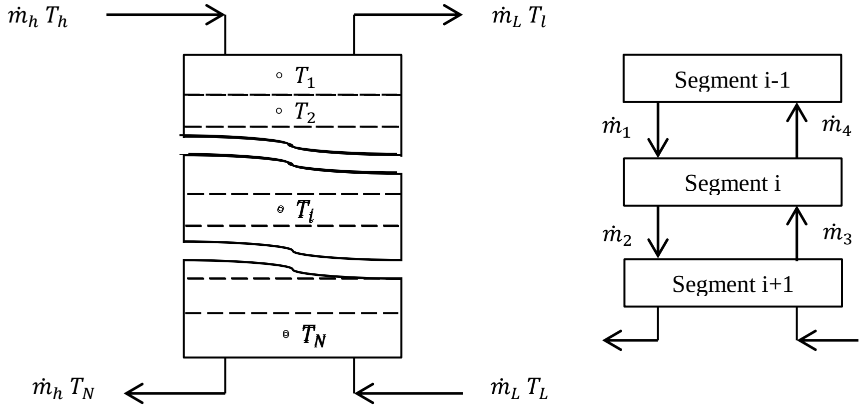


Figure-31 Stratified Thermal Storage Tank and Flow Streams Segments

An energy balance around flow streams segments is expressed by: [26]

$$M_i\, C_{p,f} \frac{dT_i}{dT} = \alpha_i\, \dot{m}_h\, C_{p,f}\, (T_h - T_i) + \beta_i\, \dot{m}_L\, C_{p,f}\, (T_L - T_i) + UA_i\, (T_{env} - T_i) \tag{4.36}$$

$$+ \gamma_i\, C_{p,f}\, (T_{i-1} - T_i) \qquad \text{if } g_i > 0$$

$$+ \gamma_i\, C_{p,f}\, (T_i - T_{i+1}) \qquad \text{if } g_i > 0$$

$$+Q_i > 0 \qquad \text{for i=1,N}$$

Where,

M_i	Mass of fluid in the ith section
$C_{p,f}$	Specific heat of the tank fluid
A_i	Surface area of the ith tank segment
α_l	Control function defined by α_i = 1 if i = S_h; 0 otherwise
β_l	Control function defined by β_i = 1 if i = S_h; 0 otherwise
γ_i	A control function defined by $\gamma_i = \dot{m}_h \sum_{j=1}^{i-1} \alpha_j - \dot{m}_L \sum_{j=1+1}^{N} \beta_i$
Q_i	Rate of energy input by the heating element to the ith segment

Energy flows and changes in internal energy are calculated by:

$$\dot{Q}_{env} = \sum_{i=1}^{N} UA_i\,(T_i - T_{env}) + \gamma_f \sum_{i=1}^{i=l}(UA)_{i,i}\,(T_i - T_f) \tag{4.37}$$

$$\dot{Q}_s = \dot{m}_L\, C_{p,f}\,(T_i - T_L) \tag{4.38}$$

$$\dot{Q}_{in} = \dot{m}_L\, C_{p,f}\,(T_h - T_N) \tag{4.39}$$

$$\Delta E = V_{\rho_f} C_{p,f}\left[\sum_{i=1}^{N} T_i - \sum_{i=1}^{N} T_i\,|_{t=tome\ 0}\right]/\mathrm{N} \tag{4.40}$$

Where,

$\dot{Q}_{env}$	Rate of energy loss from the tank to the surroundings, including boiling effects if applicable
$\dot{Q}_s$	Rate at which sensible energy is removed from the tank to supply the load
$\dot{Q}_{in}$	Rate of energy input to tank from hot fluid stream
ΔE	Internal energy change

4.3.13 Auxiliary Boiler System

TESS (Thermal Energy Systems Specialists) component of “Type 700” is used for modeling auxiliary gas fired boiler system. Basically, Type700 model is a simple steam boiler according to ASHRAE. The boiler is defined by its overall efficiency (called output/input method) and by its combustion efficiency [(input energy-stack energy)/input energy]. Using this model, the energy output is transferred to hot water fluid instead of steam flow. There are two parameters: boiler efficiency and the combustion efficiency.

4.3.14 Absorption Chiller System

TESS (Thermal Energy Systems Specialists) component of “Type 677-2” is used for modeling a double effect hot water fired absorption chiller for this study. Table 18 shows the parameters of the component.

In an absorption chiller, water is used for a refrigerant, and aqueous lithium bromide (LiBr) is used for an absorbent. Hot water is used as a heating source to give heat the diluted solution in high temperature generator, in which the water is vaporized from the diluted solution. The cooling water is used to condense the water vapour boiled off from the low-temperature generator. Then, the condensed water in the condenser is sent to the evaporator, in which the condensed water evaporates, absorbing heat from the returned chilled water, making lower temperature of chilled water supplying. This model of Double effect, hot water fired absorption chillers are most commonly used in cogeneration with district heating supply system. Figure 32 illustrates system schematic of double effect hot water fired absorption chiller and its absorption cycle. [34]

Table-18 Parameter of Double Effect Hot water-fired Absorption Chiller

Parameter	Value	Unit	Parameter	Value	Unit
Rated Capacity	13,900,000	kJ/h	Logical unit for S3 data file(default)*	41	-
Rated C.O.P	1.21	-	Number of CW temps. in S3 data file (default)*	4	-
Logical unit for S1 data file(default)*	39	-	Number of load fractions in S3 data file*	11	-
Number of HW temps. in S1 data file (default)*	12	-	HW fluid specific heat	4.19	kJ/kg/K
Logical unit for S2 data file(default)*	40	-	CHW fluid specific heat	4.19	kJ/kg/K
Number of HW temps. in S2 data file (default)*	5	-	CW fluid specific heat	4.19	kJ/kg/K
Number of CHW set points in S2 data file*	5	-	Auxiliary electricity power	40,000	kJ/h

Note: 1. * Data if default given from the catalogue in TRNSYS.
2. 1 UDRT=12,660.7 kJ/h

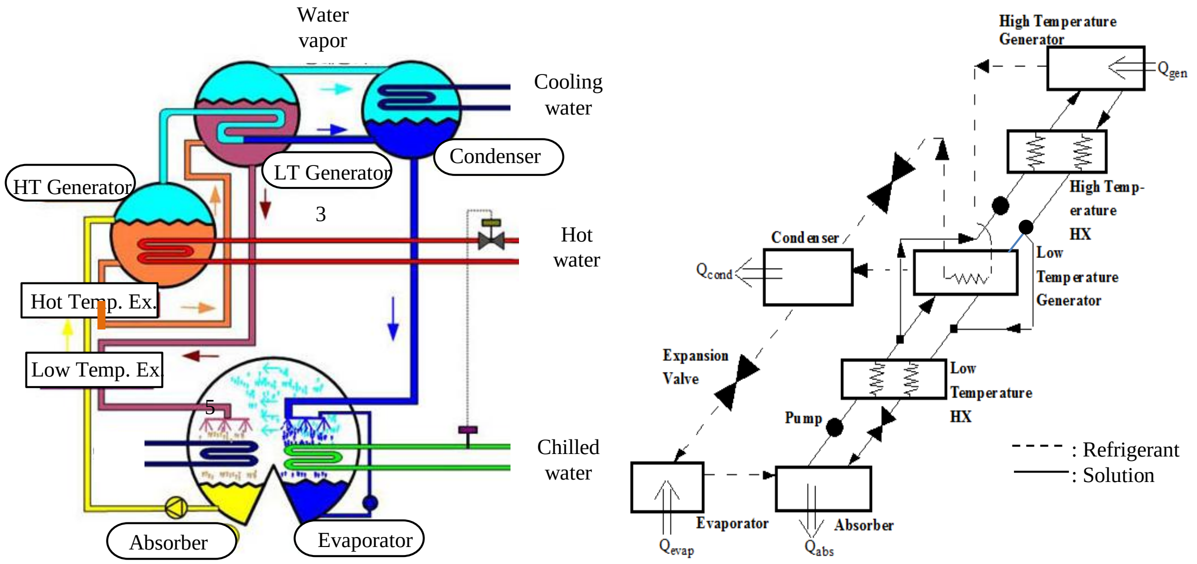


Figure-32 Schematic of Double-effect Hot water-fired Absorption chiller

The relationship between cooling load and absorption chiller is as follows: [34]

$$Q_{load} = \dot{m}_e Cp_W (T_{ei} - T_{eo}) \tag{4.40}$$

Partial load factor, PLF, defined as

$$PLF = Q_{load}/Q_{load,max} \tag{4.40}$$

Coefficient Of Performance (C.O.P) is calculated by

$$COP = f(\ PLF\ ;\ T_{chw,s}\ ;\ T_{ci}\ ;\ \dot{m}_c/\dot{m}_{c,nom}) \tag{4.40}$$

The curve of COP ration is obtained from the following equation.

$$\begin{aligned} \frac{COP}{COP_{nom}}(T_{chw,s};\ T_{ci};\ \dot{m}_c/\dot{m}_{c,nom}) &= M_0 + M_1 * PLF \\ &+ M_2 * PLF^2 + M_3 * PLF^3 + M_4 * PLF^4 \end{aligned} \tag{4.40}$$

The energy input to the absorption chiller and cooling water temperature leaving are calculated by

$$Q_{in} = \frac{Q_{load}}{COP} \tag{4.40}$$

$$T_{co} = T_{ci} + Q_{load}\ (1+\eta)/(\dot{m}_c\ Cp_w) \tag{4.40}$$

Generally, the auxiliary power consumption in kW is a function of the cooling load in tons.

$$P_{electric}\ (kW) = 0.01422 * Q_{load}\ (tons) + 5.35 \tag{4.40}$$

Where,

COP	Coefficient of performance (HHV)
COP_{nom}	Coefficient of performance at the nominal full-load conditions
Cp_w	Specific heat of the chilled water
M_{0-4}	Curve fit coefficients
$\dot{m}_c$	Cooling water mass flow rate
$\dot{m}_{c,nom}$	Nominal cooling water mass flow rate
$\dot{m}_e$	Chilled water mass flow rate
$\dot{m}_{e,nom}$	Nominal chilled water mass flow rate
η	Combustion efficiency (HHV)
$P_{electric}$	Total chiller electric energy consumed for solution pumps, controls, etc..
PLF	Part-load factor
Q_{in}	Required total heat input to the generator
Q_{load}	Total chilled water cooling load for a single chiller
$Q_{load,max}$	Nominal (rated) total chilled water cooling load for a single chiller
T_{ci}	Inlet cooling water temperature
T_{co}	Outlet cooling water temperature
T_{ei}	Inlet chilled water temperature
T_{eo}	Outlet chilled water temperature
$T_{chw,s}$	Chilled water set point (outlet chilled water temperature)

4.3.15 Cooling Tower

TESS (Thermal Energy Systems Specialists) component of "Type 510" is used for modeling a closed circuit cooling tower system for this study. Table 19 shows the parameters of the component.

Table-19 Parameter of Cooling Tower

Parameter	Value	Unit	Parameter	Value	Unit
Humidity mode(2:RH)	2	-	Design air flow rate	5367	Kg/hr
Design inlet fluid temperature	32.2	C	Air pressure at design conditions	1.0	atm
Design outlet fluid temperature	29.4	C	Rated fan power	5369	Kj/hr
Design fluid flow rate	5678	Kg/hr	Number of power coefficients	3	-
Fluid specific heat	4.19	kJ/kg.K	Power coefficient-1 (n/a)	-	-
Design ambient air temperature	35.0	C	Power coefficient-2 (n/a)	-	-
Design wet bulb temperature	25.6	C	Power coefficient-3 (n/a)	-	-

In a cooling circuit system, a hot water stream contact directly with an air stream and cooled by sensible heat transfer. The streams pathway between water and air may be configured in either counter flow or cross flow configuration. In order to increase contacting surface of water and air in the streams, a fill material is used. Water evaporates in the tower, resulting a water loss which is replaced with make-up water to the sump. The model is multi-cell counter flow cooling tower with sump.

4.4 Dispatch Control Strategy

The economic dispatch strategic logic in renewable (PV array), fuel cell, and cogeneration system is whether to charge with DC generated by PV array or to convert AC generated by cogeneration system into a hydrogen gas for utilizing fuel cell system. Generally, there may be several methods for providing the dispatch strategy. The first is the term of load-following, where the cogeneration unit just generates enough power to serve the load. The second is cycle-charging whereby the excess power is used to convert into a hydrogen gas by electrolysis whenever it runs. The last is the strategy which combines both strategies. In this study, the main purpose of providing dispatch strategy is to intend to control and manage the system such that the system can be dispatched at the request of both electricity and thermal load. Therefore, this study focuses on physical dispatch strategy using the term of load-following strategy.

The nomenclatures used in control strategy are as follows:

P_{PV}	[W] Power generated by the PV Array
P_{GT}	[W] Power generated by the gas turbine combined system (GTCS)
P_{GT_max}	[W] Rated power generated by GTCS

P_{GT_set}	[W] Power set-point for GTCS
P_{GT_min}	[W] Minimum power generated by GTCS
$P_{FC,min}$	[W] Minimum (idling) Power of the fuel cell system
$P_{FC,max}$	[W] Rated power of the fuel cell system
$P_{FC,set}$	[W] Power setpoint for the fuel cell system
$P_{Ely,min}$	[W] Minimum (idling) power of the Electrolyzer
$P_{Ely,max}$	[W] Rated power of the Electrolyzer
$P_{Ely,set}$	[W] Power setpoint for the Electrolyzer
P_{Load}	[W] Power to the load
P_{dump}	[W] Dumped power
P_{busbar}	[W] Power balance on the grid bus bar
SOC_{H2}	[-] State Of Charge of the hydrogen gas storage
EL_{low}	[-] State Of Charge for which the Electrolyzer is switched ON
EL_{up}	[-] State Of Charge for which the Electrolyzer is switched OFF
FC_{low}	[-] State Of Charge for which the Fuel Cell is switched OFF
FC_{up}	[-] State Of Charge for which the Fuel Cell is switched ON
$X_{GT.Max.Therm.}$	[W]Thermal capacity of cogeneration unit
$X_{GT.Part.Elec.}$	[W]Partial electric load portion of cogeneration unit
$X_{GT.Part.Therm.}$	[W]Partial thermal load portion of cogeneration unit
$Q_{Load.Heat}$	[W]Heating and domestic hot water load demand at time
$Q_{Load.Cool.}$	[W]Cooling load demand at time t
$Q_{FuelCell.Ther}$	[W]Thermal supply of fuel cell system at time t
$Q_{GT.Ther}$	[W]Thermal supply of cogeneration unit at time t
$Q_{Tank.Ther}$	[W]Thermal supply of thermal storage tank at time t
$Q_{AuxBolier.Ther}$	[W]Thermal supply of auxiliary boiler at time t
COP_{Abs}	[-]Absorption chiller coefficient of performance

Figure 33 represents a graphic diagram of the dispatch strategy. Excess electric power from PV array is first placed into the electrolysis, and in the case the hydrogen in the tank is full state of charge, the electricity is dumped either onto the grid or into the ground based on whether the system is a grid-connected or stand-alone, respectively. Excess thermal energy is dumped as waste heat through an exhaust. The following is the step by step dispatch strategy, which is modified from the basic concept.[26] The supervisory controller controls the Micro-grid bus bar power balance, assuming that the minimum load of gas turbine combined system, the fuel cell system, and electrolyzer are idling:

$$P_{busbar} = P_{PV} + P_{GT} + P_{FC,min} - P_{Load} – P_{Ely,min}$$

Stage-1 Excessive power ($P_{BUSBAR} > 0$)

a) If the electrolyzer is currently OFF (Idling):
    (1) If $SOC_{H2} < EL_{low}$, switch ON:
        Operate with $P_{ely,set} = P_{PV} + P_{GT} + P_{FC,min} – P_{load}$
    (2) Else, remain OFF (Idling)

b) If the electrolyzer is currently ON:
    - (1) If $SOC_{H2} > EL_{up}$, switch OFF (Idling)
    - (2) Else, keep operating and $P_{ely,set} = P_{PV} + P_{GT} + P_{FC,min} – P_{load}$

    Constraints on $P_{Ely,set}$: If $P_{Ely,set} > P_{Ely,max}$ then $P_{Ely,set} = P_{Ely,max}$

c) If $P_{Ely,max}$ was reached: $P_{dump} = P_{PV} + P_{GT} + P_{FC,min} - P_{Load} – P_{Ely,set}$

Stage-2: Power Deficit ($P_{BUSBAR} < 0$)

a) Switch off fuel cell if necessary, based on the H_2 storage tank level
    - (1) Switch Fuel cell to idling mode if the fuel cell is currently ON and SOC < FC_{low}
    - (2) Keep idling if the fuel cell is currently OFF and $SOC_{H2} \leq FC_{up}$

b) Gas turbine combined system (GTCS), Electrolyzer and Dump
    - (1) If the fuel cell is currently OFF (idling):
        - (a) Calculate the minimum operating of GTCS that generates a power excess, assuming the electrolyzer is idling.

          $(P_{PV} + P_{GT} + P_{FC,min} - P_{Load} – P_{Ely,min}) \geq 0$
        - (b) Electrolyzer operates at $P_{Ely,set} = P_{PV} + P_{GT} + P_{FC,min} - P_{Load}$
        - (c) No dumped power: $P_{Dump} = 0$
    - (2) If the fuel cell is currently ON:
        - (a) Calculate the minimum operating of GTCS that generates a power excess, assuming the electrolyzer is idling and the fuel cell is at maximum power.

          $(P_{PV} + P_{GT} + P_{FC,max} - P_{Load} – P_{Ely,min}) \geq 0$
        - (b) Assume electrolyzer is idling
        - (c) Set Fuel cell power:
            - $P_{FC,set} = P_{Load} + P_{Ely,min} - P_{PV} - P_{GT}$
            - If $P_{FC,set} < P_{FC,min}$ then impose $P_{FC,set} = P_{FC,min}$
        - (d) Set Electrolyzer power to use all power that would be dumped:
            - $P_{Ely,set} = P_{PV} + P_{GT} + P_{FC,max} – P_{load}$

The supervisory controller calculate a power set point for the controlled components in addition to the required power of GTCS. The power setpoint for the fuel cell and the electrolyzer are connected to power conditioning devices (Type 175 of TRNSYS) for electrolyzer and the fuel cell system.

Stage-3: All steps of the dispatch strategy reaches to this step, which becomes concerned with meeting the thermal load demand including cooling load. There are two pathways:

(a) If $Q_{Load.Heat.(t)}$+ $Q_{Load.Cool.(t)}$ =< ($Q_{Cogen.Ther.(t)}$ + $Q_{FuelCell.Ther.(t)}$ + $Q_{Tank.Ther.(t)}$),then reduce the discharge thermal energy from thermal storage tank.
   (i) If $Q_{Load.Heat.(t)}$+ $Q_{Load.Cool.(t)}$ = ($Q_{Cogen.Ther.(t)}$ + $Q_{FuelCell.Ther.(t)}$),then the dispatch strategy is finished for time, *t*.
   (ii) If $Q_{Load.Heat.(t)}$+ $Q_{Load.Cool.(t)}$ < ($Q_{Cogen.Ther.(t)}$ + $Q_{FuelCell.Ther.(t)}$),then excess thermal energy is dumped through the exhaust and dispatch strategy is finished for time, *t*.

(b) If $Q_{Load.Heat.(t)}$+ $Q_{Load.Cool.(t)}$ > ($Q_{Cogen.Ther.(t)}$ + $Q_{FuelCell.Ther.(t)}$ + $Q_{Tank.Ther.(t)}$) then auxiliary boiler starts to operate to meet the thermal load and dispatch strategy is finished for time, *t*.

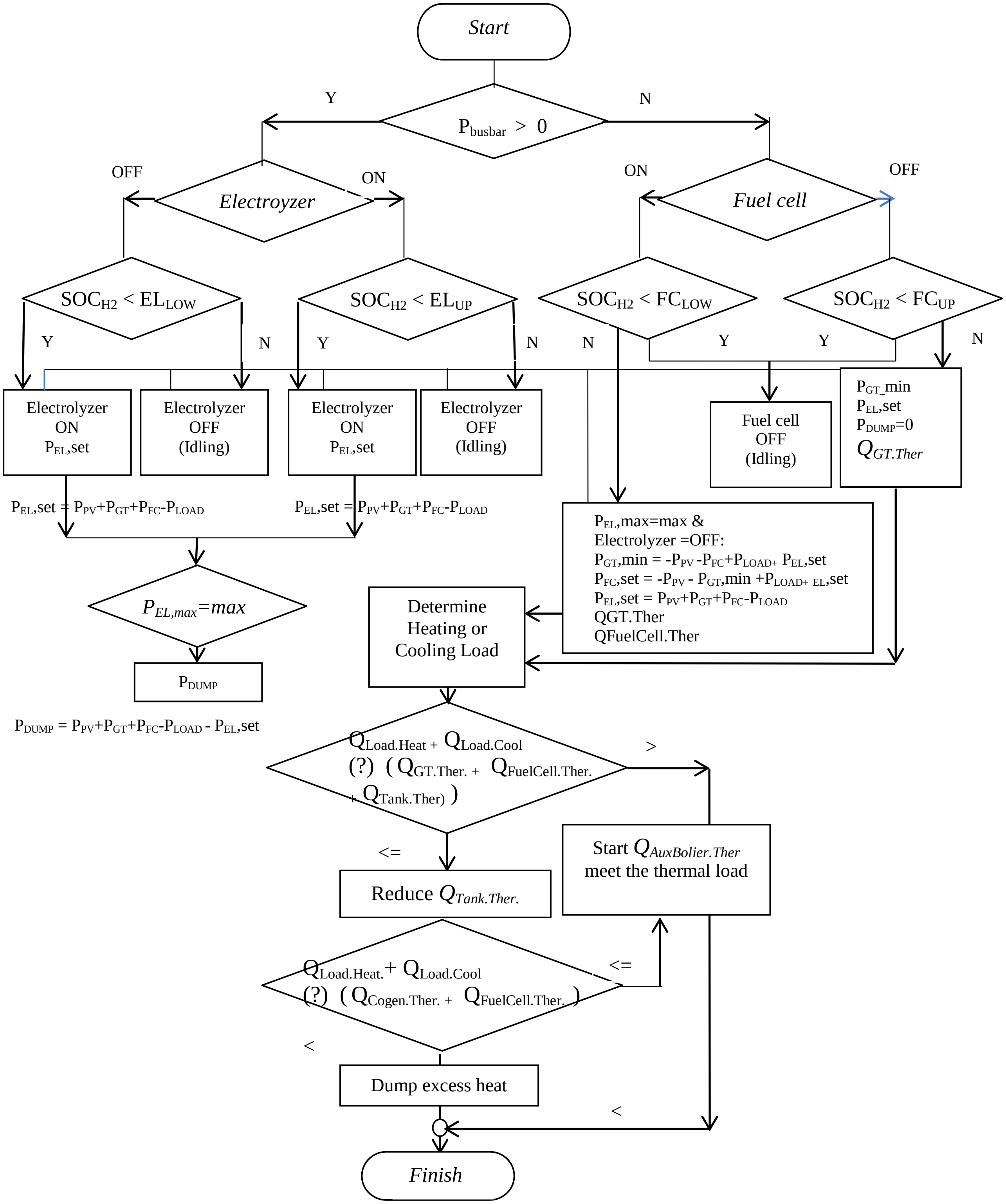


Figure-33 Schematic Diagram of Dispatch Control Strategy

Chapter 5

TRANSIENT SIMULATION AND RESULT

5.1 Main Equipment Summary and Overall Operation

The main equipment/ components applied to this cogeneration system model are shown in Table 20.

Table-20 Main Equipment Summary

Equipment/Components	Unit	Data	Equipment/Components	Unit	Data
PV Array with Inverter			Gas turbine combined		
Type	-	Crystalline	Type	-	Combined
Module Area	m^2	0.89	Gas turbine power	kW	7,100
Reference Insolation	W/m^2	1,000	Steam turbine power	kW	1,600
Insolation at NOCT*	W/m^2	800	Max. Power gen.	kW	8,700
Number of cells in series	-	36	HRSG** steam	bar	50
No. of cells in parallel	-	50,000	Unit	-	One
Max. Power Generation	kW	5,350			
Fuel Cell with Inverter			Auxiliary Boiler		
Type	-	PEMFC	Type	-	Hot water
Electrode Area	cm^2	232	Capacity	kW	15,400
Number of cells in series	-	10	Fluid temperature	°C	120
No. of cells in parallel	-	350	Fluid pressure	bar	16
Max. Power Generation	kW	3,000			
Electroluzer with Inverter			District Heating System		
Type	-	PEMFC	Fluid Type	-	Hot water
Electrode Area	m^2	0.25	Capacity	kW	18,800
Number of cells in series	-	2,000	Flow rate	ton/h	330
No. of cells in parallel	-	30	Fluid supply temp.	‘C	115~98
Max. Power	kW	4,520	Fluid return temp.	‘C	65~55
Hydrogen Storage Tank					
Type	-	Horizontal	-		
Capacity	m^3	100			
Pressure	bar	200			

Note: * NOCT: Normal Operating Cell Temperature
**HRSG: Heat Recovery Steam Generator

In order to the better understanding of hourly operation of the system, typical outputs of the model’s simulation are presented and the characteristics of system operation are investigated in this chapter. Power is generated by PV array, fuel cell system, and gas turbine combined system (GTCS). Thermal heat is produced through fuel cell and GTCS while generating electricity. In addition, auxiliary boiler is operated to follow energy demand. Figure 34 and Figure 35 illustrate the variations of power and thermal energy outputs, and component operation to meet the load.

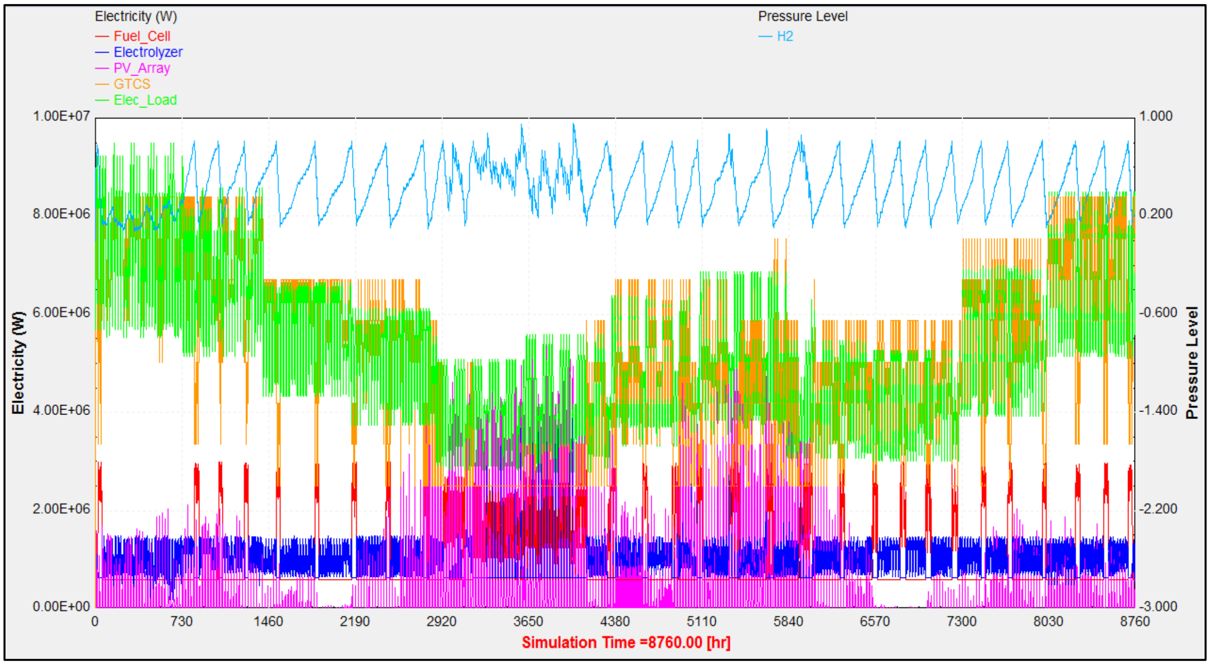


Figure-34 Variations of Electricity Output

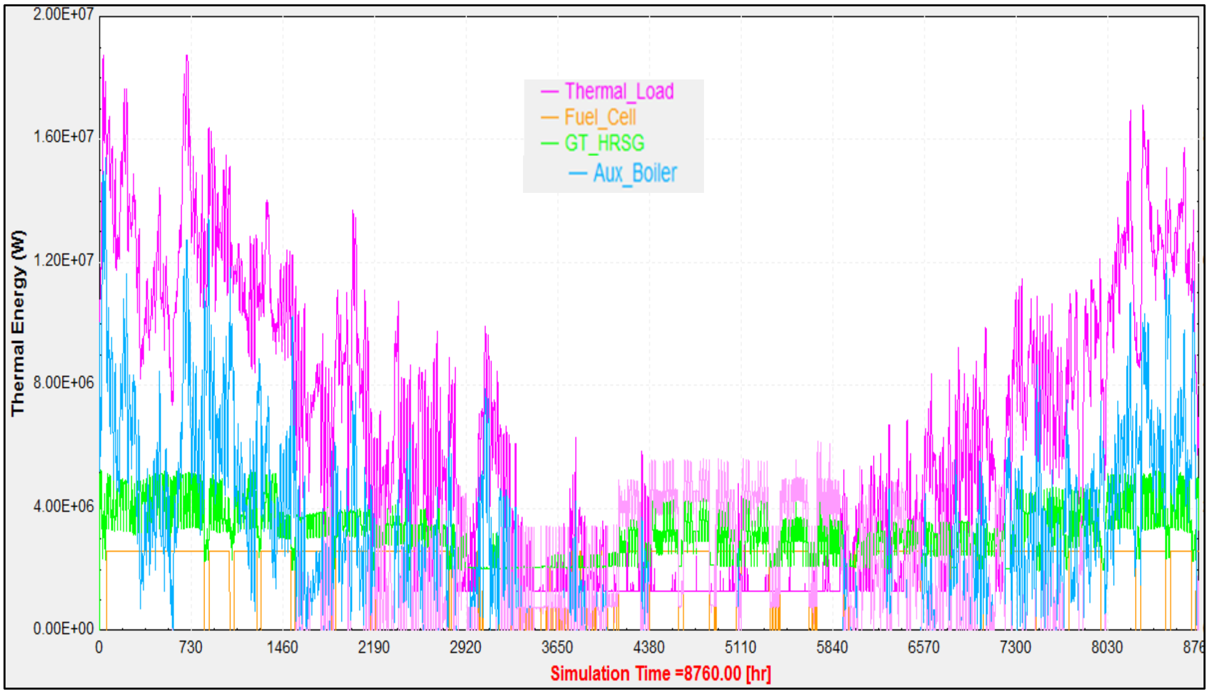


Figure-35 Variations of Thermal Energy Product

In figure 34, energy generating components of fuel cell, PV array, and GTCS produce electricity to meet the electricity load with cycle-charging control strategy. Excessive power is used to convert it to hydrogen gas through electrolysis. So, operating variation curves of electrolysis and hydrogen tank are shown in this figure. While generating electricity from the components, thermal heat is generated as a by-product.

In figure 35, by-produced thermal heat is supplied preferentially to the consumer, then auxiliary boilers (or, heating only boilers) cover the deficits to meet the load in high thermal load seasons. However, in low load seasons like in summer, the thermal heat produced may higher than the load like in this figure. In this case, the excessive thermal heat can be reserved into an accumulating system or dumped to any places.

5.2 Heat-to-Power Ratio

One of important concept related to cogeneration system is Heat-to-Power ratio. Basically, Heat-to-Power ratio is defined as the proportion of thermal energy (steam or hot water) to power (electrical or mechanical energy) produced in cogeneration system. Heat-to-Power ratio depends on performance characteristics of energy product facility.

$$\text{Heat-to-Power Ratio, } x = \frac{Heat}{Power} \tag{5.1}$$

$$Heat = \frac{x}{1+x} \tag{5.2}$$

$$Power = \frac{1}{x+1} \tag{5.3}$$

The average Heat-to-Power ratio of the facilities in this study is about 0.9, which is not a big fluctuation all the year. For the thermal and electricity load demands point of view, Heat-to-Power ratio of load in winter season is about 1.4 while that in summer season is about 0.6, which shows in Figure 36. The Heat-to-Power ratio of the facilities is lower than that of load in winter season while it is higher than that of load in summer season. In winter season, the thermal energy is produced by heating only auxiliary boiler to meet the balance thermal load. However, in summer season, the excessive thermal energy produced is to be dumped to other part or consumed by other consumers.

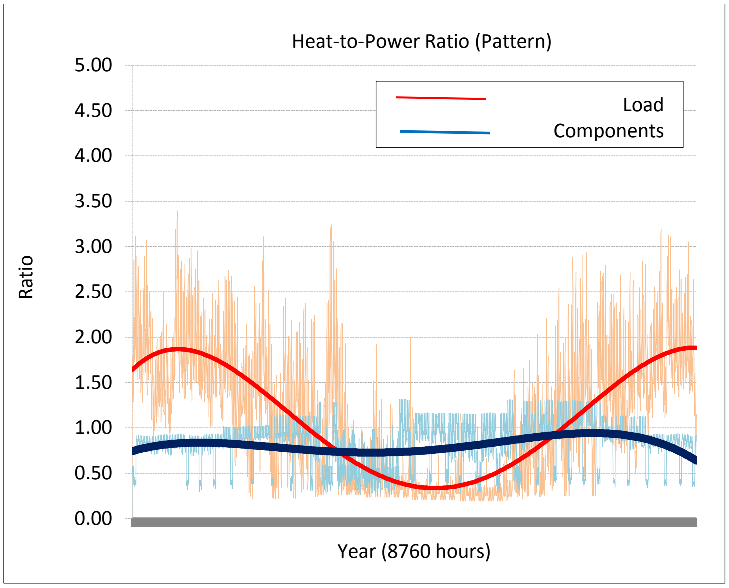


Figure-36 Heat to Power Ratio

5.3 Feasible System Configurations

This cogeneration model is capable of meeting the hourly electric and heating loads, considering each dynamic characteristic of component. The model is analyzed that the annual excessive electricity production is about 0.040 % of its power capacity and unmet load is nearly zero (0.00%). The amount of excessive electricity is too small, so it can be acceptable to a real system. The main reason why the excessive electricity can be kept within the acceptable value is installation and proper operation of electrolyser, which produces hydrogen gas using the excessive electricity while main gas turbine combined system (GTCS) operates at a constant load. In thermal energy supply, the annual excessive thermal production is about 16.5 % of its thermal capacity and unmet load is nearly zero (0.00 %). The excessive thermal energy is high because the Heat-to-Power ratio of component is higher than that of load especially in summer season. The excessive thermal energy can be reduced by introducing thermal accumulating system.

Considering lower excessive energy production and unmet load, it verifies that the cogeneration system model agree very well with the feasible system configurations. Figure 37 and Figure 38 illustrates annual excessive production and unmet load of cogeneration system model.

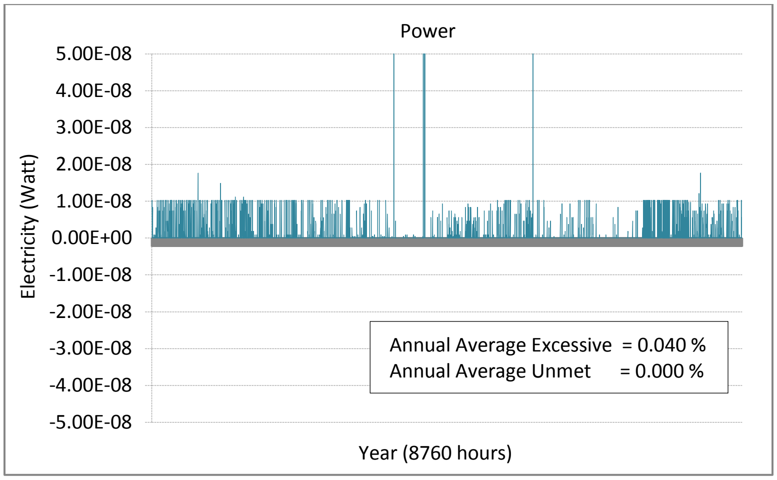


Figure-37 Annual Excessive Production and Unmet Power Load

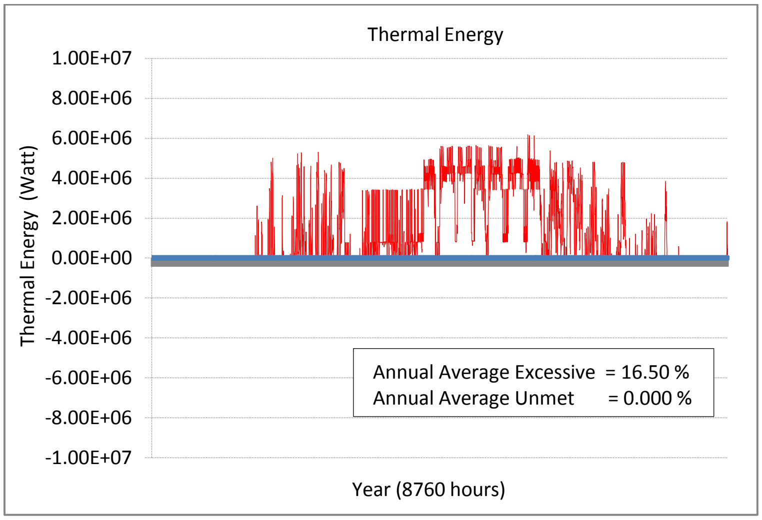


Figure-38 Annual Excessive Production and Unmet Thermal Load

5.4 Capacity Factor, Energy Supply Portion, and Renewable Contribution Ratio

One of factors to acknowledge the amount of contribution of the component to the loads is capacity factor which is defined as “the Capacity factor (CF) is the ratio of the actual energy produced in a given period, to the hypothetical maximum possible, i.e. running full time at rated power.” [35]

$$CF = \frac{Annual\ Energy\ Produced\ by\ component}{Energy\ Supply\ Capacity\ of\ component\ x\ 8760} \qquad (5.4)$$

Capacity factor is an indicator of how much energy a particular component of the system makes in a particular load. Generally, higher capacity factor may be better and more economical in a particular system configuration. However, it does not make sense to evaluate different technologies with only a capacity factor, because each technology has its own economics of both production and capacity. Normally, in cogeneration system, the capacity factor is used to judge if a system and/or component is feasible and to compare the cost of producing energy among the different energy production system. The energy supply portion (ESP) is defined in this study as the ratio of annual energy produced by a component to total energy production of the system. SP means the energy contribution ratio of a component to total system production.

$$\text{ESP} = \frac{Annual\ Energy\ Generated\ by\ component}{Total\ Energy\ Production} \qquad (5.5)$$

Renewable contribution ratio (RCR) is defined in this study as the ratio of annual energy produced by renewables to total energy production of the system. RCR is the sum of ESP of renewables.

$$\text{RCR} = \sum(ESP: Renewables) \qquad (5.6)$$

The capacity factor and energy supply portion of PV array are analyzed 7.97% and 6.66%, respectively, which means that PV array produces a small portion of total annual electricity production, comparing to its capacity. Because the PV array does not produce power without irradiation; sometimes the PV array reduces its power production according to weather condition. PV array is not dispatchable, however, the excessive electricity is used to generates hydrogen gas through electrolzer.

For fuel cell system, capacity factor and energy supply portion of electricity are 31.18% and 14.59, respectively while those of thermal energy are 74.79% and 26.28%, respectively. The capacity factor of fuel cell system is high because the fuel cell system can be operated using hydrogen fuel, which is generated by electrolyzer and being storage in hydrogen storage tank. The fuel cell system is dispatchable.

The GTCS's capacity factors are 60.05% for electricity and 61.02% for thermal energy, respectively. The factors are the highest in the system, meaning that the GTCS is main a component having the highest capacity and energy supply portion in the system. The GTCS is absolutely dispatchable.

Table 21 shows the capacity factor and energy supply portion of component.

The renewable contribution ratio (RCR) is calculated about 23.5% for the model.

Table-21 Capacity factor and Energy supply portion

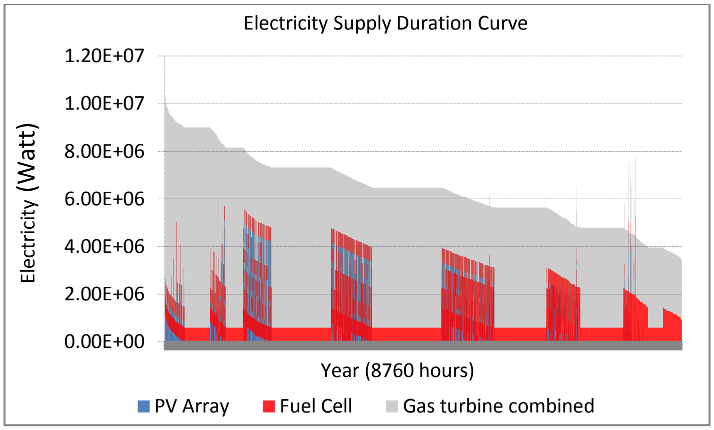
(a) Electricity

Description	Demand			Supply			
	Elec.Load	Elctrolyser	Sum	PV Array	Fuel Cell	Gas turbine combined	Sum
Max. (x 10^6 W)	9.51	4.52	9.51	5.35	3.00	8.40	16.75
Annual (x 10^6 Wh)	47,355.32	8,729.11	56,084.43	3,739.15	8,187.95	44,186.52	56,113.62
Supply Portion (%)	-	-	-	6.66	14.59	78.74	100.05
Capacity Factor (%)	56.86	22.05	67.34	7.97	31.18	60.05	38.24

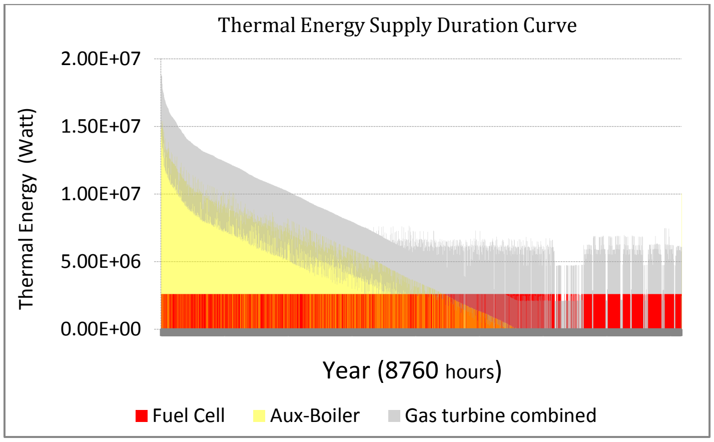
(b) Thermal Energy

Description	Demand			Supply			
	Heating	Cooling	Peak	Fuel Cell	Gas turbine combined	Aux Boiler	Sum
Max. (x 10^6 W)	18.77	10.75	18.77	2.62	5.27	15.41	23.31
Annual (x 10^6 Wh)	44,045.14	10,622.99	54,668.14	17,207.57	28,183.79	20,090.72	65,482.08
Supply Portion (%)	-	-	-	26.28	43.04	30.68	100.00
Capacity Factor (%)	26.79	11.28	33.25	74.97	61.02	14.88	32.07

Figure 39 illustrates energy supply duration curves. In the figure, the left axis value is the accumulated capacity of the components and the area of x-axis and y-axis means the energy generated by the components.



(a) Electricity



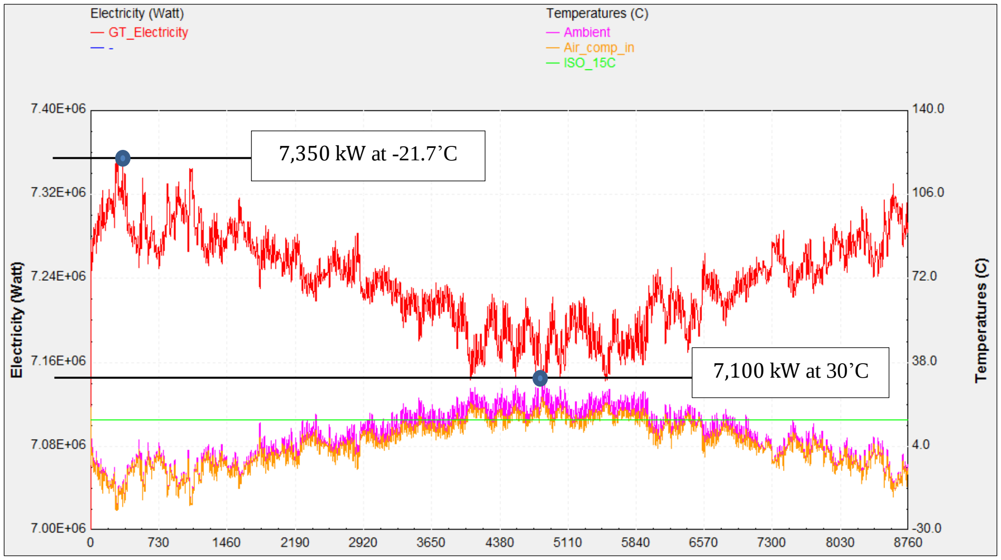
(b) Thermal Energy

Figure-39 Energy Supply Duration Curve

5.5 Gas Turbine Unit Performance at Variable Ambient Temperature

Throughout the typical meteorological year condition, the variation air temperature entering evaporative cooler ranges from -18.8℃ (winter) to 33.8 ℃ while 15 ℃ in steady state condition based on ISO (Ambient Temperature - 15 deg C, Relative Humidity - 60 % and Ambient Pressure at Sea Level). [36] The mass flow rate of air entering the evaporative cooler varies with the ambient conditions. And, the net power generated from the gas turbine system ranges from 7,100kW (summer seasons) to 7,350kW (winter seasons) while the power in ISO condition is 7,250kW because of different air density entering gas turbine system as shown in Figure 41.

The peak load occurs in winter season. Therefore, the capacity of gas turbine can be sized according to transient simulation output in winter season, which would be 7,100kW, It can downsized by 150kW from the capacity in ISO condition. Figure 41 illustrates power output from the gas turbine at transient and ISO conditions.



7,350 kW at -21.7’C

7,100 kW at 30’C

Figure 40 Power Output from the Gas Turbine at Transient Conditions.

5.6 Transient System Efficiency

Transient system efficiency is a basic data for estimating energy production cost for Time-Of-Use (TOU): dynamic rates for connecting retail customer with wholesale conditions. The model can produces predictable real time operating data such as energies’ load patterns and component’s operating characteristics which enable estimated energy production cost. So, the operator can provide dynamic rate program such as TOU considering peak load, events, and total consumption cases. The transient system efficiency of cogeneration system is defined in clause 2.2, Chapter 2 in this study.

Total cogeneration system efficiency EFF_{Cogen} , effective efficiency of separate heat and power EFF_{SHP}. , and Cogeneration Efficiency Index (CEI) are analyzed to investigate the characteristics of transient system efficiency and verify if cogeneration system is more efficient than separate heat and power generations using CEI.

The amount of solar radiation energy entering PV array is added to the energy input in this study. The annual average efficiency of the model EFF_{Cogen} is approximately 65.5%, which is about 12.6% higher than effective efficiency of separate heat and power generations EFF_{SHP} of 52.9%. The comparison is based on assumptions that the separate generations’ efficiency is 40% for power and 80% for thermal, respectively.

Cogeneration Efficiency Index (CEI) is calculated as 1.23, which means that cogeneration system is more efficient than effective efficiency of separate generations.

Figure 41 and figure 42 show transient efficiencies for cogeneration and separate generations, respectively, and figure 43 represents transient Cogeneration Efficiency Index (CEI).

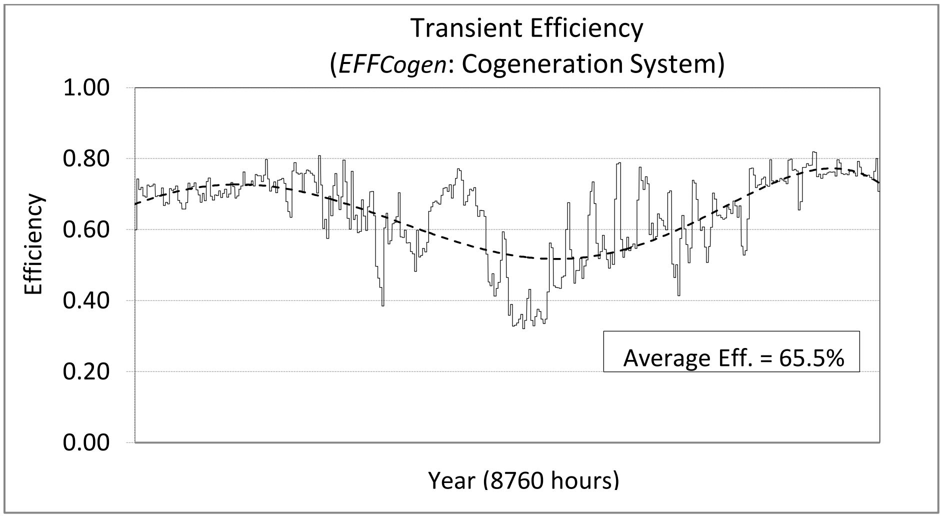


Figure-41 Transient Cogeneration System Efficiency

In figure 41, the efficiency in winter seasons is about 70% while that in summer season is about 55%. The efficiency depends on mainly several factors: the electricity and thermal load pattern that should be met, Heat-to-Power ratio of component, and ambient conditions such as air temperature and irradiation amount that can influence the performance of gas turbine unit and PV array.

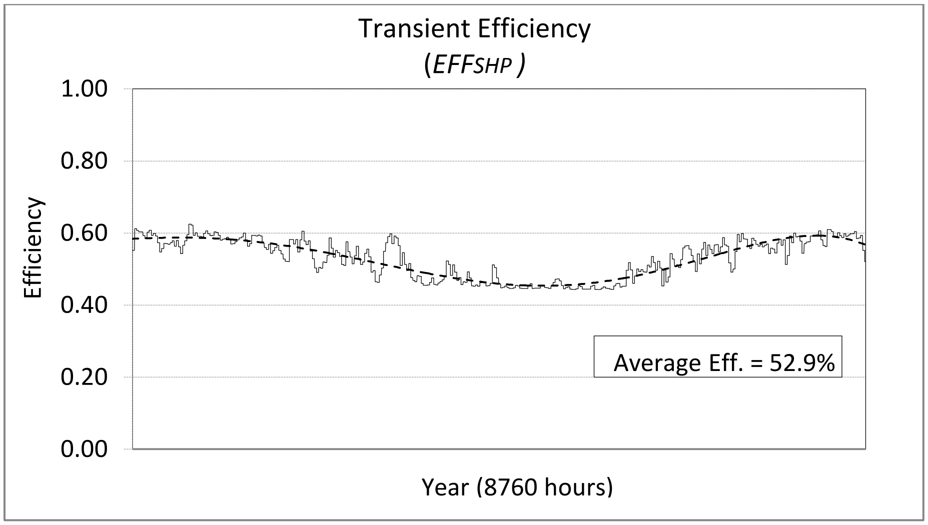


Figure-42 Transient Effective Efficiency of Separate Heat and Power Generation

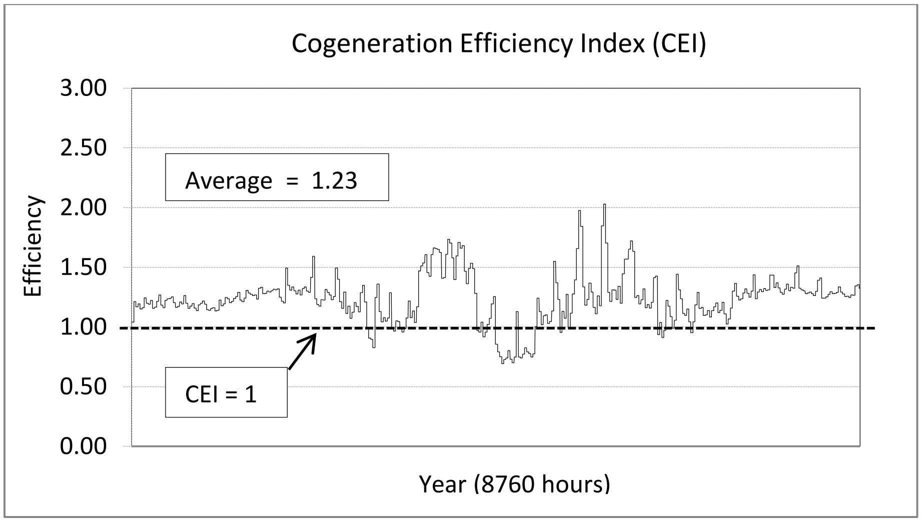


Figure-43 Transient Cogeneration Efficiency Index (CEI)

In figure 43, the annual average CEI is 1.23 showing cogeneration systems is more efficient than effective efficiency of separate heat and power generation. However, CEI level at a certain time appears below 1.0, meaning cogeneration system efficiency could be less efficient than that of separate generation, especially in summer seasons. A key factor causing low CEI is an energy unbalance between loads and energy production of the system. This phenomenon can occurs in the summer seasons with low Heat-to-Power ratio.

The transient efficiency gains of introducing the cogeneration model are the highest because of the following reasons: The higher efficiency gives benefits to the related stakeholders, conventional power plant instead should generate low temperature heat (below 115℃), diverse operating modes enable optimal operation to meet diverse load variations, and transient system efficiency provides a basic data for estimating energy production cost for Time-Of-Use.

For further investigating the simulated model, seasonal operation in summer and winter are discussed

5.7 Winter operation

A typical monthly transient performance in winter season in February (during 744 to 1488 simulation hours) is simulated and main dynamic characteristics are investigated as shown in Figure 44 for electricity generation. Basically, PV array generates direct current (DC) electricity, converts it to alternating current (AC), and supply it to electrolyzer. Gas turbine combined system (GTCS) generates electricity at a constant load. When the level status of hydrogen gas tank is down to low level setting, the GTCS generates more power and supply it to electrolyzer by which hydrogen gas is generated and stored in hydrogen storage tank until the tank level status reaches to high level setting. Fuel cell system generates electricity to meet the load if the hydrogen gas is available. Hydrogen gas is generated and consumed weekly to keep the balance of demand and supply. The electricity generated in the system can be supplied to consumer through a micro grid provided in the system or a national grid.

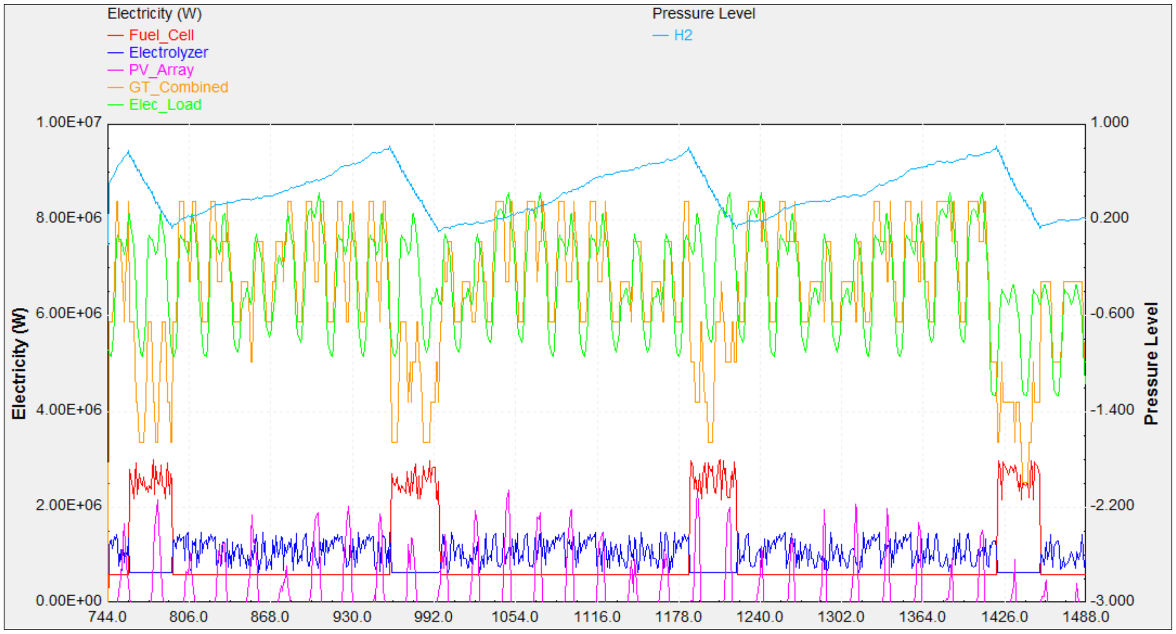


Figure-44 Transient Simulation in Winter, February – Electricity

Figure 45 illustrates thermal energy generation. The form of the thermal energy is a hot water that has high temperature, ranging from 115 ℃ to 98 ℃ for both heating and cooling purposes. Fuel cell generates thermal energy while generating electricity. which is supplied to the consumer through district heating network. There are three sources of generating thermal energy: fuel cell system, GTCS, and auxiliary boiler. The thermal storage system is not included in this model. The three sources generate thermal energy and supply it to meet the load.

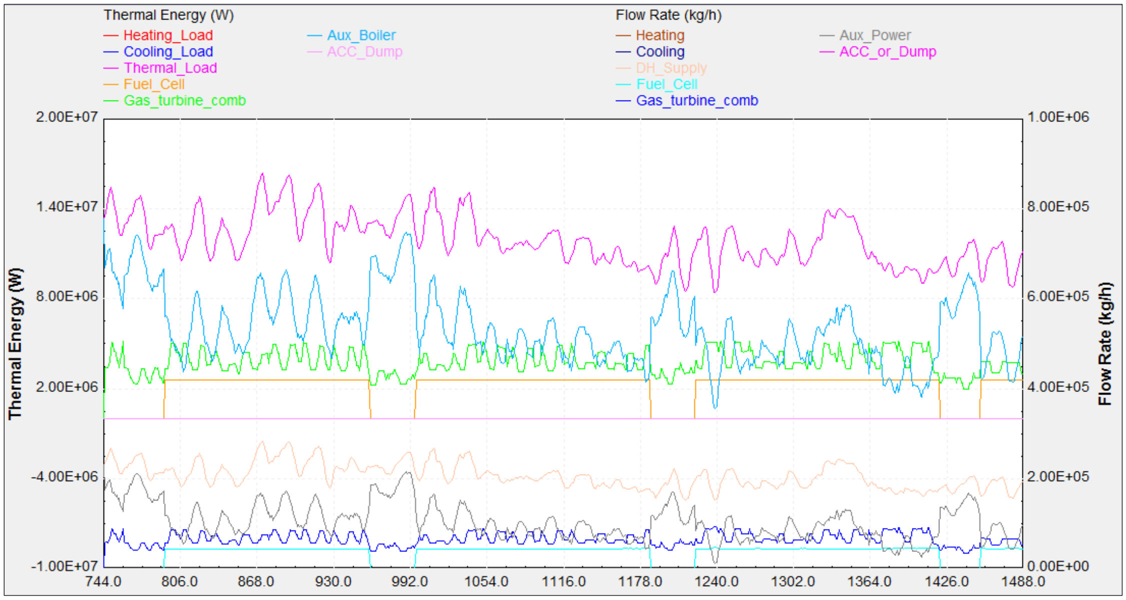


Figure-45 Transient Simulation in Winter, February – Thermal Energy

During winter operation in the typical month of February, the electricity's capacity factor of PV array, fuel cell system, and GTCS are 12.30%, 28.04%, and 81.05%, respectively. The thermal energy's capacity factor of fuel cell system, GTCS, and auxiliary boiler are 86.14%, 74.63%, and 37.71%, respectively. The capacity factors in February are higher than those in annual average because energy demand and supply are balanced and the excessive and unmet energy are analyzed nearly zero (0) %. Table 22 shows the capacity factor and energy supply portion on February.

Table-22 Capacity Factor and Energy Supply Portion on February

(a) Electricity-Februry (time 744-1488 hours)

Description	Demand			Supply			
	Elec.Load	Elctrolyser	Peak	PV Array	Fuel Cell	Gas turbine combined	Sum
Max. (x 10^6 W)	9.51	4.52	9.51	5.35	3.00	8.40	16.75
Annual (x 10^6 Wh)	5,055.69	769.94	5,825.63	490.02	625.47	5,065.20	6,180.70
Supply Portion (%)	-	-	-	7.93	10.12	81.95	106.09
Capacity Factor (%)	71.48	22.90	82.36	12.30	28.04	81.05	49.59

(b) Thermal energy-Februry (time 744-1488 hours)

Description	Demand			Supply			
	Heating	Cooling	Peak	Fuel Cell	Gas turbine combined	Aux Boiler	Sum
Max. (x 10^6 W)	18.77	0.00	18.77	2.62	5.27	15.41	23.31
Annual (x 10^6 Wh)	8,932.07	0.00	8,932.07	1,679.15	2,927.63	4,325.30	8,932.07
Supply Portion (%)	-	-	-	18.80	32.78	48.42	100.00
Capacity Factor (%)	63.97	0.00	63.97	86.14	74.63	37.71	51.51

5.8 Summer operation

A typical monthly transient performance in summer season in July (during 4,464 to 5,208 simulation hours) is simulated and main dynamic characteristics are investigated. Figure 46 shows electricity generating operation. Basically, the operating mode in summer season is very similar to that in winter season. The electricity generated in the system can be supplied to consumers through a micro grid provided in the system or a national grid.

Figure 47 illustrates thermal energy generating operation. The form of the thermal energy is a hot water that has high temperature, ranging from 115 ℃ to 98 ℃, which is supplied to a hot water absorption chiller.

During summer operation in the typical month of July, the electricity's capacity factor of PV array, fuel cell system, and GTCS are 16.71%, 40.93%, and 49.77%, respectively. The thermal energy's capacity factor of fuel cell system, GTCS, and HWB are 82.65%, 59.28%, and 0.19%, respectively.

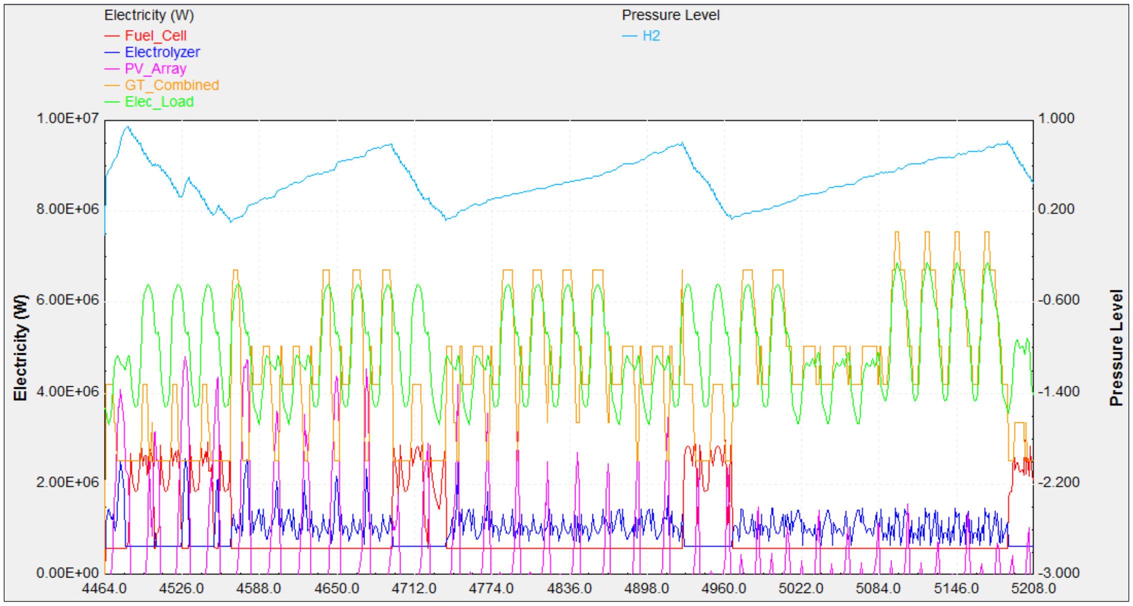


Figure-46 Transient Simulation in Winter, February – Electricity

Figure-47 Transient Simulation in winter, February – Thermal Energy

The capacity factors in July are lower than those in annual average because loads are very low and energy demand and supply are unbalanced. The excessive electricity and thermal energy are analyzed about nearly zero (0)% and 4.41 %, respectively. The unmet electricity and thermal energy are both analyzed nearly zero (0)%. Table 21 shows the capacity factor and energy supply portion on July.

Table 23 Capacity Factor and Energy Supply Portion on July

(a) Electricity-July (time 4,464-5,208 hours)

Description	Demand			Supply			
	Elec.Load	Elctrolyser	Peak	PV Array	Fuel Cell	Gas turbine combined	Sum
Max. (x 10^6 W)	9.51	4.52	9.51	5.35	3.00	8.40	16.75
Annual (x 10^6 Wh)	3,671.64	748.77	4,420.40	665.70	913.04	3,110.52	4,689.26
Supply Portion (%)	-	-	-	14.20	19.47	66.33	106.08
Capacity Factor (%)	51.91	22.27	62.50	16.71	40.93	49.77	37.63

(b) Thermal energy-July (time 4,464-5,208 hours)

Description	Demand			Supply			
	Heating	Cooling	Peak	Fuel Cell	Gas turbine combined	Aux Boiler	Sum
Max. (x 10^6 W)	0.00	10.75	10.75	2.62	5.27	15.41	23.31
Annual (x 10^6 Wh)	0.00	1,068.86	1,068.86	1,611.15	2,325.65	21.74	3,958.54
Supply Portion (%)	-	-	-	40.70	58.75	0.55	100.00
Capacity Factor (%)	0.00	13.36	13.36	82.65	59.28	0.19	22.83

5.9 Emissions

For estimating greenhouse gases (GHG) emissions emitted from cogeneration system and separate generations, the category of stationary fuel combustion sources is applied. This category source is the devices that combust gaseous fuel to produce electricity and thermal energy for residential, and commercial use as a community energy supply unit. In addition, several criteria such as facility type, fuel data, emission factors, and other emission-related information are used as well, which are provided by EPA (Environmental Protection Agency, U.S.), EIA (Energy Information Administration, U.S), and Environment Canada.

The major emissions from this category are carbon dioxide (CO_2), carbon monoxide (CO), nitrous oxide (NOx), trace amount of sulfur dioxide (SO_2), methane (CH_4), volatile organic components (VOCs), and particulate matter (PM). Among the emissions, PM emissions are typically low because the fuel is gaseous and PM itself is filterable. The amount of CH_4, CO, and VOCs produced is insignificant compared to CO_2 because they are mainly produced due to incomplete combustion conditions. Therefore, the maim emissions of CO_2, NOx, and SO_2 are calculated in this study. The operation of PV array does not include emissions because of no commotion. The operation of hydrogen fuel cell does not include concerned emissions as well. Because hydrogen is produced from electrolysis with extra electricity supplied mainly from PV array.

Calculation of pollutants is based on one of the methodologies requested by EPA's Acid Rain Program (40 CFR part 75); Tier 1. Tier 1 method is a fuel-based approach to estimate GHG emissions. Tier approach uses an emission factor that is multiplied by annual fuel use and a default heating value for that fuel.

The emission factors applied to this study are listed in Table 24.

Table-24 Emission Factors

System	Unit Type	Fuel	Emission	Emission Factor Converted (tons/10^6 Wh)	Emission Factor		Source [40]
Co-generation	Gas turbine system	Natural Gas	CO_2 :	0.18	120,000	lb/10^6 scf	AP42 Table 1.4-2
			NO_X :	0.00000097	0.64	lb/10^6 scf	AP42 Table 1.4-2
			SO_2 :	0.00000091	0.60	lb/10^6 scf	AP42 Table 1.4-2
	PV Array	Irradiation	CO_2 :	-	-		
			NO_X :	-	-		
			SO_2 :	-	-		
	Fuel Cell system	Hydrogen Gas	CO_2 :	-	-		
			NO_X :	-	-		
			SO_2 :	-	-		
	Aux. Boiler	Natural Gas	CO_2 :	0.18	120,000	lb/10^6 scf	AP42 Table 1.4-2
			NO_X :	0.00007592	50	lb/10^6 scf	AP42 Table 1.4-1
			SO_2 :	0.00000091	0.60	lb/10^6 scf	AP42 Table 1.4-2
Separate Generation	Electricity Generation	Natural Gas	CO_2 :	0.18	120,000	lb/10^6 scf	AP42 Table 1.4-2
			NO_X :	0.00000097	0.64	lb/10^6 scf	AP42 Table 1.4-2
			SO_2 :	0.00000091	0.60	lb/10^6 scf	AP42 Table 1.4-2
	Thermal Generation Boiler	Natural Gas	CO_2 :	0.18	120,000	lb/10^6 scf	AP42 Table 1.4-2
			NO_X :	0.00007592	50	lb/10^6 scf	AP42 Table 1.4-1
			SO_2 :	0.00000091	0.60	lb/10^6 scf	AP42 Table 1.4-2

Note: 1. 1 lb/10^6 scf = 1.518 x 10^-12 tons/Wh.

Emissions from various greenhouse gases (GHG) are finally converted to metric measure of carbon dioxide equivalent based on their global warming potential (GWP). GWP of a greenhouse gas is defined as " ratio of radiative forcing (both direct and indirect), from one kilogram of greenhouse gas to one kilogram of CO2 over a period of time, years" [42]. CO2 was chosen as the reference gas to be consistent with the IPCC (Intergovernmental Panel on Climate Change, U.S) guidelines. Carbon dioxide equivalent is presented in this study as “metric tons of carbon dioxide equivalents ($MTCO_2$ Eq.) “. [42] The $MTCO_2$ Eq. is the sum of metric tons of a gas multiplied by its associated GWP.

$$\mathrm{MTCO_2\ Eq.} = \sum(\text{ metric tons of a gas } \text{ x GWP of the gas }) \qquad (5.7)$$

According to calculation result, expected emissions from the cogeneration model are about 26,114 MT CO2 eq. per year while the average value of conventional separate generations are about 39,665 MT CO2 eq. per year. Compared to conventional separate generations in Ontario, the estimated annual emissions for the cogeneration model are about 34.2% (13,550 MT CO2 eq. per year) lower than those for separate plants. The average efficiencies of separate generations are assumed as 40% for electricity and 80% for thermal product. Table 25 shows the emissions comparison.

Table-25 Emissions Comparison

System	Unit Type	Capa-city (x10^6 W)	Energy Input (x10^6 Wh)	Fuel	Emission	Emission Factor Converted (tons/10^6 Wh)	Annual Emission (tons /y)	GWP	Annual Emission (MT CO_2 eq./y)
Cogen. Model	Gas turbine system	8.40	114,751	Natural Gas	CO_2 :	0.18	20,909	1	26,114
					NO_X :	0.00000097	0.11	310	
					SO_2 :	0.00000091	0.10	-	
	PV Array	5.35	32,087	Irradiation	CO_2 :	-	-		
					NO_X :	-	-		
					SO_2 :	-	-		
	Fuel Cell system	2.99	8,730	Hydrog-en Gas	CO_2 :	-	-		
					NO_X :	-	-		
					SO_2 :	-	-		
	Aux. Boiler	15.41	25,133	Natural Gas	CO_2 :	0.18	4,580	1	
					NO_X :	0.00007592	1.91	310	
					SO_2 :	0.00000091	0.02	-	
Separa-te Gen	Elect. Generation	9.51	140,284	Natural Gas	CO_2 :	0.18	25,561	1	39,665
					NO_X :	0.00000097	0.14	310	
					SO_2 :	0.00000091	0.13	-	
	Thermal Boiler	18.77	68,343	Natural Gas	CO_2 :	0.18	12,453	1	
					NO_X :	0.00007592	5.19	310	
					SO_2 :	0.00000091	0.06	-	

Note 1. 1 lb/10^6 scf = 1.518 x 10^-12 tons/Wh.
2. GWP means global warming potential.

5.10 Communications and Controls

For making proper function of cogeneration system in Smart Energy Networks (SEN), basic communications and controls are introduced to the system and consumers. The communication models or systems that describes in this clause are just one of several examples, which explain how to deploy the functions of the cogeneration communication.

For a specific example, in case of providing micro-grid for electricity supply, the cogeneration model is to provide power distribution automation on a minimum of two (2) electric circuits in the proposed area. These electric circuits are divided into outage segments of a maximum of three hundred households each, and automatically restore power if area is affected. Several assets or functions can be provided to increase reliability: for example, the System Average Interruption Frequency Index (SAIFI), which is the average number of system interruptions, the System Average Interruption Duration Index (SAIDI), which is average power outage duration for system, the Customer Average Interruption Duration Index (CAIDI), which is the average power outage duration for each customer served, and the Momentary Average Interruption Frequency Index (MAIFI), which is the average number of sub-5-minute (or "momentary") interruptions that a customer would experience.

The cogeneration system provides a high efficiency system and oil alternative energy to reduce oil consumption and replaces oil with electricity to minimize dependence on foreign oil. Several assets or functions can be provided for this purpose: Iintegrated plug-in-electric vehicles (PEV). There are variety of higher efficiencies and possible savings in Smart Energy Networks, which were described in the previous chapters. The cogeneration system provides key high efficient systems to improve asset utilization and reduce energy costs as follows: advanced metering infrastructure (AMI), smart meters (SM), wide area measurement systems (WAM), energy storage systems (ESS), plug-in-electric vehicles (PEV), and home automation networks (HAN) with web-based energy use profiles, pricing and energy management systems (EMS), and VAR control.

Table 26 shows the example of communications and controls for implementing the proper functions of cogeneration system in SEN.

Table-26 Example of Communications and Controls of Cogeneration in SEN

Objectives	Target	Source of Function	Example models/Systems
Improve Reliability	Lower blackout provability	● Fewer shortages ● Shorter shortages	● SAIFI ● SAIDI or CAIDI
	Reduced power quality events	● Fewer momentary outages ● Fewer severe sags and swells ● Lower harmonic distortion	● MAIFI
Improve Energy Security	Lower dependence on foreign oil	● Reduced oil usage ● Substituted gasoline by electricity	● CHP ● or PEV
Improve Energy Efficiency & Economic	Improved asset utilization	● Optimized generators operation ● Deferred generation capacity investment (Flattered load curve)	● AMI/Smart Meter ● Energy use profile ● Time of use pricing ● WAM ● or ESS, ● or PEV ● CHP ● Renewable Energy ● HAN
	Lower energy cost	● Flattered load curve (load shifted to off-peak period) ● Lower electricity rate (DG and CHP) ● Lower electricity consumption ● Reduced electricity losses ● Reduced natural gas losses	● HAN ● EMS ● Renewable Energy ● CHP ● or ESS, ● or PEV
	Lower O & M cost	● Reduced maintenance activity cost ● Lower equipment failure	● Diagnosis & Notification Monitor
		● Reduced Power distribution operating cost	● Automated feeder switching ● VAR control & automated voltage
		● Reduced meter reading cost	● AMI/Smart Meter
	Lower T&D losses	● Optimized T&D network ● Generations closer to load	● Renewable Energy
Environmental	Lower GHG/Carbon emissions	● Lower electricity consumption	● HAN
		● Lower T&D losses	● Renewable Energy
		● Lower emissions from	● CHP ● Renewable Energy ● Load response

Chapter 6

CONCLUSIONS AND DISSCUSSIONS

The Ontario government has ambitious goals regarding environment protection and energy supply to cope with the issues being faced. However, approaching the goals is not easy in the existing energy infrastructure. First, greenhouse gas emissions must be reduced while energy supply needs to meet the increasing demand. Second, the existing low energy-cost coal power plant of 4,400MW is expected to be replaced by gas-fired generations, but most natural gas is a foreign energy resource in Ontario. Finally, emerging renewable energy should be integrated into the grid, however, the existing grid has a limited capacity.

To approach the goals effectively, the existing energy infrastructure, supply structure, and platform should be changed to a new concept of Smart Energy Networks (SEN) beyond the Smart Grid limitations. SEN is a total energy network system consisting of grid, natural gas, and district heating and cooling systems. SEN improves system reliability, energy security and efficiency, and reduces greenhouse gas emissions by integrating communication and information technology, renewable energy, and stakeholders' active participation in effective manageable implementations.

In implementing the SEN concept, remarkable changes are expected. Firstly, the energy infrastructure will be changed from one-way communication to two-way communication. Secondly, the energy supply structure will be changed from hierarchy supply to horizontal network between energy sources. Finally, the energy platform will be shifted from a simple electricity supply to an energy supply and its related energy businesses. In addition, the energy technology will be developed to network system technology. And, energy businesses will be evolved to Distributed Generation, renewables, and total energy supply combined with electricity, natural gas, and district heating and cooling such as cogeneration system. In the new energy environment, stakeholders may face challenges and advantages. The key point is the initiatives aimed at implementing the SEN concept in the early markets with cogeneration system.

As a demonstration model in SEN, a community-scale cogeneration system is modeled using TRNSYS(Transient Analysis) software by considering SEN criteria and transient operation is simulated in this study. The electricity and thermal load are 10,013 kW and 18,767 kw, respectively. The cogeneration system model consists of 5,350 kW PV Array, 3,000 kW fuel cell system, 8,400 kw gas turbine combined system, 15,400 kW auxiliary boiler, and district heating/cooling network. It is investigated through this transient simulation study that there are significant elements to consider: 1) Transient characteristic such as hourly, daily and seasonal load variations, its patterns, and diversity factors should be investigated, which cannot be analyzed using a steady state model, 2) Heat-to-Power ratio of load and energy generation should be considered to select proper type of facilities to cope with the transient load's characteristics, 3) Excessive and unmet energy should be analyzed to investigate feasible system configuration, 4) Capacity factor and renewable contribution to energy generation should be provided to select proper facilities type, 5) Transient system efficiency should be provided for proper combination operation of PV array, fuel cell system, gas turbine combined system, and auxiliary boiler, 6) Emissions should be confirmed if it is environmental friendly, and 7) Communications and controls methodology should be prepared to deploy the proper function of the cogeneration system.

SEN has the potential to meet these goals in a more efficient, cost-effective and environmentally-sound manner. However, implementing a SEN will be a long process, for energy transformations are not revolutionary but instead are evolutionary, requiring continuous development, close cooperation between stakeholders, or a consortium for a project. Furthermore, the SEN is a very broad concept, and its implementation will be complicated and complex. Therefore, further studies on priorities for implementing a SEN, its challenges, its risks, and its collaboration are required.

The investigations of economic analysis and renewable/cogeneration system contributions to total power capacity are expected to be the subjects for further study.

Appendix A

Distributed Generation Technology and Energy Resources

Distributed Generation Technology

According to the definition of SEN, the Cluster of Distributed Generation includes wind power, photovoltaic, solar thermal, Fuel cell system, geothermal, hydrogen system, energy storage system and cogeneration system. Technology status of distributed generation is summarized in Table 27, and individually detailed technologies such as energy conversion principle, technology status and outlook, and energy resources in Ontario are followed.

Table-27 Summary of Technology State of Art for Distributed Generation

Legend: ■ Developed ▨ R&D □ Not Applicable

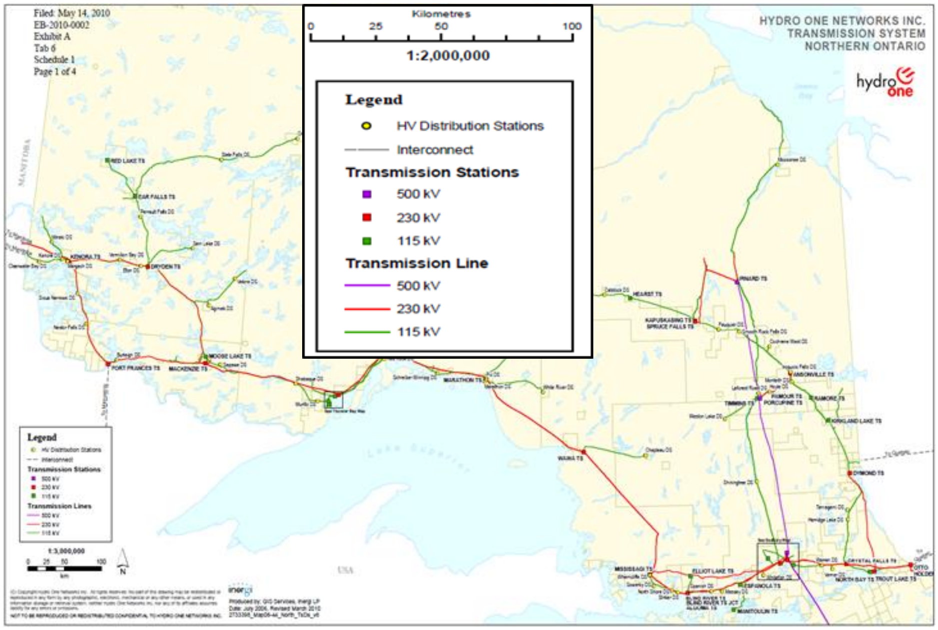
Distributed Generation		Energy Used	Products			Application		
Generator	Type		Power	Heat	Fuel	Residential	Commercial	Industrial
Wind Power	Horizontal	Wind	■	□	□	■	■	■
	Vertical	Wind	■	□	□	■	▨	□
Photovoltaic	Crystalline Silicon	Solar energy	■	□	□	■	■	■
	Thin-Film	Solar energy	■	□	□	■	▨	▨
	Concentrator	Solar energy	■	□	□	□	▨	■
Solar Thermal	Solar panel	Solar energy	□	■	□	■	■	■
	Concentrator	Solar energy	□	■	□	▨	■	■
Bioenergy	Gasification	Biomass	□	□	■	□	■	■
	Pyrolysis	Biomass	□	□	■	□	▨	■
	Power integrated	Biomass	■	■	□	□	■	■
Fuel Cell	DMFC	Hydrogen	■	■	□	□	■	■
	PEMFC	Hydrogen	■	■	□	■	■	■
	AFC	Hydrogen	■	■	□	□	■	■
	PAFC	Hydrogen	■	■	□	□	■	■
	MCFC	Hydrogen	■	■	□	□	■	■
Geothermal	Direct-Use	Geothermal	□	■	□	■	▨	□
	Hydrothermal	NG+ Geothermal	■	■	□	□	▨	■

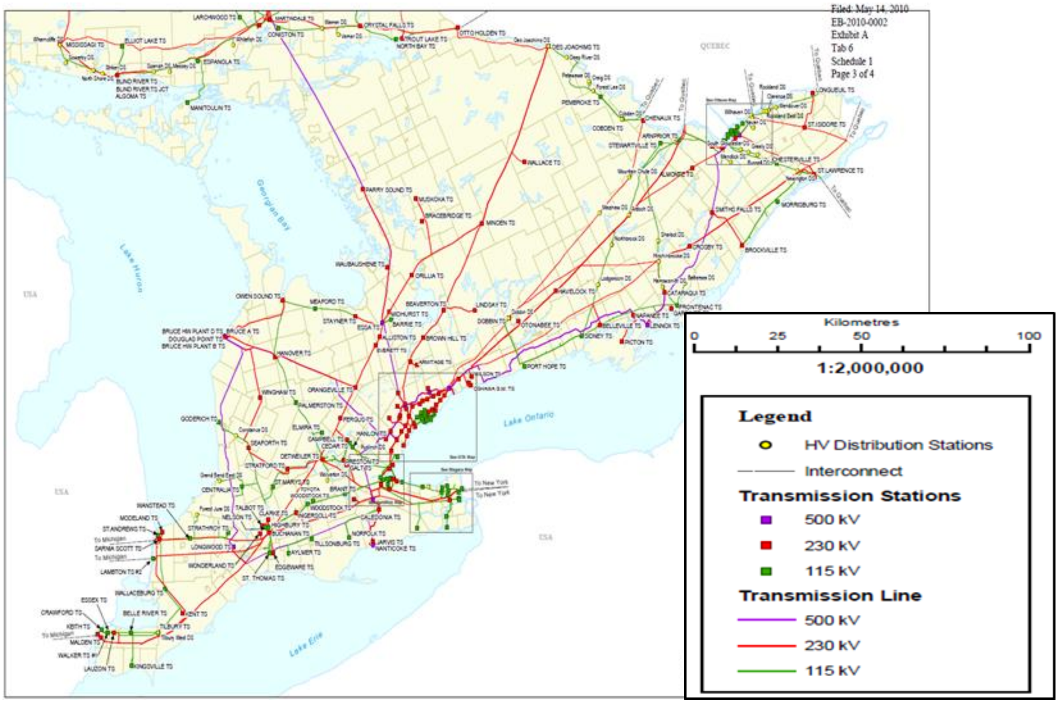
Distributed Generation		Energy Used	Products			Application		
Generator	Type		Power	Heat	Fuel	Residential	Commercial	Industrial
Hydrogen	Reforming of NG	Natural Gas			■	■	■	■
	Gasification of Coal	Coal			■			■
	Gasification, Biomass	Biomass			■		▒	▒
	Reforming, Liquids	Renewable Liquids			■		▒	▒
	Water Electrolysis	Water, Electricity			■		■	■
Energy Storage System	Super Capacitors	Electrochemical	■			▒	▒	▒
	Li-Ion Battery	Electrochemical	■			■	■	■
	Lead-Acid Battery	Electrochemical	■			■	■	■
	Compressed Air	Air		■				■
	Fly-Wheels	Electricity	■					■
CHP	Gas Turbine	NG or Biogas	■	■			■	■
	Micro Turbine	NG or Biogas	■	■		■		
	Reciprocating Engine	Diesel or NG	■	■			■	■
	Fuel Cell	Hydrogen	■	■		■	■	■

Appendix B

Energy Infrastructure in Ontario

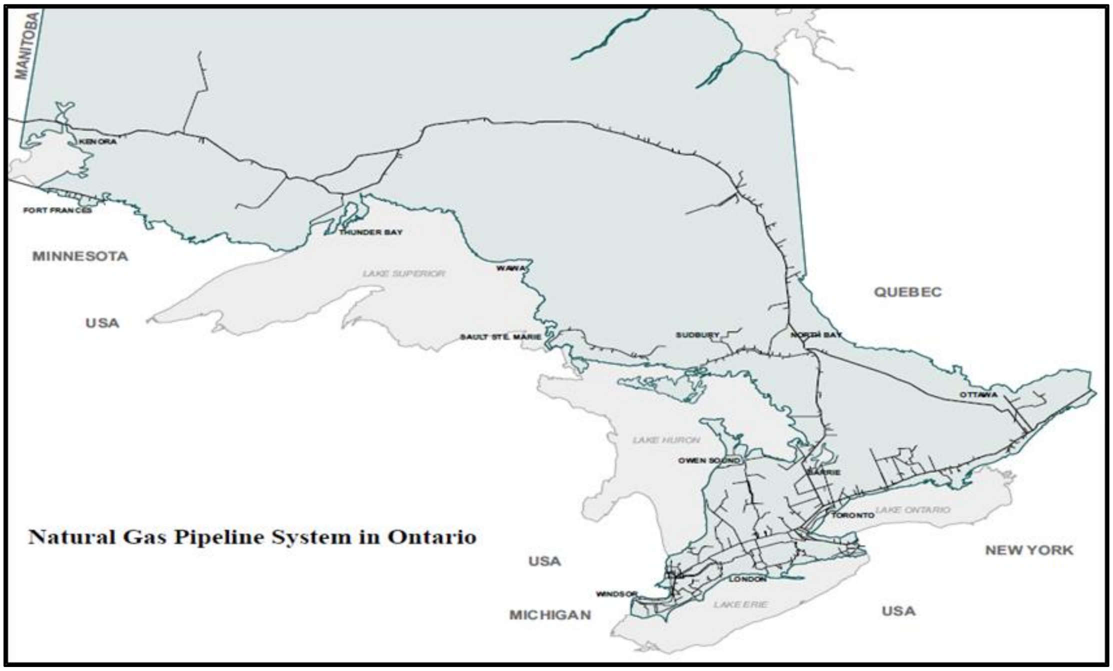
Electric line Transmission Networks



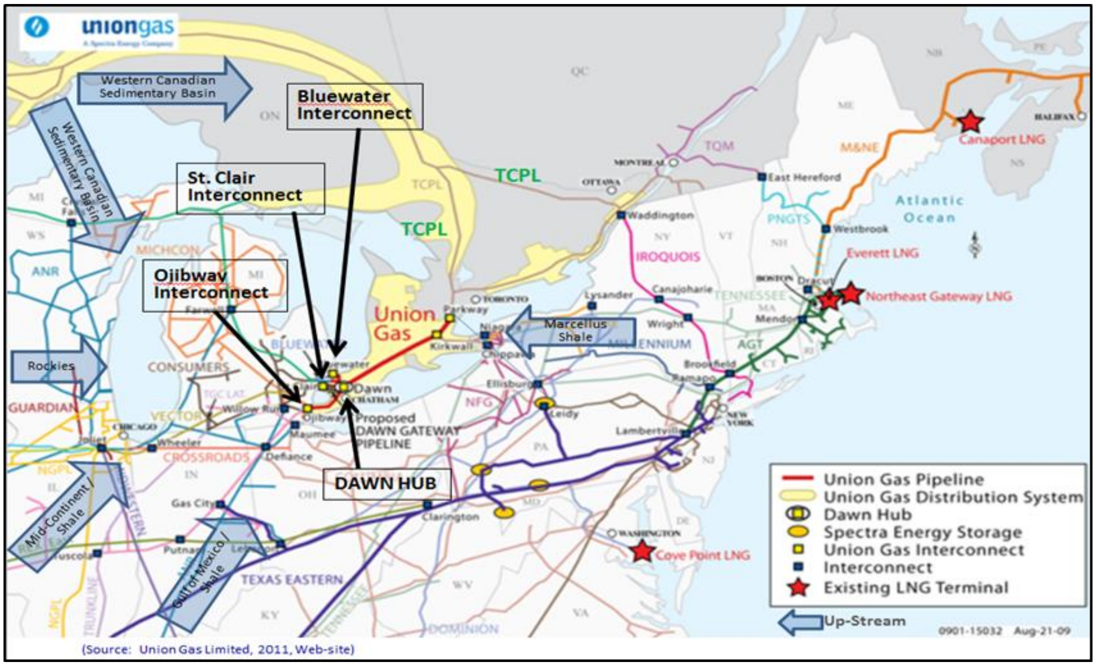


(Source: Hydro One Networks Inc. – Transmission system Ontario, 2010)

Natural Gas Pipe line in Ontario



Natural Gas Flow line in Ontario



(Source: Union Gas Limited, 2011, Web-site)

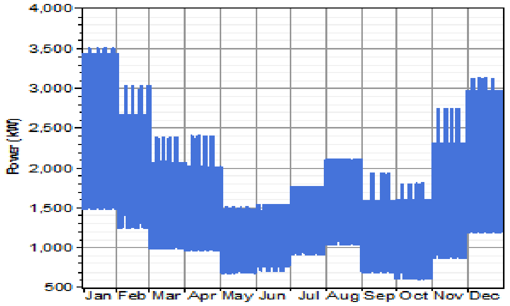
Appendix C

Data of Key Components for Cogeneration System Model

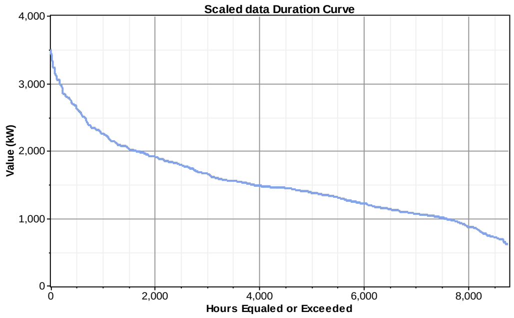
1. Load Profiles

Proposed site is David Johnston Research and Technology Park (R+T Park) and neighborhood areas in Waterloo, Ontario. The semi-analyzed data form using HOMER is present in this Appendix C.

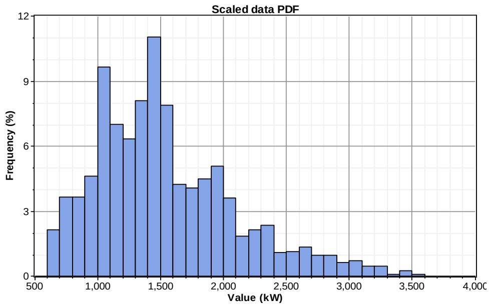
1.1 Residential (Electricity):



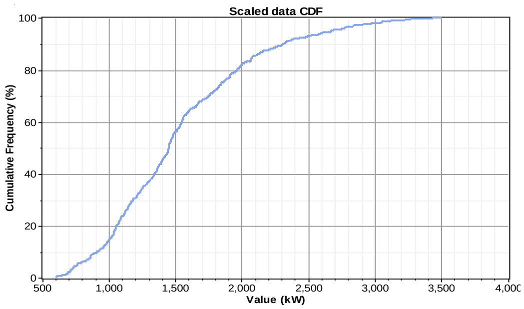
Annual Variations



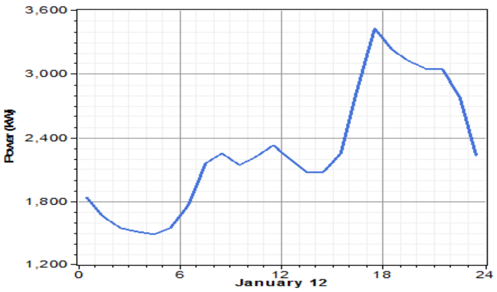
Duration



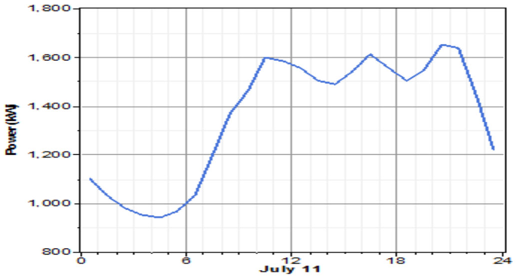
Probability Distribution Function



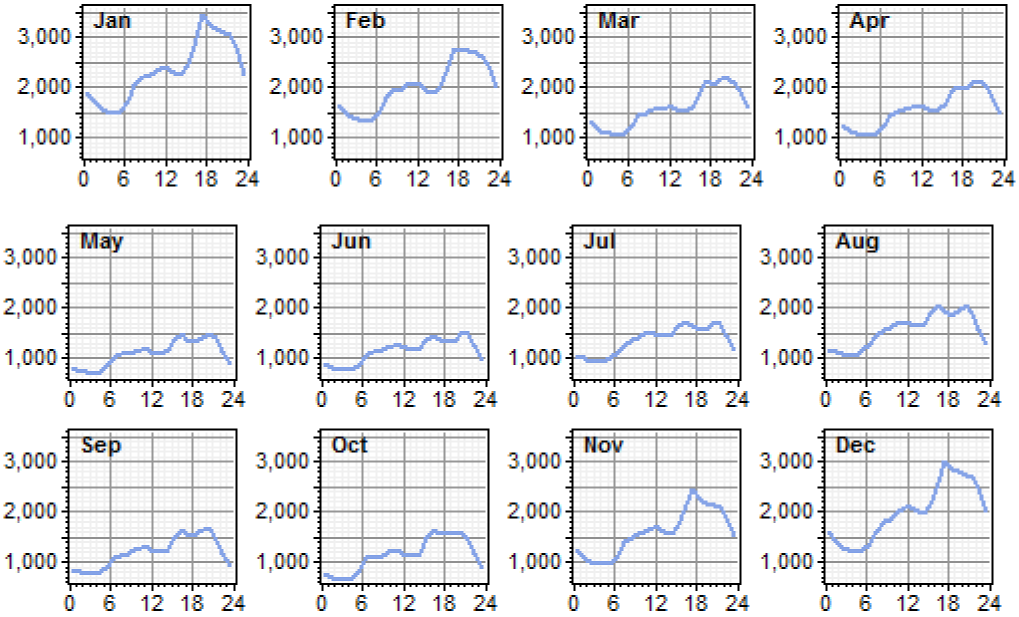
Cumulative Distribution Function



Daily Variations (Jan.12th)

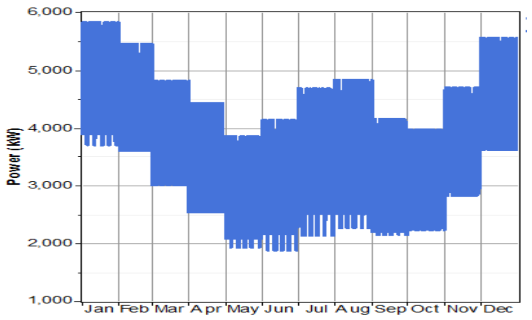


Daily Variations (July 11th)

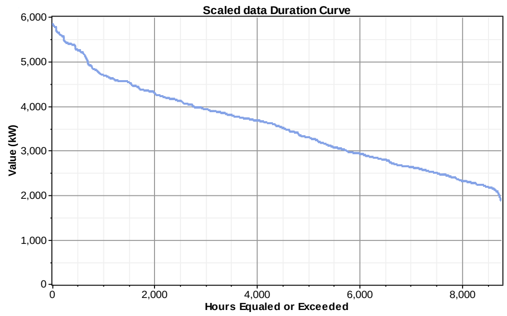


Monthly Variations

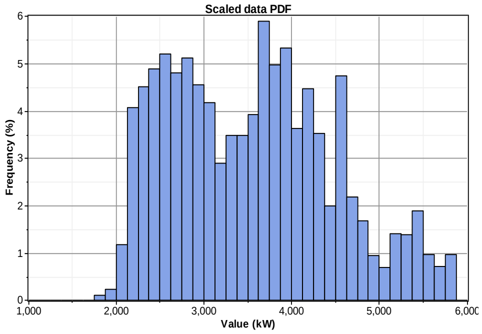
1.2 Office Building (Electricity):



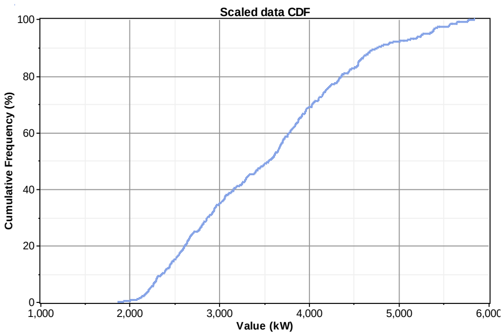
Annual Variations



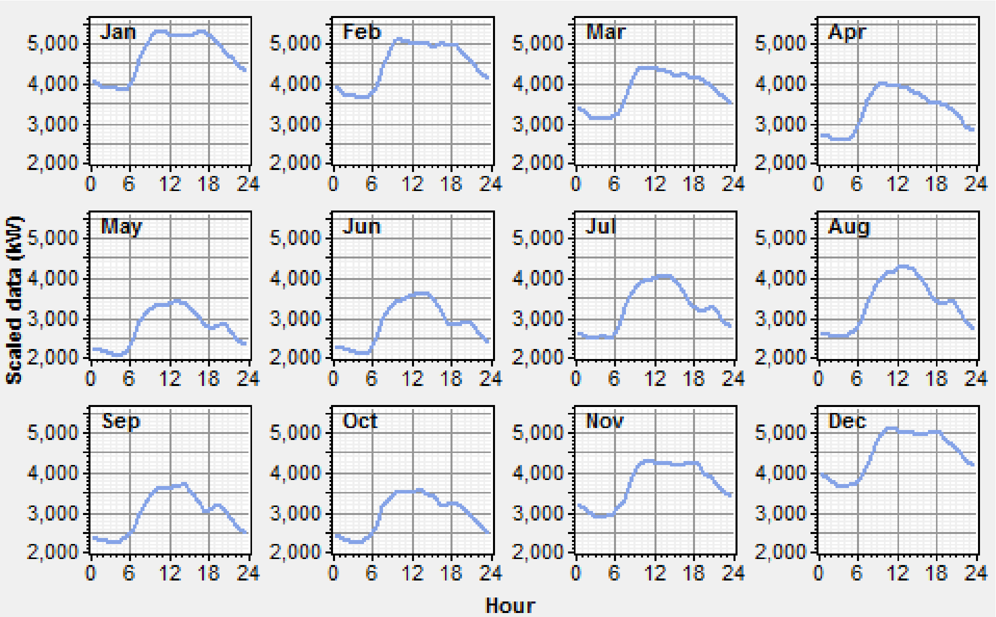
Duration



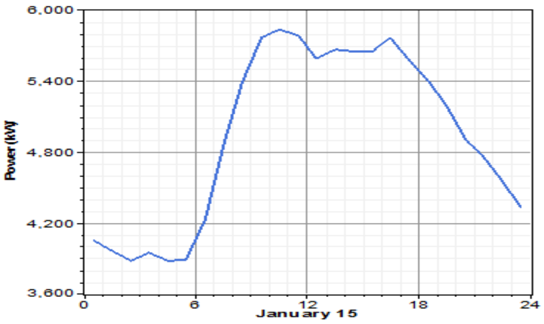
Probability Distribution Function



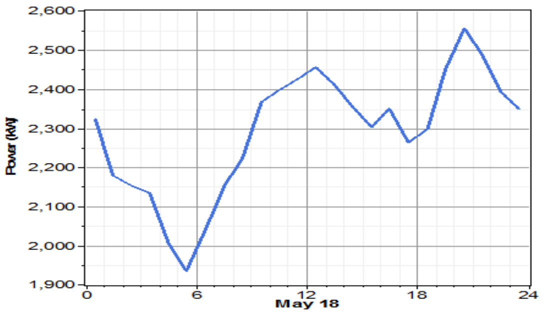
Cumulative Distribution Function



Monthly Average Variations

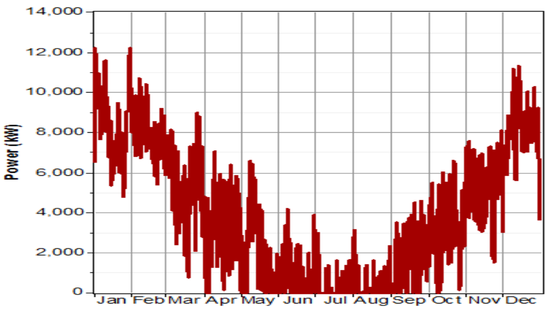


Daily Variations (Jan.15th)



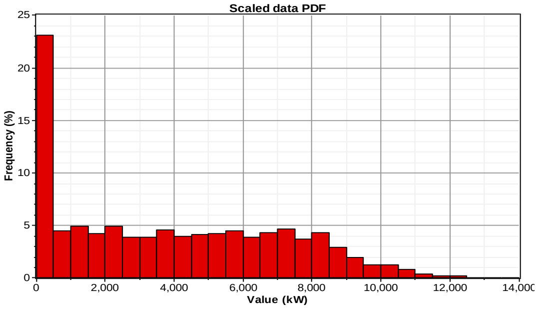
Daily Variations (May 18th)

1.3 Office Building (Thermal Load):

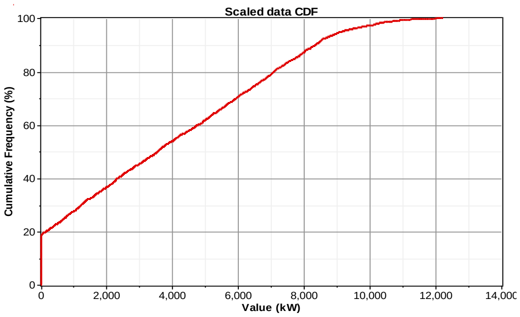


Annual Variations

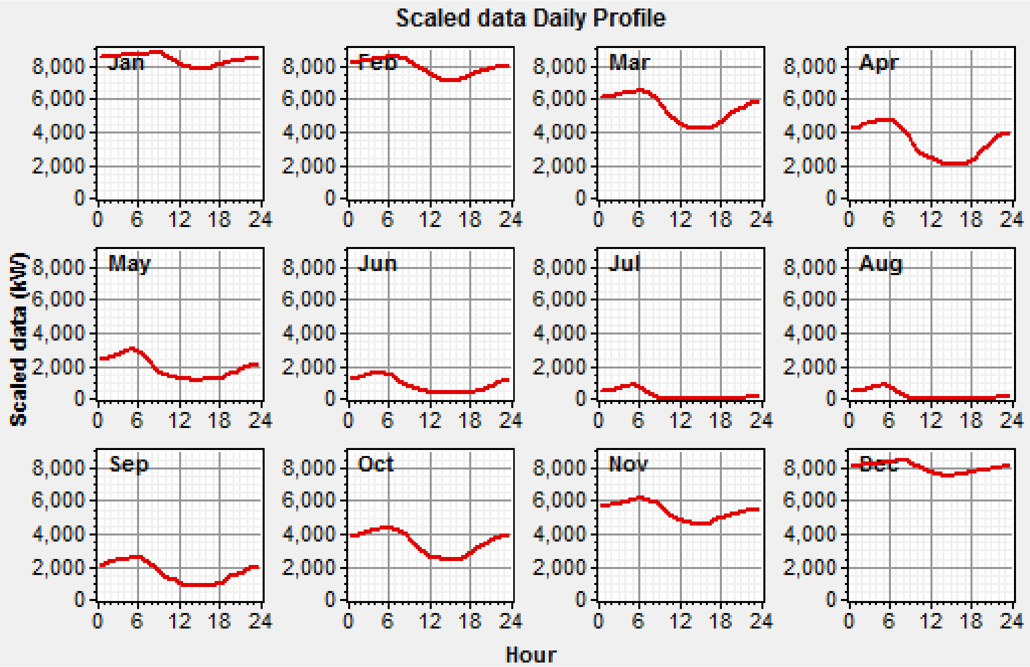
Duration



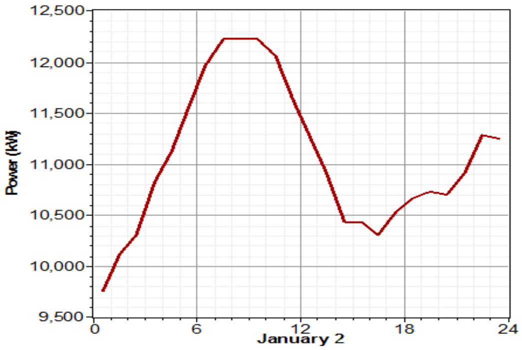
Probability Distribution Function



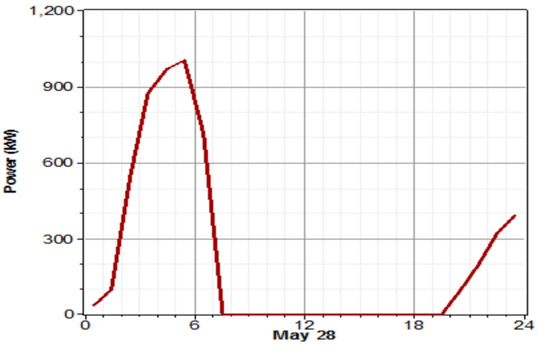
Cumulative Distribution Function



Monthly Average Variations



Daily Variations (Jan. 2nd)

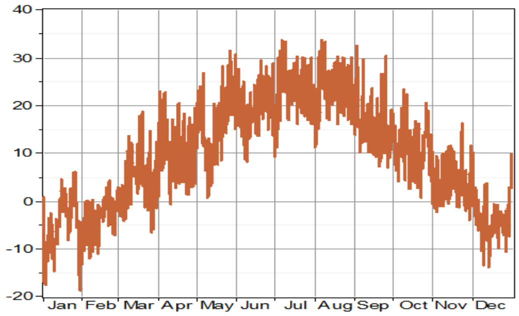


Daily Variations (May 28th)

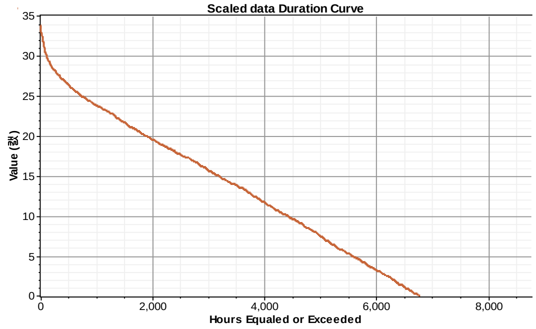
2. Weather Data

TMY2 data set which was derived from 1961 to 1990 year for 8760 hourly data in Toronto airport.

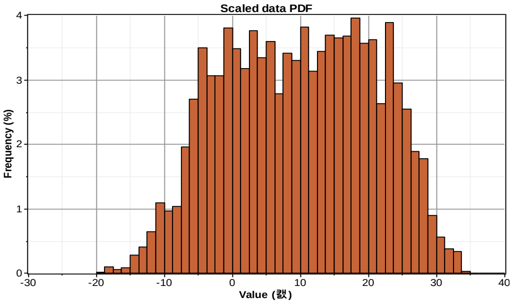
2.1 Temperature (deg. C)



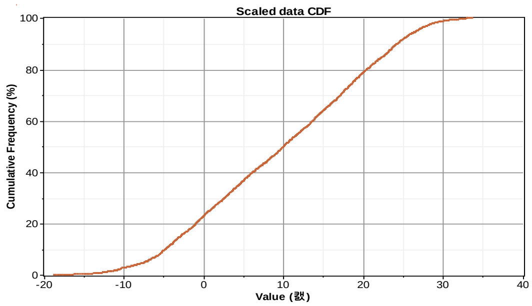
Annual Variations



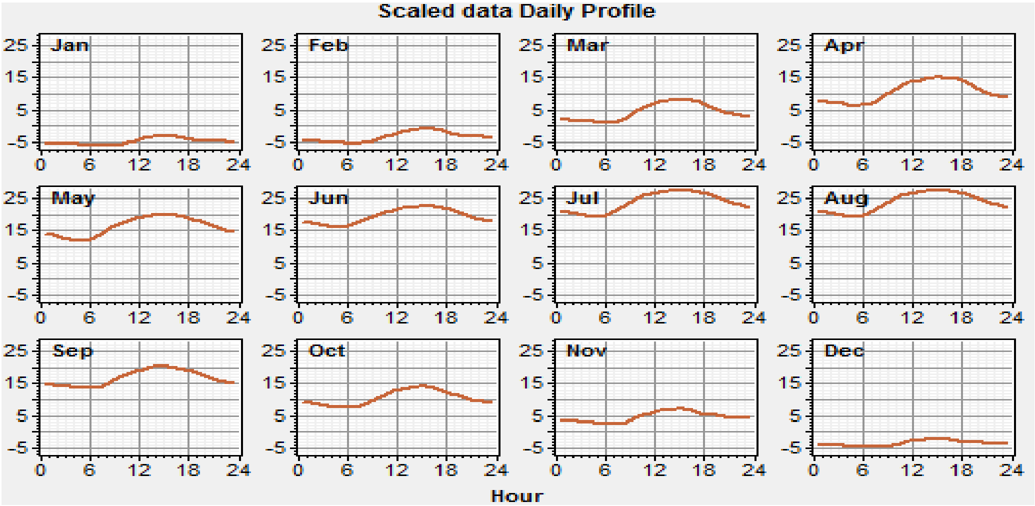
Duration



Probability Distribution Function

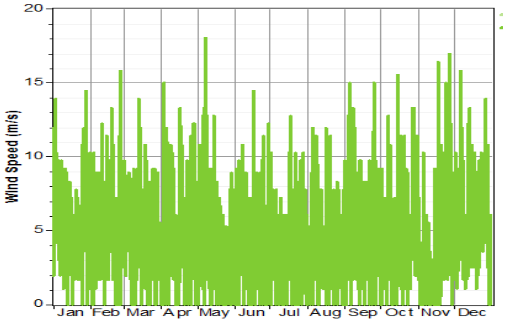


Cumulative Distribution Function

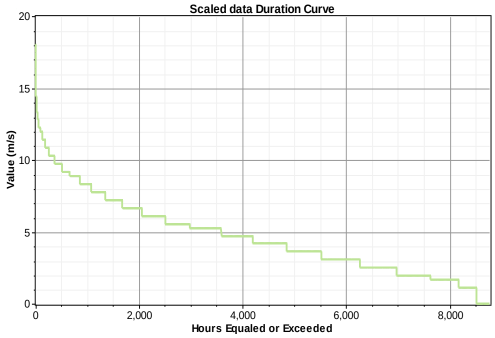


Monthly Average Variations (deg. C)

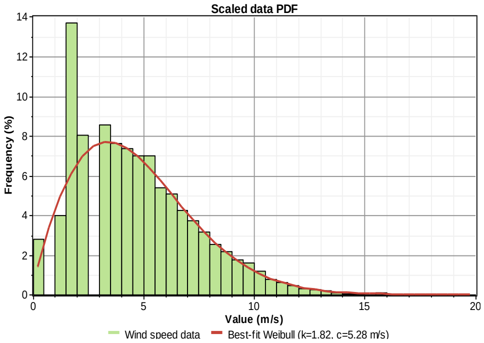
2.2 Wind Speed (m/s)



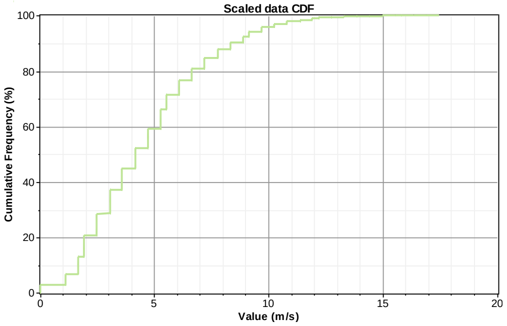
Annual Variations



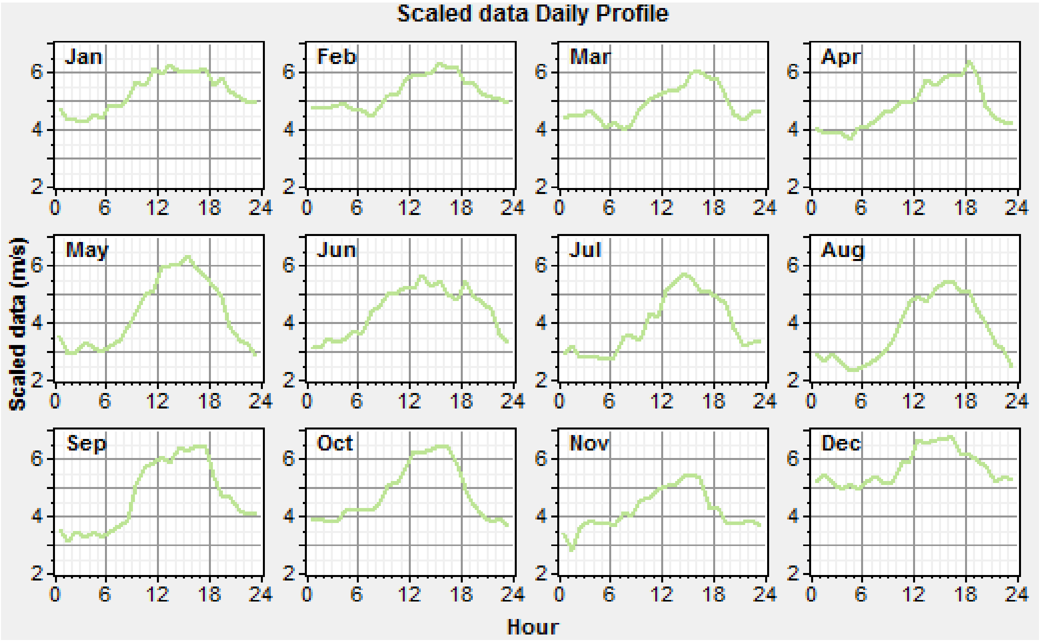
Duration



Probability Distribution Function

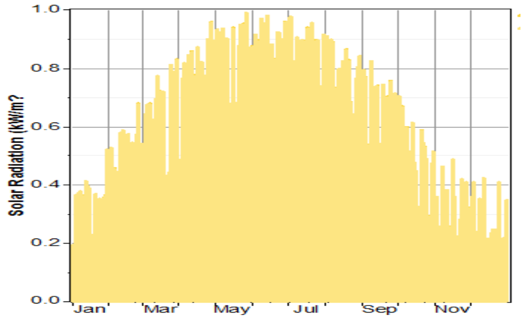


Cumulative Distribution Function

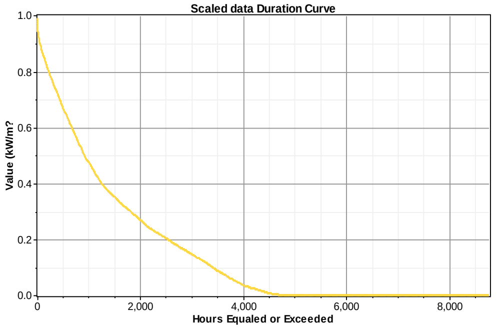


Monthly Variations (kW/m^2)

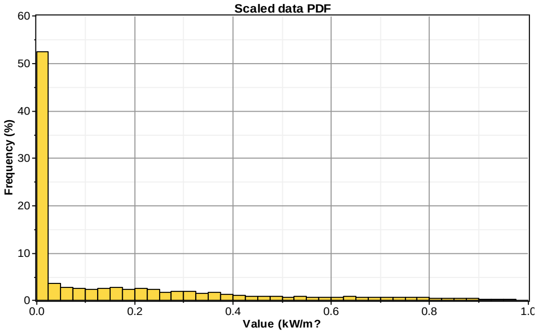
2.3 Solar Radiation (kW/m^2)



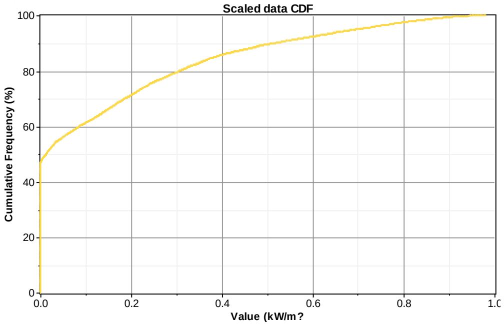
Annual Variations



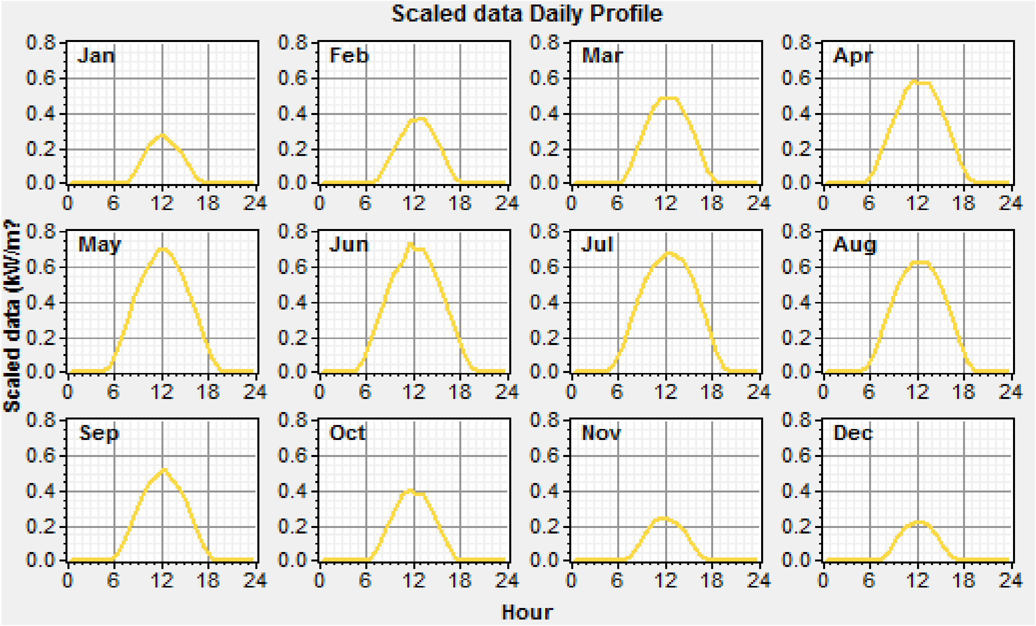
Duration



Probability Distribution Function



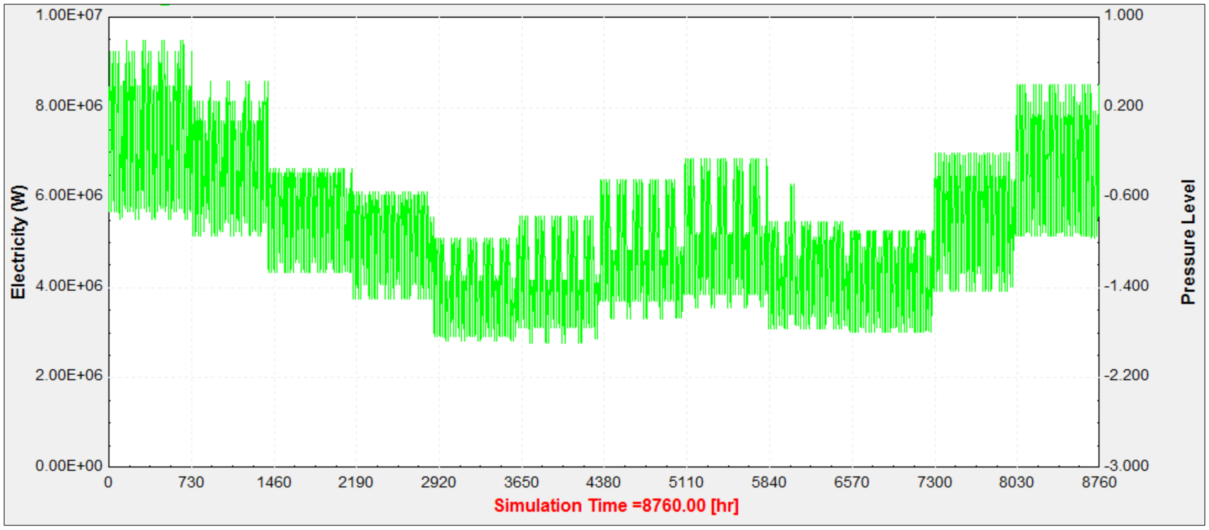
Cumulative Distribution Function



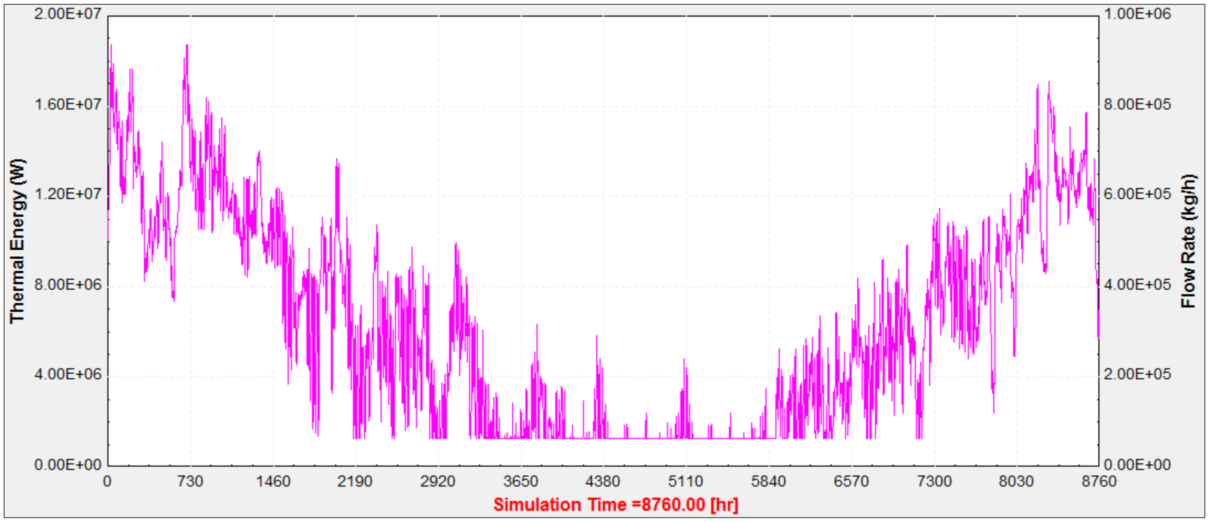
Monthly Variations (kW/m^2)

3. Loads

3.1 Electricity Load Variations

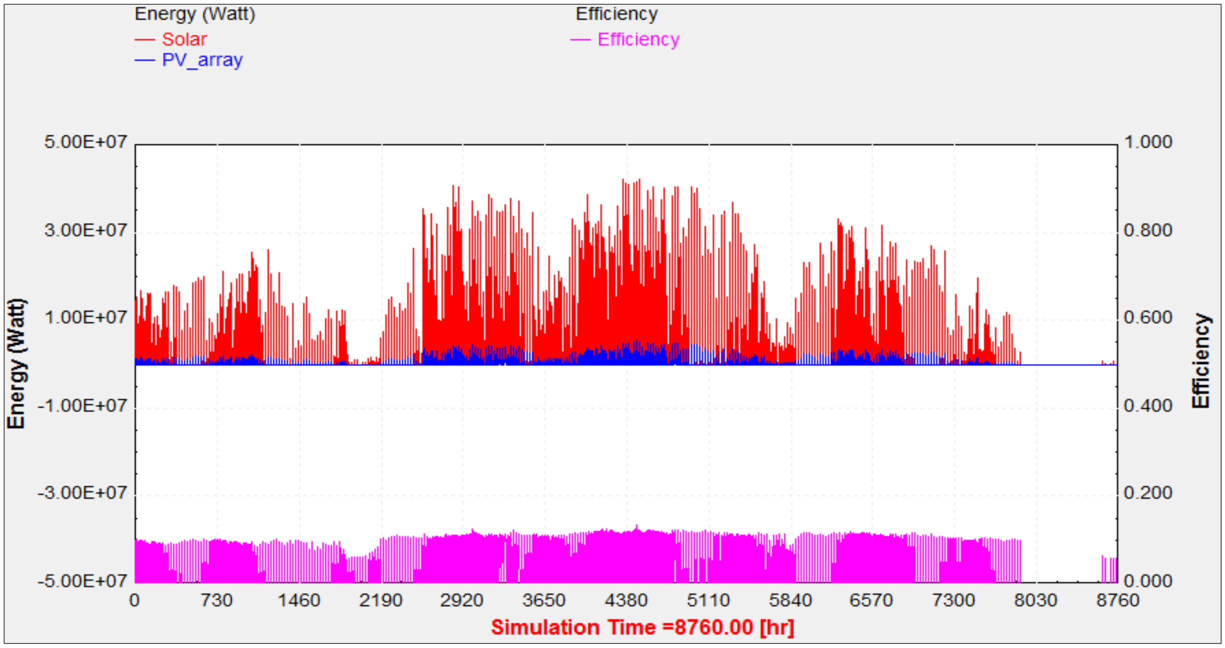


3.2 Thermal Load Variations

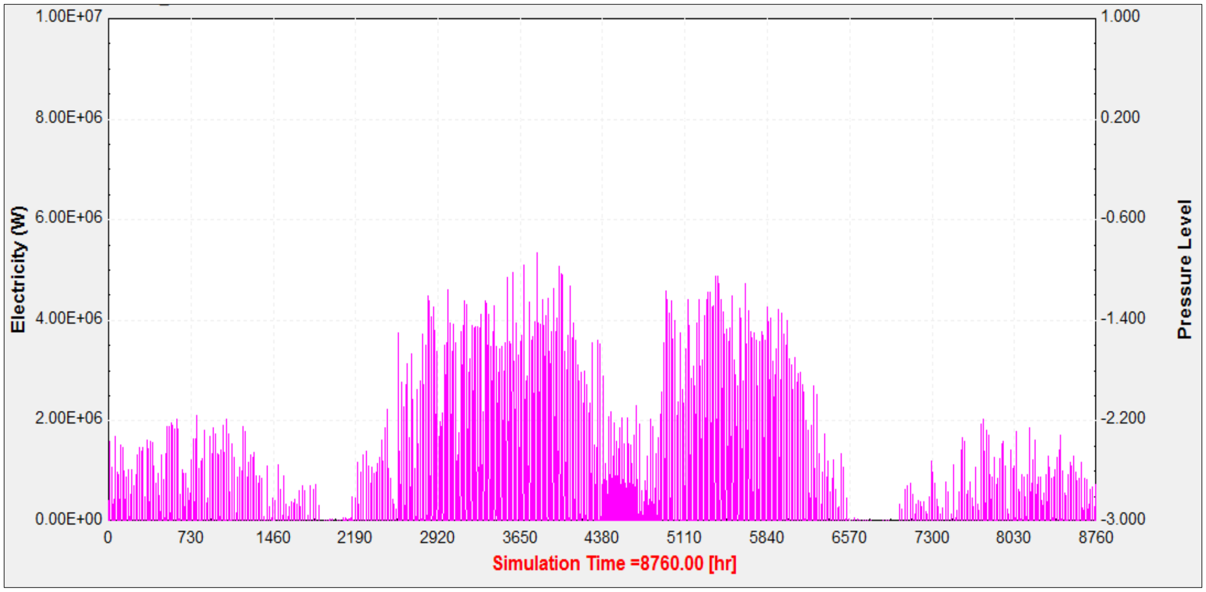


4. Photovoltaic Array including Inverter

4.1 Conversion Efficiency

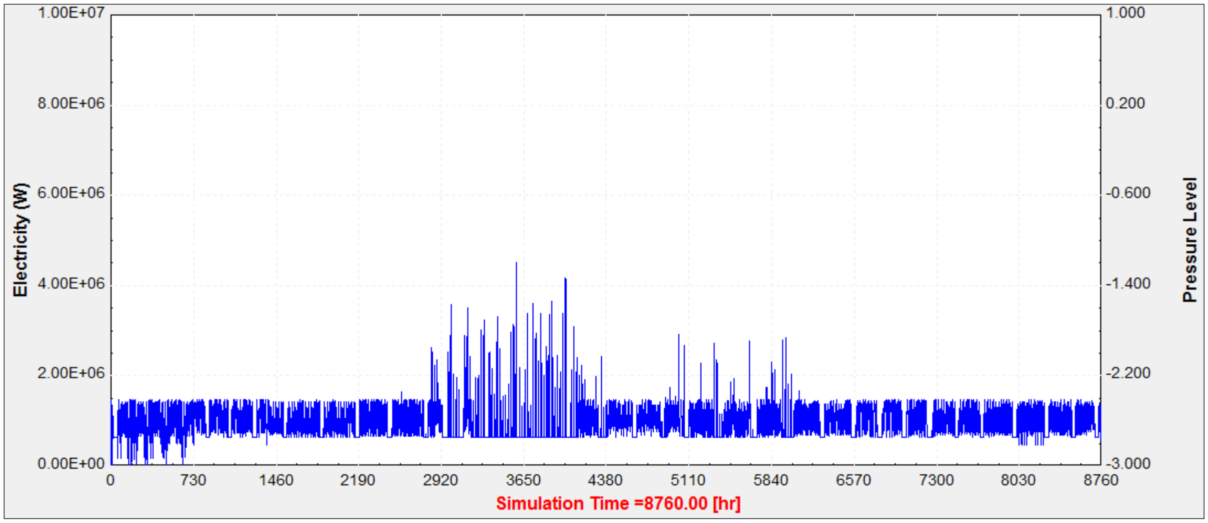


4.2 Power Generation

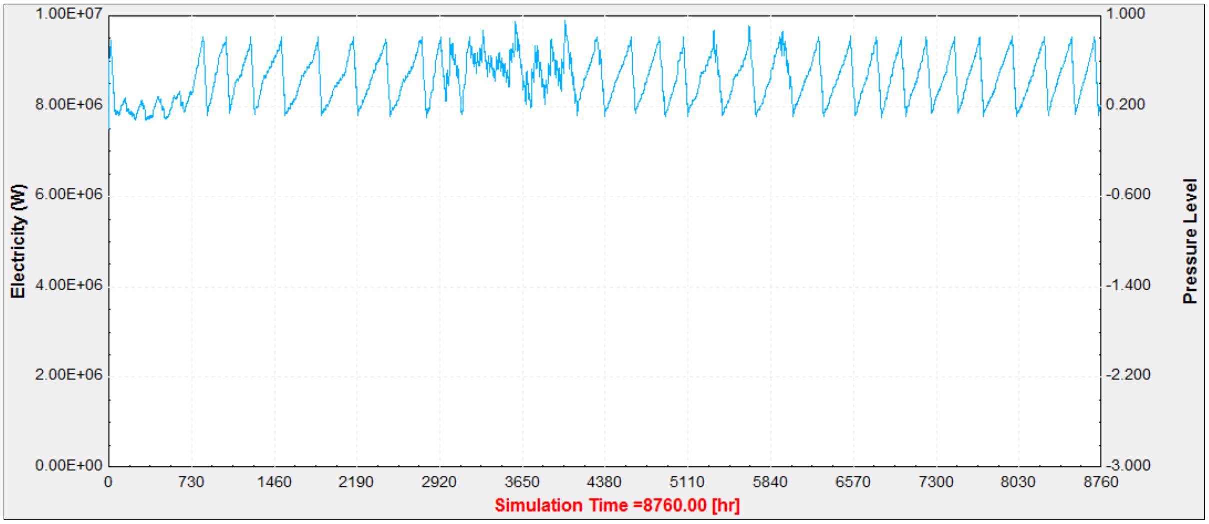


5 Electrolysis

5.1 Power Converted to Hydrogen Gas

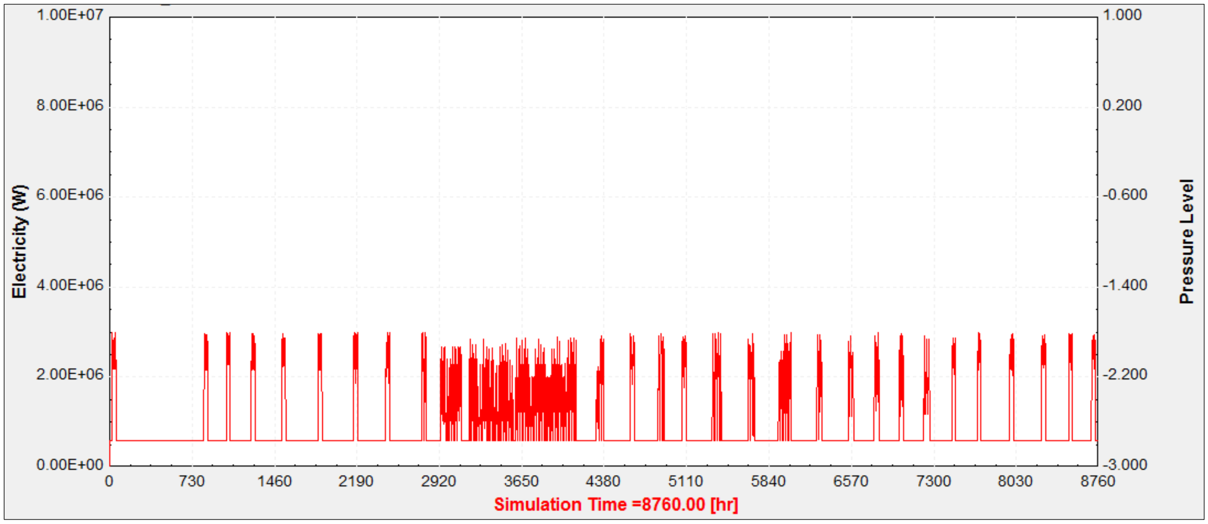


6 Hydrogen Tank Pressure Level (Charging and Discharging)

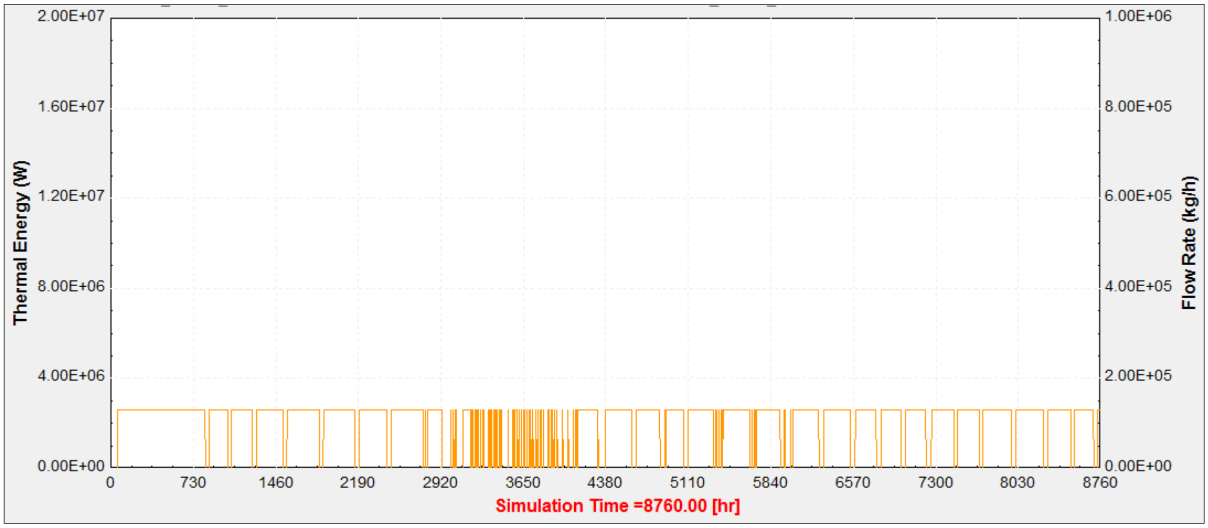


7. Fuel Cell System

7.1 Power generation

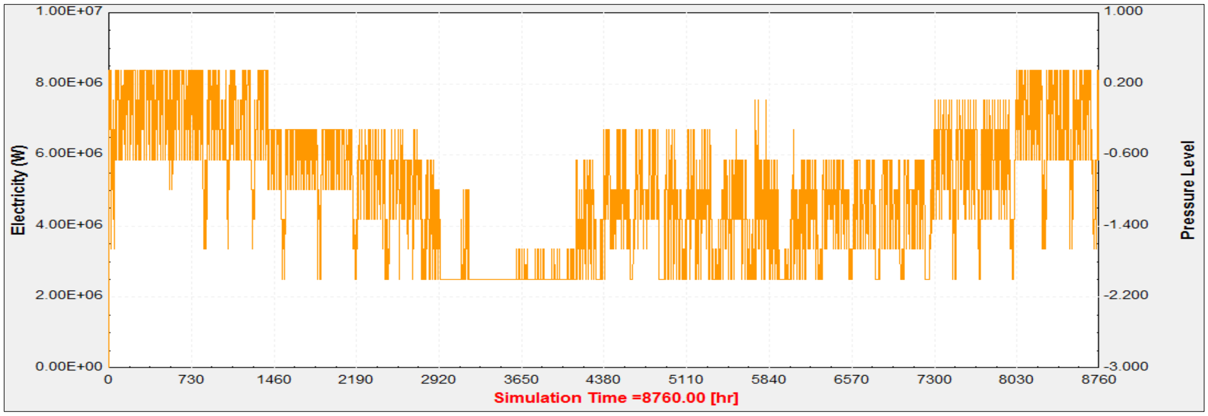


7.2 Thermal generation

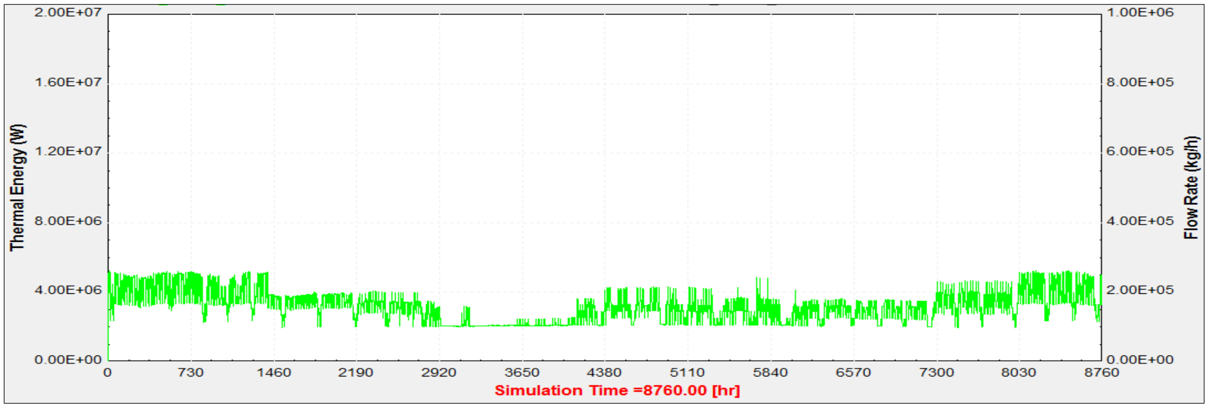


8. Gas Turbine Combined System

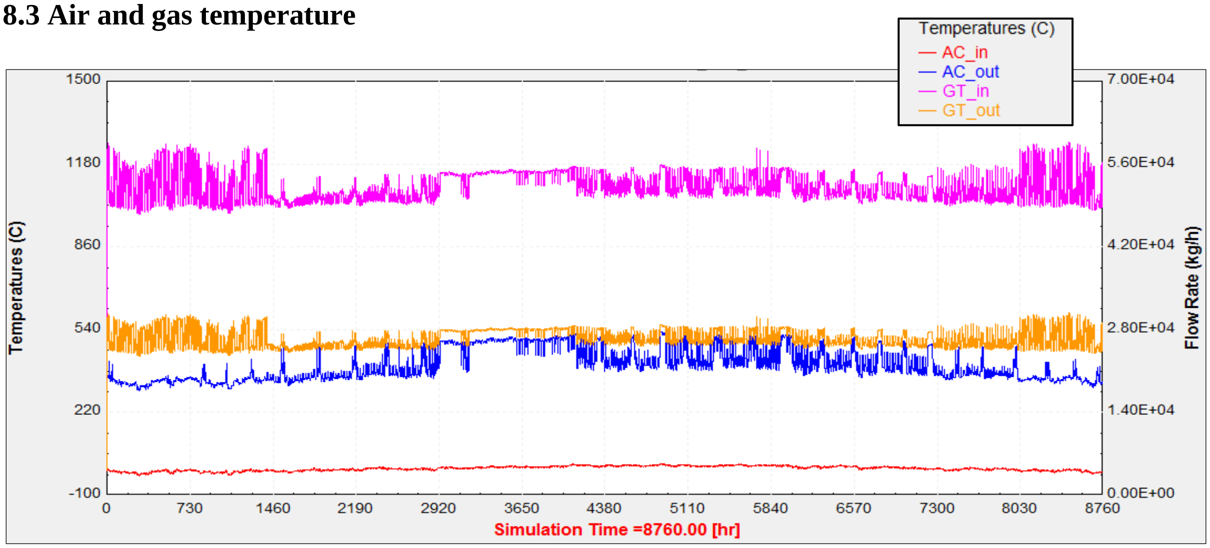
8.1 Power generation



8.2 Thermal generation

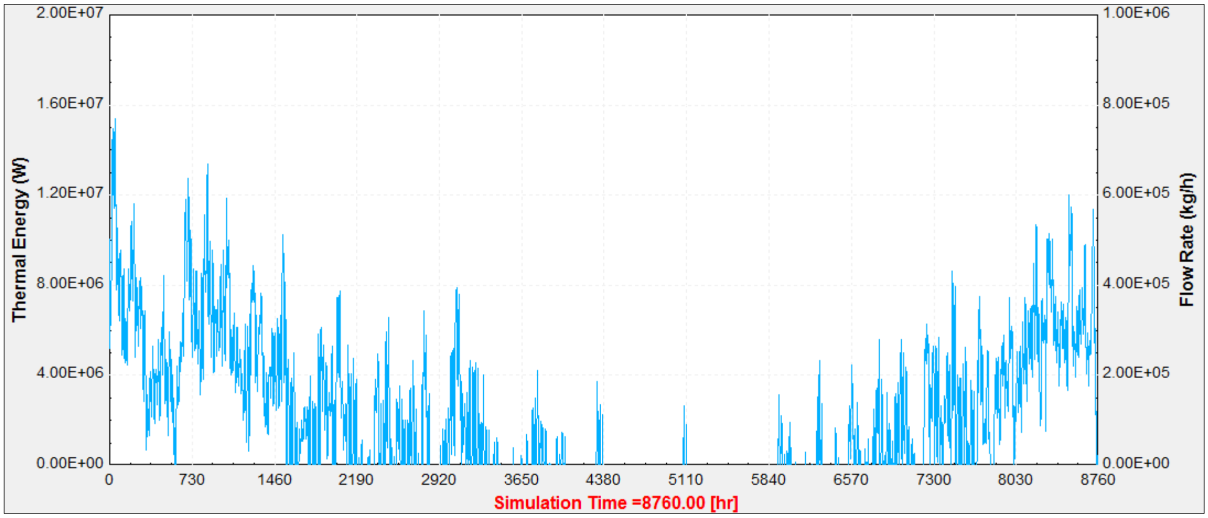


8.3 Air and gas temperature

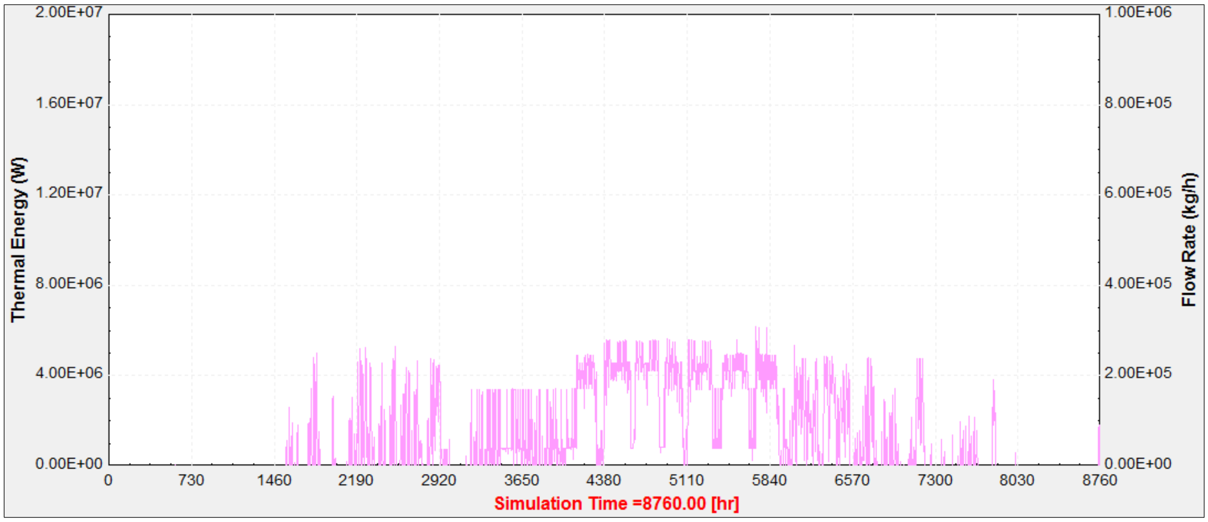


9. Auxiliary Boiler

9.1 Thermal Generation



10.Thermal Dump or Accumulation



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