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ECONOMICS OF LOCAL GREEN HYDROGEN FOR BUILDING HEATING IN CANADA

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***Abstract*—A** combined heat pump and local green hydrogen system is proposed for residential building heating and grid electricity load peak-shaving in Toronto. Using the system, and based on urban physics simulations conducted by the Vertical City Weather Generator (VCWG) software for an entire year in 2020, the electricity cost for building heating can be reduced when there is large variation in diurnal electricity price. For instance, under the Time Of Use (TOU) electricity pricing scheme, if the prices between off-peak and on-peak periods change from 4.5 to 15.5 Cents kW-hr^{-1}, there is incentive for cost savings. However, with current electricity pricing (off-peak to on-peak of 8.7 to 15.5 Cents kW-hr^{-1}) and the high cost of ownership for the local green hydrogen system, the economics of the system is not justified. Even with favorable electricity pricing, the payback on investment will be at least approximately 11 to 19 years. If grid electricity load peak-shaving is desired, such a system requires large variation in diurnal electricity price, system price reduction, regulatory policy, and financial incentives.

***Keywords*—Building Decarbonization; Heating Demand; Heat Pumps; Green Hydrogen**

I. INTRODUCTION

There is international consensus that the world ought to reach net zero Greenhouse Gas Emissions (GHG) by 2050. However, decarbonization of various industries impose different levels of cost and GHG abatement potential. As Fig. 1 shows the carbonomics cost curve, the agriculture, forestry, land use, and power generation have lower carbon abatement cost and potential to reduce GHG emissions [1], while decarbonizing transportation, buildings, iron/steel, cement, and chemical manufacturing industries is more expensive [2].

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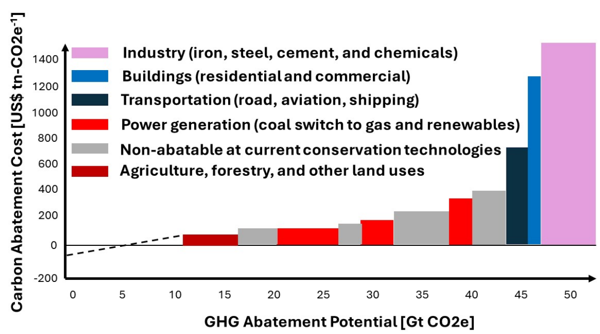

Figure. 1. Carbonomics cost curve, adapted from [2].

A. Economics of Hydrogen as an Energy Carrier

Hydrogen has a unique place to decarbonize industries that are hard to abate otherwise, in which electricity from renewable sources cannot be used [2]. Some examples include 1) long range transport, where battery storage capacity limits the use of electric vehicles, ships, and airplanes, 2) high grade heat for industry (e.g. steel making), and 3) building heating in cold climates [3]. These applications are already evident from the carbonomics cost curve of Fig. 1.

In Canada, the lowest cost avenues to produce hydrogen are 1) blue hydrogen: Steam Methane Reforming (SMR) with Carbon Capture, Utilization, and Storage (CCUS), and 2) green hydrogen: electrolysis from renewable power. By 2030 the costs for producing hydrogen using these technologies are projected at CA\$1-2 kg-H_2^{-1} and CA\$3.2 kg-H_2^{-1}, respectively [3]. If fossil fuels are to be eventually phased out, attention is needed for development of electrolysis technologies. Currently, three electrolysis technologies are available, according to Table I: alkaline, Proton Exchange Membrane (PEM), and Solid Oxide (SO) electrolyzers.

TABLE. I
ELECTROLYSIS TECHNOLOGIES [2].

Electrolyzer	Alkaline	PEM	SO
Development	Commercial	Commercial	Demonstration/Pilot
Cost [US$ kW^{-1}]	600-1,100	800-1,250	>1,850
H_2 Efficiency [%]	52-70	55-75	74-85
Oper. Temp. [°C]	60-80	50-85	600-1000
Oper. Pres. [Bar]	1-30	30-80	-
Response Time	1-10 min	1 s - 5 min	high
Load Range [%]	10-110	20-160	20-100
Stack Life [hr]	60-90 k	30-80 k	10-40 k

B. Hydrogen for Building Heating

Decarbonization of buildings involve reducing buildings' embodied and operational carbon emissions. The operational carbon emissions primarily result from use of fossil fuels (e.g. natural gas and fuel oil) and grid electricity that is associated with GHG emissions (e.g. coal/natural gas power plants) [4]. In Canada, space and water heating account for 60% and 19% of energy use for residential buildings [3]. Many pathways have been proposed on the use of hydrogen to meet the building energy demands.

The existing infrastructure for natural gas can be converted for use by hydrogen. It is estimated that up to 10-20% hydrogen blending is possible in the existing natural gas pipeline networks for use by the same appliances (i.e. furnaces and hot water heaters). However, this approach is not without its challenges with greater blending ratios: hydrogen diffusion through steel pipes, material embrittlement, leaks, low ignition temperature/energy, low energy density on a volume basis, and accuracy of metering, all of which require major capital investment for retrofitting existing infrastructure or building new ones [2], [3], [5]–[7].

Many studies advocate the use of fuel cell technologies for Combined Heat and Power (CHP) applications for buildings. CHP greatly improves the thermodynamic efficiencies of energy systems [8], [9]. Commercial units involve technologies such as Proton Exchange Membrane Fuel Cells (PEMFC), Solid Oxide Fuel Cells (SOFC), Molten Carbonate Fuel Cells (MCFC), and Phosphoric Acid Fuel Cells (PAFC). For a ∼1-kWe unit the prices range from CA$ 20,000 to CA$ 45,000 [5]. There are two main problems with this approach: 1) the availability of a hydrogen pipeline is uncertain, and 2) the system payback period is well beyond the system operational life.

Use of hydrogen for heating alone may be more practical given the current state of technology. 1) A direct flame combustion H_2 burner is functionally identical to gas burners, and with further engineering innovation may be operationalized cost effectively. 2) A catalytic burner passes hydrogen gas over a highly reactive metal catalyst, which undergoes exothermic chemical reaction to produce heat without a flame. 3) Gas heat pumps operate on similar principles to electric heat pumps, while instead of an electric vapor compressor, gas is combusted to provide the heating energy for the phase change [5]. Challenges to overcome on this front are flame stability, flame speed, storage, leaks, and low ignition temperature/energy.

C. Objectives

From fundamental thermodynamics, use of heat pumps for building heating and cooling is preferred when green electricity is available. This is true since their Coefficient of Performance (COP) can reach up to 3.5 in moderate climates [7]. This means that a heat pump only needs to consume 1/3.5 amount of electricity to provide the equivalent amount of heating ($W = Q_H/COP$). However, in cold climate, their COP drops to 1 at temperatures as low as 253.15 K. Further, heat pumps struggle under water freezing conditions and typically experience faults that degrade their performance [10].

The diurnal and seasonal timing of electricity prices can determine the optimal mix of energy sources and systems for buildings [5]. Figure 2 shows the electricity prices in winter and summer based on the Time Of Use (TOU) scheme in Ontario. Generally, off-peak electricity is the cheapest over night from 1900 to 0700 regardless of the season, while the mid-peak and on-peak timing varies for the winter and summer. A key related question is whether there is economic incentive to locally store energy from the grid during off-peak periods and use it during on-peak periods. Perhaps such an approach will best complement the use of heat pumps for building heating and alleviate load stresses on power generation and electricity grid systems.

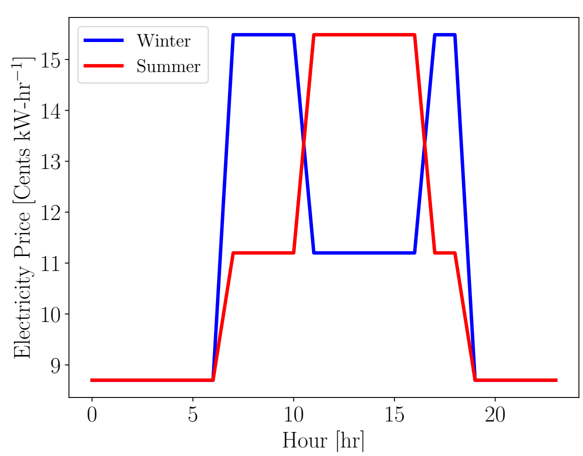

Figure. 2. Electricity price in Ontario as of January 2024 under the Time Of Use (TOU) scheme.

Use of batteries for this purpose is prohibitive given their limited capacity, particularly in storage of energy for building heating, and reliance on unsustainable materials. Alternatively, local green hydrogen can be used for time-shifting of energy use and storage of energy. This approach further eliminates the need for hydrogen pipelines.

The objective of this paper is to propose a system that combines a heat pump with a hydrogen electrolyzer/storage/burner system for grid electricity load peak-shaving of a residential building to meet its heating demand. The alkaline electrolyzer is considered for its low cost and lack of reliance on rare, precious, and expensive metals. There is no heating supplement via natural gas, as this fossil fuel should be ultimately phased out. The economics of the system are investigated for Ontario given different 1) electrolyzer capacities and 2) off-peak electricity prices.

II. METHODOLOGY

A. Building Energy Model

A hypothetical, typical, single-detached, low-rise, and two-storey residential house in Ontario is considered. The single-detached building type accounts for 52.6% of residential building stock in Canada [4]. Using the Vertical City Weather Generator (VCWG v1.4.7) software, the building sensible/water heating demands and outdoor temperature are simulated for a full year. VCWG is an urban physics model forced with weather files in a rural area to predict urban weather and building performance variables [11]–[13]. The weather file is generated for the year 2020 in Toronto using the ERA5 reanalysis data product [14].

B. Heat Pump and Hydrogen Systems

Figure 3 shows the building heating system diagram. The heat pump and hydrogen systems complement one another. The heat pump system's COP responds to the outdoor temperature in a linear fashion from 1 to 3.5 corresponding to temperatures from 253.15 K to 308.15 K, respectively [4], [10]. The hydrogen system is comprised of an alkaline electrolyzer, hydrogen storage tank, and a hydrogen burner. The electrolyzer's hydrogen and heat efficiencies are assumed at 0.660 and 0.315, respectively. The hydrogen efficiency defines what fraction of input electrical power is converted in chemical energy of hydrogen. The heat efficiency determines what fraction of input electrical power is converted to waste heat due to shunt currents, over potentials, and ambient heat. All such heat is utilized to meet the building heating demand. The remaining fraction of electrical power (0.025) is lost due to impurities in H_2 and O_2 [15]. The thermodynamic analysis does not require specifying the hydrogen system pressures and temperatures. However, it is assumed that the system operates at low pressure (less than 10 bar) but high enough temperatures (greater than 60 K) to make waste heat utilization possible.

Figure 4 shows the system control flow chart. When electricity price is in the off-peak schedule, the electrolyzer system only starts operating if the waste heat of the electrolyzer is equal or less than the total building heating demand. This is to ensure that the electrolysis heat is utilized. The electrolyzer is not operated when electricity pricing is in the mid-peak or on-peak schedules. Hydrogen is combusted to meet the heating demand of the building only during mid-peak and on-peak periods, subject to hydrogen availability in the storage tank. The thermal energy released by combustion is calculated

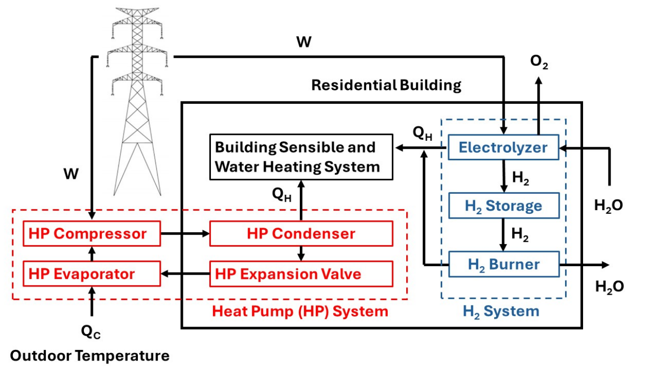

Figure. 3. System diagram for building heating combining the heat pump and hydrogen electrolyzer/storage/burner subsystems.

using the burner efficiency of 0.95 and a Higher Heating Value (HHV) of 140 MJ kg-H_2^{-1}.

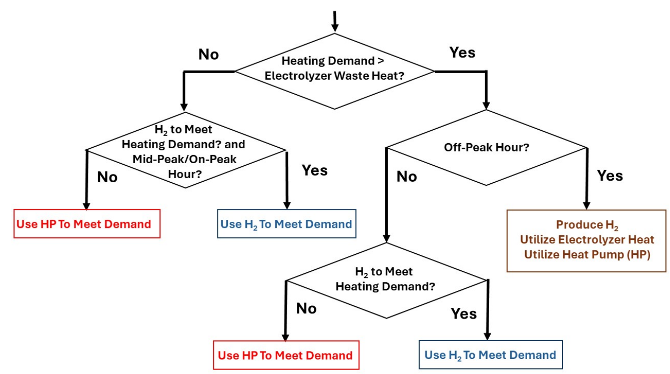

Figure. 4. System control flow chart.

The simulations are conducted considering hourly weather data (specifically outdoor temperature) and building energy performance metrics. For a full year of analysis in 2020, five electrolyzer capacities (0, 20, 40, 60, and 80 W m^{-2}) and three off-peak electricity prices (2, 4.5, and 8.7 Cents kW-hr^{-1}) are considered. Results are provided per building footprint area.

III. RESULTS AND DISCUSSION

A. Building Heating Demands

Figures 5 and 6 show the building sensible and water heating demands in January and July, respectively. As noted, in January the demand is dominated by sensible space heating, while in July the primary need for heating is for water.

B. System Thermodynamics

The thermodynamics of the system will be demonstrated using the case with electrolyzer capacity of 40 W m^{-2}. The results are shown for months of January (cold) and July (hot) for brevity although results are available for every month of the year. Figures 7 and 8 show the electricity consumption for the heat pump and electrolyzer. In January, the electolyzer consistently operates during off-peak periods, but in July, it is only operational when there is enough overall heating demand on fewer number of days. The water heating demand alone in

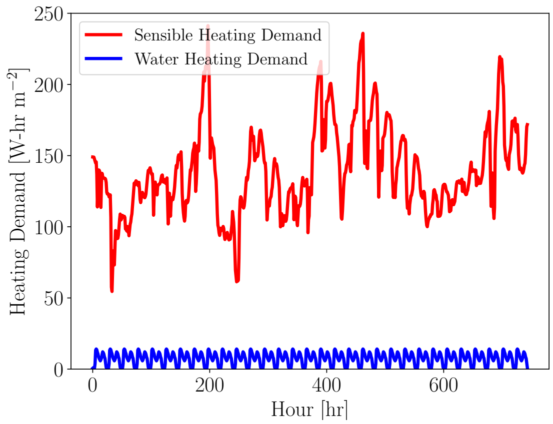

Figure. 5. Building heating demand in January.

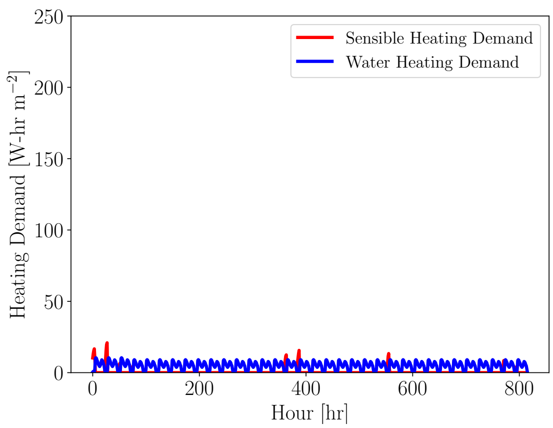

Figure. 6. Building heating demand in July.

July is smaller than the waste heat of the electrolyzer, so it is mostly not operational.

Figures 9 and 10 show the hydrogen storage level for January and July. Due to diurnal use of hydrogen in January, the storage level cycles up (off-peak) and down (mid-peak and on-peak), showing great utilization for hydrogen, while in July hydrogen utilization is more limited for water heating if there is enough storage available. At ambient temperatures (25 °C), the top mass level (0.01 kg-H_2 m^{-2}) can be stored at 0.1 MPa ($\sim$1 bar) or 1.0 MPa ($\sim$10 bar) in volumes of 0.12 m^3 m^{-2} or 0.012 m^3 m^{-2} respectively.

Figures 11 and 12 show the breakdown of sensible heating load met by the heat pump, electrolyzer, and hydrogen in January and July. In January, the hydrogen system consistently supplies the heating demand during mid-peak and on-peak periods, while in July it has no utility for space heating.

Figures 13 and 14 show the breakdown of water heating load met by the heat pump, electrolyzer, and hydrogen in January and July. In January, water heating is consistently met by hydrogen during mid-peak and on-peak periods, while in July hydrogen is utilized on fewer number of days due to limited storage.

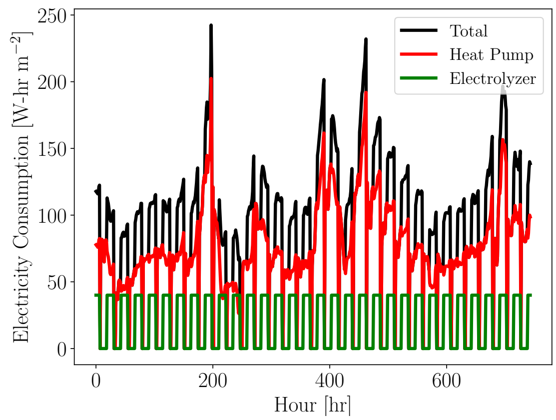

Figure. 7. System electricity consumption in January.

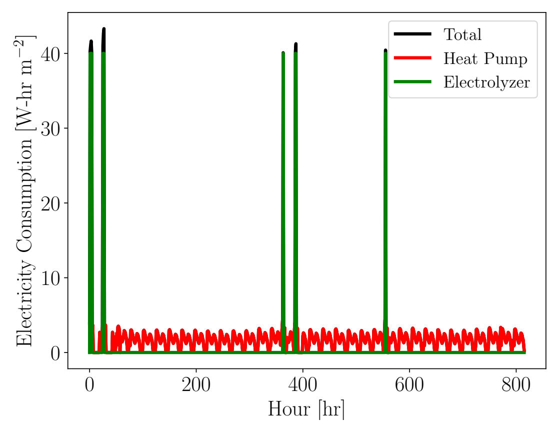

Figure. 8. System electricity consumption in July.

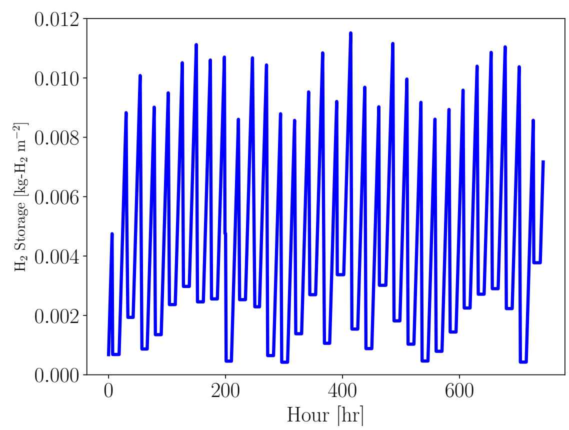

Figure. 9. System hydrogen storage in January.

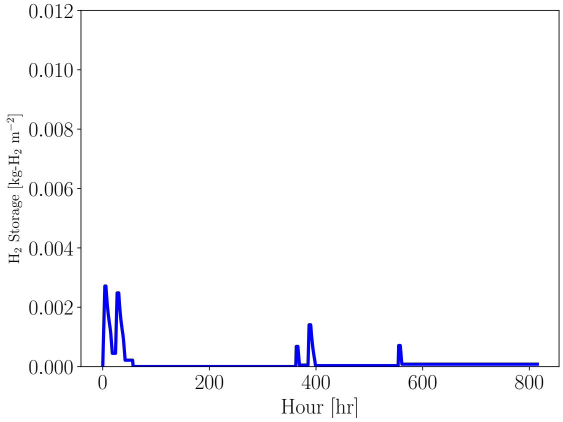

Figure. 10. System hydrogen storage in July.

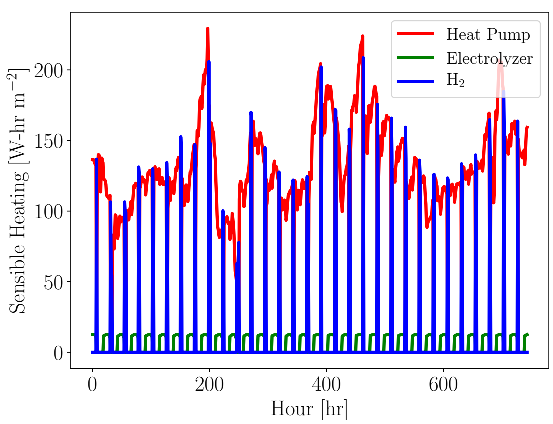

Figure. 11. System sensible heating in January.

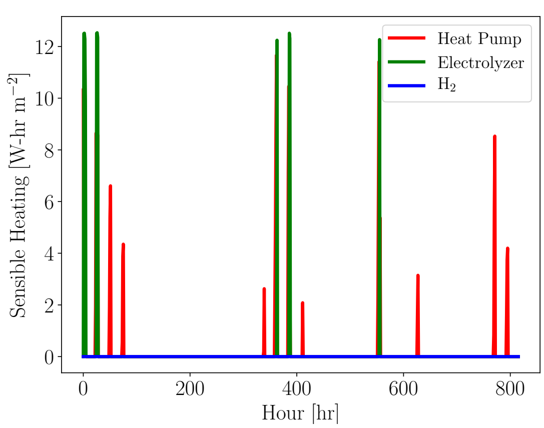

Figure. 12. System sensible heating in July.

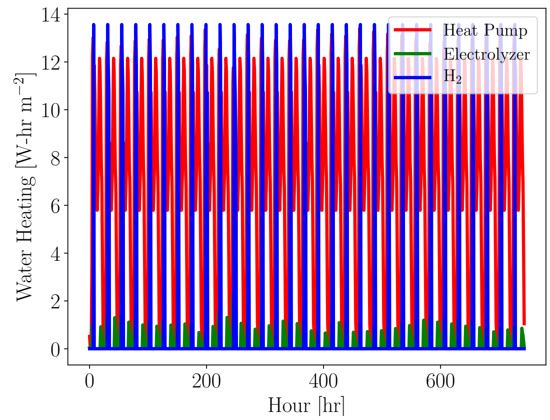

Figure. 13. System Water heating in January.

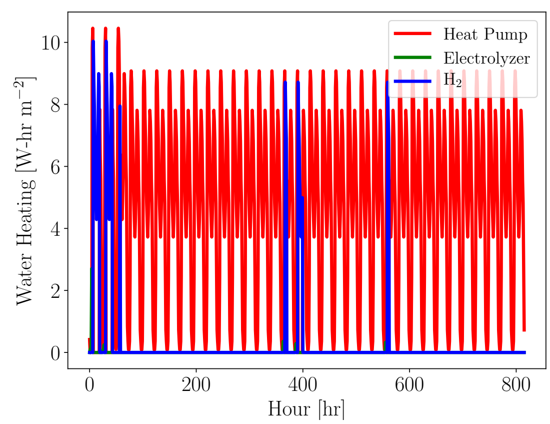

Figure. 14. System Water heating in July.

C. System Economics

Figures 15 and 16 show the electricity costs associated with off-peak prices of 2 (hypothetical) and 8.7 (current) Cents kW-hr^{-1}. When the hydrogen system is used, it can be seen that electricity costs are lower for the off-peak price of 2 Cents kW-hr^{-1}, while they are higher for the off-peak price of 8.7 Cents kW-hr^{-1}.

The annual overall electricity cost savings due to the hydrogen system are shown in Table II. Annual savings are only possible for off-peak prices less than 4.5 Cents kW-hr^{-1}. As an example for economic justification, when the off-peak price is 2 Cents kW-hr^{-1}, for an electrolyzer capacity of 20 W m^{-2}, the annual cost of ownership for the hydrogen system shall not exceed 1.49 CA\$ m^{-2}. Looking at Table I, alkaline electrolyzers cost US\$ 0.6-1.1 W^{-1}. So for an electrolyzer capacity of 20 W m^{-2} the cost of the hydrogen system will be at least US\$12-22 m^{-2} or CA\$16-29 m^{-2}. The payback on investment will be at least approximately 11-19 years, not considering the hydrogen storage/burner costs, maintenance, and the time value of money.

This analysis shows that currently local green hydrogen is

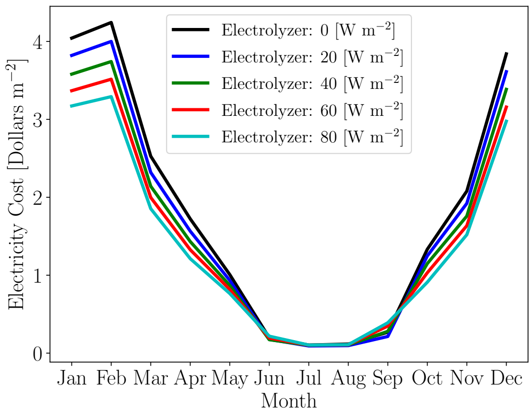

Figure. 15. Electricity cost of the building heating system when off-peak electricity price is 2 Cents kW-hr^{-1}

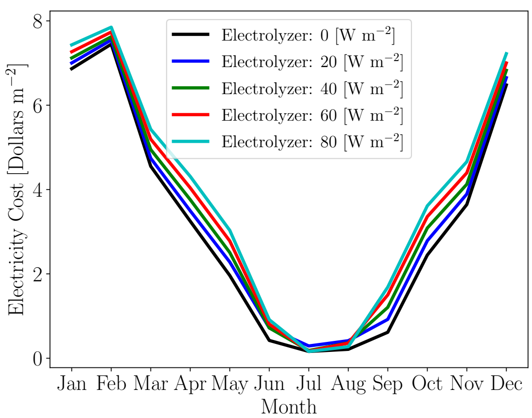

Figure. 16. Electricity cost of the building heating system when off-peak electricity price is 8.7 Cents kW-hr^{-1}

not economically justified for building heating applications, and that grid electricity load peak-shaving is costly.

IV. CONCLUSIONS

A combined system based on local green hydrogen and heat pump can be proposed for building heating applications in cold climate, such as in Toronto. This strategy can help grid electricity load peak-shaving and reduce electricity costs. Using the system, and based on urban physics simulations conducted by the Vertical City Weather Generator (VCWG) software for an entire year in 2020, the electricity cost for building heating can be reduced when there is large variation in diurnal electricity price. Under the Time Of Use (TOU) electricity pricing scheme, if the prices between off-peak and on-peak periods change from 4.5 to 15.5 Cents kW-hr^{-1}, there is incentive for cost savings. However, with current pricing (off-peak to on-peak of 8.7 to 15.5 Cents kW-hr^{-1}) and the high cost of ownership for the system, the economics of the system is not justified. Even with favorable electricity pricing, the payback on investment will be at least approximately 11 to 19 years. This study shows that large variation in diurnal electricity price, system price reduction, regulatory policy, and financial incentive are needed to economically justify the local green hydrogen for building heating and grid electricity load peak-shaving in Toronto, Canada.

TABLE. II
ANNUAL ELECTRICITY COST SAVINGS [CA$ M^{-2}] DUE TO USING THE HYDROGEN SYSTEM.

Electrolyzer Cap. [W m^{-2}]	0	20	40	60	80
Off-Peak: 2 Cents kW-hr^{-1}	0	1.49	2.77	3.88	4.96
Off-Peak: 4.5 Cents kW-hr^{-1}	0	~ 0	~ 0	~ 0	~ 0
Off-Peak: 8.7 Cents kW-hr^{-1}	0	-2.68	-4.41	-6.55	-8.53

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