An Optimization Strategy for Managing Surplus Electricity through P2G Pathways

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Abstract

Ontario has a high dependency on nuclear and renewable energy, with more than 85% of its electricity supplied from non-carbon-based sources. Due to the intermittency and inflexibility of the generators, surplus electricity (SBG) is generated when supply exceeds demand. This paper aims to develop a mathematical model for power-to-gas (P2G) energy system, converting SBG into hydrogen to be used by end-users. The four end-users studied were renewable natural gas sector (RNG), hydrogen-enriched natural gas sector (HENG), mobility sector and industry sector. Two scenarios were considered for the model: Scenario 1, where a single pathway was considered for implementation and Scenario 2, where the four pathways were integrated into one system for a combined installment. The objective of this model is to minimize the total cost and maximize emission offset with a lifetime of 20 years. The modelling and optimization were carried out in Python using mixed integer linear programming (MILP) based approach. The Scenario 1 results showed that replacing industry feedstock by hydrogen is more cost-efficient than other sectors. The Scenario 2 results showed that the system can reduce 470,595 tonnes of CO_2 per year, which is 95% of the maximum achievable offset and utilize 57% of the surplus electricity.

Keywords

Mixed integer programming, Power-to-Gas, Operation and design optimization, Hydrogen economy, Excess energy

1. Introduction

To many jurisdictions across the world as well as the general public, reducing their carbon fuel dependency and greenhouse gas emission is becoming an increasingly greater priority. For example, the State of California has committed to reducing its carbon emissions by 40% by 2030 [1]. Many other governments have been devoting similar efforts in recognizing the importance of carbon footprint reduction. Until the current iteration of its government, Ontario has also been a big promoter of decarbonization [2]. Ontario has a large dependence on renewable power generation could be used as an important tool for carbon footprint reduction in the province [3,4]. However, power output from existing non-carbon-based sources (i.e., nuclear, hydro, solar, wind, and biofuel) cannot be adjusted easily to match consumer demand. The slow ramping rates in nuclear generators and the uncontrollable nature of renewable energy sources make it impossible to fine-tune the output of these power plants. Therefore, a constant discrepancy between supply and demand is inevitable [4].

When electricity supply exceeds demand, surplus electricity is generated, which Ontario lacks an internal market for an effective management system. This surplus generation is currently managed by exportation and curtailment, which is a process where the capacity of generators is involuntarily reduced, resulting in economic loss [5]. There exists an opportunity to develop a storage system of the sort that uses this surplus generation. This will allow for higher utilization of non-carbon energy within Ontario, achieving carbon emission reduction, while preventing excess green energy from involuntary exports or curtailment.

As a response to this opportunity, a Power-to-Gas (P2G) system is recommended. P2G is a system in which the surplus generation could be stored and distributed as chemical energy, effectively linking the supply from the power grid to the demand in the gas grid. Briefly, a P2G system uses the surplus electricity generation to facilitate hydrolysis via

PEM electrolyzers, in which the hydrogen is sent to various end-users [6]. P2G is an attractive solution for surplus clean energy management with a positive side-effect of carbon emission offset.

The overall goal of this paper is to develop optimization model for cost-optimized Power-to-Gas energy systems for Ontario. There are four hydrogen end-users studied in the project: P2G to renewable natural gas (RNG), to hydrogen-enriched natural gas (HENG), to mobility fuel, and to industry [7,8]. By substituting a set amount of hydrogen demand from the end-users with clean hydrogen produced from P2G, an internal market for surplus generation can be implemented while achieving carbon emission offset. In the model, the P2G energy hubs for the four pathways will first be modelled separately (Scenario 1) and then the four pathways will be incorporated in one system (Scenario 2). Number of equipment, hydrogen flow and energy flow will be calculated in Python using MILP to optimize total cost and emission offset for the system.

2. System Description

2.1 Scenario 1: Individual Pathways

P2G to Renewable Natural Gas. A commonality shared between all P2G models is that they all begin with the energy input being fed into electrolyzers, where the hydrogen is either sent directly for use or reserved in storage units aided by pre-storage compressors. In the RNG model, the hydrogen is reacted with carbon dioxide to produce methane, which can be upgraded as renewable natural gas [6]. The carbon dioxide required for this pathway is captured from biogenic sources such as farms and processed in digestors [4, 6]. Then, the produced RNG is injected directly into the NG grid such that 10% of the grid volume is of renewable sources.

P2G to Hydrogen-Enriched Natural Gas. In the HENG model, the produced hydrogen is directly injected into the NG grid. Like the industry model, no other equipment is required to facilitate this pathway. The hydrogen is injected in the NG grid such that 5% of the grid volume is hydrogen, such that there are no adverse effects to end-users of NG.

P2G to Mobility Fuel. In the mobility pathway, booster compressors units are required to increase the pressure of the hydrogen flow to the level required in the fuelling stations (350 bars). Then, through the fuelling stations, hydrogen is distributed for use in fuel-cell vehicles whenever FCV drivers come to the stations for a refuel.

P2G to Industry. In the industry model, the electrolyzer and storage tank outlet pressures are sufficient for industrial feed conditions, so the hydrogen can be sent directly to the plants without safety or compatibility issues [4]. Therefore, no additional units of equipment are required in the industry pathway.

The schematic diagrams of the above pathways are shown in Figure 1 below.

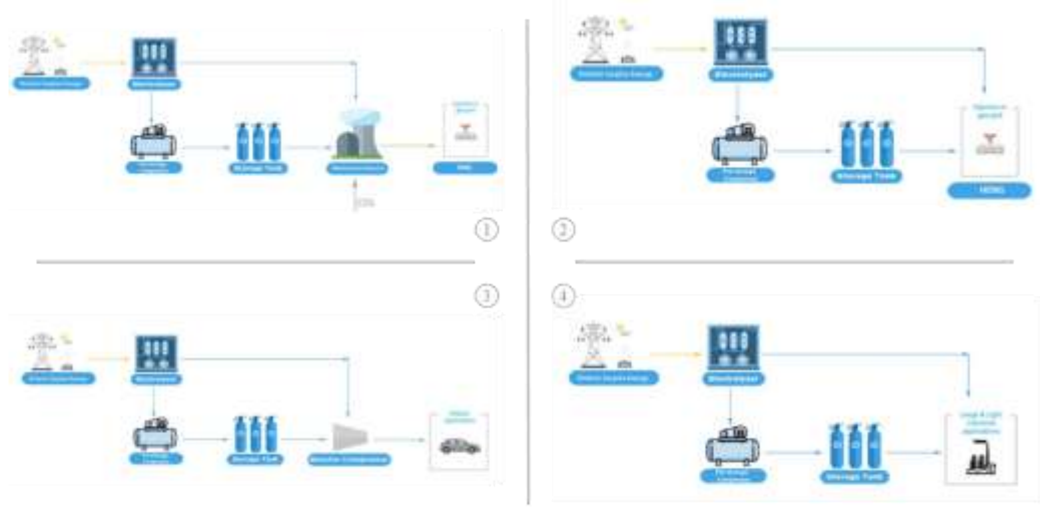

Figure 1 Schematic diagrams for Scenario 1 with 1) P2G to NG 2) P2G to HENG 3) P2G to Mobility 4) P2G to Industry

2.2 Scenario 2: Combined Models

This model combines the four individual pathways into a single energy hub, as shown in Figure 2. In this design, the distribution and allocation of hydrogen into each end-user occur proceeding the electrolysis and storage steps. The implication is that the conversion of electrical to chemical energy occurs in a centralized hub. The produced hydrogen is then sent to the four end-users while undergoing identical unit operations as the individual pathway models. A necessary alteration to be noted is that the top two pathways (RNG and HENG) both arrive on NG grid injection, satisfying the same NG demand.

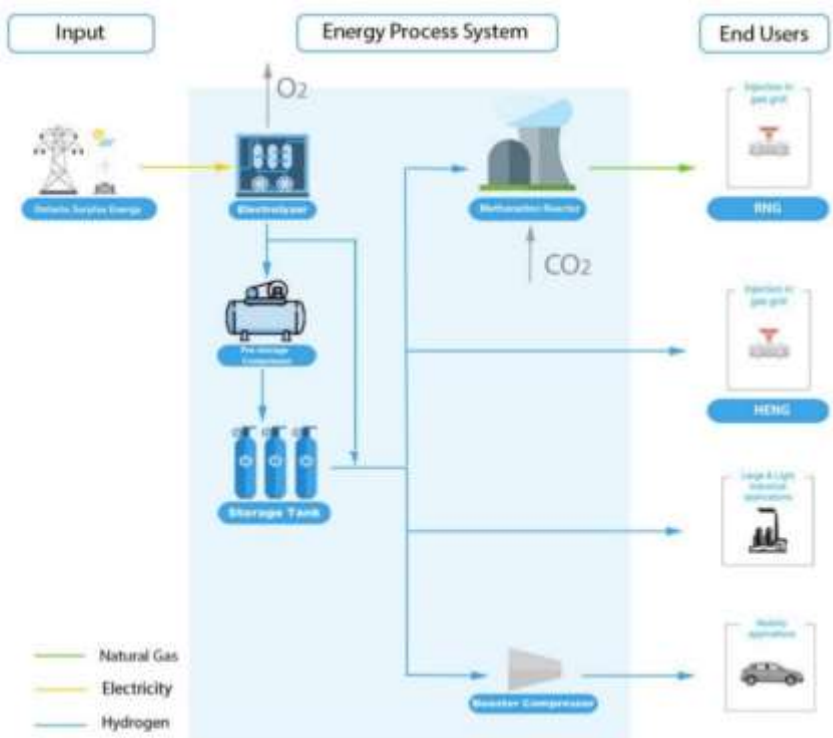

Figure 2 Schematic diagram for scenario 2: Combined Mod

3. Methodology

The modeling consists of three phases – pre-processing, optimization model design, and post-processing.. The first step is to collect the P2G technology and market information. These include technical specifications, electricity supply, demand, and cost, hydrogen demand, emission level, and technology costs. The second step is to construct optimization equations and simulate the optimization in Python. The model yields four major outputs – optimal number of equipment, hourly energy flow, total cost, and CO2 emission offset. The last step is post-processing the results.

3.1 Modelling

The primary objective of this program is to minimize cost. The capital cost of this system consists of the costs of different equipment depending the pathway, for example, renewable natural gas (RNG) consists electrolyzers, compressors, tanks, reactor, and the upgrading unit. The operating costs include the costs of carbon dioxide, the electricity costs consumed by the electrolyzers and the compressors, the costs of water consumption, and the operating costs of the upgrading unit (for RNG specifically) [6]. The total cost is the sum of capital and operating costs, adjusted to the current year value.

$$\text{Minimize: Total Cost} = \text{CAPEX} + \text{OPEX} * \text{TVM} \quad \text{Eq.1}$$

$$\mathrm{CAPEX} = \sum_{i=1}^{N_{electrolyzer,max}} C_{electrolyzer,i} + \sum_{all\ equipment} C_{equipment,i} \quad \text{Eq.2}$$

$$\mathrm{OPEX} = \sum_{h=1}^{8640} C_{water\ consumption,h} + \sum_{h=1}^{8640} C_{all\ equipment,h} \quad \text{Eq.3}$$

The two major constraint equations include the hydrogen flow equation and inventory equation for storage tanks. The hydrogen flow is restricted by the electrolyzer efficiency and the power input. The inventory level is determined by the level in the previous hour and the flows in and out of tank. Other restrictions such as demand constraint and technological constraint must be taken into consideration too. For example, in RNG pathway, the RNG composition in the grid can only be made up to 10%; the flow is restricted by the reactor efficiency and hydrogen flow; and the required carbon dioxide flow depends on the stoichiometry of the reaction [9].

The emission offset is the emission discrepancy between the emission produced using the existing energy hub configuration and the emission produced using our proposed hub configuration. The new emission can be calculated as the sum of emission produced from each of the equipment such as electrolyzers, storage tanks as well as generating electricity. The emission offset can then be calculated as follows.

$$\text{Emission Offset} = \text{Emission}_{before} - \text{Emission}_{after} \quad \text{Eq.4}$$

In order to find the maximum possible offset that this system can achieve, the first stage program ignores the minimization of cost to find the maximum emission offset. Then, in the second stage, the minimum cost at an offset level (φ) is determined. In this project, φ is set at 0.50 [10,11].

$$\text{Emission Offset} \geq \varphi * \text{Emission Offset}_{max} \quad \text{Eq.5}$$

$$\varepsilon - \text{Objective}$$

$$\text{Maximize: Emission Offset}_{max} = \text{Emission}_{NG} - \text{Emission}_{HENG} \quad \text{Eq.6}$$

3.2 Solution Method

Due to the nature of MILP modeling, the cost must be converted into linear equations if it was non-linear. In the proposed energy hub, the model of electrolyzer and methanation reactor need to be adjusted due to this reason. The number of electrolyzers are determined by the minimum and maximum capacity of the electrolyzer. In order to keep the programming linear, the costs must be formed into an array, in which the individual binary indicators corresponding to the number of electrolyzers are multiplied to the corresponding element in the array [6].

$$N_{electrolyzer} = \sum_{i=1}^{N_{electrolyzer,max}} i * \alpha_i \quad \text{Eq.7}$$

$$\sum_{i=1}^{N_{electrolyzer,max}} \alpha_i \leq 1 \quad \text{Eq.8}$$

The cost scaling of the methanation reactor unit it thought to be linear with the maximum required capacity. However, the cost must equal to 0 instead of k (the intercept) when the optimal capacity is 0. Therefore, a binary variable was introduced to account for that exception.

$$C_{reactor} = \gamma * RNG_{max} + k * \alpha_{RNG} \quad \text{Eq.9}$$

$$\alpha_{RNG} = \begin{cases} 0 \text{ if } RNG_{max} = 0 \\ 1 \text{ otherwise} \end{cases} \quad \text{Eq.10}$$

4. Results

4.1 Scenario 1 Model Results

In the current scenario, the four pathways are studied separately. Table 1 summarizes the four separate pathway model results. The result shows that the optimization model satisfying the hydrogen demands from the four pathways, is achieved.

Table 1 Individual model result summary

Pathway	RNG	HENG	Transportation	Industry
Hydrogen Supplied (m^3/year)	30,631,669	3,980,367	1,071,886,985	114,975,000
CO_2 supplied (m^3/year)	7,960,734	-	-	-
# Electrolyzers	81	9	1,702	246
# Pre-storage Compressors	61	7	1,449	177
# Booster Compressors	-	-	514	-
# Tanks	196	26	60,469	504
Total lifetime cost ($ MM)	228	30	38,821	546
Emission Offset (tonne CO_2/year)	12,119	8,936	282,220	165,057
% of Maximum Emission Offset	89	98	93	97
Cost-to-Emission-Offset Ratio ($/ (tonne CO_2/year))	18,774	3,328	137,554	3,309
SBG Utilization (%)	1.27	0.16	44.27	4.75
Water Consumption (m^3/year)	12,253	1,592	428,755	45,990

The number of equipment, electricity, and water utilized by the P2G systems are proportional to the hydrogen demands from the pathways. The number of electrolyzers corresponds to the maximum hourly surplus electricity utilized in each pathway. In the P2G system, hydrogen storage tanks are essential due to three main reasons. The first reason is to accommodate the demand when there is no surplus electricity. Secondly, tanks are used to store energy during the low-price time points. Thirdly, an overall lower emission level can be achieved if the electricity with lower emission potential is stored. Therefore, storing the electricity that is produced during low lifecycle emission factor periods is beneficial for emission reduction. An increase in the number of tanks means that the hydrogen inflow to the storage tanks is increased. To accommodate this, the number of pre-storage compressors also needs to increase.

Because hydrogen demand is the highest from the transportation pathway, significantly higher quantity of equipment and resources are used in the pathway compared to others. The transportation pathway has the highest total lifetime cost due to additional equipment, such as pre-storage booster. The cost-to-offset ratio is the lowest in the industry pathway, even though the demand is the second highest out of the four pathways. This is because approximately 18 times more emission offset was able to be reached compared to HENG pathway (lowest demand pathway). In other words, it is more cost-efficient to replace the industry feedstock hydrogen than replacing some of the conventional NG with renewable gases or replacing gasoline vehicles with FCV's.

Percentage of maximum emission offset measures how much emission offset was realized relative to the maximum achievable emission offset when cost is not taken into account for each pathway. For all the pathways, 89% or higher offset was achieved. Moreover, this result implies that it may be unnecessary to increase the cost of the systems in order to achieve a slightly higher carbon emission offset

4.2 Scenario 2 Model Results

In this scenario, the four pathways are combined into one P2G system. The total hydrogen demand is 1.22*109 m3 per year. Figure 3 shows the allocation of the hydrogen to the four pathways. Note that the hydrogen demand from each pathway in this scenario is the same as Scenario 1. Since hydrogen demand is the highest from the mobility sector, the sector is supplied with 88% of the total hydrogen supplied by the combined P2G system.

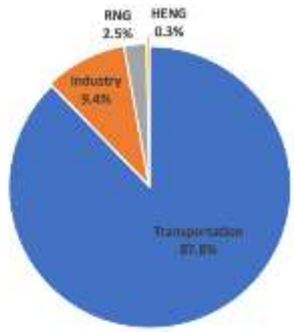

Figure 3 Combined model hydrogen distribution to four pathways

Table 2 summarizes Scenario 2 and Scenario 1 (total equipment and resources needed for the four pathways) results. The number of electrolyzers in Scenario 2 is 84% of the number of electrolyzers that would be required to accommodate all four separate pathways in Scenario 1. This implies that there would be some idle electrolyzers when the four pathways are running separately. The number of electrolyzers in Scenario 2 is nearly the same as the transportation pathway's number of electrolyzer from Scenario 1. The number of pre-storage compressors is also lower in Scenario 2 than the total number for all pathways in Scenario 1. This implies that there would some idle equipment when the four pathways are running in Scenario 1.

The SBG utilization in the combined model (57%) is higher than the total SBG utilizations from the four pathways in Scenario 1 (50%), though the hydrogen supplied to each pathway remains the same. This means more surplus electricity is converted into hydrogen and stored in the tanks. This is directly portrayed in the number of tanks – 1.2 times more tanks are needed in Scenario 2 compared to the total number of tanks from all pathways in Scenario 1.

The total lifetime cost of the combined P2G system ($47.5 billion) is about 1.2 times higher than the sum of the total lifetime cost of all the pathways Scenario 1 ($39.6 billion). This is primarily due to the higher number of tanks in Scenario 2. Because of such high cost of storage tanks, although a slightly higher emission offset can be reached in Scenario 2 compared to the total emission offset achieved in Scenario 1, the cost-to-emission offset ratio is 1.2 times higher in Scenario 2. Thus, it can be concluded that it is more cost-efficient to run the four pathways separately rather than in one centralized system.

Table 2 Scenario 2 and Scenario 1 results (sum of all pathways) summary

System Sizing Variables	**Scenario 2 Result**	**Scenario 1 Result (sum of all pathways)**
Hydrogen Supplied (m^3/year)	1,221,474,021	
CO_2 supplied (m^3/year)	7,960,734	
# Electrolyzers	1,705	2,038
# Pre-storage Compressors	1,386	1,694
# Booster Compressors	514	
# Tanks	74,533	61,195
Total lifetime cost ($B)	47.5	39.6
Emission Offset (tonne CO_2/year)	470,595	468,331
% of Maximum Emission Offset	95	-
Cost-to-Emission-Offset Ratio ($/ (tonne CO_2/year))	100,875	84,607
SBG Utilization (%)	57	50
Water Consumption (m^3/year)	488,590	

5. Conclusion

Based on the scenario 1 model results, the most dominant component contributing to the capital cost (CAPEX) is hydrogen storage tanks across all pathways. The second largest cost is PEM electrolyzers in all pathways except for the transportation pathway. The most dominant component contributing to annual operating cost (OPEX) is purchasing electricity for all four pathways. There is also a significant cost regarding purchasing carbon dioxide gas for methanation reaction for RNG. Based on the cost per emission offset, the industry pathway seemed to be the most efficient in terms of achieving the greatest reduction in carbon emission with a given budget.

Based on the scenario 2 model results, the model required 1,705 electrolyzers, 1,386 pre-storage compressors, and 514 booster compressors, 74,533 storage tanks at the total lifetime cost of 47.5 billion dollars and achieved an emission reduction of 470,595 tonnes of carbon dioxide per year of operation, which is 95% of the maximum achievable offset. Notably, the cost of the combined system is greater than the sum of the costs of the individual systems from Scenario 1, which was 39.6 billion dollars. This was due to more storage units being required as the hours with little to no surplus generation required a greater amount of hydrogen production at once in the combined model, which meant that a larger volume of hydrogen had to be stored in previous hours. On the other hand, if one pathway within the combined model had to be chosen for expansion, the industry pathway would be the best choice, as it is the most efficient pathway to achieve the lowest unit cost per emission offset.

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Biographies

Lingyi (Jane) Gu, **Jeeyoung Kim** and **Joohyung Ko** are chemical engineering students from University of Waterloo, currently pursing their specialization in data science as data scientists. Their capstone project on Power-to-Gas energy system provides an optimized approach to manage surplus electricity in Ontario using mixed integer linear programming method. This paper is based on their Capstone project results.

Azadeh Maroufmashat is a senior postdoctoral fellow in Chemical Engineering, University of Waterloo. She obtained her B.Sc. degree in Mechanical Engineering in 2007 and her M.Sc. and Ph.D. in energy system engineering in 2010, and 2015, respectively, all from Sharif University of Technology, Tehran, Iran. During her PhD, she was a visiting scholar at the University Waterloo. Now she is working on different projects related to the modeling and optimization of different energy conversion and storage systems at University Waterloo as a postdoctoral fellow. Her research interests lie at the intersection of energy system modeling, optimization and policy recommendations and her research contributions have been to the optimal integration of sustainable energy generation and storage technologies with the current energy system. She has investigated the technical, environmental, and economic aspects of urban energy system modeling (a Micro-grid application), and power-to-gas as a feasible energy storage technology and a low-carbon sustainable energy alternative for transportation and for the hydrogen economy. Her future research will be to addressing climate change issues in large scale energy system modeling.

Michael Fowler is a Professor and is cross-appointed to the Department of Mechanical and Mechatronics Engineering at the University of Waterloo. Professor Fowler's research focuses on electrochemical power sources in vehicles, specifically degradation analysis and control of batteries in hybrid and plug-in hybrid power trains. His interest takes him into the modelling of fuel cells and requires simulating the performance and reliability of fuel cells and batteries. Professor Fowler's research group is interested in performance evaluation, diagnostics, and forensics associated with fuel cell stacks, single cells and batteries. His study of fuel cell failure mode and reliability also encompasses the extensive development of polymers due to their function as the fuel cells' electrolyte, gas diffusion layer and blending of polymers for conductive bipolar plates. His expertise in fuel cell technology has landed him the position of co-faculty supervisor of competitive vehicle team design projects; ChallengeX and EcoCar where he has supervised the development of two fuel cell vehicles, and two plug-in hybrid vehicles. Professor Fowler assists these teams with their design, construction, implementation and testing of hybrid vehicles. He also supervises other award-winning student teams in the design of Green Energy Systems.

Ali Elkamel is a Professor of Chemical Engineering. He is also cross appointed in Systems Design Engineering. Prof. Elkamel holds a BSc in Chemical Engineering and BSc in Mathematics from Colorado School of Mines, MS in Chemical Engineering from the University of Colorado-Boulder, and PhD in Chemical Engineering from Purdue University – West Lafayette, Indiana. His specific research interests are in computer-aided modelling, optimization and simulation with applications to energy production planning, carbon management, sustainable operations and product design. Professor Elkamel is currently focusing on research projects related to gas production and processing, integration of renewable energy in oil and gas operations, and the utilization of data analytics (Digitalization), machine learning, and Artificial Intelligence (AI) to improve process and enterprise-wide efficiency and profitability. Prof. Elkamel activities include supervising post doctorate and research associates, advising graduate/undergraduate students and participation in both university and professional societal activities. Professor Elkamel is also engaged in initiating and leading academic and industrial teams, establishing international and regional research collaboration programs with industrial partners, national laboratories and international research institutes.