Assessing the potential of surplus clean power in reducing GHG emissions in the building sector using game theory; a case study of Ontario, Canada

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Abstract: This work assesses the potential of surplus electricity in reducing greenhouse gas (GHG) emissions in the building sector. The assessment is done by modelling the interaction of government and energy consumer using game theory. The government can provide discounted power to energy consumer by covering a fraction of the off-peak price to encourage the replacement of natural gas consumption with electricity. This replacement reduces GHG emissions from the building sector. Energy consumer adopts electricity-based technologies only if it leads to a lower heat and electricity supply cost. Cost-effectiveness of solid oxide fuel cell, air–source heat pump (ASHP), and battery and hydrogen storage are assessed as alternatives to natural gas combined heat and power (CHP) and boiler technologies. The modelling results show that ASHP is the only technology that can compete with natural gas CHP and boiler. ASHP is chosen by the energy consumer when discounts of 4.5 cents/kWh or more for off-peak electricity are available. The analysis also showed that CHP could be completely replaced by grid power at discount value of 4.5 cents/kWh and up. Natural gas boilers continue playing a role in building heating supply even under increased discount for off-peak electricity price.

1 Introduction

1.1 Building and residential energy sector: energy consumption and emissions

The residential sector was the third largest consumer of final energy in the world in 2016 after transportation and industry sectors [1]. Residential sector also accounted for 19% of total final energy and about 37% of electricity consumption in Organisation for Economic Co-operation and Development (OECD) countries in 2016 [1]. In 2015, the residential sector accounted for more than 17% of secondary energy use and 13% of greenhouse gas (GHG) emissions in Canada [2]. In the same year, 42% of energy consumption in the residential sector in Canada was from natural gas [2]. Building sector was also among the top three contributors to Ontario's GHG emission in 2013 [3]. In Ontario, space and water heating accounted for 80% of energy consumption in the residential sector in 2016 [2]. Space and water heating demand are mostly supplied by natural gas in Ontario. In the electricity generation sector, however, natural gas plays a marginal role. About 95% of Ontario's electricity generation mix was generated from emission-free resources in 2017, as shown in Fig. 1.

![Ontario's power generation mix in 2017](http://creativecommons.org/licenses/by/3.0/)

Fig. 1 Ontario's power generation mix in 2017 [4]

Another notable feature of Ontario's electricity system is the abundance of surplus renewable power during off-peak hours. In 2017 in Ontario, 3.33 TWh of variable generation (wind and solar) was dispatched down to electricity supply and demand [5]. In the same year, 0.96 TWh of nuclear power was curtailed to manage surplus baseload generation [5]. According to Ontario Power Generation's 2017 annual report [6], 5.9 TWh of hydropower generation in 2017 was curtailed due to surplus baseload generation.

1.2 Alternative heat and electricity supply technologies for the building sector

The widespread use of fossil fuels in the building sector and the notable role of this sector in overall GHG emissions have attracted attention toward technologies that can supply heat demand in the building sector with lower emissions. Fuel cells and heat pumps are technologies that have been reported in the literature as promising alternatives for decarbonising heat in the building sector. Renewable hydrogen energy has the potential to reduce fossil fuel consumption in the building sector and facilitate the integration of distributed generation capacity [7, 8]. Fuel cell combined heat and power (fuel cell CHP) systems have advantages such as carbon dioxide (CO₂) emission reduction and increasing grid independence [9]. Application and techno-economic performance of fuel cell technologies as CHP systems for building applications have been analysed in the literature. Chang et al. [10], for instance, analysed the operation of a combined cooling, heating, and power (CCHP) system on a hybrid proton-exchange membrane fuel cell (PEMFC) and solar collectors. A mathematical model was developed in [10] to evaluate the effect of parameters such as ambient temperature on the efficiency of the CCHP system. Napoli et al. [11] performed a techno-economic analysis of PEMFC and solid oxide fuel cell (SOFC) technologies in CHP applications. The goal of Napoli et al. in [11] was to assess and compare the potential of PEMFC and SOFC technologies in reducing energy consumption and increasing energy performance.
in residential buildings. Jing et al. [12] developed a model for optimal sizing of a CCHP model based on SOFC technology. The results from the model in [12] showed that the proposed system has an environmental advantage compared with a conventional CCHP system. Pellegrino et al. [13] performed a techno-economic analysis for the use of micro-CHP systems for residential applications based on SOFC technology. Pellegrino et al. in [13] stated that government support schemes are necessary for introduction of SOFC micro-CHP systems into the European market.

Integration of fuel cells with other energy conversion and storage technologies has also been studied in the literature. Ren et al. [14], for instance, developed a model for finding the optimal operation of a hybrid solar/fuel cell/battery system. The model developed in [14] was used to optimise the supply of residential heat and electricity demands while minimising cost and CO\(_2\) emissions.

Operation and cost-effectiveness of heat pump have also been studied and analysed in the literature due to their significant potential in energy saving and heat decarbonisation [15]. Liu et al. [16] developed a model for assessing the feasibility and potential of a ground-source heat pump with an auxiliary boiler for an office building in a cold climate. The results from the analysis done in [16] showed that the proposed system could solve the cold accumulation problem and also reduce energy consumption. Ikeda and Ooka [17] developed a model for optimising the operation of a hybrid battery/thermal energy storage/air-source heat pump (ASHP) to minimise operating cost. Basso et al. [18] analysed coupling CHP and heat pump systems for off-design operation in residential buildings. Sichilulu and Xia [19] developed a model for optimal control of a hybrid solar/diesel/battery/heat pump system to minimise energy cost.

Integration of fuel cells and heat pumps is another area of interest in the literature. Vialeto and Rokni [20], for instance, proposed a coupled SOFC and heat pump system for supplying heat and electricity demands for a residential building. The results from the authors’ analysis in [20] showed that the proposed system could be a promising alternative for household application due to its energy saving and distributed generation potential. Sorace et al. [21] performed a techno-economic analysis of a coupled fuel cell CHP and heat pump system. Both PEMFC and SOFC were considered in the analysis. The results from the analysis done in [21] showed that an SOFC-based system leads to a higher energy saving; however, the high investment cost is a barrier to the widespread use of such systems.

Upfront costs and electricity costs are recognised as barriers to the deployment of alternative technologies such as heat pumps and fuel cells [19, 22, 23]. In that sense, energy incentives can play a vital role in the roll-out of alternative technologies such as fuel cells and heat pumps. The literature shows that the effects of incentives on the deployment of those technologies, however, is limited and it is mostly focused on incentives for energy conservation or electricity peak shaving measures. Asensio and Delmas [24], for instance, assessed the effect of non-price incentives (environment and health-based information treatments) on energy conservation. Asensio and Delmas in [24] stated that such incentives were effective in energy savings. Patteuuw et al. [25] analysed the effect of direct load control and dynamic time-of-use (TOU) pricing incentives for improving grid operation. Patteuuw et al. in [25] used a joint optimisation method for optimising the operation of the electricity grid and residential energy system. Zheng et al. [26] investigated the effect of tariffs on demand response provision by residential consumers using storage technologies. Di Pilla et al. [27] aimed at optimising the distribution of retrofit energy incentives in Italy. Di Pilla et al. in [27] used linear programming (LP) to find a scheme that maximises energy savings and minimises retrofit costs.

As already stated, the high upfront cost is one of the main barriers to widespread deployment of hydrogen and heat pumps technologies and governments can provide incentives in favour of such technologies to help overcome this barrier. For instance, the renewable heat incentive is a policy pursued by the UK government to encourage switching to heating technologies that can reduce GHG emissions. Through this policy, financial incentives are provided for home owners to invest in biomass systems, ASHPs, ground–source heat pumps, and solar thermal systems [28].

1.3 Potential of surplus renewable power for the decarbonising building sector

Models developed for finding the most cost-effective energy-efficiency measures and combinations of technologies for supplying heat demand are abundant in the literature. Pensini et al. [29], for instance, developed a mathematical model for finding the optimal size of the heat pump, heat storage, and boiler technologies for supplying heat demand. Pensini et al. in [29] developed a cost minimisation model to assess the potential of surplus renewable power for supplying heat demand. Nässén and Holmberg [30] proposed an optimisation model to minimise the total cost of heat and hot water supply. Heat and hot water supply cost included a capital investment of technologies, operation, and maintenance cost of technologies, fuel cost, and carbon price. Nässén and Holmberg in [30] developed the optimisation model to assess the cost-effectiveness of end-use energy-efficiency measures in Sweden. Zeng et al. [31] developed a mathematical model for optimal sizing and operating a CCHP/ground-source heat pump/thermal storage coupled system for a residential building. The multi-objective optimisation problem developed in [31] with environment, economic, and energy saving criteria was solved using a genetic algorithm. Yousefi et al.[32] used a genetic algorithm for the optimal design of a hybrid energy system consisting of combustion engine/photovoltaic (PV)/solar thermal/boiler/chiller. Yousefi et al. in [32] used different objective functions of cost saving, energy saving, and GHG emission reduction and then used analytic hierarchy process to find the most profitable answer. Lindberg et al. [33] developed a model for optimal design and operation of technologies for a zero energy building. The developed model was used to minimise the cost of energy supply for a case study of a school building, where different technologies including boilers, CHP, PV, solar thermal collector, heat storage, ASHP, and ground–source heat pump were considered. Using the multi-objective optimisation problem developed in [31] with environment, economic, and energy saving criteria was solved using a genetic algorithm. Yousefi et al. in [33] were able to analyse how the policy incentives affect technology selection. Ahmadi et al. [34] developed a multi-objective optimisation problem for finding the optimum design parameters of a hybrid heat recovery/Organic Rankine Cycle/ejector refrigeration cycle/domestic water heater/PEM electrolyser for a residential building application. The objectives considered in [34] were cost and system exergy efficiency within the genetic algorithm were used to solve the optimisation problem. Timmons et al. [35] developed a model to find the most cost-effective method for decarbonising building energy consumption. Their analysis is, however, focused on the consumption side and is focused on finding the least expensive way to reduce emissions in the building sector whether it is energy conservation or renewable power generation.

Reviewing the studies focused on the decarbonisation of the building energy sector shows that the majority of the literature attempted to minimise the cost of supplying heat and electricity to consumers. The total cost incurred includes capital cost, operation, maintenance cost, and fuel cost of heating and electricity supply technologies. Although different algorithms have been suggested for solving such problems, a gap in the literature in this area is considering the role of different stakeholders in the energy system. While many governments all over the world have initiated policies and programmes to promote the adoption of low-carbon technologies in the building sector, the governments’ objective, and decisions and how they can affect the energy consumer’s decision have not been analysed in depth, and the interaction of stakeholders in the energy system has been neglected. In this work, we are assessing if a government policy of discounting surplus clean power can be effective in the deployment of alternative and distributed heat supply technologies in the building sector. There are two stakeholders engaged in that policy: government and energy consumer. Government’s policy considered in this work is in the form of providing power in off-peak hours at a discounted...
price for the energy consumer to encourage adoption of electricity-  

based technologies instead of natural gas-based technologies to  
reduce GHG emissions. Reduction of GHG emissions in the  
building sector is beneficial to the government since it leads to a  
lower social cost of carbon (SCC).

The government tries to reduce GHG emissions with the lowest  
level of incentives. Energy consumer will adopt new technologies  
if it leads to a lower cost for them as its objective is minimising  
heat and electricity supply cost.

The potentials of SOFC, ASHP, and battery and hydrogen  
energy storage technologies in reducing GHG emissions are  
investigated in this work. SOFC systems are chosen as they have a  
better performance in lowering energy consumption as well as  
yearly savings compared with PEM technologies in residential  
applications [9, 11]. ASHP is considered in this work as they are  
the most common heat pump system used in residential  
applications [36, 37]. The popularity of ASHPs is due to their  
lower investment cost even though ASHPs have lower heat output  
and coefficient of performance (COP) compared with ground-  
source heat pumps [38]. Batteries are also among the technologies  
considered in this work due to their vital role in facilitating the  
total integration of emission-free electricity generation technologies  
[39]. Province of Ontario in Canada is chosen as a case study for  
the proposed model. As already stated, natural gas is widely used  
in the residential sector in Ontario. However, the available clean  
surplus power in the province may have the potential to replace  
natural gas consumption.

In that sense, the developed model in this work contributes to  
the literature by providing a tool for assessing the potential of  
surplus clean power in reducing GHG emissions in Ontario,  
Canada in the presence of government incentives. This assessment  
is done by considering the objectives of both energy consumer  
and government which is a gap in the literature. Using game theory for  
modelling the interaction between stakeholders in the energy system  
with emission reduction policy is another contribution of  
this work. The results of such analysis will also help in analysing  
the effect of electrifying the heating sector in electricity and natural  
gas consumption.

2 Methodology

2.1 Model description

There are two stakeholders engaged in the deployment of  
mentioned technologies: government and energy consumer. Game  
theory is used in this work to model the interaction between the  
government and the energy consumer. The objective of the energy  
consumer in the model is minimising the cost of supplying its heat  
and electricity demands. This cost includes upfront cost and  
operation and maintenance cost of technologies, as well as  
electricity and natural gas purchase costs. Government's objective  
function (GOF) is maximising carbon emission reduction with the  
lowest incentives paid. The incentive that the government provides  
to energy customer is defined as a discount on the off-peak  
electricity price, the energy consumer can buy off-peak power at a lower price. For instance, if the discount  
value is 1 cent/kWh and off-peak electricity price is 6.5 cents/kWh, the energy consumer pays 5.5 cents/kWh of electricity purchased at  
off-peak hours to the distribution company. The remaining 1  
cent/kWh from electricity cost is paid by the government to electric  
utility companies. As a result, electric utility companies receive the  
same price for the electricity they sell to the energy consumer.

While the energy consumer pays the full price at mid-peak and  
on-peak hours, lower off-peak power prices will reduce the  
operation cost of technologies which use electricity to supply heat  
and electricity demands including SOFC, ASHP, and battery. The  
lower operation cost gives those technologies an advantage over  
natural-gas-based technologies of CHP and boiler. This advantage  
will encourage the consumer to replace natural gas consumption  
with electricity consumption. This replacement will reduce GHG  
emissions, and subsequently the SCC from the building sector  
which is beneficial to the government.

GOF is defined as the save SCC minus the incentives paid as  
shown in (1). Government's aim is minimising its objective  
function by increasing emission reduction and decreasing the  
number of incentives it pays

$$\text{GOF: } \text{Max}(f) = \text{SCC} \times (\text{emission reduction}) - (\text{incentives paid})$$

(1)

In (1), incentives paid is defined as the energy consumer's  
electricity purchase at off-peak hours multiplied by the discount  
value, $x$ in cents/kWh as shown in the equation below:

$$\text{incentives paid} = (\text{residential energy consumer's } \text{off-peak electricity purchase}) \times x$$

(2)

The government pays the discount value to the electric utility  
company on behalf of the consumer. Emission reduction in (1) is  
calculated compared with the base case, where no discounts are  
provided.

The energy consumer's optimisation problem is shown in (3)–  
(8). The energy consumer's objective function (ECOF) is  
minimising heat and electricity supply cost as shown in the  
equation below: (see (3)). In (3), TCC is an annualised capital cost  
of technology $i$, TO&MC is an annual operation and maintenance  
cost of energy conversion and storage technology $i$ and  
off-peak electricity consumption. The two stakeholders in our  
problem have conflicting objectives. While the government aims at reducing  
GHG emissions with the lowest level of incentives paid, the energy  
consumer only considers the cost of supplying heat when it decides  
about the technologies it invests on. As a result, we have used a  

game theory approach instead of a single optimisation modelling  
approach in this work.

The SCC is used in this work to evaluate the cost-efficiency of  
the government’s policy in reducing GHG emissions. The SCC is a  
criterion to measure the incremental damage GHGs cause and is  
used in evaluating the policies implemented for reducing GHG  
emissions [40, 41]. SCC is used to monetise the effects of an added
Fig. 4 shows the algorithm used for solving the game theory problem in this work. In Fig. 4, big $M$ is a very large positive number and $j$ is an index for different discount values $(x)$. $x$ can take values between 0 and 6 cents/kWh with 0.5 cents/kWh steps. The game theory problem is solved for different values of SCC increasing from 0 to 260 CAD/tonne of CO$_2$ emission. Solving the problem using different SCC value helps us understand how the stakeholders behave when the government's assumed the cost of CO$_2$ emission changes.

The highest GOF and its associated ECOF show the equilibrium state for the problem. In an equilibrium state, none of the stakeholders (players) in the problem have an incentive to deviate from its decisions. In other words, the energy consumer has its minimum objective function at a certain government discount value $(x)$, and the government has its maximum objective function with that $x$ equilibrium state of each SCC value.

The problem is formulated as two separate LP problems in general algebraic modelling system. The optimisation problems for government and energy consumer are solved iteratively.

2.2 Inputs to the model

In this section, inputs to the model are presented.

If the energy consumer replaces natural gas consumption with electricity consumption, GHG emissions from the building sector decrease. The source of the electricity used by the energy consumer, however, affects total GHG emission reduction in the province. As a result, we are using hourly electricity generation emission factors in Ontario to calculate the net GHG emission reduction in Ontario from replacing natural gas with electricity in the building sector. Emission factors from the operation and maintenance of electricity generation technologies in Ontario are shown in Table 1 adopted from data available in [44].

CO$_2$ emission factor for natural gas is assumed to be 0.2 kg/kWh [45].

The natural gas residential rate is assumed to be 1.79 cents/kWh based on the rates reported in [46]. Table 2 shows the on-peak, mid-peak, and off-peak hours in Ontario.

Residential electricity rates in Ontario are assumed to be the values shown in Table 3.

Assumed characteristics of technologies considered in this work are shown in the Appendix.

2.3 Case study

As already stated, the province of Ontario in Canada is chosen as a case study for the proposed model. Temperature data for Waterloo, Canada is taken from the University of Waterloo weather station available in [49] and is used in this work for calculating heat pump efficiency.

Heat and electricity demands from one of Wilfrid Laurier University residences located in Waterloo, Ontario, Canada is used in this work as demand input to the model. Figs. 5 and 6 show the hourly electricity and heat demand over a year for the residence considered in this work. The heat and electricity demands in the residence change throughout the year depending on the number of students living in the residence.

3 Results and discussion

In this section, the results and outputs of the solution of the game theory model are presented. The results include the government and energy consumer's objective value, level of discounts, amount of emission reduction, and selected size of technologies by the energy consumer in the equilibrium state for each SCC value. We are also presenting the share of different technologies in supplying heat and electricity demands. All monetary values are in 2017 CAD.

3.1 Optimum incentive values, GOF, and ECOF

Fig. 7 shows the GOF for different SCC and incentive values. In Fig. 7, the equilibrium state for each SCC is shown by black dots.
As can be seen in Fig. 7, no discount is provided by the government in the base case since the SCC is considered to be zero. In other words, the government has no interest in paying incentives if a tonne of CO$_{2}$e emission has zero social cost. When SCC increases, however, the government is willing to provide discounts to reduce GHG emissions from the building sector. When SCC increases to 20 CAD/tonne of CO$_{2}$e, it is high enough for the government to start paying discount incentives. Although the government is willing to provide more discounts when SCC increases, Fig. 8 shows that the government sometimes pays the same discount level for different SCC values. This is due to the discrete space of government’s decision variable. It is assumed that government is only able to choose discrete values of 0, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, and 6 for $x$. As a result, the government will choose the same $x$ value for a higher SCC since increasing $x$ will not maximise its objective function.

Fig. 8 shows the emission reduction in the equilibrium state for different SCC values. As can be seen in Fig. 9, the ECOF decreases with increase in SCC value and as the energy consumer receives more discounts. As the off-peak price becomes less expensive for the energy consumer, energy consumer can supply its heat and electricity demands with a lower cost, and at the same time reduces more GHG emissions. Fig. 9 also shows that the GOF increases with increase in SCC value which is a result of the increased cost of carbon and increased emission reduction by the energy consumer.

These trends in Figs. 7 and 9 show that a policy of discounting off-peak power for the energy consumer and paying part of its price by the government is beneficial to both stakeholders: SCC is reduced for the government (an increase in GOF) while the energy consumer can supply its heat and electricity demands at a lower cost (a decrease in the ECOF).
3.2 Electricity and heat supply mix for the energy consumer

Table 4 shows the sizes of selected technologies by the energy consumer for different SCC values. Table 4 shows that only three technologies of ASHP, CHP, and boiler are chosen by the energy consumer for different SCC and discount values. In Table 4, the capacity of ASHP increases when more discounts are available. Higher discounts mean the energy consumer can buy off-peak power at lower prices, which give ASHP an advantage over boiler and CHP. The energy consumer invests on more ASHP capacity when lower off-peak electricity prices are available, and at the same time invests less on CHP and boiler capacities. The energy consumer, however, starts using an ASHP only when a discount of 4.5 cents/kWh (x = 4.5) is provided by the government.

Fig. 10 shows the share of different technologies in supplying heat demand. More discounts for electricity cost encourages the energy consumer to replace a higher share of its natural gas consumption with electricity. As can be seen in Fig. 10 and Table 4, the share of boiler in meeting heat demand changes slightly with an increase in discount level, whereas the share of CHP is entirely replaced by ASHP when the discount incentive is equal to or higher than 1 cent/kWh (x ≥ 1).

Fig. 11 shows the share of different technologies in supplying the energy consumer's electricity demand. As can be seen in Fig. 11, CHP supplies more than 80% of the electricity demand in the base case when no discount is available (x = 0). However, lower electricity prices will lead the energy consumer to use more grid power to supply its electricity demand instead of running a CHP. All the electricity demand is bought from the grid when the off-peak power discount is ≥4.5 cents/kWh of off-peak power (x = 4.5) as shown in Fig. 11. This level of discount is chosen by the government when the SCC has a value between 120 and 180 CAD/tonne of CO₂e as shown in Table 4. Replacing CHP with ASHP and grid electricity increases electricity purchase from the grid compared with the base case. This increase can be up to six times when a discount incentive of 4.5 cents/kWh (x = 4.5) is available. Electricity and natural gas consumption ratio to the base case for different levels of SCC are shown in Fig. 12.

When receiving discounts, the energy consumer's off-peak grid electricity purchase increases. However, this increase is not limited to off-peak hours. When electricity is discounted in off-peak hours, the energy consumer's electricity purchase from the grid increases in mid-peak and on-peak hours too. Fig. 13 shows electricity purchase from the grid at different hours for different SCC values. As can be seen in Fig. 13, the change in consumer's selected technologies will increase electricity consumption in off-peak hours as well as mid-peak and on-peak hours, even though the discount is provided only at the off-peak hours. This observation shows the need for planning for supplying the increased demand in...
It should also be noted that despite the replacement of CHP electricity generation with grid power, natural gas remains the dominant energy carrier for the energy consumer in all levels of SCC and provided discounts as shown in Fig. 14. At SCC of 260 CAD/tonne of CO$_2$e, the discount incentive value is 5.5 cents/kWh ($x = 5.5$). This discount level means the energy consumer only pays about 15% of the electricity price at off-peak hours (TOU rate for an off-peak hour is assumed to be 6.5 cents/kWh). However, the energy consumer's natural gas consumption still consists of 70% of the energy consumer's total energy consumption. This high share of natural gas shows that discounting off-peak electricity for the deployment of alternative technologies is not enough for a significant reduction in natural gas consumption in the building sector. Effect of increasing natural gas price through policies such as carbon tax and its effect on natural gas consumption and consumer's total cost should then be further investigated if heat electrification in a region or country is to be pursued.

### 3.3 Sensitivity analysis

A sensitivity analysis on the electricity price for the energy consumer showed that with a ±20% change in electricity rates compared with the reference case, ASHP, boiler, CHP, and power grid are still the only systems and technologies the energy consumer uses for supplying its heat and electricity supply. Table 5 shows the sensitivity analysis done on electricity rates for the energy consumer for an SCC value of 140 CAD/tonne of CO$_2$e.

As can be seen in Table 5, the optimal level of discounts for the government is reduced with both electricity price increase and decrease. The optimal discount level for the government for an SCC value of 140 CAD/tonne of CO$_2$e is 4 and 2.5 cents/kWh of off-peak electricity for 20% higher and 20% lower electricity prices, respectively. With a 20% decrease in electricity prices, the government decreases discount level to near 50% as it knows electricity prices are low enough for the energy consumer to replace a fraction of its natural gas consumption with electricity even with low discounts. Receiving a lower discount, however, the energy consumer uses a lower capacity heat pump (22 kW compared with 46 kW in reference price case). With a 20% decrease in electricity price, the energy consumer emits more emissions compared with the case with reference prices shown in Table 3. However, the government is saving more carbon emission per dollar discounts they pay compared with the case with reference to electricity prices. For an extreme case of 50% decrease in electricity price, the government pays no incentive while it has a higher objective value compared with reference electricity price case due to the reduced carbon emission by the energy consumer.

### Table 4 Sizes of selected technologies by the energy consumer for the different SCC values

| SCC (CAD/tonne of CO$_2$e) | X, cents/kWh | Battery capacity, kWh | Hydrogen storage, kWh of hydrogen | ASHP capacity, kW | CHP capacity, kW | SOFC capacity, kW | Electrolyser capacity, kW | Boiler capacity, kW |
|-----------------------------|--------------|-----------------------|----------------------------------|------------------|----------------|------------------|------------------------|-------------------|
| 0 (base case)               | 0            | 0                     | 0                                | 108              | 0              | 0                | 0                      | 941               |
| 20                          | 0.5          | 0                     | 0                                | 101              | 0              | 0                | 0                      | 945               |
| 40                          | 0.5          | 0                     | 0                                | 101              | 0              | 0                | 0                      | 945               |
| 60                          | 0.5          | 0                     | 0                                | 101              | 0              | 0                | 0                      | 945               |
| 80                          | 0.5          | 0                     | 0                                | 101              | 0              | 0                | 0                      | 945               |
| 100                         | 1            | 0                     | 0                                | 88               | 0              | 0                | 0                      | 952               |
| 120                         | 4.5          | 0                     | 46                               | 0                | 0              | 0                | 0                      | 915               |
| 140                         | 4.5          | 0                     | 46                               | 0                | 0              | 0                | 0                      | 915               |
| 160                         | 4.5          | 0                     | 46                               | 0                | 0              | 0                | 0                      | 915               |
| 180                         | 4.5          | 0                     | 46                               | 0                | 0              | 0                | 0                      | 915               |
| 200                         | 5            | 0                     | 63                               | 0                | 0              | 0                | 0                      | 892               |
| 220                         | 5            | 0                     | 63                               | 0                | 0              | 0                | 0                      | 892               |
| 240                         | 5            | 0                     | 63                               | 0                | 0              | 0                | 0                      | 892               |
| 260                         | 5.5          | 0                     | 78                               | 0                | 0              | 0                | 0                      | 870               |
With a 20% higher electricity prices for an SCC of 140 CAD/tonne of CO$_2$, the optimal discount level for the government is 4 cents/kWh of off-peak electricity consumption which is lower than the 4.5 cents/kWh of off-peak electricity consumption offered for the reference electricity prices. Facing higher electricity prices and lower discounts, the energy consumer uses a smaller heat pump (21 kW compared with 46 kW) and keeps using CHP with a capacity of 76 kW. As the government knows the electricity prices are too high for the energy consumer, it limits the level of discounts which leads to a 40% reduction in emission savings.

It should be noted that a change in electricity price affects the objective of electricity generation companies. Electricity generation companies' decisions are not considered in this work and will be a topic for future research for the authors.

4 Conclusion

In this work, game theory is used to model the interaction of government and an energy consumer for assessing the potential of off-peak power in reducing GHG emissions in the building and residential sector. The government in this work provides discounts at off-peak electricity for the energy consumer to encourage the replacement of natural gas with electricity in the building sector. This replacement is beneficial to the government as it leads to a lower SCC, for which the government is responsible. The government's objective is then defined as reducing SCC with the lowest level of incentives it pays to the energy consumer. The incentive is in the form of discounting a part of TOU price the energy consumer has to pay in off-peak hours. The discount rate is covered by the government, so the electric utility company still received the same price for off-peak power sold to the energy consumer.

The energy consumer, however, will only replace natural gas with electricity if it leads to a lower heat supply cost for them. In the base case (i.e. no discount for off-peak electricity), the energy consumer uses boiler and CHP to supply heat demand and uses grid and CHP to supply electricity demand. However, the energy consumer may use ASHPs, SOFC, battery storage, HENG, or more grid power to supply its demand if it leads to a lower cost for them.

When the level of off-peak electricity purchase discount incentive increases to 4.5 cents/kWh, the energy consumer starts replacing CHP and some of the boiler capacity with an ASHP and more grid power purchase. CHP is not a cost-effective technology for the energy consumer when it can purchase off-peak hour 4.5 cents/kWh lower than the price in the base case. Boiler, on the other hand, is always used by the energy consumer regardless of the level of discount available.

The analysis in this work shows that ASHPs are the only technology the energy consumer will use if it has discounts for purchasing off-peak power at a lower price. ASHPs can replace natural gas-based technologies if discounts for electricity purchase are available while SOFC and battery systems are not used by the energy consumer even when it is exempted from paying a significant cost of its off-peak power purchase. However, natural gas remains the dominant energy carrier even in the high level of off-peak power discount which shows the need for investigating other policies if significant natural gas consumption reduction in the building sector is targeted. Our analysis also showed that with a 20% increase and 20 and 50% decrease in electricity rates change in electricity rates, ASHP, boiler, CHP, and power grid remain the only systems chosen by the energy consumer.

The developed model in this work helps in better understanding of the energy consumer's reaction to emission reduction policies from the government. In that sense, running this model shows us what size and combination of technologies will the energy consumer adopt when it receives subsidies from the government. Knowing the energy consumer's favourite technologies, we can calculate the added electricity demand or reduced natural gas consumption and associated carbon emissions in the building sector.

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6 References

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Table 6 shows the assumed characteristics of technologies considered in this work.
| Technology                     | Capital cost          | Operation and maintenance cost | Electrical efficiency              | Heating efficiency | Lifetime, years |
|-------------------------------|-----------------------|---------------------------------|-----------------------------------|--------------------|-----------------|
| battery [50, 51]              | 396 CAD/kWh           | 6.5 CAD/kWh/yr                  | 85% round trip, 0.17% self-discharge rate per day | NA                 | 10              |
| internal combustion engine CHP [52, 53] | 735 CAD/kW           | 0.02 CAD/kWh                    | 30%                              | 50%                | 20              |
| boiler [12]                   | 60 CAD/kW             | 0.00065 CAD/kWh                 | 85%                              | NA                 | 20              |
| SOFC [12, 54]                 | 3900 CAD/kW, 1560 stack replacement cost (CAD/kW) | 0.026 CAD/kWh | 45 | 40 | 5 (stack lifetime) |
| ASHP [21]                     | 486 CAD/kW            | assumed to be 1% of the capital cost (CAD/kW/year) | NA | COP is assumed to change linearly between 1.2 and 3.5 for temperatures -25 and 18 based on the COP proposed in [37] | 20 |
| hydrogen storage tank [55]    | 37 CAD/kWh of hydrogen capacity | assumed to be 0.5% of the capital cost (CAD/kWh of hydrogen capacity/year) | NA | NA | 20 |
| electrolyser [56]             | 1076 CAD/kW, stack replacement cost assumed 30% of electrolyser capital cost | assumed to be 4% of the capital cost (CAD/kW/year) | 5.9 kWh electricity consumption/m$^3$ of hydrogen | — | 7 (stack lifetime) |