

Optimal Operation of Cogeneration Plants in Industrial Facilities

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Abstract

The objective of this work is to develop a comprehensive model for the industrial facility's energy system. In order to model the current energy system, we simulated each technology including the gas turbines, HRSG, duct burners, and boilers based on historical data from the company. After finding the hourly energy demand including electricity, steam, hot water, and cold water, we developed an hourly-based optimization model to determine the operation strategy of the current technologies to minimize total energy cost. Then we compared the optimization results with the current situation at the company. The results suggests 4% saving in total utility expenditure and 3% saving in natural gas consumption which is equal to the saving of 4500 tons of CO₂ emission.

Keywords

Mixed integer programming, Operation optimization, Cogeneration system.

1. Introduction

Determining the optimal power dispatch or energy management strategy in a cogeneration facility is a conceptually challenging task. Consider an industrial plant which requires electricity, -either generated internally or purchased from the grid, heating, and cooling. This cogeneration facility has gas turbines, Heat Recovery Steam Generators (HRSGs), stand-alone steam and hot water boilers, steam-driven chillers, and electric chillers. Steam must be generated to meet the process demand, to operate turbine driven chillers, and may be used in heat exchangers to generate hot water to meet comfort heating demand. Chilled water must be generated to maintain CHP cooling, provide the process and comfort cooling demands and condense excess steam.

Equipment efficiencies often vary with ambient temperature, humidity, and operating load, requiring dynamic models to estimate performance. The plant demand itself (electricity, steam, hot water, and chilled water) may vary depending on type of day, the time of the day, and the season. Clearly, operating complex cogeneration utility systems based on heuristic rules may not be optimal; a more systematic approach is needed[1,2].

Given that the utility requirements (steam, heat, electricity, and cooling) for a production period are known, we want to determine the optimal energy dispatch for the industrial facilities division. The optimal energy dispatch strategy refers to the total amount of self-generated electricity, purchased electricity, and purchased natural gas consumed by each technology when costs are minimized. It determines which units in the cogeneration facility should be operational and at what levels. As we allow the utility requirements to change from period to period, this can also be considered a multi-period optimal power dispatch procedure.

The objectives of minimizing the energy usage in a process, minimizing the cost of purchased and generated utilities, and optimally operating the cogeneration system and the process are linked together.

2. System Description

In order to develop an optimal power dispatch strategy, we suggest a systematic approach that begins by looking at the energy efficiency of each significant consumer or generator in the cogeneration system. Each unit will have a power stream in and a power stream out. Initially, we take an approach where the output power of a unit operation can be modeled as a linear function of the power in. If linear efficiency equations are not sufficiently accurate, then nonlinear equations such as polynomial approximations may be used. The first improvement on this model will be to include other factors such as the ambient conditions. A nominal efficiency model of the process can be developed using both manufacturer's test data and operational data of highest available resolution and quality. In some cases where hourly resolution does not exist, daily or monthly profiles can be made to mimic similar equipment's performance. Moreover, we try to omit data that includes periods prior to either scheduled or unplanned maintenance. For some units, for example steam or electric driven chillers, very simple energy efficiency equations will prove accurate. However, for some units, such as a gas turbine, this simple approach will not work. Allowing that we can account for the operating energy efficiency of each utility component, we must assemble this information in a fashion that allows us to meet target electrical, steam, and cooling water demands at a minimum cost. Here, by the construction of a mixed-integer programming (MIP) problem, we can determine an optimal operational strategy within optimization program.

The need for mixed-integer variables occurs because at the optimal solution, some available energy unit operations may be on = 1 or off = 0. For example, in the GTG/HRSG assembly, energy enters as natural gas, which fires the gas turbine to produce electricity. We developed a function, which relates the energy rate out to the energy rate in for the gas turbine. The same natural gas feed firing the gas turbine also produces steam from the HRSG. The HRSG only produces steam if the gas turbine is in operation. A function will be developed, which relates the natural gas energy rate in to the steam energy production rate out.

Table 1 provides unit operation efficiencies for all major energy conversion technologies. For example, from Table 1 for duct burner equation, 1m³ of natural gas will produce 15.4 kg steam per hour or 11.86 kW.

Table 1: Summary of Unit Operation Efficiencies

Equipment	Energy- In			Energy -Out			
	Electricity (kW)	Steam (kW)	Natural gas	Electricity(kW)	Steam(kg)	CW(COP)	hot water(kWh)
Gas turbines(GT)			1	$-0.0031*NG^2+13.7296*NG+2.5306*T-9537$			
Heat Recovery steam generators (HRSG)			1		$1.56*NG(m3)+7689$		
Duct burner			1		$15.4*NG(m3)$		
Steam boiler 1			1		$13.6*NG(m3)-23$		
hot water boiler			1				$8.5*NG(m3)$
Electric chillers	1					1/.65-1/.71	
Steam chillers		1				.985	

Based on the historical data for the gas turbines, we found the correlation between generated power, efficiency and ambient temperature. It was also shown that there is a polynomial correlation between natural gas consumption in the gas turbine and generated power as presented in Table 1.

The hourly Ontario electricity price (HOEP) and monthly average natural gas is considered for the modeling as shown in Figure 1 and Figure 2[4].

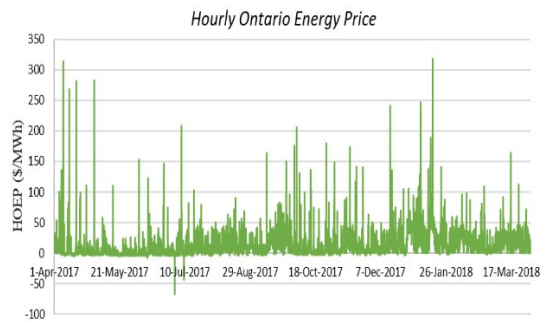


Figure 1: Hourly Ontario Energy Price for the 2018 Fiscal Year.

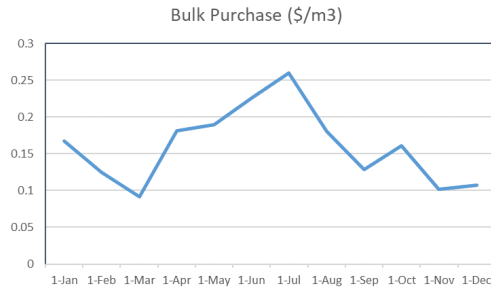


Figure 2: Monthly average Price for natural gas in 2018 Fiscal Year.

3. Methodology

We can now provide an overview of our solution approach to the optimal dispatch problem as shown in Figure 3. We specified the plant electrical, steam, and cooling demands (energy rate out) of the process on an hourly basis. These demands are fixed and thus independent of how the cogeneration system chooses to operate. For example, if chilled water is generated from steam chillers, the additional required steam load to do so (above the process needs) is internal to the cogeneration system and will be accounted for by the equations and the system constraints. The optimal solution to the energy dispatch problem is derived by varying which units are operational (on/off) and at what energy input rates, so as to meet the required electrical, steam, hot water, and chilled water demands of the process while minimizing the cost of purchased natural gas and purchased electricity [5].

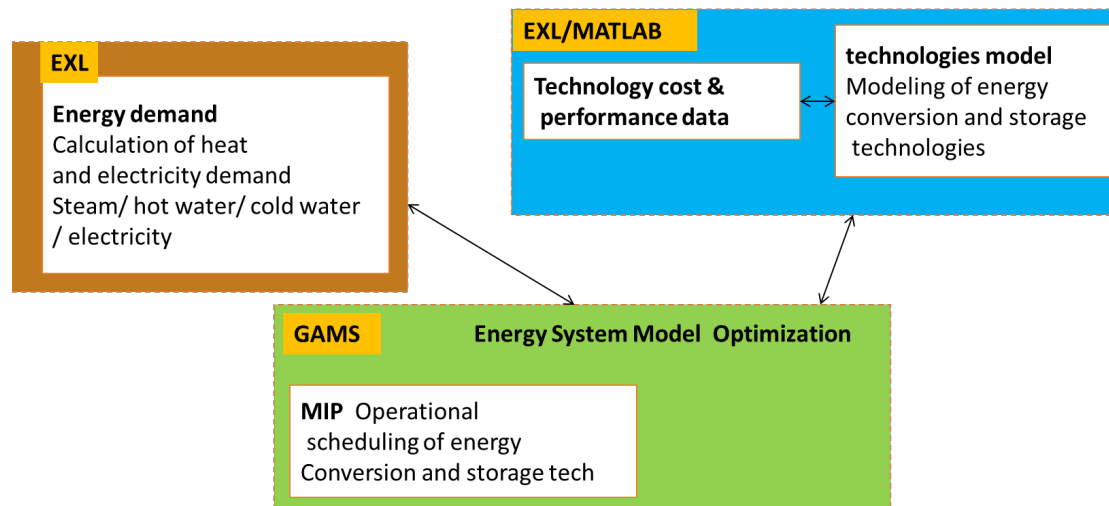


Figure 3: Modelling approach implemented in optimizing TMMC's integrated energy system

The power dispatch model for the cogeneration system can be formulated as an MIP (Mixed integer programming) optimization problem with the objective to minimize costs as such:

Minimize Costs= Fixed Natural gas cost+ Variable Natural gas cost+ Fixed electricity cost+ Variable electricity cost

Subject to:

- Material and energy balances
- Equipment efficiencies

- Equipment capacities
- Logical constraints

3.1 Modelling

The objective function is to minimize the total cost of purchased natural gas and purchased/imported electricity for the 2018 fiscal year (Apr 2017- March 2018) as shown in Eq. 1. The simulation is conducted over this year with hourly resolution.

$$\text{Min cost} = \sum_{i=1}^{8760} (NG_h^{\text{purchased}} \times \text{Price}_h^{NG}) + \sum_{i=1}^{8760} (Elec_h^{\text{purchased}} \times \text{Price}_h^{\text{elec}}) + \text{Global_adjust_fee} + \text{firm_demand_cost} \quad (1)$$

Where $Elec_h^{\text{purchased}}$ and $NG_h^{\text{purchased}}$ is the electricity and natural gas purchased from the grid. $\text{Price}_h^{\text{elec}}$, Price_h^{NG} are calculated as explained in the previous sections.

Electricity Constraint: Electricity demand is met by the generating electricity via gas turbine and by purchasing some from the utility grid. The hourly demand for the 2018 fiscal year was equal to the sum of generated and purchased power less the electricity which was sent to the chillers, since this will be decided by the model (Eq. 2).

$$\text{Demand}_h^{\text{elec}} = \text{Elec}_h^{\text{purchased}} + X_h^{GT1} \times \text{Elec}_h^{GT1} + X_h^{GT2} \times \text{Elec}_h^{GT2} - \text{Elec}_h^{RC} \quad (2)$$

Where X_h^{GT1} and X_h^{GT2} are the binary variables corresponding to the Off (0) and On (1) conditions of the gas turbines.

Natural Gas Constraint: Natural gas consumption is defined as the summation of natural gas consumed by the different technologies including gas turbines, duct burners, steam boilers, and hot water boilers (assumed constant) in each hour (Eq. 3).

$$NG_h^{\text{purchased}} = X_h^{GT1} \times NG_h^{GT1} + X_h^{GT2} \times NG_h^{GT2} + NG_h^{DB1} + NG_h^{DB2} + NG_h^{SB1} + NG_h^{SB2} + NG_h^{SB3} + NG_h^{HWB} \quad (3)$$

Steam Constraint: Steam demand is provided by the operation of HRSGs with and without supplemental firing and three steam boilers. $X_h^{DB1}, X_h^{DB2}, X_h^{SB1}, X_h^{SB2}, X_h^{SB3}$ are the binary variables corresponding to the off (0) and on (1) operation of duct burners and steam boilers (Eq. 4).

$$\text{Demand}_h^{\text{steam}} \leq X_h^{GT1} \times \text{steam}_h^{\text{HRSG1}} + X_h^{GT2} \times \text{steam}_h^{\text{HRSG2}} + X_h^{DB1} \times \text{steam}_h^{DB1} + X_h^{DB2} \times \text{steam}_h^{DB2} + X_h^{SB1} \times \text{steam}_h^{SB1} + X_h^{SB2} \times \text{steam}_h^{SB2} + X_h^{SB3} \times \text{steam}_h^{SB3} - \text{steam}_h^{\text{STC}} \quad (4)$$

There is a possibility of generating steam more than it is actually needed, the extra steam will be sent to the steam dump condenser which the model will calculate.

Hot Water Constraint: Hot water is supplied by the hot water boilers and the thermal energy storage system.

$$\text{Demand}_h^{\text{HW}} = \text{HW}_h - QH_h^{\text{char}} + QH_h^{\text{dis}} \quad \text{in heating seasons} \quad (5)$$

Where: HW_h is the hot water that is generated in each hour by hot water boilers and QH_h^{char}, QH_h^{dis} represent the energy that is charged or discharged from the hot water storage tanks.

Chilled water Constraint: Chilled water is supplied by the electric chillers, steam chillers and the thermal energy storage system (Eq.6).

$$Demand_h^{CW} = CW_h - QC_h^{char} + QC_h^{dis} \quad \text{at cooling season} \quad (6)$$

$$CW_h = \sum_{RC} CW_h^{RC} + \sum_{STC} CW_h^{STC} \quad RC: \{RC01, RC02, RC03, RC04, RC203, RC204\}, STC: \{STC202, STC301\}$$

Where CW_h is the cold water that is generated in each hour by chillers and QC_h^{char}, QC_h^{dis} represent the energy that is charged or discharged from the chilled water storage tanks.

Note that the hot water storage tanks are only available in heating seasons, and chilled water storage tanks are only available in cooling seasons.

Storage Constraint: The amount of energy in the storage tanks for each hour is equal to the energy stored in previous hour plus the amount of energy which is charged or discharged. std_loss is the coefficient for the efficiency of storage systems (Eq. 7).

$$st_h = std_{loss} * st_{h-1} + Q_h^{char} - Q_h^{dis} \quad (7)$$

Energy balance of each technology: The energy generated by each technology is related to the input energy as shown in Table 1(Eq. 8).

$$tech_h^{output} = \eta \cdot tech_h^{input} \quad (8)$$

Ramp-up/ Ramp-down Constraint: It takes approximately 1 hour to ramp up the gas turbine and approximately two hours to ramp down as shown in the following equation.

$$\begin{aligned} Elec_h^{GT} - Elec_{h-1}^{GT} &\leq Elec_{max}^{GT} \\ Elec_h^{GT} - Elec_{h-1}^{GT} &\leq -Elec_{max}^{GT} * .5 \end{aligned} \quad (9)$$

Scheduling Constraints: We considered some equations for the scheduling of gas turbines and HRSGs. Since HRSG#1 can operate as an independent boiler with the aid of supplemental firing (guillotine mode), we define this constraint in the model. This incorporates the 2 hour cool down that is required after GTG #1 shuts down, in order to start up in Guillotine mode safely (Eq. 10).

$$(1 - X_h^{GT1}) \cdot (1 - X_{h-1}^{GT1}) \leq X_h^{DB1} + X_{h+1}^{DB1} \quad (10)$$

Since HRSG #2 can only operate if gas turbine #2 operates, we defined the following equation:

$$X_h^{DB2} \leq X_h^{GT2} \quad (11)$$

3.2 Solution Method

The nonlinear equations are linearized using mathematical linearization methods. The mathematical formulation of the aforementioned model is based on the mixed integer linear dynamic programming method which is carried out in

the General Algebraic Modeling System Software [6]. The MILP dynamic problem is solved by the CPLEX solver [7].

4. Results

The annual financial savings resulting from the implementation of the optimal energy management dispatch strategy are shown in Figure 4. Overall the model's suggestions would result in a 4% decrease in the Company's energy expenditure during Fiscal Year 2018, which corresponds to approximately \$390,000. As such there is a 4.7% increase in annual electricity and 16% reduction in natural gas costs.

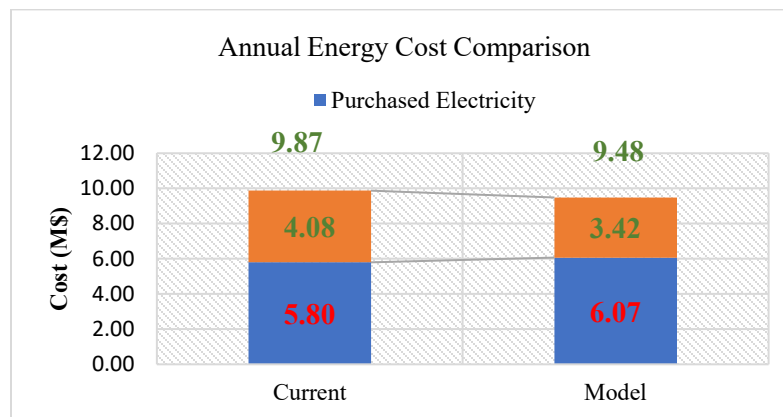


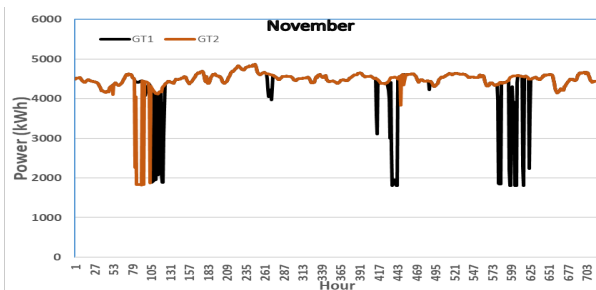
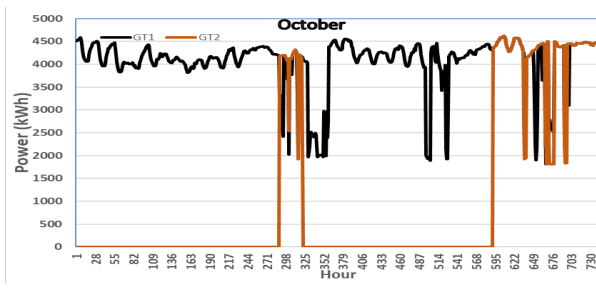
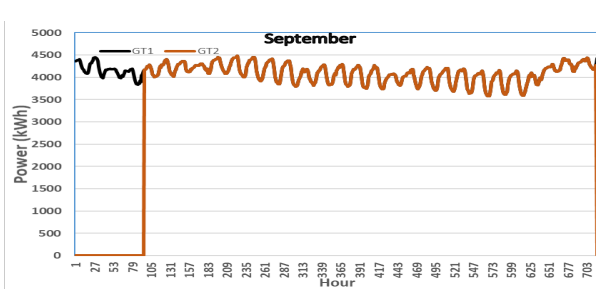
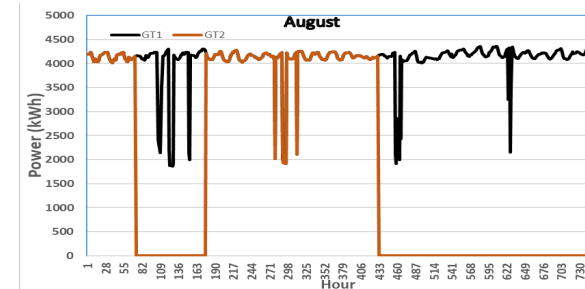
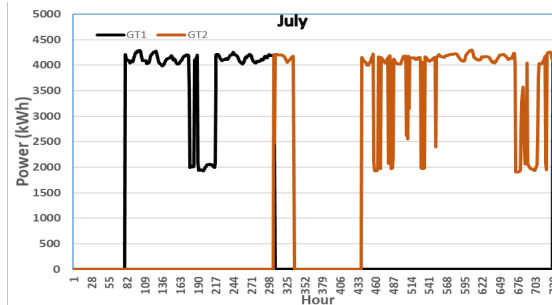
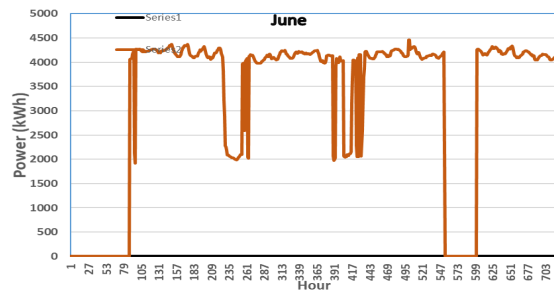
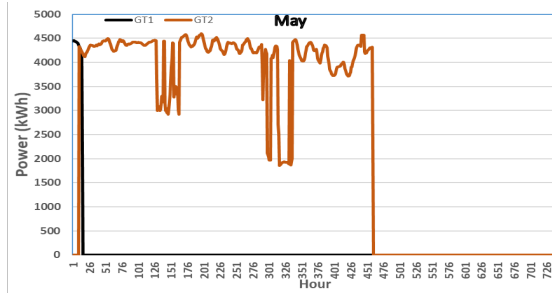
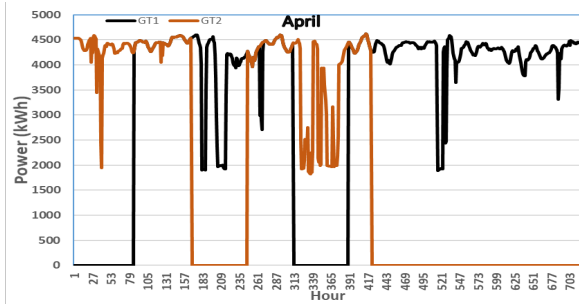
Figure 4: Annual energy cost comparison of the TMMC with the optimized result of the model.

The optimization results show that electricity consumption has been increased by 7%, however, there is a 9% of reduction in natural gas consumption compared to the current situation.

This reduction in natural gas consumed results annually in a 5500 tonne decrease in CO₂ emissions, given the Final Emission Factor of NG to be 2.41 kg CO_{2,e} per m³ of NG.

4.1 Optimal operation of gas turbines:

The following figure shows the hourly operation of gas turbines. Each color represents one of the gas turbines. These figures show how the model chooses to ramp-up and down the gas turbines in different months. Moreover, they show when the gas turbines should be on or off.



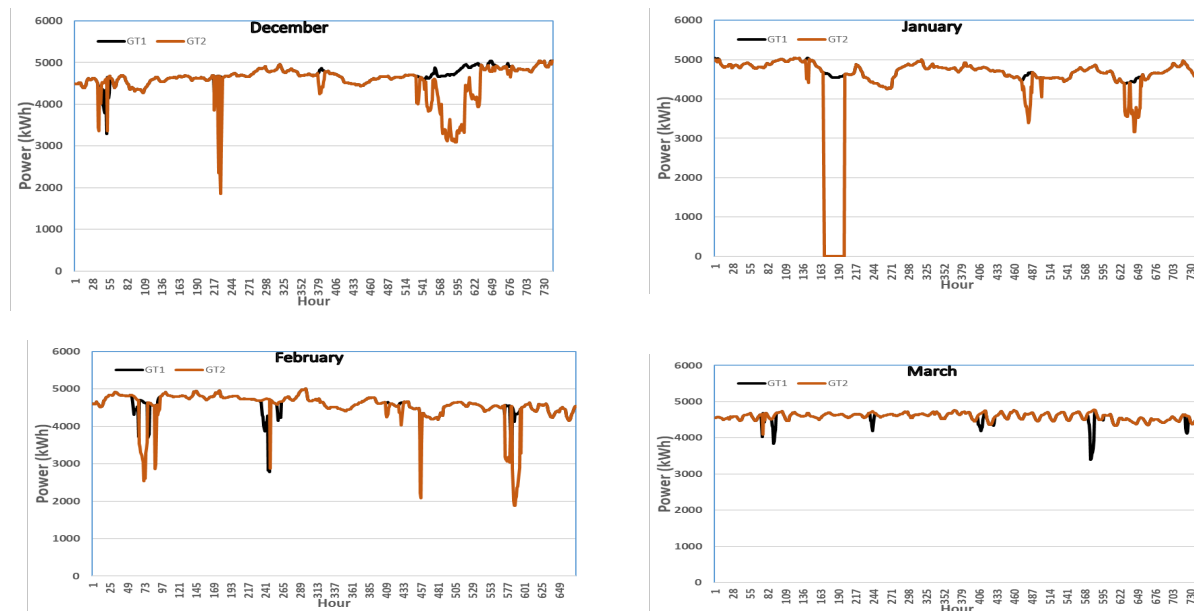


Figure 5: Gas turbine electricity generation profile suggested by the optimal model for each month of fiscal year 2018

The results suggest that using electric chillers in heating seasons can be a better option in cost and energy saving. Moreover, using a steam based electrical generator can be a good option for the future especially during summer. If gas turbines can ramp up and down within their reasonable part load operation range (40-50% to 110%), they can save on natural gas consumption and reduce the number of start-ups and shut downs. Therefore, the company can manage the number of start up/ shut down by scheduling the GTs in their part load operations and they can save on greenhouse gas emissions by scheduling the CHP units.

5. Conclusion

this paper developed a comprehensive model for the industrial facility's energy system. First, each technology is simulated including the gas turbines, HRSG, duct burners, and boilers based on historical data from the company. Then a mixed integer linear programming approach was used to optimize the operation strategy of the current technologies to minimize total energy cost. Then we compared the optimization results with the current situation at the company. The results suggest 4% saving in total utility expenditure and 3% saving in natural gas consumption which is equal to the saving of 4500 tons of CO₂ emission.

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Biographies

Azadeh Maroufmashat is a 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. She has a number of advising experiences; as examples of successful mentorship, the teams that she co-advised, was the Grand prize winner (2016) and honorable winner (2018) of the Hydrogen student design contest, held by the Department of Energy (DOE) of the United States.

Nick Preston is a Masters student in the Department of Chemical Engineering at the University of Waterloo. Mr. Preston completed his BAS in Chemical Engineering in 2019, with his fourth year design project focusing on the optimal design of an automotive manufacturer's energy system using Power-to-Gas technology. His current research focuses on the computational optimization of real world constrained vehicle routing problems for the transportation and logistics industry. He hopes to extend his work to include the simulated use of rechargeable zero emission vehicles in heavy transport as a method for developing strong practical business cases in Ontario.

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.