Applications of Utility-Scale Power to Gas Energy Storage Systems in Smart Grids

HEMAYATULLAH SAMIULLAH

A THESIS SUBMITTED TO THE FACULTY OF GRADUATE STUDIES IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

OF

MASTER OF APPLIED SCIENCE

GRADUATE PROGRAM

IN

ELECTRICAL ENGINEERING AND COMPUTER SCIENCE

YORK UNIVERSITY, TORONTO, ONTARIO

December 2018

ABSTRACT

Utility-scale Power-to-Gas (PtG) is defined as one of the emergent and promising technologies of energy storage systems. In PtG, the electric energy is transformed into renewable hydrogen and/or Synthetic Natural Gas (SNG), which can then be injected, transported, stored, and used at a later time in the gas network for heating and/or electrical generation. The fast dynamic response of the electrolyzer unit of PtG technology makes it also a suitable technology to provide several grid services and thus retain the grid flexibility for power system operators under high penetration levels of variable Distributed Energy Resources (DERs). Further, the production of hydrogen from PtG can create a potential market for hydrogen-powered electric vehicles. In this respect, the development of PtG technologies will create potential interactions between electrical, gas, and transportation sectors.

This thesis aims to develop the engineering tools required to simulate, design, and optimize the operation of utility-scale PtG energy storage. First, a co-simulation platform for power and gas distribution networks is developed. The co-simulation platform could help quantifying the role of PtG technology in shaping

the future of power distribution systems. Using the co-simulation platform, several research studies can be carried out such as operation scheduling and planning of power and gas networks. Thus, the platform is expected to be immensely useful for power and gas operators and planners. Second, a new formulation is developed in this thesis for the optimal design i.e., sizing, of PtG energy storage. The developed formulation aims at minimizing the capital and operation costs of PtG and maximizing the harvested power during periods of surplus i.e., low demand and high power generation. Third, a new mathematical formulation is proposed for the optimal production scheduling of hydrogen, i.e., from PtG, to supply fuel cell electric buses. The proposed formulation takes into account the operation requirements of both power distribution and electric bus transit networks. Several case studies have been carried out to validate the effectiveness of the proposed engineering tools.

ACKNOWLEDGMENTS

In the name of Allah, all praises to Allah for the strengths and His blessing who gives me in completing this thesis. Alhamdulillah,

It is my genuine pleasure to express deep sense of gratitude and thanks to my mentor and supervisor Dr. Hany E. Farag for his keen interest and dedication to help his students. Above all his busy schedule his support is visible in every single line of this thesis. His timely advice and scientific approach have helped me to accomplish this work.

I would like to express my truthful gratitude to my supervisor for course project Dr. Ali Hooshyar I thank you for you patient throughout the entire course and the knowledge you have shared with me during the course I learn a lot form you that helps to great extent to complete my thesis.

Not forgotten, my appreciation to all my research team members specially my friends Nader Ashraf El-Taweel and Mohamd Zaki for their continues help and support for completing this task.

Lastly I appreciate my beloved parents; and also my brothers and sister for their endless love, prayers and encouragement. To those who indirectly contributed in this research, your kindness means a lot to me. Thank you very much.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYM

A.Variables

BHP_{km}	Brake horsepower consumed by the gas compressor, HP
$G_{s,P2G}$	Gas generation in P2G
$G_{d,GPG}$	Gas consumption in GPG
$P_{d,PtG}$	Power consumed by PtG, MW
$P_{g,GPG}$	Power generated by GPG MW
$P_{GC,km}$	Power consumed by compressor, MW
$G_{gas,km}$	Standard gas flowrate in the pipeline, $m3/h$
$G_{GC,Km}$	Natural gas flow in the compressor $m3/h$
P_m, P_k	The nodal gas pressure at both ends of the pipeline, kPa
Π_k, Π_m	$\Pi_k = P_k^2, \Pi_m = P_m^2$, k P_a^2
$S_{gas,km}$	gas flow in the pipeline from the node k to m, measured in MW
D_{km}, L_{km}	The inside diameter of the pipe in meter, the pipe length in kilometer

B.Parameters

c_K	Specific heat ration for the natural gas
E_c	Compressor parasitic efficiency, 0.99 for centrifugal units
G_K	The gas flow at node k, $m3/h$
$G_{S,K}$	The gas supply at node k, $m3/h$

$G_{d,K}$	The gas demand at node k, $m3/h$
HR	The heat rate, MJ/ MWh
K_{GC}	Constant of compressor
LHV	Lower heating value, MJ/m3
P_b	Gas pressure
$P_{g,i}$	The active power generated of bus i, MW
$P_{d,i}$	The active power demand of bus i, MW
$Q_{g,i}$	The reactive power generated of bus i, MVar
$Q_{d,i}$	The reactive power demand of bus i, MVar
$R_{km} = C_{km}^2$	Hydraulic resistance Coefficient of the pipeline $kPa^2/(m3/h)^2$
T_s	Suction temperature of compressor, R
T_b	Gas temperature at base condition, K(273+C)
$T_{a,km}$	Average absolute temperature of pipeline, (K(273+C)
V	Bus voltage
Y	Nodal admittances
Z_a	Average compressibility factor
γ_G	The natural gas specific gravity, dimensionless
η_c	Compression efficiency
η_{GPG}	The energy efficiency of GPG
η_{P2G}	The energy efficiency of PtG

Chapter1

Thesis Overview

1.1 Motivations

Distributed and renewable energy resources (DERs) play a pivotal role to meet the objectives of increasing security and reliability of energy supply and reducing greenhouse gas emissions [1]. Hence, the electric power system is moving rapidly towards an increased penetration of DERS. Yet, the increased penetration of DERs has created a paradigm shift of the way electricity is generated, traded, and distributed. Although such shift in electricity systems is unparalleled, it is accompanied with serious technical challenges that might reach the point of diminishing returns. It has been noted in the last few years that the complication of the electricity system operation escalated due to the exponential increase of variable DERs such as solar and wind [2].

Energy Storage Systems (ESSs) have recently become matters of significant interest to mitigate various existing and imminent issues of evolving power systems [3]. The operation of an ESS benefits the grid operator and/or the private owner(s) of the ESS through the following main functionalities: (i) the ESS is jointly operated with wind/solar generation units to address the issues arisen as a result of sporadic availability of variable DERs; (ii) the ESS is jointly operated with loads to shift the energy consumption from peak to off–peak periods; and (iii) the ESS is operated to achieve some technical services for the grid. Examples of such technical services include but not limited to: enhancing the system stability, reducing the system losses, and improving the power quality.

Several utility-scale energy storage technologies have been proposed and developed in the last couple of decades. Each technology has its own features and operation characteristic and thus the choice of the right technology for each application is vital towards the successful adoption of ESSs in power grids [4]. Among such technologies, utility scale Power-to-Gas (PtG) has been recently introduced as a potential means to provide a long-term e.g., seasonal, storage for the surplus of power generation from variable DERs such as solar and wind. Further, PtG will also facilitate seamless integration between power and Natural Gas (NG) networks when the produced Synthetic Natural Gas (SNG) from PtG is injected into the NG pipelines. To that end, several recent publications have focused on the integration of PtG into power and gas systems. In [5], the authors evaluated the environmental impact of storing renewable energy in the form of gas and concluded that it is environmental friendly. The authors in [6] discussed the operational impact of PtG on transmission networks of both power and gas transmission systems. The purpose of the research in [6] was to construct a model to assess the integration of PtG in the energy system and simulate its impacts on the electrical and gas transmission systems. However, the study was done for each grid individually. In [7], the authors evaluated the coordination of PtG facility and wind power generation. In [8], the authors evaluated the energy saving ability, the potential reduction in operation costs, and the investment opportunities of both power and gas grids when operating together as one integrated system. There are also other references that focused on PtG technology as an energy storage technique and evaluated its economic feasibility [9], [10]-[11].

PtG will not only facilitate integration between power and NG networks, but also the produced gas, whether Hydrogen or SNG, can be utilized as a renewable fuel to run Hydrogen and NG vehicles, respectively. In this regard, PtG can potentially integrate three low-carbon systems i.e., power, NG, and transportation, in a unified framework. Research and development in the applications of utility-scale PtG in power grids is still in its early stages and, thus, not too much work has been done in this area.

1.2 Thesis layout

Based on the above discussions, this thesis aims to develop the engineering tools required to simulate, design, and optimize the operation of utility-scale PtG energy storage. Figure 1-1 shows a schematic diagram of the thesis layout. As depicted in the figure, *Chapter 2* reviews the different types of utility-scale energy storage technologies and summarizes the operation features and characteristics of each technology. In *Chapter 3*, a co-simulation platform for power and gas distribution networks is developed. The co-simulation platform is utilized to conduct several simulation studies such as operation scheduling and planning of power and gas networks. In *Chapter 4*, a new optimization model is developed to design the size of PtG energy storage. The developed optimization model aims at minimizing the capital and operation costs of PtG and maximizing the harvested power during periods of surplus power generation. In *Chapter 5*, a novel mathematical formulation is presented for the optimal scheduling of hydrogen production from PtG in order to supply fuel cell electric buses. The developed formulation takes into account the operation requirements of power distribution and electric city bus transit networks. In each chapter, several case studies have been carried out to validate the effectiveness of the proposed engineering tools. *Chapter 6* summarizes the thesis contribution and identified future works.

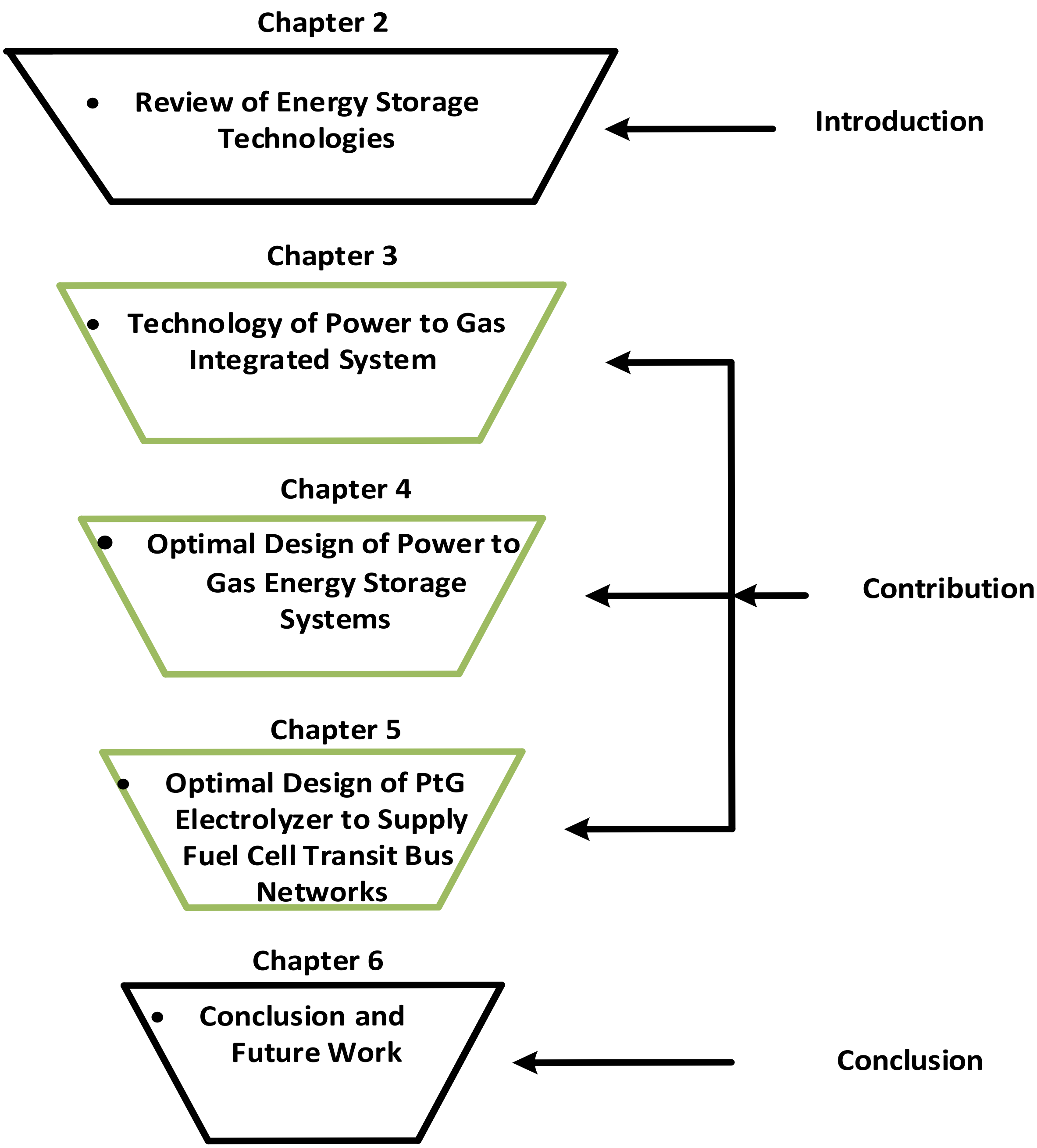

Figure 1-1 Thesis Overview

Chapter 2

Review of Energy Storage Technologies

2.1 Introduction

The role of alternative energy in supplementing and securing energy systems has been well demonstrated [12]. In particular, DERs will play a vital role in diversifying energy systems sustainably. By the year 2040, renewable energy is projected to be the second largest source of electrical generation (behind NG) and will account for 33% of global power supply, according to the most recent International Energy Agency report [13]. The growth rates in this model from various energy sources would result in renewables accounting for nearly half of the new power generation by 2040.

Renewables, particularly solar and wind, supply intermittent power as these sources only produce energy when the sun is shining or the wind is blowing [14]. Consequently, it is necessary to normalize their irregular contributions to the total power supply so that the load placed on the power grid is accurately met. This is achieved in several ways, depending on the degree of influence the intermittent energy has on the overall grid and the time-scale of interaction. On the scale of seconds to minutes, power stabilization is achieved through large banks of capacitors, spinning reserves, batteries, and mechanical flywheels [15]. These methods account for minimizing variation in power output from both conventional and renewable energy sources by storing and releasing small amounts of energy. For energy variation on the scales of minutes to hours, spinning reserves, quick acting NG plants, and hydroelectric generating stations (including both pumped and non-pumped hydro), can adequately account for the variation in intermittent renewable energy output power [16]. As a result of these technologies, energy storage over time frames ranging from seconds to hours is largely achieved with known and demonstrated methods. However, moving to longer time scales from hours to overnight, global energy storage capacities ranging from 1.9-45.0 x 1016 J will be needed by 2040 to ensure power is supplied consistently as the proportion of intermittent energy increases. Current energy storage capacity is a meager 1.4 x 1014 J, and thus meeting future goals will require innovative methods.

In order to understand the best method(s) to meet future energy goals, we must first identify the characteristics of a good ESS to effectively compare and contrast various technologies. At the most essential level, an efficient energy storage system (ESS) will have the ability to return a high proportion of the energy initially invested [17]. This concept is referred to as energy return on investment (EROI), which is a ratio that measures the amount of energy returned by a process over the energy initially invested given as follow:

$$EROI = \frac{\text{Energy Return of Process}}{\text{Energy Loss of process}} \tag{2.1}$$

One can notice that a more efficient ESS will have a higher EROI. As both the numerator and the denominator are in units of energy, the resulting ratio is a dimensionless measurement of efficiency. EROI is a very useful metric to assess the use of energy storage, but additional factors must be evaluated. For example, if one type of energy is converted to another, e.g. electricity is used to generate hydrogen, the characteristics of each medium of energy must be considered. Furthermore, it is important to factor in more than energy efficiency when determining the utility of an ESS.

In addition to a high EROI, better ESS would have some or all of the following features:

- High-energy density
- High capacitance
- Fast discharge and recharge rates
- Minimal energy loss over time
- Efficient coupling with an existing system of power generation
- Cost effective
- High cycle-life
- Minimal impacts on natural phenomena

These criteria create the basis from which ESS can be judged upon, and each method will have its own strengths and weaknesses.

2.2 Classification of Energy Storage

In literature there are various types of classification for energy storage technologies. In this thesis, energy storage technologies are classified into four main categories: their interaction to power grid, services that can provide to the grid, short-term and long-term energy storage capabilities, and the way/medium at which the energy is stored. Figure 2-1 shows a schematic diagram of the three categories.

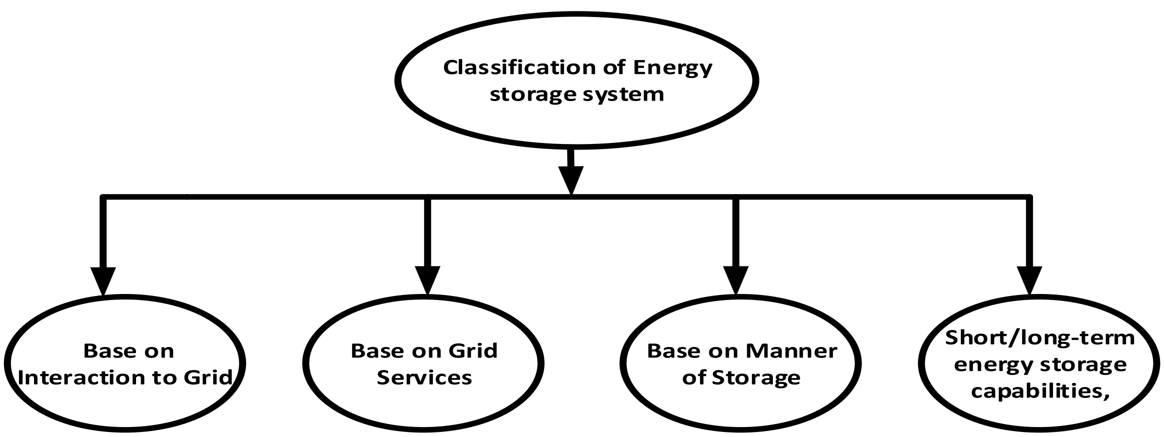

Figure 2-1 Energy storage classifications

2.2.1 Interaction to Power Grid

The Independent Electricity System Operator (IESO) in Ontario has classified energy storage technologies based on the way they interact with the power grid into three types: type1, type 2 and type 3 [18].

Type 1 – Energy storage technologies that are capable of withdrawing electrical energy from the power grid, storing the withdrawn energy for a certain period of time and then re-injecting such energy back into the grid [18]. Examples include, but are not limited to, batteries, flywheels, compressed air, and pumped hydroelectric.

Type 2 – This type represents energy storage technologies that absorb power from the grid and store the energy for a certain period of time. However, instead of injecting it back into the grid, the stored energy is used to displace power demand of their host facility at a later time [18]. Heat storage is an example of these technologies.

Type 3 – It represents energy storage technologies that would only consume power from the grid, but convert it into a storable form of energy or fuel that is subsequently used in an industrial, commercial or residential process. Fuel production (hydrogen or methane), steam production and electric vehicles, are examples of Type 3 energy storage [19].

2.2.2 Services Provision to the Power Grid

ESSs are capable of providing several valuable services in different applications that address the needs for flexible grid resources. The following are potential examples of service provision for ESSs to power grids.

Generation Side – ESSs can be applied to provide grid services in support of or instead of generation resources [20]. Supporting power generation plants with different services can increase their efficiency and lifetime, thus resulting in less fuel consumption and less greenhouse gas emissions per kWh. Further, ESSs located near renewable power generation units installed in sub-transmission or transmission networks can provide capacity firming, ramp rate control, and frequency regulation. This will, in turn, facilitate better integration of renewable generation and ensuring system stability. Moreover, ESS located at a generation site can be used for energy trading (arbitrage) by shifting the produced energy, i.e.

charging during low-price periods and discharging during peak-hours. Energy storage technologies categorized as Type 1 are potential examples of the generation side.

Transmission and Distribution System – ESSs located in the transmission grid can reduce transmission congestion and support transmission infrastructure to extend equipment lifetime and defer investments. They can also provide similar ancillary services as the ones connected at the generation site, e.g. reserves, frequency regulation, load following, etc. Such services are expected to improve the system reliability and reduce the need for additional generation resources to operate in partial load.

ESSs in the distribution network close to demand side could provide grid ancillary services such as load levelling, voltage support, and power quality and is able to relieve distribution substations and feeders and, thus, defer investments. This will in turn facilitate seamless integration for high penetration of renewable energy resources. Another mechanism for ESS to support renewable power integration is by being placed closely to the renewable generation resources in order to provide services such as capacity firming, ramp rate control, and time-shift.

End-Consumer – ESSs installed behind the meter at the consumer end can help to reduce the electricity bill by peak limiting and thus reducing demand charges, or by time-of-use shifting. They can also use to ensure power service reliability and quality for sensitive equipment [20]. In combination with renewable energy resources, ESSs installed at the consumer side can also increase the self-consumption of the generated energy or ensure that it is fed into the grid at the economically best time. An example of such scenario is Grid-Tied Photovoltaic and Battery Storage Systems in the end users.

2.2.3 The way energy is stored

As depicted in Figure 2-2, energy can be stored in different forms (mechanical, thermal, electrical, electrochemical, and chemical). An example of energy storage technologies for each form is also shown in the figure. Among these technologies, the most common types of energy storage that offers potential storage of energy from renewables are batteries, thermal energy storage, mechanical flywheels, power to gas (PtG), and pumped storage hydroelectric.

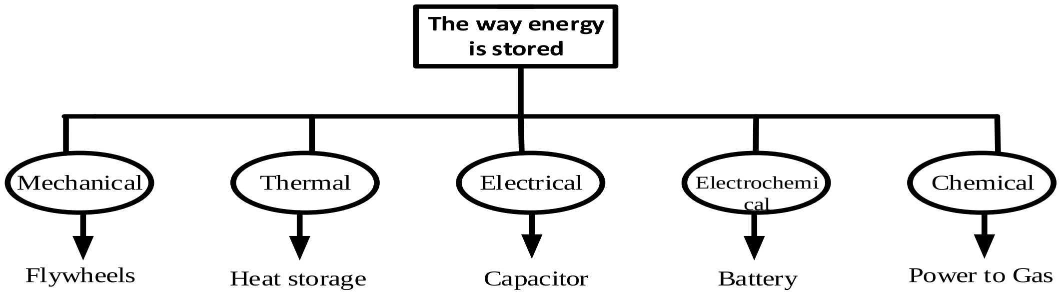

Figure 2-1 Different means of storing the withdrawn energy of ESSs from the grid

2.2.3.1 Batteries

Batteries are the most familiar method of energy storage. A battery is a closed system that converts stored chemical energy into electrical energy via the application of a load. Once a battery's stored chemical energy has been exhausted, applying a potential voltage to the cell can restore the electrochemical potential. Lithium- ion (Li-ion) is the most familiar type of batteries as it has the highest energy density among batteries [21]. The density of the batteries, combined with their durability and low operating temperature, makes them ideal for small-scale applications e.g., portable electronics and transportation. Further, they have a very low self-discharge rate and a high life cycle. Li-ion batteries typically cost three times as much as other batteries, meaning they suffer an economic disadvantage when considering them for use in utility-scale applications. Lead-acid (PbA) batteries are comparatively cheaper, simpler to manufacture, and have the lowest self-discharge rate of any battery. The main disadvantages of PbAs are a low recharge rate and a low life cycle [22]. Batteries that are more suitable for utility-scale energy storage and stabilization include sodium-sulfur and redox-flow batteries [23].

Redox-flow batteries utilize the oxidation and reduction of a liquid electrolytic solution, where energy is stored by reducing a solution and can be released by oxidizing the same solution [24]. The primary benefit of this method is high scalability, as a larger tank can be built to store more electrolytic solution. The reduced solution can be stored almost indefinitely, and the rate at which energy is released is highly tunable. The primary downfall of this technology currently is that it has a very low energy density [25].

2.2.3.2 Thermal Energy Storage

Thermal energy storage is a broad category in which the thermal energy is stored in a medium and used to generate heat in order to produce steam and power a turbine. The media of storage vary greatly; it ranges from earth, to water, to more technologically advance and expensive options such as molten salt [26]. The most developed type of thermal energy storage is pumped heat electrical storage (PHES) [27]. In this process, a heat pumped powered by electricity is used to drive energy from a cold to a heat sink. Adiabatic containers maintain the thermal differential until the energy is needed, at which time heat is transferred via a gas from the heat sink to the cold sink in order to power a heat engine. The overall efficiency could approach 75-80%, although it diminished as storage time increases, considering the heat and cold sinks are not perfectly adiabatic [28].

2.2.3.3 Flywheels

In flywheels, the electrical energy is stored in the form of kinetic energy. Although the operation concept of a flywheel is well known, utility-scale flywheels used for grid energy storage have several distinctive features [29]. The primary loss of energy in flywheels is the heat resulting from friction. Placing the flywheel in a vacuum and using permanent and electromagnetic bearings as stators that the flywheel is not in physical contact with its support could minimize friction. A single flywheel can have a capacity of up to 9 x 105 J, and is able to absorb or discharge energy instantaneously [30]. The drawback is that they are capital intensive, and have high losses over time, ranging from 3-20% per hour. For these reason, flywheels are unable to effectively store energy for more than several hours and thus are very limited in the storage of intermittent renewable energy resources.

2.2.3.4 Power to Gas

Power to gas (PtG) is a method of converting electrical energy into gaseous fuel. There are currently three pathways for this particular type of conversion, and all utilize the electrolysis of water to generate hydrogen that is then combusted or reacted in a variety of ways [31].

- In the first method, generated hydrogen is used to directly supplement the natural gas grid.
- The second method utilizes the Sabatier reaction, where hydrogen is reacted with carbon dioxide to form methane and water. The methane is then used to supplement the natural gas grid.
- In the third method, hydrogen is mixed with a biogas, where it can undergo a Sabatier reaction to improve the quality of the biogas.

These methods have been demonstrated to store the energy generated from intermitted renewable energy resources at an efficiency rate of more than 60% [32]. With regards to environmental impacts, PtG storage technologies are shown to pair more efficiency with intermittent renewable energy generation than with traditional energy sources. This is largely due to the ability of renewable energy resources to produce very cheap electricity during off-peak hours while traditional power generation is fully utilized during this period to supply a base load of power to the grid. Also, a very important aspect of the PtG process is that it does not generate a net increase in greenhouse gases, as shown in the schematic diagram presented in Figure 2-3. Utility-scale PtG technology is relatively new, and it does not yet make up a significant portion of energy storage. Several countries are investing in the development of utility-scale PtG: Germany, USA, and Canada [33]. PtG has the distinct benefit of being easily integrated with existent natural gas (NG) networks. However, further research is necessary to improve efficiencies so that this technology can compete economically with other methods of energy storage.

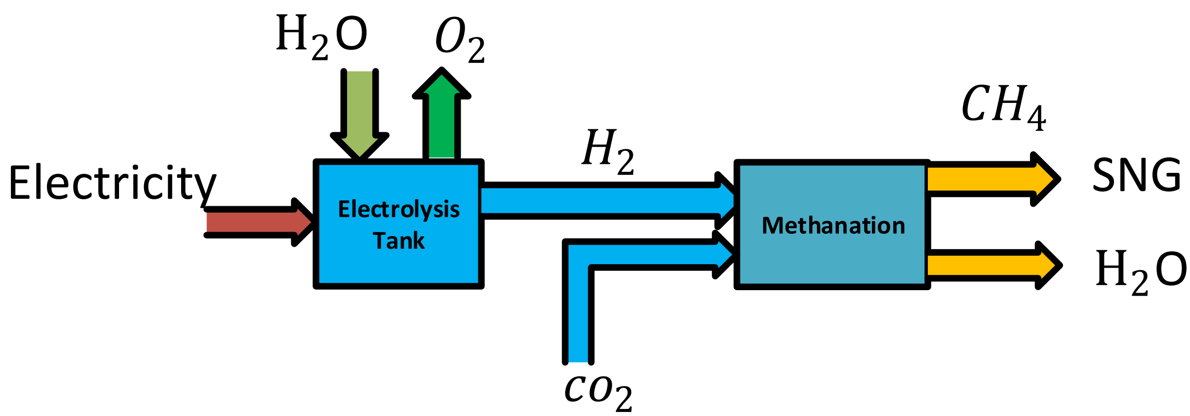

Figure 2-3 Electrolysis diagram in PtG energy storage systems

Electrolyzer:

Let's consider the electrolyzer, which is at the heart of green hydrogen production. This system consists of two electrodes (an anode and a cathode) separated by an electrolyte (in which free ions carry the electric charge), as well as a catalyst. Today several technologies are mature, amongst which the alkaline electrolyzer (hydroxide ions are transported through an alkaline solution) and the proton exchange membrane (PEM). In the latter, liquid electrolyte (the alkaline solution) is replaced by a solid polymer electrolyte. Both of these technologies work at low temperature, i.e. 100 °C, and present a conversion efficiency of around 70 %. But better solutions are just around the corner with high-temperature electrolysis (about 800 °C), a process that is currently under development. This technique is used in solid oxide electrolysis cells (SOEC), which make conversion efficiencies of up to 95 % a possibility, provided that the system can be supplied with an external heat source in order to reduce power needs and thereby increase their electrical efficiency. This benefit in efficiency will significantly reduce hydrogen production costs (by around 30 %) when compared to low temperature technologies. It will also meet the needs of mass-scale hydrogen production when connected to a solar power plant, or any other large-scale renewable energy power source.

2.2.3.5 Pumped Storage Hydroelectric Power

Pumped storage hydroelectric generating stations use electricity to pump water from a lower to a higher reservoir. This energy can be recovered by releasing the water from the upper reservoir to power a generator [34]. The overall efficiency of such reversal process could exceed 80%. Pumped storage is currently used to store both traditional and intermittent renewable energy, where water is pumped during times of low demand at a low cost and then used to generate electricity during times of high demand, which can be sold at a high cost [35]. Pumped storage has several benefits, among which the most salient is its responsiveness to power demands from the grid, so it can easily normalize irregularities in power demand on an hour to daily basis. Once established, a pumped-hydro station can be cycled thousands of times, and the system has very small loss in energy over time. However, pump-hydro is geographically restricted because it needs appropriate water resources and a suitable location for an upper and a lower reservoir [36]. Further, the installation of a pumped hydro storage system requires drastic land use change, as at least one reservoir is constructed. Additionally, the hydrologic ecosystem that the energy storage system exists with can be altered when water temperature, nutrient concentration, turbidity, flow, and many other factors are affected.

2.2.3.6 Compressed Air Energy Storage

Compressed air energy storage (CAES) is a widely used and economically efficient method of storing energy on a utility scale. The principle of CAES operation relies on filling an underground geologic cavern with compressed air [37]. This air can then be heated and released and then used to spin a gas turbine generator. CAES effectively decouples the compression and expansion cycle of a conventional gas turbine to allow the temporal separation of the use of a fuel and the generation of electricity [38]. The most important benefit of CAES is the large power capacity that a single CAES site can hold i.e., the capacity of a single CAES can vary from 1.8 to 10.8 x 1011 J. CAES is also relatively temporally stable; where the compression can last for more than a year. The efficiencies for CAES-based systems typically range from 60-80%. Also, the capital investments range from $400 to 800 per kW. Combined, these factors make CAES the leading utility scale energy storage technology.

The main drawbacks of CAES are that sites are geographically restrained. The underlining technological foundation is geologically restricted, specifically to requiring a large and stable geological cavern or aquifer. For this reason, the application of CAES system is limited to specific geological contexts. Although geologic caverns are not rare over a wide swath of land, they must be in close proximity to a large gas turbine plant in order for a CAES system to be economically feasible [39]. It is this factor that results in the implementation of a small number of CAES systems in a highly economic manner. Here it is noteworthy that CAES Cannot be paired with power generation plants such as coal-fired, nuclear, wind, or solar.

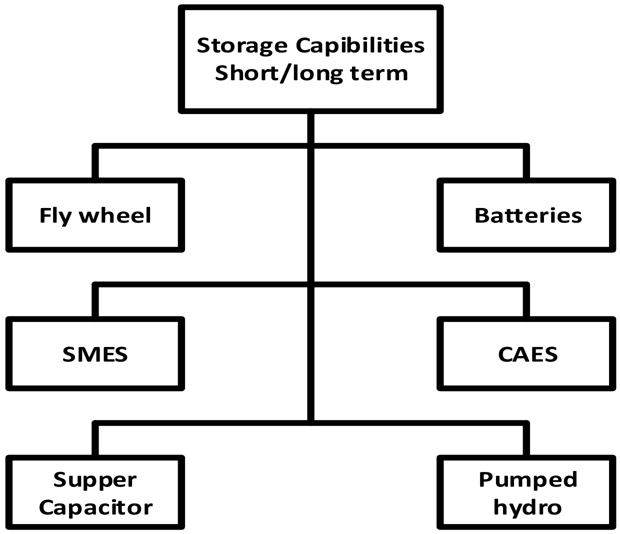

Figure 2-4 Classification of energy storage based on the storage capability

2.2.4 Storage Capabilities

ESS technologies can be also classified according to the period of energy storage into short term and long term. Figure 2-4 shows the types of ESS technologies classified into short and long term technologies.

2.3 EES installed capacity worldwide

The energy storage technology application varying based on its capability of providing the required services to power grid. The first largest installed energy storages capacity is the Pumped hydro storage (PHS) that provides 99% of all

Table 2-1 capacity of EES systems used in electricity grids

No	**EES**	**MW**	***MWH***
1	*Pumped hydro storage*	*127,000 MW*	*1,500,000 MWh*
2	*Compressed Air Energy Storage*	*440 MW*	*3,730 MWh*
3	*Sodium Sulphur Battery*	*316 MW*	*1,900 MWh*
4	*Lithium Ion Battery*	*~70 MW*	*~17 MWh*
5	*Lead Acid Battery*	*~35 MW*	*~70 MWh*
6	*Nickel Cadmium Battery*	*27 MW*	*6,75 MWh*
7	Flywheels	<25 MW	<0,4 MWh
8	Redox Flow Battery	<3 MW	<12 MWh

storage facility with 127 GW, which is 3% of global generation of power capacity. The second most widely used energy storage technology is Compressed Air Energy Storage (CAES) [40]. The third largest installed energy storage capacity is NaS. This storage technology is installed in so many countries around the world e.g., Japan, France, Germany, UAE and USA in 223 locations with a total capacity of 316 MW. Table 2-1 shows the installed capacity of installed EES systems used in electricity grids. It is expected that a large quantity of other EES to be installed given the emerging market needs for different applications.

Chapter 3

A Co-Simulation Platform for Power and Natural Gas Networks

3.1 Introduction

PtG is a new concept, which enables the transformation of surplus power generation to hydrogen by electrolysis, or even to methane by an additional methanation process. The produced gas can then be sold directly or stored for future usage [41]. Recent studies have shown that PtG and gas-fired power generation (GPG) technologies can potentially play an important role in the energy system [42]. On another avenue, the penetration of renewable energy resources has been increasing for the last few decades. Of the existing renewable energy resources, wind and solar energy production systems have been seeing an increased application [43]. The variability associated with the wind and solar systems production, introduces instants where the energy production is beyond the system demands and as such the curtailment of excess generation has to be adopted to ensure the system's stable operation [44]-[45].

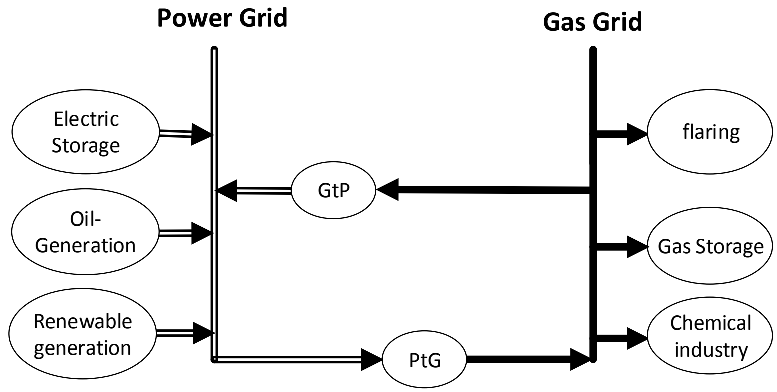

Figure 3-1 an overview of integrated power and gas networks

An alternative to the curtailment and waste of the excess renewable power generation is to store the excess power using energy storage technologies [46]-[47]. PtG is one of the most promising technologies of energy storage [48]. In PtG, the electrolysis of water is used to produce hydrogen or Synthetic Natural Gas (SNG).

Hence the excess power is stored in the gas network in the form of gas and is then used to supply gas demand or in converting it back to electricity using GPG units during times with high power demand [3]. Figure 3-1 gives an overview of the PtG concept and how it connects the gas and power networks. Several recent publications have focused on the integration of PtG into power and gas systems. In [49], the authors evaluated the environmental impact of storing renewable energy in the form of gas and concluded that it is environmental friendly. The authors in [50] discussed the operational impact of PtG on transmission networks of both power and gas transmission systems. The purpose of the research in [50] was to construct a model to assess the integration of PtG in the energy system and simulate its impacts on the electrical and gas transmission systems. However, the study was done for each grid individually. In [51], the authors evaluated the coordination of PtG facility and wind power generation. In [52], the authors evaluated the energy saving ability, the potential reduction in operation costs, and the investment opportunities of both power and gas grids when operating together as one integrated system. There are also other references that focused on PtG technology as an energy storage technique and evaluated its economic feasibility [53]. The optimization of the integrated power and gas system was investigated in [54]. In [55], a co-optimization scheduling of the integrated system was proposed.

In this chapter, a co-simulation platform for power and gas distribution networks is developed. The co-simulation platform could help quantifying the role of PtG technology in shaping the future of energy distribution systems. Using the co-simulation platform, several research studies can be carried out such as operation scheduling and planning of power and gas networks. Thus, the platform is expected to be immensely useful for power and gas operators and planners.

3.2 PtG CO-SIMULATION PLATFORM

The power and gas co-simulation platform comprises three sets of equations; first, equations describing the distribution power network behavior; second, equations describing the distribution gas network behavior and finally, equations describing the connection between the two networks. The equations describing the power network behavior are the steady-state power flow model. In this work, a global formulation for the problem of power flow in distribution networks is briefly presented. The first step in the problem formulation is to designate the injected current $I_{i,inj}$ at any bus i as a representative of the sum of all the branch currents connected with bus i so that the injected current can be given as follows:

$$I_{i,inj} = \sum_{j=1, j \neq i}^{n_{br}} I_{ij} \tag{3.1}$$

Where n_{br} is the number of branches in the distribution network. Using (3.1) and the relation between the branch voltage V_{ij} and branch current I_{ij} between two buses *i* and *j* in the distribution network, the injected apparent power S_i at bus *i* can be expressed as:

$$S_i = V_i \left(\sum_{j=1, j \neq i} y_{ij} (V_i - V_j) \right)^* \tag{3.2}$$

where y_{ij} is the admittance between two nodes i and j and (*) is the conjugate. From (3.1) and (3.2), the calculated active power P_i and reactive power Q_i at each bus i can be given as formulated in (3.3) and (3.4), respectively.

$$P_i = \sum_{\substack{j=1 \\ j \neq i}}^{n_{br}} \left(|V_i|^2 |y_{ij}| \cos(\theta_{ij}) - |V_i||V_j||y_{ij}| \cos(\theta_{ij} + \delta_j - \delta_i) \right) \quad (3.3)$$

$$Q_i = \sum_{\substack{j=1 \\ j \neq i}}^{n_{br}} \left(|V_i||V_j||y_{ij}| \sin(\theta_{ij} + \delta_j - \delta_i) - |V_i|^2 |y_{ij}| \sin(\theta_{ij}) \right) \quad (3.4)$$

where θ_{ij} is the angle of the admittance between buses i and j, and δ_i, δ_j are the voltage angles of buses i and j, respectively. In active power distribution networks, DG units are installed along the distribution feeders. The majority of such DG units are interfaced via *dc-ac* power electronic inverter systems [56]. The power flow models of DER units depend on its control scheme, which may vary with the DER type. Yet, most of the DER units are not utility owned and are characterized by being intermittent energy sources e.g., wind and solar. The deployment of smart inverters interfacing the DERs and the grid has created seamless control of the reactive power and/or power factor of DER units. Also, active power curtailment (i.e. de-rating) can be applied to provide full control of the generated power of DER units. For this reason, DER units can be modeled as controlled PQ buses. Hence, the active and reactive power mismatch equations of each bus *i* can be given as follows:

$$\Delta P_i = P_{g,i} - P_{d,i} - P_i \qquad (3.5)$$

$$\Delta Q_i = Q_{g,i} - Q_{d,i} - Q_i \qquad (3.6)$$

where $P_{d,i}$ and $Q_{d,i}$ are the active and reactive power demand at bus *i*, and $P_{g,i}$ and $Q_{g,i}$ are the active and reactive power generation at bus *i*, respectively.

Similar to the power flow problem, in order to describe the gas flow, there is a gas pressure variable associated with each node in the gas distribution network and a gas flow variable associated with each pipeline in the gas network. One gas node in the gas network is typically assumed as the reference node. Corresponding to the gas flow variables, there is a nodal gas balance equation for each gas node. Similarly, corresponding to each gas flow variable there is a corresponding pipeline flow equation [57].

The relation between the gas flow in the pipeline and the pressure at its terminals can be given as [57]:

$$r_k^2 - r_m^2 = R_{km} G_{gas,km}^2 \qquad (3.7)$$

Where r_k and r_m are the gas pressure in *kPa* at nodes *k* and *m*, respectively; R_{km} is the hydraulic resistance coefficient of the pipeline; and $G_{gas,km}$ is the standard gas flow rate in the pipeline in m^3/h measured at the base temperature and pressure. The steady state flow rate of an isothermal gas is affected by various factors, including the pressure drop, friction factor, type flow regime in pipeline, gas temperature, pipe diameter, and other parameters related to the type of gas. Equation (3.8) hereunder gives the formula to calculate the gas flow rate in a pipeline [57]

$$G_{gas,km} = C(\frac{T_b}{\alpha_b})D_{km}^{2.5}(\frac{\rho_k^2 - \rho_m^2}{L_{km}\gamma_G T_{a,km} Z_a f_{km}})^{0.5} E_{P,km} \qquad (3.8)$$

Where C is a constant; T_b and α_b are the gas temperature and pressure at base conditions, respectively; D_{km} and L_{km} are the inner diameter in meter and the length of the pipeline in km, respectively. γ_G is a dimensionless the natural gas specific gravity; $T_{a,km}$ is the average absolute temperature of the pipelines; Z_a represents the average compressibility factor; f_{km} is the friction factor; and $E_{P,km}$ is the pipeline efficiency. To that end, the nodal gas balance equation maintains that the sum of inflow and outflow at each gas node should be zero, and is given as follows:

$$G_i^s - G_i^{dem} - \sum_{m=i} G_{gas,km} = 0 \qquad (3.9)$$

Where G_i^s and G_i^{dem} are the gas supply and gas demand in m^3/h, respectively at node i; and $G_{gas,km}$ is the standard gas flow rate in pipeline in m^3/h.

Here, it is worth noting that the connection between the gas network and the electric network occurs at three types of components, namely the compressors, gas-fired power generation units and power to gas units. Gas compressor units have the responsibility to compensate the pressure drop in the network. Gas compressors are one of the main components of the gas network and they need energy to balance the pressure in the gas grid. This energy is taken from the electricity grid. The brake horsepower ($P_{BHP,km}$) of gas compressor is related to the compressor ratio and gas flow rate from the compressor and it can be written as follow:

$$P_{BHP,km} = K_{GC,km} Z_a F_{GC,km} [\frac{T_s}{E_c \eta_c}][\frac{C_k}{C_k - 1}][[\frac{p_m}{p_k}]^{\frac{c_k - 1}{c_k}} - 1] \quad (3.10)$$

Where K_{GC} is a Constant of compressor; $G_{GC,km}$ is natural gas flow in the compressor in m^3/h; T_s is Suction temperature of compressor in ^oR. E_c is the compressor parasitic efficiency, which is 0.99 for centrifugal units; η_c is the compression efficiency; C_K is Specific heat ratio for the natural gas; and P_m and P_k are nodal gas pressure at both ends of the pipeline measured in *kPa*.

Given that, GPG units consume gas to produce electric power, the relation between the consumed gas by each unit and its electric power production can be given as follows:

$$G_d^{GPG} = (\frac{3600}{\eta_{GPG} LHV}) P_s^{GPG} \tag{3.11}$$

Equation (3.11) shows the amount of gas demand for power generation; where G_d^{GPG} the amount of is required gas for power generation, P_s^{GPG} is the amount of power generated by GPG, η_{GPG} is the energy efficiency of gas to power conversion and LHV is the lower heating value in MJ/m^3.

$$G_s^{PtG} = (\frac{3600\,\eta_{PtG}}{LHV}) P_d^{PtG} \tag{3.12}$$

Similarly, equation (3.12) shows the amount of gas storage from power to gas conversion, where G_s^{PtG} the generated gas from the PtG unit is, P_d^{PtG} is the electric power consumed by PtG and η_{PtG} is the efficiency of the PtG unit.

It is worth noting that, the *LHV* is known as net calorific value, and is defined as the amount of heat released by combusting a specified quantity (i.e. initially at 25°C) and returning the temperature of the combustion products to 150°C, which assumes the latent heat of vaporization of water in the reaction products is not recovered.

3.3 CASE STUDIES

The set of algebraic equations of power and gas distribution networks has been coded and solved in Matlab environment. Figure 3-2 shows the integrated system utilized to test the formulated power and gas flow problem. As shown in the figure, the integrated system composed of the 33-bus Baran power distribution test system connected to a 7-node gas network. Three equal-sized Photovoltaic (PV) units of 1.25 MVA are located at buses 18, 25 and 33. The generation and load profile for a typical day with 15-minutes time step is shown in Figure 3-3 the main gas source is located Table 3-1 shows the gas pipeline data.

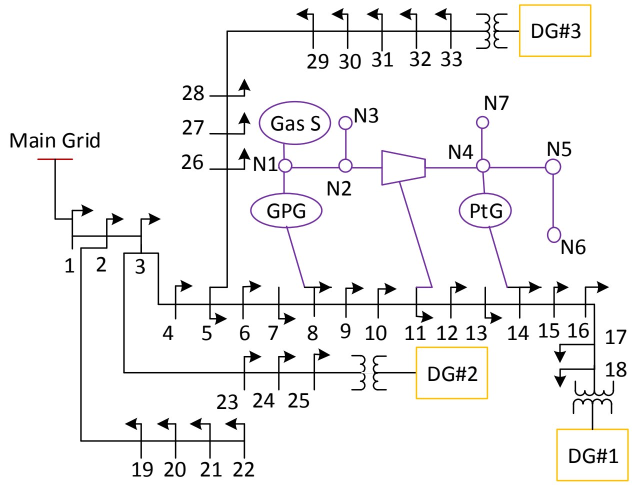

Figure 3-2 the integrated power and gas distribution networks

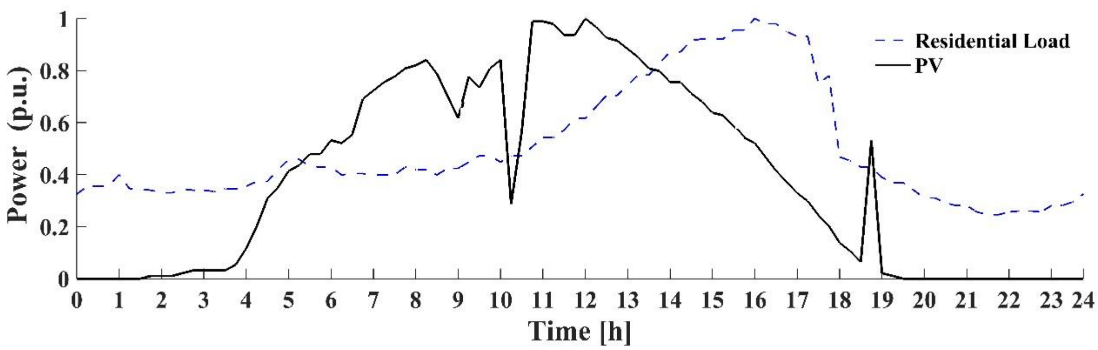

Figure 3-3 Load and generation profile of the studied test system

Table 3-1 Gas pipeline data

Branch	**From node**	**To node**	$R_{km}\ kpa^2/(m^3/h)^2$
1	*1*	*2*	*0.0003*
2	*2*	*3*	*0.0004*
3	*2*	*4*	*0*
4	*4*	*5*	*0.00025*
5	*5*	*6*	*0.0002*
6	*4*	*7*	*0.0003*

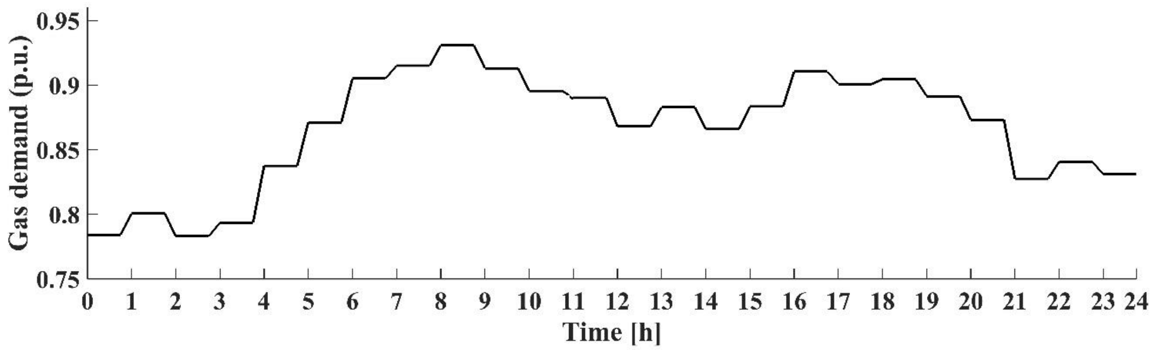

Figure 3-4 Gas Demand profile in per unit

The normalized daily gas consumption profile is shown in Figure 3-4. As depicted in Figure 3-2, there are three connection points between the power and gas networks. The GPG is located between node N1 and bus 8; the compressor is placed between bus 12 and branch 3 and the PtG is installed at bus 14 and N4. The GPG is assumed to a fixed gas amount of 12,000 m3/h for the studied day.

Two case studies are carried out to test the proposed platform. In the first case study, the PtG is deactivated. In the second case study, PtG is activated during the periods at which the power generated by PV units exceeds the total power demand in the system. In such a case, the PtG is operated as a dispatchable load to prevent the substation reverse power flow.

Figure 3-5 shows the maximum voltage in the 33-bus system during the studied day without and with the activation of PtG. As shown in the figure, a voltage rise problem occurs due to the reverse power flow at times when production is at a peak. As depicted, the problem of voltage rise can be mitigated by effectively activating the PtG unit during such periods, which facilitate the high penetration of renewable generation. When the produced gas of PtG is injected into the gas grid, it will affect the gas flow and pressure. Figure 3-6 and Figure 3-7 show the daily gas flow between N1 and N2 and the pressure at N2 without and with the activation of PtG, respectively. As shown in Figure 3-6, the gas flow between N1 and N2 decreases when the PtG unit is activated to compensate for high PV production. When the renewable gas produced by PtG is injected into the gas system, the flow of the gas supply decreases, which is reflected on the gas flow of N1-N2 pipeline. Nonetheless, the pressure of N2 increases when the PtG is activated, where the gas flow decreases.

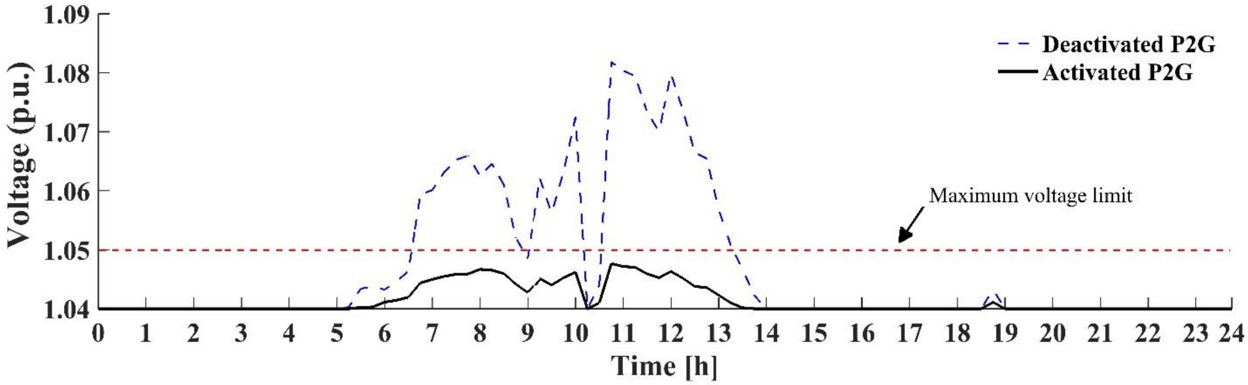

Figure 3-5 studied system maximum bus voltage with and without PtG

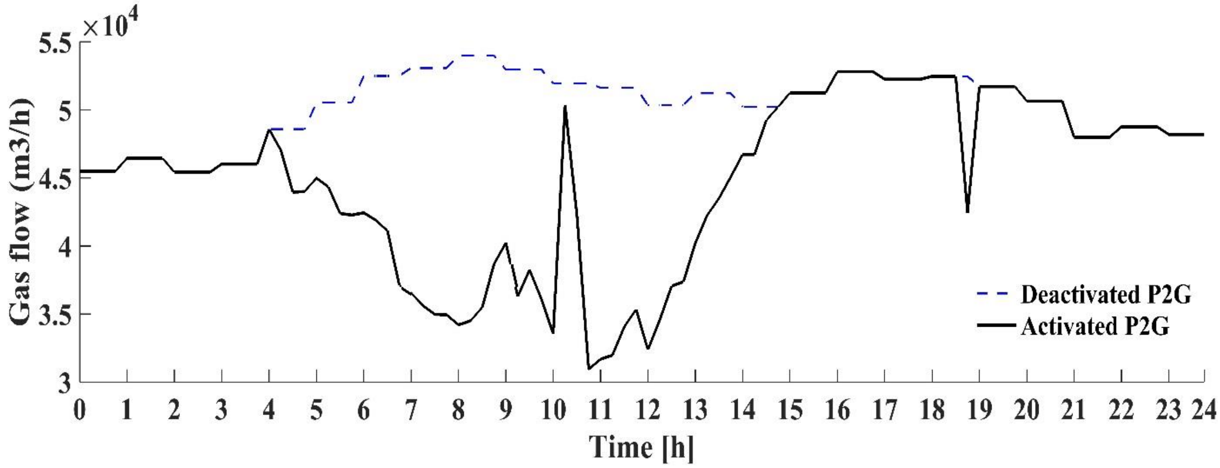

Figure 3-6 Gas flow between nodes N1 and N2 with and without PtG

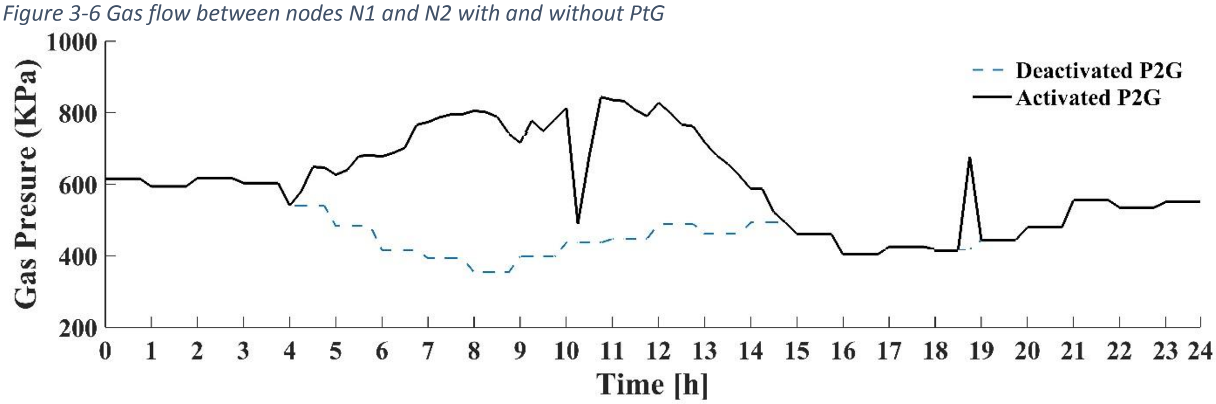

Figure 3-7 Pressure of node N2 with and without PtG

Chapter 4

Optimal Design of Power to Gas Energy Storage Systems

4.1 Introduction

The 21st century required that power industries should use smart equipment in classical power grid and this will cause variation in the performance of power systems; specifically the optimum use of power energy in the near future [58]. Some changes are required to take places for instances, use of controllable load, penetration of renewable energy and increasing the use of energy storage technology can be efficient solutions to create the balance between the production and consumption in conventional power grids [59].

ESS is playing a vital role in providing multiple services in several electricity markets. However, the benefits and risks of ESS participation vary across the type of markets and time of participation. In this chapter, a review of three different types of markets, at which ESS could potentially participate, is presented. Also, a new formulation for the optima sizing of PtG energy storage is developed.

4.2 Review of Electricity Markets

4.2.1 Energy arbitrage market

Price arbitrage is for storage to charge during low price periods and discharge during high price periods, but this requires a significant price difference to ensure the initial investment can be repaid [60]. However, the uncertainty for energy arbitrage is from price variations, which cannot be predicted accurately. This is possible in all countries with a wholesale energy market.

4.2.2 Ancillary service markets

Numerous ancillary service markets exist worldwide, with several commercial frequency response markets. ESS is involved with a payment structure reflecting its operation, which normally consists of two fees: the availability fee and response energy fee [61]. Frequency response (FR) markets vary across the world depending on system requirements, but FR is an essential resource to ensure stable energy network operation, to which ESS can contribute. In the FR market, the risk comes from the customers' behaviors, causing system frequency to fluctuate.

4.2.2 Distribution Network Operator's market

The Distribution Network Operator (DNO's) market is focused on the deferral of network investment by reducing peak energy flows. The introduction of ESS allows the peak load on the electricity networks to be reduced [62]. By providing proper peak shaving and/or congestion management services to DNOs, ESS can help save the investment and operation and maintenance costs of distribution networks.

4.3 Formulation of the Optimization Model

In this work a new formulation is developed to optimize the electrolyzer size that would produce hydrogen fuel to supply a hydrogen consumer facility e.g., transportation. The developed formulation aims at minimizing the capital and operation costs of the electrolyzer. Simultaneously, the algorithm aims to coordinate the operation of the electrolyzer unit across the seasons of the year. This is to maximize the harvested power during periods of surplus power i.e., low demand and low electricity prices. Using such algorithm, hydrogen generation facility will generate and store hydrogen during periods/seasons of low electricity prices for later use e.g., arbitrage.

4.3.1 Objective Function:

The objective function of the optimization problem is defined to minimize the annualized capital expenditure (CAPEX) and the operation expenditure (OPEX) as follows:

$$Minimize: \; CAPEX + OPEX \tag{4.1}$$

The annualized CAPEX is given as the product of the electrolyzer capital cost and the maximum of the electrolyzer operation (i.e.,P_t^{Elz}) in MW over the optimization horizon, which is divided by the electrolyzer life span (i.e., LS), as shown in equation (4.2).

$$CAPEX = \frac{max\{P_t^{Elz}\} \times C^{Elz}}{LS}, \quad \forall \, t \in T \tag{4.2}$$

where, C^{Elz} is the capital cost per MW, and t denotes for the optimization time step within the optimization time horizon T given as follows:

$$T = \{1, 1 + \Delta t, \cdots\cdots, t, \cdots\cdots, N_t - \Delta t, N_t\} \tag{4.3}$$

where, Δt and N_t represents the optimization horizon time step and number of time steps, respectively.

The annualized OPEX in the objective function is given as the product of the electrolyzer operation set points and: (i) the electricity prices (i.e., E_t^{Prc}) in \$/MW, and (ii) the electrolyzer operation cost (i.e., OC^{Elz}) in \$/MW as follows:

$$OPEX = \sum_{t \in T} P_t^{Elz} \times (E_t^{Prc} + OC^{Elz}), \forall\, t \in T. \tag{4.4}$$

Where, the operation cost is given as follows:

$$OC^{Elz} = \frac{3\% \times CAPEX \times LS}{8760} \tag{4.5}$$

4.3.2: Electrolyzer constraints:

The objective function in (4.1) is subject to the electrolyzer operation constraints. Equation (4.6) expresses the hydrogen outflow of the electrolyzer unit as a function of its input power [61].

$$F_t^{Elz} = P_t^{Elz} \times \beta^{Elz} \times \eta^{Elz} \tag{4.6}$$

where, F_t^{Elz} denotes the outflow of the electrolyzer unit, β^{Elz} is the conversion factor of the electrolyzer in m^3/MW, η^{Elz} is the efficiency of the electrolyzer unit. As such, the conversion factor of the electrolyzer unit is determined based on Faraday constant (F), Faraday's efficiency (η^F), and the electrolyzer input voltage (v^{Elz}), as shown in (6) [61].

$$\beta^{Elz} = \frac{\eta^F}{2 \times F \times v^{Elz}} \tag{4.7}$$

Also, it is worth noting that the electrolyzer hydrogen generation is constrained to satisfy the hydrogen demand as follows:

$$\sum_{t \epsilon T} F_t^{Elz} = \sum_{t \epsilon T} F_t^{Dem}, \quad \forall\, t \epsilon T \tag{4.8}$$

where, F_t^{Dem} denotes the hydrogen demand by the customer.

4.3.3: Power network constraints:

The formulated optimization model is subjected to the power distribution system power mismatch constraints given in (4.9)-(4.10).

$$\Delta P_{i,t} = P_{i,t}^{gen} \; - \left(P_{i,t}^{dem} + \alpha_i P_t^{Elz}\right) - P_{i,t} = 0, \quad \forall\, t \epsilon T \;\; \wedge \;\; i \epsilon I \tag{4.9}$$

$$\Delta Q_{i,t} = Q_{i,t}^{gen} \; - Q_{i,t}^{dem} - Q_{i,t} = 0, \quad \forall\, t \epsilon T \;\; \wedge \;\; i \epsilon I \tag{4.10}$$

where, i is an index for the power distribution system nodes within the set of nodes I; $P_{i,t}^{gen}$ and $Q_{i,t}^{gen}$are the active and reactive power generation, respectively; $P_{i,t}^{dem}$ and $Q_{i,t}^{dem}$ are the active and reactive power demand. Here, it is worth noting that α_i represents the interconnection between the electrolyzer and the power distribution system. As such, α_i is equal to one, if the electrolyzer is connected to node i, otherwise it is equal to zero. $P_{i,t}$ and $Q_{i,t}$ are the active and reactive power at node$i$, which are given as follows:

$$P_{i,t} = V_{i,t} \sum_{i' \epsilon I} V_{i',t} \times Y_{ii'} \times Cos(\delta_i - \delta_{i'} - \theta_{ii'}), \quad \forall\, t \,\epsilon\, T \;\; \wedge \;\; i \,\epsilon\, I \tag{4.11}$$

$$Q_{i,t} = V_{i,t} \sum_{i' \epsilon I} V_{i',t} \times Y_{ii'} \times Sin(\delta_i - \delta_{i'} - \theta_{ii'}), \quad \forall\, t \,\epsilon\, T \;\; \wedge \;\; i \,\epsilon\, I \tag{4.12}$$

where, $V_{i,t}$ denotes the voltage magnitude at node i; $Y_{ii'}$ represent the line admittance between node i and node i'; δ_i is the voltage angle at node i; and $Y_{ii'}$ is the admittance angle between node i and node i'. The objective function is also subjected to the power distribution node voltage and line capacity constraints as shown in equations (4.13) and (4.14), respectively.

$$V_{i,min} \leq V_{i,t} \leq V_{i,max} \tag{4.13}$$

$$P_{i,t} \leq P_{i,max} \tag{4.14}$$

4.4 Case Study

A case study is carried out in this section to validate the effectiveness of the proposed optimization model. To that end, the system data during the planning period is normalized annually. Without loss of generality, the studied year is divided into four seasons and each season is represented by a single day. Hence, the entire year is represented by four days. The time step of each day is assumed to be one hour. Figure 4-1 shows the electricity price for each day in each season. The data is obtained from the IESO website [63]. Figure 4-2 shows a typical load profile for each season represented in a day [63]. The hydrogen demand is assumed to be 3060 m^3/day (i.e., 255 kg) of hydrogen on a daily basis.

Fig. 4-3 shows the 33-bus power distribution system. As shown in the figure the electrolyzer unit is assumed to be connected at node 9. Where, the power distribution system node voltages are constrained to their minimum and maximum voltage limit of 0.95 pu and 1.05 pu, respectively, as per the ANSI code regulation [64]. In addition, the power distribution system lines are constrained to their Physical capacity of 10 MW. The integrated electrolyzer unit into the power distribution system has a hydrogen conversion factor of 360 m^3/MW, operational efficiency of 60%, and a capital cost of 1.25 M$/MW [61].

To that end, the developed optimization model takes place to optimize the electrolyzer unit size and operation to supply the hydrogen demand. In addition, the optimization model exploits the lower electricity prices to generate hydrogen, in order to minimize the OPEX.

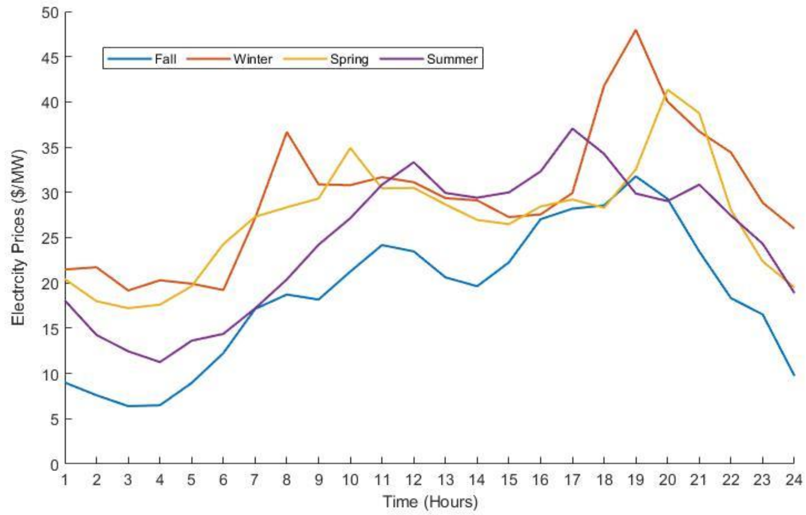

Figure 4-1 Electricity price of the four days representing the four seasons

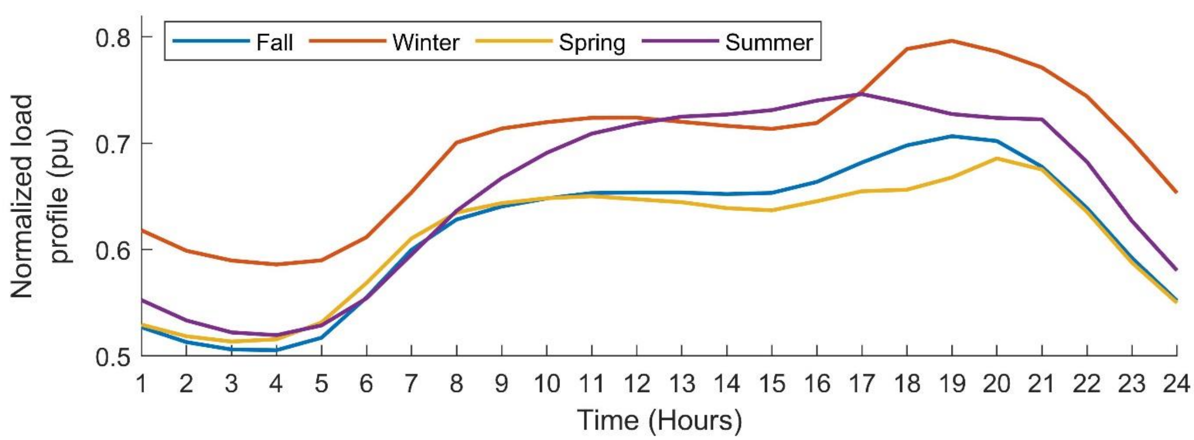

Figure 4-2 Load profile of the year in each season

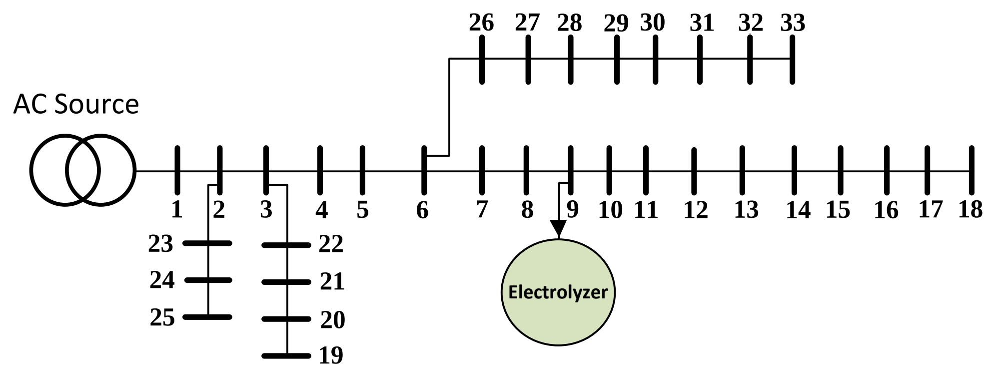

Figure 4-3 the studied 33-bus power distribution system

Figure 4-4 shows the optimal operation of the electrolyzer across the simulated four different seasons. As shown in the figure, the maximum capacity of the electrolyzer is 2.17 MW that have a capital cost of $2.7M. As such, the annual OPEX is estimated at 507.4 k$/year. Figure 4-5 shows the voltage profile of the electrolyzer unit. As can be seen in the figure, the electrolyzer voltage is maintained within the allowable voltage boundaries specified by the ANSI code [64].

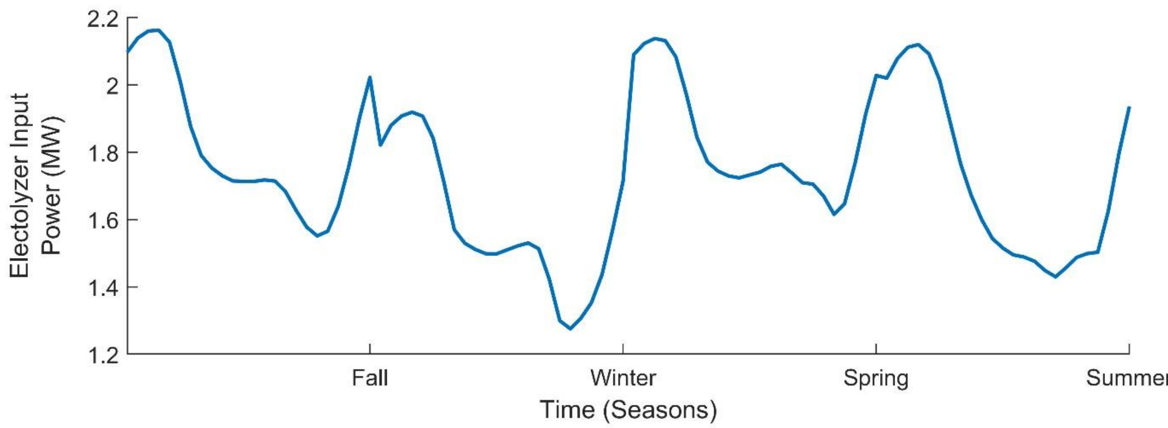

Figure 4-4 Electrolyzer Operation schedule

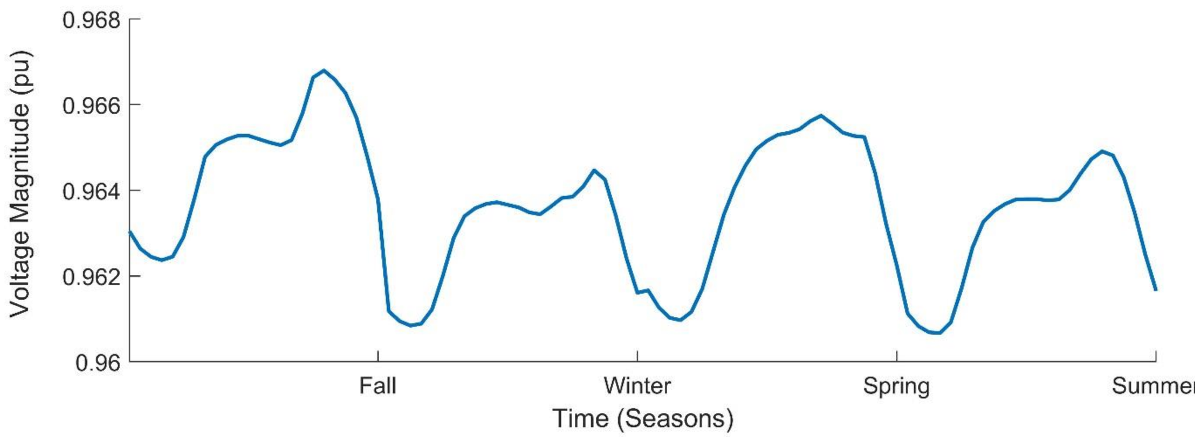

Figure 4-5 Electrolyzer interconnection node (i.e., Bus 9) voltage

Figure 4-6 shows the hydrogen generation during the time of the day across the studied seasons. As shown in the figure, the production of hydrogen is high during the night until the early morning hours due to the low electricity prices and low power demand during the overnight periods. However, the hydrogen production is low during the daily peak power demand that corresponds to high electricity prices.

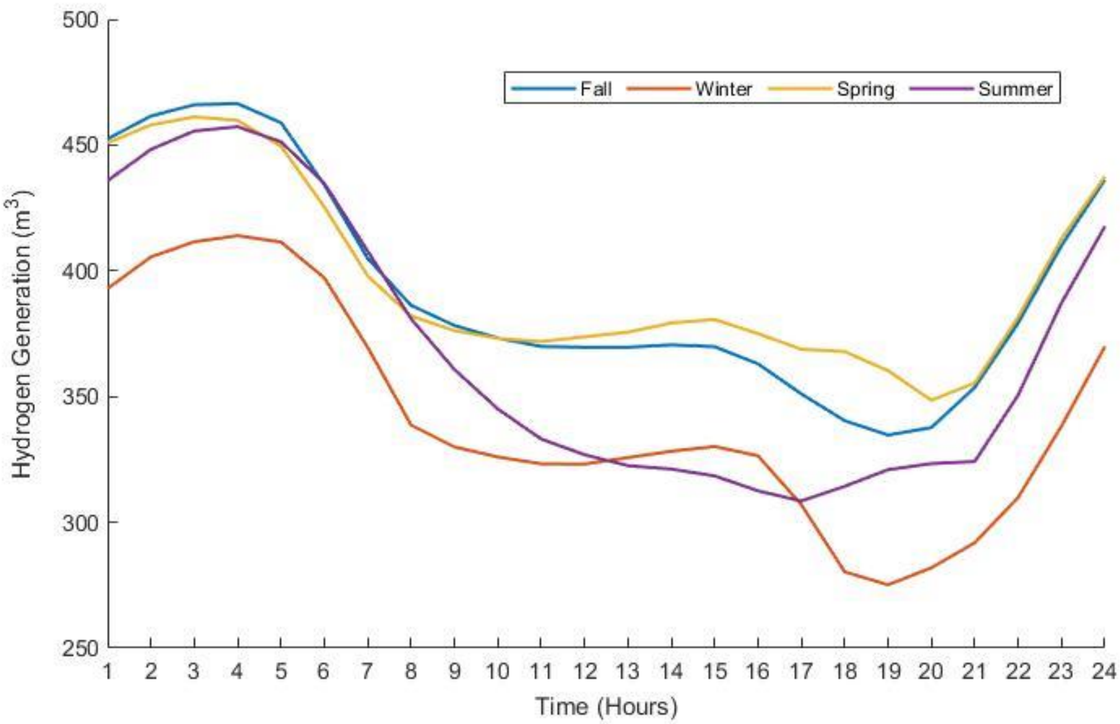

Figure 4-6 Hydrogen production across the simulated seasons.

Chapter 5

Optimal Design of PtG Electrolyzer to Supply Fuel Cell Transit Bus Networks

5.1 Introduction

Environment Canada has forecasted that greenhouse gas (GHG) emissions will rise to 862Mt by 2020 in Canada, which corresponds to a rise of over 15% compared to 2010 [65]. Oil and gas, energy, and transportation are identified as the main sectors that contribute to GHG emissions in Canada. The transportation sector contributes over 22% of global GHG emissions, a share that is often flagged as a target for potential emissions reduction [66]. For this reason, alternative powertrain technologies have been under close analysis to identify suitable replacements for the traditional oil-dependent Internal Combustion Engine (ICE). Electric Vehicle (EV) technologies are regarded a promising replacement for its ICE counterpart [67]. Transportation sector is thus on the verge of a paradigm shift to mitigate global GHG emissions, through the utilization of electric transportation systems.

5.1.1 Hydrogen's Overview

In industry, innovation and industrialization must work to reverse the balance of power between the production of hydrogen using fossil fuels and green hydrogen produced by electrolysis. As a means to store energy and create a bridge between the electricity and gas networks, this energy system must be addressed as a whole in order to intelligently and successfully negotiate the energy transition.

In the transport and mobility sector, hydrogen-powered vehicles are part of the wide array of zero-emission solutions. They have a vital role to play in meeting the objective fixed by various governments around the world to stop selling vehicles that emit greenhouse gases by 2040. It is already upon us and we must get ready by planning the complementary development of different alternative fuels.

Different EV technologies have been proposed and are further being developed, such as: hybrid electric vehicles (EVs), plug-in hybrid EVs, battery EVs, and Fuel cell EVs. A brief introduction of each technology is given hereunder:

5.1.2 Hybrid EVs

Hybrid EVs were proposed to improve the efficiency and reduce the GHG emission of the ICE. Hybrid EVs can also tackle the deficiencies of battery EVs such as short driving range, the need for charging infrastructure, and long refuelling time limitations [68]. Hybrid EVs utilize a conventional ICE propulsion system integrated with an ESS (i.e., battery or supercapacitors), and an electrical motor. In hybrid EVs, the ICE is used to either charge the battery or directly drive the vehicle. The electrical motor, on the other hand, is utilized to recover the kinetic energy by the regenerative braking system during deceleration situations. This, in turn, improves the overall efficiency [69].

5.1.3 Plug-in Hybrid EVs

Plug-in hybrid EVs have the same characteristics of hybrid EVs in addition to their abilities to be plugged into the electrical grid to be charged [70]. This feature allows for powering the vehicles from zero-emission energy resources. Plug-in hybrid EVs are designed to get most of its power from the electrical propulsion system, while the ICE acts as a backup powertrain.

5.1.4 Battery EVs

It has been argued that battery EVs are the cleanest powertrain technology, especially if the charged power is completely drawn from renewable energy resources [71].Battery EVs have two main concepts of refuelling (i.e., recharge the battery packs): on-board battery charging or battery swapping. Currently, Li-ion outcompete other types of batteries, due to it high energy density [72]. Battery EVs retains some adoption barriers in the market due to: 1) life cycle and degradation of batteries; 2) high cost of purchase; 3) lack of public charging infrastructure; and 4) impacts of adopting high EVs on the utility grid [73].

5.1.5 Fuel cell EVs

Fuel cell EVs utilize hydrogen fuel and air to generate electricity from fuel cell. The generated electricity is used to propel the vehicle or to be stored in a storage device (i.e., batteries or supercapacitors). Unlike battery-based EVs, fuel cell vehicles are characterized by high system efficiency and long driving range [74]. However, fuel cell vehicles is characterised by high cost and short life span. Furthermore, the lack of hydrogen fuelling stations infrastructure is identified as the key barrier to the adoption of fuel cell vehicles.

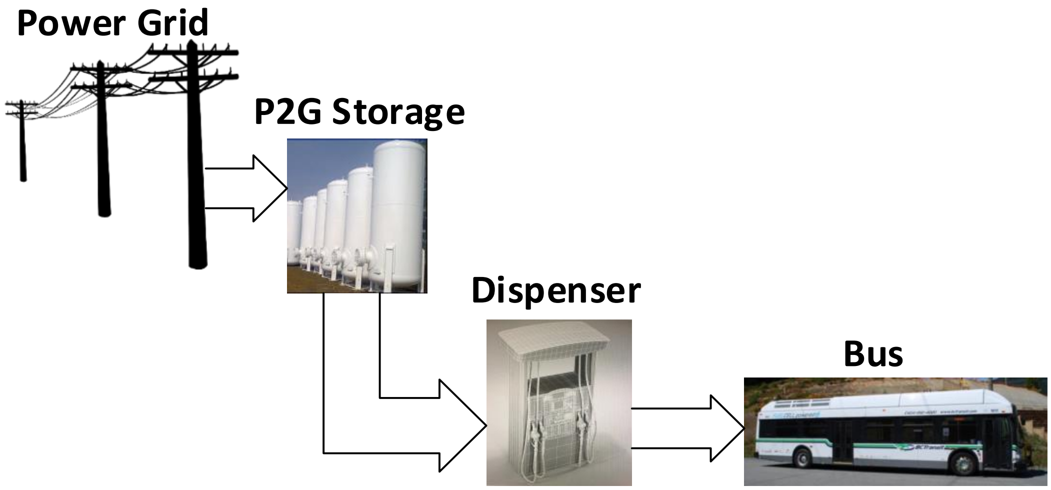

Figure 5-1 a schematic diagram of powering FCEBs using PtG technology

5.2 Fuel Cell (Hydrogen) Electric Buses

Among different types of vehicles, electrification of transit vehicles (e.g. public, campuses, and schools) is seen as a suitable context to reduce transportation-related GHG emissions, where it offers defined routes, timely operation, and share infrastructure among several other parameters that could aid the implementation of EV technology [75]. Unlike All Battery Electric Buses, Fuel Cell Electric Bus (FCEB) technologies have short refueling time i.e., 3 to 5 minutes, and can run for long distances i.e., about 300 miles to refuel [76]. FCEBs will produce zero-emission when the hydrogen is produced using the electrolyzer of PtG during the periods of surplus renewable energy resources i.e., well to wheel production of hydrogen has zero emission [77, 78]. Figure 5-1 shows a schematic diagram for the integration of power and transportation systems in order to produce the required hydrogen to power FCEBs. As depicted in the figure, the produced hydrogen from the electrolyzer could be stored in a hydrogen tank i.e., the gas storage network to be utilized in a later time to fuel the FCEBs. Hence, the excess renewable power is basically stored in the gas storage network in the form of hydrogen and is then used to supply hydrogen demand to the local transit buses network. There are several ongoing demonstration projects for the implementation of FCEBs. For instance, Japan targets to have 6000 fuel cell cars, 100 FCEBs and 35 Hydrogen refueling station by 2020 for the Olympic Games [79].

In addition to the above characteristics of the FCEB technologies, there are a number of other reasons that make hydrogen (in compressed form) and fuel cells would appear to be a suitable option for electric buses:

- They return regularly to a depot thus minimizing fuel infrastructure requirements;
- They are "large", thus minimizing the need for compactness of the technology;
- Subsidies may be available from urban authorities in order to demonstrate urban pollution reduction commitments

- They operate almost continually over long periods, thus making fuel-efficient technology more attractive.

In terms of the mechanical properties, the total force for driving a FCEB can be written as follow [80]:

$$F_T = \sum R = R_W + R_S + R_A + R_I \qquad (5.1)$$

where R_W is rolling resistance, R_S slope resistance, R_A air resistance and R_I inertial resistance. The force can be also represented in a detailed formula as:

$$F_T = \left(m + \frac{\Theta_w}{r^2}\right)\frac{d_v}{d_t} + \frac{1}{2}pC_d A_f V^2 + mgC_r\cos(\alpha) + mg\sin(\alpha) \qquad (5.2)$$

where *m* is the vehicle gross mass, *w* is the wheels inertia, *r* is the wheel radius, *ρ* is the air density, C_d is the aerodynamic drag coefficient, A_f is the vehicle frontal area, g is the acceleration of gravity, Cr is the friction coefficient and α is the road angle which is set to zero for the evaluation driving cycle. The Citaro Fuel Cell Hybrid transit bus from Mercedes Benz is used as a reference for the vehicle parameters. The simplified formula for power demand of a bus can be defined as follow

$$P_m = V_T * v \qquad (5.3)$$

The size and location of tank in a vehicle can be design with the help of the equation

$$L = W_B - (2F + G + H + I) \tag{5.4}$$

it explains that the size and location of tank in vehicle is varies based on the type of vehicle for instance smaller size and high volume size as the height and wide of vehicle changes the exact location and size of the tank in vehicle will be design with the help of equation (5.4).

5.3 Proposed Optimization Model

In this section, an optimization model is developed for the daily schedule of hydrogen production in order to supply a FCEB transit network. The model is formulated to optimize the cost of producing the hydrogen required to supply a FCEB network for the next day i.e., day ahead.

4.3.1: Objective Function of the Optimization Model:

The objective function of the optimization model is formulated as follows:

$$Minimize: \sum_{t \in T} P_t^{Elz} \times E_t^{Prc} \forall\, t \in T. \tag{5.5}$$

where P_t^{Elz} is the power consumed by the electrolyzer and E_t^{Prc} is the price of electricity at each time instant t. The time t denotes for the optimization time step within the optimization time horizon T given as follows:

$$T = \{1, 1 + \Delta t, \cdots\cdots, t, \cdots\cdots, N_t - \Delta t, N_t\} \quad (5.6)$$

The objective function represents the daily electricity cost of the hydrogen required to supply the FCEBs. It is noted that Δt and N_t represent the optimization horizon time step and number of time steps, respectively.

4.3.2: FCEB Hydrogen Demand:

The objective function in (5.1) is subject to the satisfaction of the FCEBs hydrogen demand for the next day. Such constraint can be represented mathematically as follows:

$$F_{transit}^{Dem} = \sum_{t \in T} F_t^{Elz}, \quad \forall\, t \in T \quad (5.7)$$

where $F_{transit}^{Dem}$ denotes the total hydrogen demand by the transit sector. The amount of required hydrogen per day for a FCEB transit network is calculated as:

$$F_{transit}^{Dem} = \sum_{b=1}^{N_{FCEB}} h_R \times l_{trip} \times N_{tr} \quad (5.8)$$

where h_R is the rate of hydrogen consumption in kg per kilometer, l_{trip} is the length of each trip for each bus b, N_{tr} is the total number of trips for each bus b per day, and N_{FCEB} is the total number of operating buses in the transit network . It is noteworthy that $F_{transit}^{Dem}$ cannot exceed the capacity of the hydrogen tank H_{cap} given as follows:

$$F_{transit}^{Dem} \leq H_{cap} \tag{5.9}$$

4.3.3: Power Flow and Electrolyzer constraints:

The objective function is subject to the electrolyzer operation constraints described in chapter 4 i.e., equations (4.6)-(4.8). It is also subject to the power flow and voltage constraints of the distribution system stated in (4.9)-(4.14).

5.4 Simulation Results

The optimization model described above has been coded in MATLAB environment and solved using its optimization toolbox. Figure 5-2 shows the integrated system of power and FCEB transit systems. As shown in the figure, the integrated system composed of the 33-bus Baran power distribution test system connected to through electrolysis in bus to Hydrogen storage systems. Three equal-sized Photovoltaic (PV) units of 1.25 MVA are located at buses 18, 25 and 33.

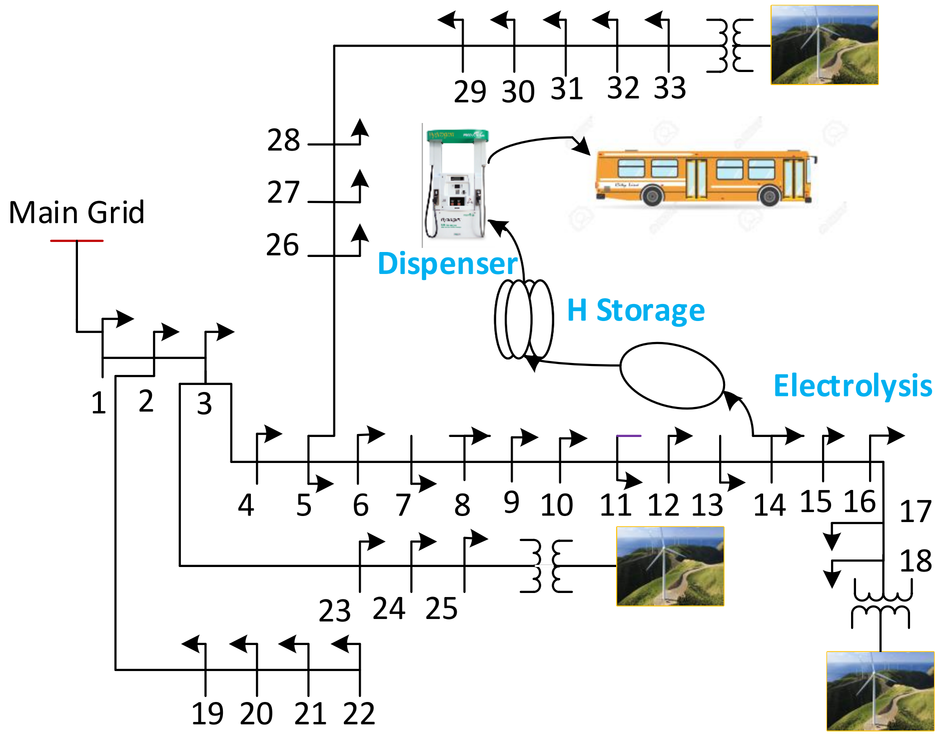

Figure 5-2 integrated power and FCEB transit networks

the electrolyzer is arbitrary allocated at bus # 14 of the power distribution system.

The electricity price of the studied day is shown in Figure 5-3 below. Figure 5-4 shows the daily electric load profile of the test system.

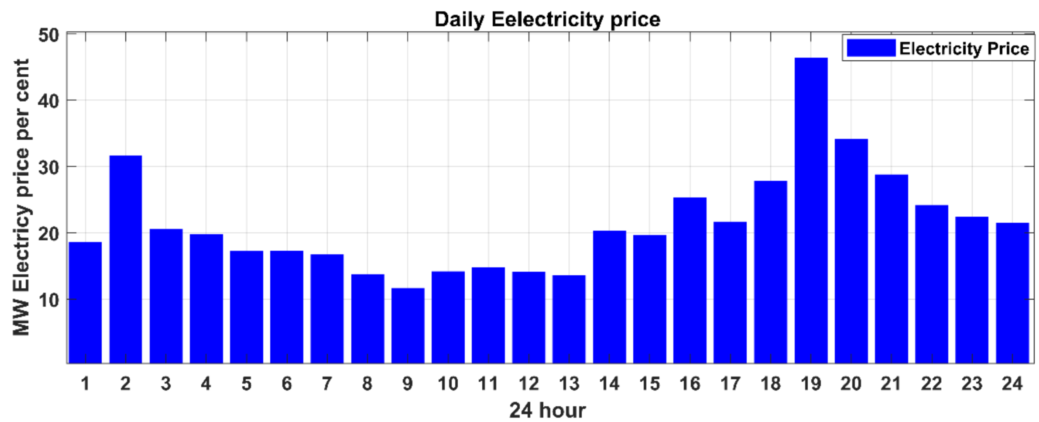

Figure 5-3 Daily electricity price

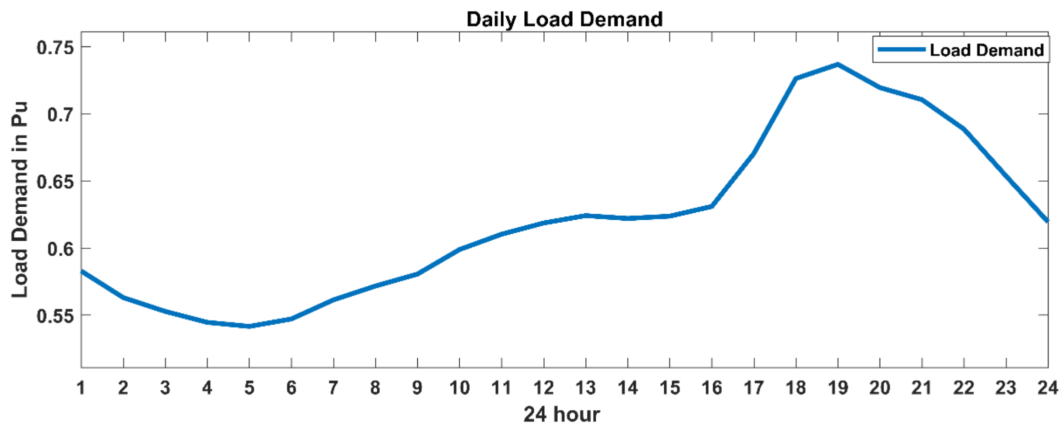

Figure 5-4 Daily load demand of the studied system

Three different real transit bus systems with different sizes are studied. The transit networks under study are Belleville, Stratford, and Cornwall located in Ontario, Canada. The typical public bus as shown in the figure above requires 0.1548 kg of Hydrogen per kilometer. The above estimation is from fuel cell bus network that was implemented for four years in BC Canada. To elaborate more for each studied network, the amount of required hydrogen to supply the FCEBs is calculated based on equation (3.12) and the transit data summarized in Tables 5-1, 5-2, and 5-3 for the three networks under study, respectively. Figures 5-5, 5-6, and 5-7 shows the optimized scheduling of the hydrogen production for three networks under study, respectively.

Table 5-1 Studied Belleville transit network

Rout ID	**Length (Km)**	**Trip**	***Route Name***	***H in KG***
1	*9.564*	*24*	*Plaza Dundas*	*22.95*
2	*9.705*	*31*	*Parkwood Heights*	*30.086*
3	*12.392*	*29*	*College East*	*35.93*
4	*9.601*	*28*	*Mall North Front*	*26.88*
5	*9.448*	*31*	*Parkdale mall*	*29.28*
6	*10.378*	*24*	*Avondale*	*33.07*
7	12.157	29	Loyalist	35.25
8	9.998	28	North Part	27.99
9	8.508	23	Quinte Sport Center	19.568

Table 5-2 Studied Straftford transit network

Rout ID	**Length (Km)**	**Trips**	***Route Name***	***H in KG***
1	*7.7*	*32*	*Huron*	*38*
2	*8.2*	*32*	*East end*	*40.6*
3	*10*	*32*	*McCartly*	*49.53*
4	*9.5*	*32*	*Queensland*	*47.1*
5	*11.7*	*32*	*Devon*	*48.1*
6	*9.7*	*32*	*Downie*	*57.96*

Table 5-3 Studied Cornwall transit network

Rout ID	Length (Km)	Trip	*Route Name*	*H in KG*
1	*12.837*	*30*	*Pitt*	59.6
2	*11.058*	*30*	*McConnell*	51.35
3	*11.28*	*30*	*Sunrise*	52.38
4	*10.346*	*30*	*Cumberland*	48.05
5	*10.22*	*31*	*Brookdale*	49.04
6	*9.901*	*30*	*Montreal*	46
7	12.076	28	Riverdale	52
8	11.76	7	Community Service Eest	19.3
9	17.76	9	Community Service West	24.7
10	13.8	3	Supplementary 1	6.41
11	19.9	1	Supplementary 2	3.1
12	18.2	3	Supplementary 3	8.45

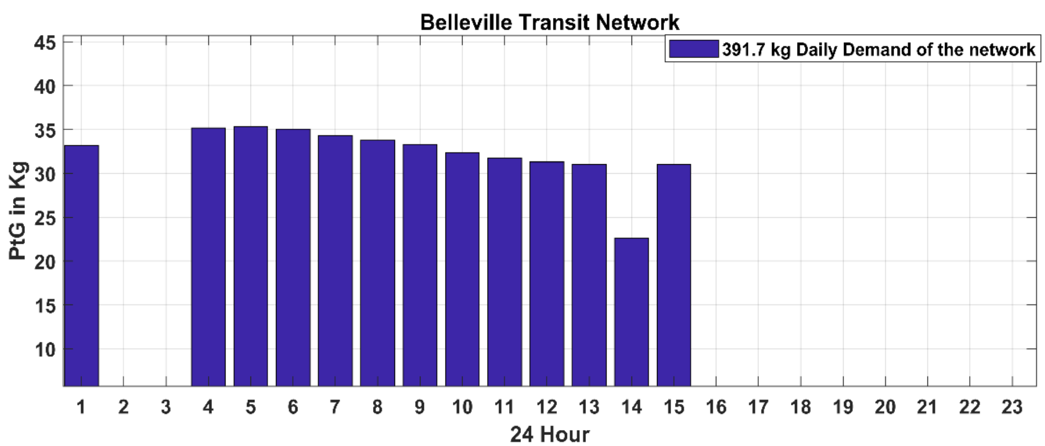

Figure 5-5 Optimized hydrogen production for Belleville

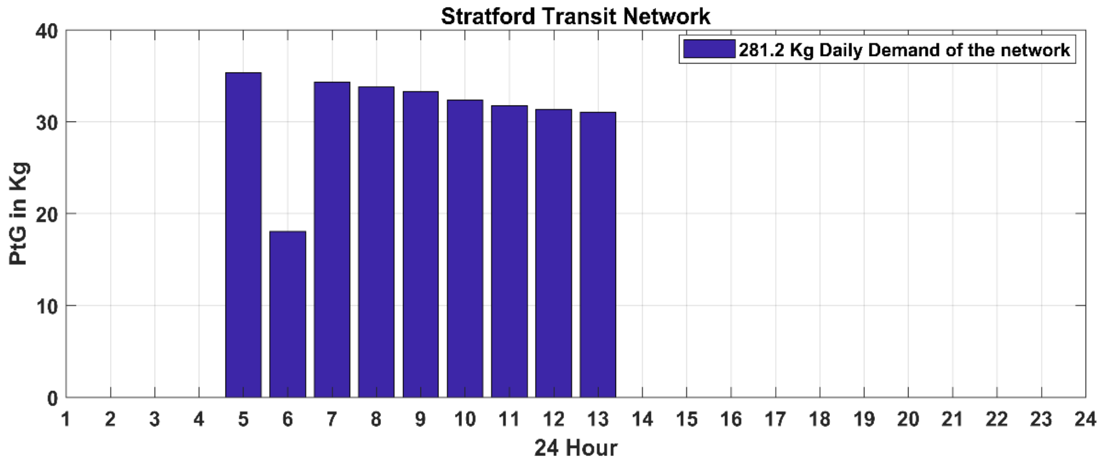

Figure 5-6 Optimized hydrogen for Stratford

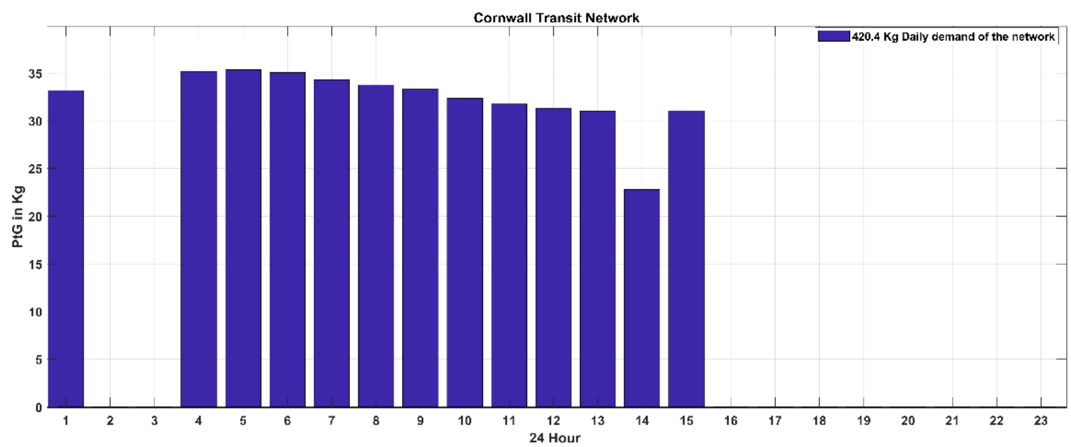

Figure 5-7 Optimized hydrogen production for Cornwall

In order to simulate a large amount of hydrogen demand, the three networks are combined and represented as one transit network and the simulation result is plotted in the following graph 5-8: The total amount of demand gas is 1093.3 kg.

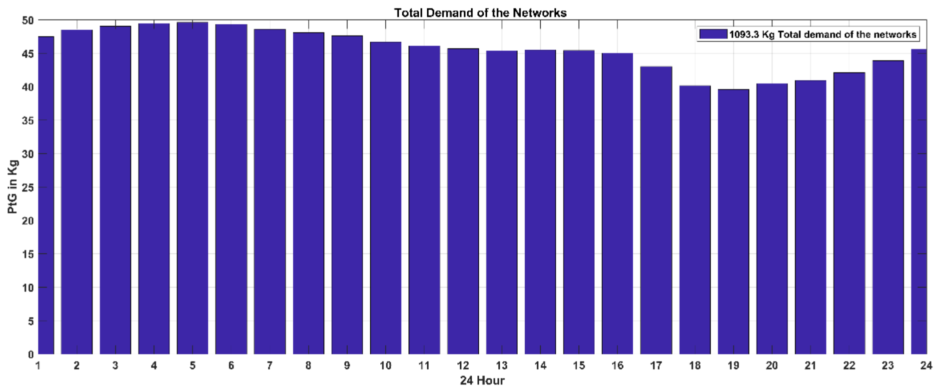

Figure 5-8 Optimized hydrogen of all three networks together

The simulation results of all three studied networks: Belleville, Stratford and Cornwall, shows that the optimized model will provide required amount of hydrogen for each network with the cheapest price. As shown in Figure 5-5, the hydrogen can be mostly produced for the network in the interval of [3:30 am – 3:30 pm], times of less power demand and convenient price. The same study is implemented for Stratford and Cornwall bus networks and the results are demonstrated in Figures 5-6 and 5-7, respectively. As shown in Figure 5-s6, the right time for producing the Hydrogen demand for the buses in this network is found to be [4:30am -1:30 pm]. The time interval for producing the amount of Hydrogen in for Cornwall is found to be almost the same as it is for Belleville with little changes because the required amount of hydrogen for both network is almost the same i.e., 391.7 kg for Belleville and 420.4 kg for Cornwall.

Chapter 6

Contribution and future works

This chapter summarizes the main contributions and findings of this thesis and states future work.

6.1 Thesis Summary

Utility-scale PtG is a new type of energy storage technologies, which enables the transformation of surplus power generation to hydrogen by electrolysis, or even to methane by an additional methanation process. The produced gas can then be sold directly or stored for future usage. This thesis aims at developing the modeling tools required to simulate, design, and optimize the operation of utility-scale PtG energy storage to quantify its benefits for potential applications in smart grids.

Toward that end, in chapter 1 of this thesis, the motivation for the research work is defined and thesis layout is presented. Chapter 1 introduces energy storage technologies as potential means to mitigate key challenges in sustainable energy: reducing GHG emission from energy sectors, seamless integration for renewable energy resources, electrification of transportation, and production of renewable gas.

In chapter 2, different types of utility-scale energy storage technologies have been reviewed and compared. In literature one can find various types of classification for energy storage technologies. In this thesis, energy storage technologies are classified into four main categories: their interaction to power grid, services that can provide to the grid, short-term and long-term energy storage capabilities, and the way/medium at which the energy is stored.

A co-simulation platform for both power and NG distribution networks is proposed and developed in chapter 3. The developed co-simulation platform aims at quantifying the impacts of PtG technology on both power and NG distribution networks. In chapter 4, a mathematical model for the optimal sizing of PtG energy storage to supply a hydrogen demand has been formulated. The objective function of the optimization model is to minimize the capital and operation costs of PtG. Chapter 5 has introduced a new formulation for the optimal design and production scheduling of hydrogen, i.e., from PtG, to supply public transit bus networks. The proposed formulation takes into account the operation requirements of both power distribution and electric bus transit networks. There are several case studies that have been carried out in chapters 3 to 5 in order to validate the effectiveness of the proposed engineering tools.

6.2 Contribution

As a result throughout the research period, several contributions have been achieved in this thesis. ***First***, a co-simulation platform for power and gas distribution networks is developed [81]. The co-simulation platform could help quantifying the role of PtG technology in shaping the future of energy systems. Using the co-simulation platform, several research studies can be carried out such as operation scheduling and planning of power and gas distribution networks. Thus, the platform is expected to be immensely useful for the operators and planners of power and gas distribution networks.

Second, a new mathematical formulation has been developed in this thesis for the optimal design i.e., sizing, of PtG energy storage. The developed formulation aims at minimizing the capital and operation costs of PtG. The formulation also aims to maximize the harvested power during periods of surplus energy i.e., low demand and high power generation. The formulated model could be utilized to assess the technical and economic feasibility of PtG energy storage and quantify its potential role to facilitate seamless adoption for high penetration of renewable energy resources.

Third, a new mathematical formulation is proposed for the optimal sizing and production scheduling of hydrogen, i.e., from PtG, to supply fuel cell electric bus transit networks. The proposed formulation takes into account the operation requirements of both power distribution and electric bus transit networks. Transit network operators could potentially use the developed model to design and optimize the operation of their fuel cell buses.

6.3 Future work

Many countries around the world set ambitious target to replace conventional energy generation with Renewable energy resources [82],[83]. The German government, for instance, is targeting 80% share of renewable energy resources in electricity generation by 2050. ESS technologies will play a major role in meeting the ambitious targets of renewable energy penetration levels. Hence, future work may include the following:

- Develop dynamic models for ESS technologies to study their technical role of responding to grid services such as frequency regulation
- Extend the work of fuel cell electric buses to include electric cars and distributed hydrogen fueling stations
- Develop a model to compare the techno-economic aspects of centralized MW-scale versus distributed community kW-scale hydrogen production facilities
- Assess the impacts of safety challenges for hydrogen storage on the future adoption for high penetration of fuel cell electric vehicles.

BIBLIOGRAPHY

[1] Ali A, Li W, Hussain R, He X, Williams BW, Memon AH. “Overview of current microgrid policies, incentives and barriers in the European Union, United States and China”. Sustainability. vol. 9, pp. 7-1146

[2] DOE U. Quadrennial Technology Review 2015. US Department of Energy, Washington, DC 2015

[3] T. Möbius and D. Gunkel, "The optimal placing of energy storages in Germany in 2020 — An implementation of a DC-load flow model," 11th International Conference on the European Energy Market (EEM14), Krakow, pp. 1-5. , 2014

[4] Z. Wang et al., "Research on the active power coordination control system for wind/photovoltaic/energy storage," 2017 IEEE Conference on Energy Internet and Energy System Integration (EI2), Beijing, pp. 1-5, 2017

[5] A. Remaci, C. Merlo, O. Curea, A. Hacala and V. Guerre, "Renewable Electricity conversion and storage: Focus on Power to Gas process, EMR modelling and simulation," PCIM Europe 2016; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, Nuremberg, Germany, pp. 1-8, 2016,

[6] S. Clegg and P. Mancarella, "Integrated Modeling and Assessment of the Operational Impact of Power-to-Gas (P2G) on Electrical and Gas Transmission Networks," in IEEE Transactions on Sustainable Energy, vol. 6, no. 4, pp. 1234-1244, Oct 2015.

[7] S. Chen, Z. Wei, G. Sun, K. W. Cheung and Y. Sun, "Multi-Linear Probabilistic Energy Flow Analysis of Integrated Electrical and Natural-Gas Systems," in IEEE Transactions on Power Systems, vol. 32, no. 3, pp. 1970-1979, May 2017

[8] J. H. Huang, H. S. Zhou, Q. H. Wu, S. W. Tang, B. Hua and X. X. Zhou, "Assessment of an integrated energy system embedded with power-to-gas plant," 2016 IEEE Innovative Smart Grid Technologies - Asia (ISGT-Asia), Melbourne, VIC, pp. 196-201, 2016

[9] D. Alkano and J. M. A. Scherpen, "Distributed Supply Coordination for Power-to-Gas Facilities Embedded in Energy Grids," in IEEE Transactions on Smart Grid, vol. 9, no. 2, pp. 1012-1022, March 2018

[10] I. Diaz de Cerio Mendaza, B. P. Bhattarai, K. Kouzelis, J. R. Pillai, B. Bak-Jensen and A. Jensen, "Optimal sizing and placement of power-to-gas systems in future active distribution networks," 2015 IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA), Bangkok, pp. 1-6, 2015

[11] S. Clegg and P. Mancarella, "Storing renewables in the gas network: modelling of power-to-gas seasonal storage flexibility in low-carbon power systems," in IET Generation, Transmission & Distribution, vol. 10, no. 3, pp. 566-575, 2016

[12] E. G. Cazalet, "Role of storage technologies for increased deployment of distributed and renewable resources," 2010 Innovative Smart Grid Technologies (ISGT), pp. 1-1, Gothenburg, 2010,

[13] Denholm, Paul, Erik Ela, Brendan Kirby, and Michael Milligan. "The role of energy storage with renewable electricity generation," 2010

[14] j. Rugolo, and M.J. Aziz, “Electricity storage for intermittent renewable sources,” Energy & Environmental Science, vol. 5, pp. 7151-7160, 2012

[15] K. Turitsyn, P. Sulc, S. Backhaus and M. Chertkov, "Options for Control of Reactive Power by Distributed Photovoltaic Generators," in Proceedings of the IEEE, vol. 99, no. 6, pp. 1063-1073, June 2011

[16] D. Alkano, and J. Scherpen “Distributed supply coordination for Power-to-Gas facilities embedded in energy grids” IEEE Trans. on Smart Grid, vol. PP, no. 99, May 2016

[17] A Oberhofer, P Meisen. Energy storage technologies & their role in renewable integration. Global Energy Network Institute. P, Jul 2012

[18] IESO Report: Energy Storage March 2016

[19] Carnevali, C., R. Genova, P. Jenné, M. Mazzuchelli, M. Reijalt, and G. Priano. "Fuel cell electric buses and perspectives: High V. LO-city project authors." In Energy Conference and Exhibition (ENERGYCON), 2012 IEEE International, pp. 1039-1043, 2012

[20] N Günter, A Marinopoulos. “Energy storage for grid services and applications: Classification, market review, metrics, and methodology for evaluation of deployment cases”. Journal of Energy Storage vol. 1; 8, pp.226-34. Nov 2016

[21] A. Akhil, "Trends and status of battery energy storage for utility applications," Proceedings of the Tenth Annual Battery Conference on Applications and Advances, Long Beach, CA, USA, 1995, pp. 273-277

[22] Spiers D. “Batteries in PV systems,” InPractical Handbook of Photovoltaics (Second Edition) pp. 721-776, 2012

[23] Akinyele, D., Belikov, J. and Levron, Y., “Battery storage technologies for electrical applications,” Impact in stand-alone photovoltaic systems. Energies, vol. 10:11, pp.1760, 2017

[24] Shigematsu, T., “Redox flow battery for energy storage,” SEI technical review, vol.73, pp.5-13. 2011

[25] Ahmad, S., and M. Sorou. Contents lists available at ScienceDirect “Renewable and Sustainable Energy Reviews”

[26] Elkin, B., L. Finkelstein, T. Dyer, and J. Raade. "Molten oxide glass materials for thermal energy storage." Energy Procedia vol.49, 772-779, 2014

[27] D. Axel. "Assessment of Pumped Heat Electricity Storage Systems through Exergoeconomic Analyses." PhD diss., Technische Universität, 2017

[28] Sabihuddin S, Kiprakis AE, Mueller M. A “numerical and graphical review of energy storage technologies,” Energies. 29; vol.8 pp. 172-216, Dec 2014

[29] Amiryar, Mustafa E., and Keith R. Pullen. "A review of flywheel energy storage system technologies and their applications." Applied Sciences vol. 7, no. 3: 286, 2017

[30] Plater, Bryan B., and James A. Andrews. "Advances in flywheel energy-storage systems." Power Pulse. Darnell Group, 2001

[31] International Electrotechnical Commission. "Electrical energy storage white paper." Geneva, Switzerland: International Electrotechnical Commission: pp.1-78, 2011

[32] L. Markus, R. Tichler, H. Steinmüller, and M. Koppe. "The power-to-gas concept." In Power-to-Gas: Technology and Business Models, pp. 7-17, 2014

[33] Eveloy V, Gebreegziabher T. A “Review of Projected Power-to-Gas Deployment Scenarios,” Energies. Vol.12, pp.11(7):1824, Jul 2018

[34] T. M. Masaud, K. Lee and P. K. Sen, "An overview of energy storage technologies in electric power systems: What is the future?" North American Power Symposium, Arlington, TX, pp. 1-6, 2010

[35] Sternberg A, Bardow A. “Power-to-What?” Environmental assessment of energy storage systems. Energy & Environmental Science; vol.8(2): pp.389-400, 2015

[36] P. Filip. "Environmental Impacts of Pumped Storage Hydro Power Plants." Master's thesis, Institutt for vann-og miljøteknikk, 2014.

[37] Wang J, Lu K, Ma L, Wang J, Dooner M, Miao S, Li J, Wang D. “Overview of compressed air energy storage and technology development,” Energies. Vol.13, pp.10(7):991. Jul 2017

[38] S. Samir, and Robert H. Williams. "Compressed air energy storage: theory, resources, and applications for wind power." Princeton environmental institute report vol. 8, 2008

[39] Meiwes, H. "Technical and economic assessment of storage technologies for power-supply grids." Acta Polytechnica 49, no. 2, 2009

[40] https://www.iec.ch/whitepaper/pdf/iecWP-energystorage-LR-en.pdf

[41] J. Ye, R. Yuan “Integrated natural gas, heat, and power Dispatch considering wind power and power-to-gas,” Sustainability, vol. 9, no. 4 pp. 602, Apr 2017

[42] E. Bompard, F. Boni-Castagnetti, G. Chicco, A. Mazza, L. Piantelli, and E. Pochettino. "Report on Opportunities and Options for PtG in Power Systems." 2017.

[43] KPMG in Singapore “Global Trendsin Renewable Energy”

[44] Dawn S, Tiwari PK, Goswami AK. “A Joint Scheduling Optimization Strategy for Wind and Pumped Storage Systems Considering Imbalance Cost & Grid Frequency in Real-Time Competitive Power Market,” International Journal of Renewable Energy Research (IJRER), vol.31; 6(4), pp. 1248-59, Dec 2016

[45] F. Hosseini, M. Niroomand, “Instantaneous Responses of on-grid PV Plants to Changes in Environmental and Weather Conditions,” International Journal of Renewable Energy Research (IJRER), vol.6, no.4, pp.1296-306, Dec 3. 2016

[46] Mahamadou AT, Mamadou BC, Brayima D, Cristian N. Ultracapacitors and batteries integration for power fluctuations mitigation in wind-PV-diesel hybrid system. International journal of renewable energy research (IJRER). Vol.17, pp. 86-95, Jun 2011

[47] S. Faias, J. Sousa and R. Castro, "Contribution of energy storage systems for power generation and demand balancing with increasing integration of renewable sources: application to the Portuguese power system," 2007 European Conference on Power Electronics and Applications, Aalborg, pp. 1-10, 2007

[48] M. Qadrdan, M. Abeysekera, M. Chaudry, J. Wu, N. Jenkins “Role of power-to-gas in an integrated gas and electricity system in Great Britain”Int J Hydrogen Energy, vol.40, no. 17, pp. 5763–5775, May 2015

[49] Brinkman G. “Economics and environmental effects of hydrogen production methods,” School of Public Policy, 2003

[50] Vandewalle J, Bruninx K, D’haeseleer W. “A mixed-integer linear operational model of a coupled electricity, natural gas and carbon energy system with power to gas,” Online: https://www. mech. kuleuven. be/en/tme/research/energy_environment/PublicationsEnergyandenvironment/Last accessed on:880. Dec 2014

[51] Zahedi A. “Technical analysis of an electric power system consisting of solar PV energy, wind power, and hydrogen fuel cell,” InPower Engineering Conference, AUPEC 2007. Australasian Universities, pp. 1-5, IEEE. Dec 2007

[52] X. Yu, G. Zhu, S. Wang and Y. Ding, "Economic Impact of Power to Gas in Integrated Electricity and Gas System with High Wind Penetration," 2018 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia), Singapore, pp. 640-645, 2018

[53] R. Chen, J. Wang and H. Sun, "Clearing and Pricing for Coordinated Gas and Electricity Day-Ahead Markets Considering Wind Power Uncertainty," in IEEE Transactions on Power Systems, vol. 33, no. 3, pp. 2496-2508, May 2018

[54] D. Li, C. Gao and S. Xuemei, "Study on coupled planning of power grid and gas network considering P2G device," IEEE Conference on Energy Internet and Energy System Integration (EI2), Beijing, pp. 1-6, 2017

[55] Q. Zeng, J. Fang, Z. Chen, J. Li and B. Zhang, "A multistage coordinative optimization for sitting and sizing P2G plants in an integrated electricity and natural gas system," 2016 IEEE International Energy Conference (ENERGYCON), Leuven, pp. 1-6, 2016

[56] M. M. A. Abdelaziz, H. E. Farag, E. F. El-Saadany and Y. A. I. Mohamed, "A Novel and Generalized Three-Phase Power Flow Algorithm for Islanded Microgrids Using a Newton Trust Region Method," in IEEE Transactions on Power Systems, vol. 28, no. 1, pp. 190-201, Feb, 2013

[57] Q. Zeng, J. Fang, J. Li, Z. Chen, "Steady-state analysis of the integrated natural gas and electric power system with bi-directional energy conversion," Applied Energy, vol.184, pp. 1483-92, Dec, 2016

[58] EU Commission. Renewable Energy Road Map–Renewable energies in the 21st century: building a more sustainable future. Communication from the Commission to the Council of the European Parliament, COM (2006), 2007

[59] Crabtree G. "Integrating Renewable Electricity on the Grid," A Report by the APS Panel on Public Affairs. American Physical Society: Washington, DC 2010

[60] Salles MB, Huang J, Aziz MJ, Hogan WW. "Potential Arbitrage Revenue of Energy Storage Systems," in PJM. Energies; vol. 10, pp. 8:1100, Jul 2017

[61] N. A. El-Taweel, H. Khani, and H. E. Z. Farag, "Hydrogen Storage Optimal Scheduling for Fuel Supply and Capacity-Based Demand Response Program under Dynamic Hydrogen Pricing," IEEE Trans. Smart Grid, In Press, Aug. 2018

[62] Chua KH, Lim YS, Morris S. Energy storage system for peak shaving. International Journal of Energy Sector Management, vol.4, pp. 3-18, Apr 2016

[63] Power Data, IESO, Toronto, Canada. [Online]. Available: http://www.ieso.ca/power-data

[64] ANSI Std. C84.1, "American National Standard for Electric Power Systems and Equipment–Voltage Ratings (60 hertz)", 2006

[65] http://www.oag-bvg.gc.ca/internet/English/parl_cesd_201410_e_39845.html

[66] Mahmoud M, Garnett R, Ferguson M, Kanaroglou P. Electric buses: A review of alternative powertrains. Renewable and Sustainable Energy Reviews, pp. 673-84. Sep 2016

[67] C. Carnevali, R. Genova, P. Jenné, M. Mazzuchelli, M. Reijalt and G. Priano, "Fuel cell electric buses and perspectives: High V.LO-city project authors," 2012 IEEE International Energy Conference and Exhibition (ENERGYCON), Florence, pp. 1039-1043, 2012

[68] K. S. Grewal and P. M. Darnell, "Model-based EV range prediction for Electric Hybrid Vehicles," IET Hybrid and Electric Vehicles Conference 2013 (HEVC 2013), London, pp. 1-6, 2013

[69] Clegg, S. J. "A review of regenerative braking systems." 1996

[70] R. J. Broderick and J. J. Bzura, "Investigation of plug-in hybrid EVs (PHEVs) and their effects on power distribution systems in the NE and SW united states: Summary of a panel session presentation," 2009 IEEE Power & Energy Society General Meeting, Calgary, AB, pp. 1-4, 2009

[71] Un-Noor F, Padmanaban S, Mihet-Popa L, Mollah MN, Hossain E. A "comprehensive study of key electric vehicle (EV) components, technologies, challenges, impacts, and future direction of development", Energies, vol. 17; pp. 8:1217, Aug 2017

[72] Gao Z, Chin CS, Chiew JH, Jia J, Zhang C. "Design and Implementation of a Smart Lithium-Ion Battery System with Real-Time Fault Diagnosis Capability for Electric Vehicles," Energies, vol. 27, pp.10:1503. Sep 2017

[73] Impey, Guy. "Electric vehicle charging: impact review for multi-user residential buildings in British Columbia." 2013

[74] G. Graber, V. Galdi, V. Calderaro and A. Piccolo, "A method to size the stack and the battery of a fuel cell vehicle reducing the fuel consumption," AEIT International Annual Conference, Cagliari, pp. 1-6, 2017

[75] A. F. Burke and M. Miller, "Fuel efficiency comparisons of advanced transit buses using fuel cell and engine hybrid electric drivelines," Collection of Technical Papers. 35th Intersociety Energy Conversion Engineering Conference and Exhibit (IECEC) (Cat. No.00CH37022), Las Vegas, NV, USA, 2000, vol.2, pp. 1333-1340

[76] https://www.energy.gov/sites/prod/files/2016/11/f34/fcto_state_of_states_2016.pdf

[77] https://www.ucsusa.org/clean-vehicles/electric-vehicles/how-clean-are-hydrogen-fuel-cell-vehicles#.W8ZBQXtKiUk

[78] B. K. Ahn and T. W. Lim, "Fuel Cell Vehicle Development at Hyundai-Kia Motors," 2006 International Forum on Strategic Technology, Ulsan, pp. 199-201, 2006

[79] https://rctom.hbs.org/submission/tokyos-surprise-for-the-2020-olympics-hydrogen-the-energy-for-next-generation/

[80] Gillespie TD. Vehicle dynamics. Warren dale. 1997

[81] H. Ziarmal, H. E. Farag, N. A. El-Taweel and M. Abdelaziz, "A Co-simulation platform for power and gas distribution networks," 2017 IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA), San Diego, CA, pp. 891-895, 2017

[82] Heffels T, McKenna R, Fichtner W. Long-term modelling of power-to-gas capacity developments and operation in the German power system. InSustainable Energy Policy and Strategies for Europe, 14th IAEE European Conference, International Association for Energy Economics October Oct 2014

[83] Strunz S. The German energy transition as a regime shift. Ecological Economics, vol. 1, no.100, pp.150-8, Apr 2014