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Prosumers and energy pricing policies: When, where, and under which conditions will prosumers emerge? A case study for Ontario, Canada

Elizaveta Kuznetsova^{1,*} and Miguel F. Anjos^{1,2}

¹*GERAD and Department of Mathematics and Industrial Engineering, Polytechnique Montreal, C.P. 6079, Succ. Centre-Ville, Montreal, QC, Canada H3C 3A7*

²*School of Mathematics, University of Edinburgh, Edinburgh EH9 3FD, United Kingdom*

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Abstract

There has recently been a rapid emergence of electricity prosumers at all levels of the grid. Energy policy seems to be more adaptive to the needs of large-scale prosumers, but small-scale prosumers have been largely ignored. If there are enough small-scale prosumers their behaviour may be disruptive for the entire grid. At the same time, the scepticism about the feasibility and profitability of their disconnection remains. This paper contributes to the exploration of these issues by analyzing the impact of billing policy on the profitability of investment in prosumer schemes, such as Net Metering and Off-grid, in Ontario (Canada). We conclude that the recent fast improvement in commercial storage technologies has made it possible for prosumers to become fully electricity self-sufficient even in locations with low availability of renewable energy sources. While our profitability analysis shows that Off-grid will likely remain unprofitable for the next ten years, it reveals some important findings. The profitability of Net Metering is currently comparable with that of Off-grid. For Ontario, this means that a prosumer would need to increase the investment threefold to switch from Net Metering to the grid-disconnected mode, but the profitability of this decision would be decreased only by a factor of two. Critical locations where disconnection is more profitable are characterized by a high share of fixed costs in the total electricity bill. The profitability of disconnection increases faster with the increase of fixed charges. This indicates that the billing policy has a direct impact on the consumer decisions. We have compared three locations (Atikokan, Hawkesbury and Espanola) characterized by different variable and fixed costs in consumer electricity bill. We found that a five fold increase in the variable cost (with the same fixed cost) increases the Off-grid profitability by 10%, while a three fold increase in the fixed cost (with the same variable cost) increases the profitability by 26%. If the shares of variable and fixed costs are unchanged in the future, the Off-grid profitability may almost double between 2019 and 2030. If the cost trend of recent years is maintained, i.e., decrease of variable costs and increase of fixed costs, then the disconnection may become an attractive option.

*Corresponding author, elizaveta.kuznetsova@gerad.ca

Index terms— Energy system, energy policy, variable and fixed costs, electricity prosumer, Net Metering, Off-grid scheme, profitability

Nomenclature

Sets

$c \in C$	Energy consumer/prosumer
$t \in T$	Energy planning time step (h)
$y \in Y$	Billing time period ($year$)

Parameters

η	Yield of the photovoltaic (PV) panel defined as electrical power of one module in kW divided by the area of one module in m^2 (kW/m^2)
η^{El}	Efficiency of electrolyzer
η^{FC}	Efficiency of fuel cell
η^{Mod}	Efficiency of hydrogen compression, storage and dispension module
ϕ	Hemispherical insolation 0.8 (kW/m^2)
$C_y^{avoided}$	Total cash flow related to gains and avoided payments in electricity bill at year y (CAD)
c^{peak}	Maximum hourly peak demand of the household recorded over a year (kW)
c_t^{el}	Electricity load of the consumer c at time step t (kW)
$CAPEX_y$	Capital investments in renewable energy sources (RES) installations to become a prosumer at year y (CAD)
EB_m	Monthly electricity bill of consumer (CAD)
ER_y	Electricity rate at year y (CAD/kWh)
FF	PV module fill factor
GHI_m	Monthly average global horizontal irradiation (GHI) (shading not included) (kW/m^2)
GHI_t	GHI at time step t (kW/m^2)
I^{sc}	PV module short-circuit current (A)
I_t	Electrical current of PV module (A)
K^I	Current temperature coefficient of PV module ($A/^\circ C$)
K^V	PV voltage temperature coefficient ($V/^\circ C$)
MSC_y	Fix service charge at year y (CAD)
N	Number of modules in the PV array

p_m^{PV}	Mean monthly PV energy output, (kWh)
p_t^{PV}	Power generated by the locally installed PV at time step t (kW)
PI_c	Profitability index for investment for consumer c
PR	Performance ratio or coefficient for losses of the PV installation
r	Discount factor
R^{bat}	Relative battery size defined as the total level of charge divided by the total consumption for the time period T (kWh/MWh)
$R^{ch,Min/Max}$	Minimum and maximum power to be charged to the electric battery (kW)
$R^{disc,Min/Max}$	Minimum and maximum power to be discharged from the electric battery (kW)
$R^{H_2,ch,Min/Max}$	Minimum and maximum power to be charged to the hydrogen storage in energy content equivalent (kW)
$R^{H_2,disc,Min/Max}$	Minimum and maximum power to be discharged from the hydrogen storage in energy content equivalent (kW)
$R^{H_2,Min/Max}$	Minimum and maximum acceptable levels of the hydrogen storage charge in energy content equivalent (kWh)
$R^{Min/Max}$	Minimum and maximum acceptable levels of the electricity storage charge kWh
R^{PV}	Relative PV installation size defined as the total energy generated by the installation divided by the total consumption for the time period T (kWh/kWh)
r_d^{peak}	Daily load peak coefficient dependent on the week day and the depicting the difference between week days and weekend load (%)
r_h^{peak}	Hourly load peak coefficient depicting load behaviour hourly and dependent on the season (%)
R_t	State of electric battery charge at the time step t (kWh)
$R_t^{H_2}$	State of hydrogen storage charge in energy content equivalent at the time step t (kWh)
r_w^{peak}	Weekly load peak coefficient dependent on the season (%)
$RTSR_y^{Connection}$	Line and transformation connection service rate at year y (CAD/kWh)
$RTSR_y^{Network}$	Network service rate at year y (CAD/kWh)
SCR_T	Ratio between the self-consumed energy and the total energy production for the time period T
SSR_T	Ratio between the self-consumed energy and the total energy demand for the time period T

T_t^m	PV module temperature at time step t ($^{\circ}\text{C}$)
T^{aofNOT}	Ambient temperature of 20°C used for nominal operating temperature test of PV module ($^{\circ}\text{C}$)
T^{NOT}	Nominal operating temperature of PV module ($^{\circ}\text{C}$)
T^{STC}	PV module temperature at Standard Test Conditions equal to 25°C ($^{\circ}\text{C}$)
T_t^a	Ambient module operational temperature at time step t ($^{\circ}\text{C}$)
Tax_y	Taxes percentage at year y
V^{MPP}/I^{MPP}	PV module voltage (V) and current (A) at maximum power point
V^{oc}	PV module open-circuit voltage (V)
V_t	Electrical voltage of PV module (V)
VC_y	Distribution volumetric rate at year y (CAD/kWh)
$VCLV_y$	Distribution low voltage rate at year y (CAD/kWh)

Variables

$\delta_t^{ch/disch}$	Binary decision variables for charging and discharging of electric battery at time period t
$\delta_t^{H_2, ch/disch}$	Binary decision variables for charging and discharging of hydrogen storage at time period t
b_t	Power shortage for consumer at time step t (kW)
l_t^{PV}	Power used from PV at the time step t (kW)
$R_t^{ch/disch}$	Power charged/discharged from the electricity battery (kW)
$R_t^{H_2, ch/disch}$	Power charged/discharged from the hydrogen storage (kW)
w_t^{PV}	Power injected to the grid or lost from its locally installed PV at time step t (kW)

1 Introduction

Policies such as feed-in-tariff (FIT) that support the transition toward cleaner energy system promote a wide adoption of RES and stimulate a fast decrease in their installation costs. RES integration is relevant not only for the high- and medium-voltage grids. High electricity rates, continuously decreasing technologies costs, and increasing environmental awareness lead to the emergence of small-scale prosumers [1]. In Canada, end-use transition is important to ensure a reliable and clean energy system. The New Energy Vision for Canada [2] envisages that by 2030 the majority of Canadians will have the option to become prosumers, through residential and commercial building solar panels, district heating, and distributed storage. Provincial statistics suggest that this goal

is reasonable. In Alberta, the total installed capacity of microgenerators (of less than 5 MW) increased by a factor of 5.8 between 2015 and 2019, reaching 4,283 participants (prosumers) [3]. In Quebec, the number of self-generators (of less than 50 kW) increased from 58 to 147 between 2013 and 2017; in 2016 they generated 295.4 MWh [4]. British Columbia reported a six fold increase in Net Metering prosumers (of less than 100 kW) between 2013 and 2019, with about 1,850 participants in 2019 and over 14 MW of total installed capacity [5].

In some jurisdictions electricity tariff structures not only create a financial incentive for self-consumption, but also may encourage prosumers to disconnect from the grid. In Australia, under current tariff and incentive arrangements for stand-alone systems, up to 10% of consumers could choose to go off-grid by 2050 [6], accepting the implications for their energy reliability. The high cost of environmental policies led around 16% of German companies to become self-sufficient in 2014, with another 23% announcing their intention to become self-sufficient in the future [7]. Grid defection for residential prosumers may not be profitable in Germany before 2025 [8]. However, by 2018 100,000 home electric batteries have been installed [9] and the emergence of commercial seasonal storage technologies [10] is preparing the groundwork for disconnection. A similar tendency has been observed in other countries, such as the US, where businesses have started to invest in electricity generation installations to gain a certain degree of self-sufficiency [11].

A growth in industrial-scale prosumers willing to disconnect would present an immediate major threat to conventional energy systems. Energy policies to mitigate these undesirable effects are implemented more quickly for these large prosumers, they are subject to different exemptions and reliefs [12]. However, since commercial RES and storage options are becoming increasingly affordable, residential consumers may also choose a path of disconnection. When their number reaches a critical threshold they may considerably impact the operation of the energy system by amplifying the already noticeable effect of large consumers [13]. A well-known example is a total net load in the shape of the so-called duck curve due to the massive penetration of PV generation [14].

Various studies have explored prosumers emergence and their energy self-sufficiency. [15] analyze the self-consumption potential for different sizes of PV/battery installations in several European countries (Portugal, Italy, Greece, Romania, France, Denmark, and the UK). They simulate residential loads, PV generations, and battery dispatch and assume a reward policy similar to FIT. They found that tariff structure and the difference between electricity buying and selling rates were key drivers for self-consumption [15]. Complete self-sufficiency was not realistic without excessively oversizing the PV installation. Going further, [16] reasonably concluded that economy of scale has an effect on electricity self-sufficiency: in Europe it may be profitable for a district of several hundred households to become self-sufficient. [17] explores electricity self-sufficiency (via PV array and electric battery installations) for low-population-density areas in Germany and the Czech Republic. Based on a standard load profile (SLP), detailed spatial maps of the PV and storage requirements show that purely electrical self-sufficiency (for electrical appliances only) of single-family houses may be possible in these locations for certain installation sizes. These results were achieved for locations with high a RES capacity factor (CF) [18], e.g., a PV CF above 20%, and modest typical electricity consumption per capita [19].

This paper explores self-sufficiency feasibility and profitability by considering the more extreme case of Ontario (Canada), which is characterized by high typical electricity consumption and a

modest potential for PV. Our paper contributions are as follows:

- Based on the studies of European countries, we explore the PV and electric battery potential for Ontario. We attach particular importance to improving the model accuracy, i.e., we take into account the thermal sensitivity of the household load, and for the PV power output we consider the variability of the solar irradiation and the ambient temperature. We conclude that above a certain threshold the increase of PV capacity has no effect on household self-sufficiency. Instead, full autonomy can be achieved by focusing on storage solutions. Thus, we identify a promising track for future research on complete self-sufficiency.
- In the Ontario context, we ask *“Is it possible to operate in disconnected mode?”* We also introduce hydrogen-based seasonal storage into the prosumer power dispatch model; this type of seasonal storage may be able to provide full yearly self-sufficiency even for northern Ontario households. It also allows to close a loop of the PV power usually lost periods of high solar irradiation. Until now this power surplus has been injected into the grid [15] or curtailed [17].
- We analyze the history of Ontario pricing policies, discuss potential changes in legislation, and consider various costs (i.e., energy and power, transmission and distribution costs) to determine the profitability of investment in 100% self-sufficient installations. This analysis is done under pricing policy projections and technologies costs trends.
- We ask *“When and where it is profitable to become a prosumer?”* We thus identify the critical geographical locations in Ontario where disconnection is worthwhile. We determine the corresponding levels of variable and fixed costs in the tariff structure, suggesting ways to develop energy policies that involve small-scale prosumers in the global energy management process.

2 From electricity consumer to prosumer

2.1 Household consumption and load

The monthly electricity consumption of a typical residential customer is used by the independent regulator to illustrate the impact of different policies on the consumer’s electricity bill. This typical monthly consumption is defined using data for several years: the previous annual consumption reported by residential users and the total number of customers each year [20]. In 2016 the standard level of consumption for Ontario households was determined to be 750 kWh/month [20]. It is mainly composed of consumption from electrical appliances, lighting, and space cooling. This value has been confirmed by several studies. [21] finds (based on 25 homes monitored in the Greater Toronto Area (GTA)) an average electricity usage of between 600 and 1200 kWh/month for an average home size of 225 m². [22] reports (based on 23 households in Ottawa) the maximum annual peak to be less than 1.1 kW which is equivalent to a typical consumption of less than 486 kWh/month.

The household load profile depends on the number and type of electrical appliances and their use. Taking into account the difficulty of collecting large amounts of reliable information and building complex models, the top-down approach, based on detailed chronological collection of

overall electricity demand, is used [23]. Note that the load model provides an average smooth load profile, which will differ from the real-time measurements of a single household:

$$c_t^{el} = c^{peak} \cdot r_w^{peak} \cdot r_d^{peak} \cdot r_h^{peak}, \forall c, t \quad (1)$$

The load sensitivity is represented by the increase in the load as the temperature changes from the typical neutral temperature of around 19 °C. While Europe has a strong demand-temperature relationship in winter and a minor load increase in summer [24], North America demonstrates stronger summer correlation because of the massive use of cooling installations [25]. A similar tendency for summer-temperature correlation is present in the south of Canada, and in Ontario the winter peak dominates the summer peak for locations above about 46° of latitude [26].

This study considers a household with no cooling system (typically situated in northern Ontario) with a maximum hourly peak demand c^{peak} over a year of **1.7 kW**. This corresponds to 750 kWh of average monthly electricity consumption (Figure 1).

Figure 1: Load profile of households with typical monthly consumption and example of seasonal temperature variations for Atikokan in the north of Ontario (in 2018).

2.2 Power dispatch model

The goal of this paper is not to propose an optimal RES generation portfolio for a given prosumer such as that in [27] for partial self-sufficiency. We instead show the near-future feasibility of the Off-grid mode. We reviewed several RES options, including solar and wind, and choose to assume generation by PV array, currently the most accessible RES for residential use.

Figure 2: Abstract scheme of prosumer power flows to dispatch.

In grid-connected mode, prosumer tends to minimize its electricity bill by maximizing the avoided cost through optimal equipment management. For a grid-disconnected prosumer, this minimization is replaced by the maximization of self-sufficiency, which is expressed as the minimization of the electricity shortage b_t and the PV array generation surplus w_t^{PV} given the forecasted hourly operational conditions.

$$\text{Minimize } \sum_{t \in T} (b_t + w_t^{PV}) \quad (2)$$

s.t.

$$p_t^{PV} - c_t^{el} \geq w_t^{PV} - b_t - R_t^{disc} + R_t^{ch} \quad (3)$$

$$c_t^{el} \leq l_t^{PV} + R_t^{disc} + b_t, \forall t \quad (4)$$

$$p_t^{PV} \geq R_t^{ch} + l_t^{PV} + w_t^{PV}, \forall t \quad (5)$$

$$l_t^{PV} \geq 0, b_t \geq 0, w_t^{PV} \geq 0, \forall t \quad (6)$$

$$R_t \leq R_{t-1} - R_t^{disc} + R_t^{ch}, \forall t \quad (7)$$

$$R_t = R_{t=0}, R^{Min} \leq R_t \leq R^{Max} \forall t \quad (8)$$

$$\delta_t^{ch} \cdot R^{ch,Min} \leq R_t^{ch} \leq \delta_t^{ch} \cdot R^{ch,Max} \forall t \quad (9)$$

$$\delta_t^{disc} \cdot R^{disc,Min} \leq R_t^{disc} \leq \delta_t^{disc} \cdot R^{disc,Max} \forall t \quad (10)$$

$$0 \leq \delta_t^{ch} \leq 1, 0 \leq \delta_t^{disc} \leq 1, \forall t \quad (11)$$

$$\delta_t^{ch} + \delta_t^{disc} \leq 1, \forall t \quad (12)$$

This formulation minimizes b_t and w_t^{PV} for a given planning horizon T (2). The prosumer equipment consists of a PV array coupled with battery storage, and the power balance is specified by (3) and (4). The electrical load c_t^{el} is met by the PV power output l_t^{PV} and the power R_t^{disc} discharged from the battery. The remaining load b_t is covered from the grid (if the prosumer is connected), and left uncovered otherwise (if the prosumer is disconnected) (4). The power from PV R_t^{ch} is directed into the battery, and w_t^{PV} is the lost power that could be not used to cover prosumer load nor to be stored due to the battery storage limit (5). Constraint (7) models the dynamics of the usable state of charge (SOC) of the battery. Constraint(8) specifies the initial battery conditions and its charging and discharging limits. Constraints (9) and (10) limit the power that can be charged and discharged depending on the battery type (e.g., fast charger). Constraints (11) and (12) ensure that the battery is not charged and discharged simultaneously. We handle the non-linearity of (9) and (10) via the Big M method. The efficiency of the battery and inverter are not taken into account.

2.3 Prosumer performance indicators

Several key performance indicators (KPI) are defined in [15] to determine the size of the equipment and to evaluate the performance of the power dispatch algorithm. The KPI of the relative PV and battery sizes [15] are used to identify the size of the power installations:

$$R^{PV} = \frac{\sum_{t \in T} p_t^{PV}}{\sum_{t \in T} c_t^{el}}, \left[\frac{kWh}{kWh} \right] \quad (13)$$

$$R^{bat} = \frac{R^{Max}}{\sum_{t \in T} c_t^{el}}, \left[\frac{kWh}{MWh} \right] \quad (14)$$

The self-sufficiency rate (SSR) and self-consumption rate (SCR) are the ratio of the self-consumed energy and the annual electricity demand, and the ratio of self-consumed electricity and the annual PV production, respectively:

$$SSR_T = \frac{\sum_{t \in T} (l_t^{PV} + R_t^{disc})}{\sum_{t \in T} c_t^{el}} \quad (15)$$

$$SCR_T = \frac{\sum_{t \in T} (l_t^{PV} + R_t^{disc})}{\sum_{t \in T} p_t^{PV}} \quad (16)$$

2.4 PV potential

2.4.1 PV power output profile

The PV CF for Ontario is in the range 0.103 to 0.118 kWh/kW/year [28]. The hourly GHI data for several years for different locations was retrieved from [29]. The output from the PV array is

calculated using the following mathematical model accounting for the technical characteristics of the panels, the GHI and the loss of module efficiency with the increase of ambient temperature [30, 31]. The hourly temperature values in different Ontario locations are available from [32], and the technical PV characteristics are shown in Table 1.

$$T_t^m = T_t^a + GHI_t \cdot \left(\frac{T^{NOT} - T^{aofNOT}}{\phi} \right) \quad (17)$$

$$I_t = GHI_t \cdot \left(I^{sc} + K^I \cdot (T_t^m - T^{STC}) \right) \quad (18)$$

$$V_t = V^{oc} - K^V \cdot T_t^m \quad (19)$$

$$FF = \frac{V^{MPP} \cdot I^{MPP}}{V^{oc} \cdot I^{sc}} \quad (20)$$

$$p_t^{PV} = N \cdot FF \cdot V_t \cdot I_t \quad (21)$$

Equation (17) calculates the PV module temperature T_t^m , which helps to identify the module current (18) and voltage (19). Equation (20) provides the fill factor coefficient FF based on the module technical specification. Finally, (21) estimates the power output of the PV array.

Table 1: Technical specification of PV module [33]

Watt peak, kW	0.3
Performance ratio	0.75
Module area, m ²	1.635
Yield, %	18.35
Open circuit voltage, V	44.71
Short circuit current, A	8.947
Voltage at maximum power, V	37.23
Current at maximum power, A	8.06
Voltage temperature coefficient, V/C	-0.152014
Current temperature coefficient, A/C	-0.0044735
Nominal operating temperature, °C	47

2.5 Matching PV generation and household demand with a battery

In aggregate, the total annual power output of a PV array is able to cover an annual household load. For Atikokan (a northern location with modest solar insolation) annual household consumption is around 9,000 kW, and the annual PV generation is 9,970 kW with a 9 kW array. In practice, the solar insolation has hourly and seasonal variations. In the best-case scenario (typically in summer), solar insolation is available for 30% of the day, and the electric battery enables to shift the excess of solar power to hours when the sun is down. Figure 3a illustrates the household power dispatch in summer, it shows that a 10 kWh battery of rapid charge (of less than 6 h) can accomplish this task. However, at the same time, considerable amount of electricity which can be used neither to cover household consumption nor to store in the battery is lost because of the limited battery capacity

(Figure 4). The total amount of electricity lost per year for a typical household in Atikokan is 3,340 kWh or 34% of the total PV generation.

The most challenging issue is that solar availability is much lower in fall and winter. During these periods, the PV power output is available at best for only a few hours during the day (see Figure 3b). The PV generation barely meets 25% of the daily household demand, the battery is hardly used, and no PV energy is lost. The electricity shortage is particularly important (Figure 4). The total annual unmet electricity demand for a typical household in Atikokan is 3,280 kWh or 36.6% of the annual demand.

Figure 3: Example of power dispatch for Atikokan household of typical consumption, 9kW PV array, and 10kWh battery (allowing fast charge/discharge of 2h): 5 days in a) July and b) January.

Figure 4: PV energy losses and unmet energy demand per week for typical household in Atikokan with 9 kW PV array and 10 kWh battery.

We reproduced the exercise of [15] showing the influence of the battery R^{bat} and PV array R^{PV} sizes on SSR and also studied the impact of the installations on SCR (Figure 5). Increases in R^{bat} and R^{PV} improve the self-sufficiency. However, this increase has diminishing returns on the SSR, i.e., with every additional kW for PV and kWh for the battery the SSR gain decreases. At the same time, the increase in capacity increases the PV energy losses (Figure 5a).

Figure 5: a) SSR and b) SCR for different battery and PV sizes for an Atikokan household.

We also considered the installation capacity needed for full household self-sufficiency. Figure 6a shows that a sufficiently large storage capacity allows enough PV surplus to be stored until it needed to achieve complete electricity self-sufficiency. For this purpose, a storage of more than 2 MWh would be required for an Attikokan household. However, increased PV generation will not lead to complete self-sufficiency in northern locations, where the solar insolation can be extremely low or even nil for several days in a row: the SSR plateaus at 0.9. It shows that a seasonal storage is essential to ensure electricity self-sufficiency.

Figure 6: Complete self-sufficiency for Atikokan household for two extreme cases: a) increase only in battery capacity and b) increase only in PV array capacity.

3 Is it possible to operate in disconnected mode?

3.1 Seasonal storage: Closing the loop of PV power losses

Given the scale of storage necessary, a potential technology is hydrogen storage with power-to-gas and gas-to-power solutions (Figure 7); we refer to this as hybrid hydrogen storage (HHS). HHS is no longer investigated purely for large-scale and industrial applications, but has been integrated into studies of microgrids and smart homes designs [34]. Ontario also considers hydrogen technologies to be integrated into its Smart Home Roadmap by 2030 [35].

Figure 7: Abstract scheme of hybrid hydrogen storage: power-to-gas, hydrogen storage, and gas-to-power.

The major challenges of HHS are related to the storage technology itself. It must be a commercially available or mature technology able to store gas of several MWh in energy content (see Section 2.5) and appropriate for residential households, with minimum maintenance and space requirements. As a consequence, operations research studies of residential energy management generally consider hydrogen technology as a short-time storage for partly self-sufficiency. Under good solar and wind potential, complete off-grid operation can be achieved via a combination of a PV array, a wind turbine, an electric battery, a fuel cell continuously supplied from a hydrogen

station, and possible load shifting [36]. HHS of [37, 38] can support a stand-alone RES, allowing residential districts to achieve eight days of autonomy in the absence of solar insolation. [39] shows a rare attempt to use HHS as a real seasonal storage powered by a PV array. They consider the operation of an independent living and working capsule with a 200 kWh (5.3 kg of hydrogen) HHS for complete self-sufficiency.

In recent years, HHS has become available for household real-life applications [40]. These include the seasonal storage of several megawatts of total usable capacity available on the market since 2018 [41, 42] and was used for a fully self-sufficient house built in Bavaria in 2019 [10].

We consider HHS in our exploration of electricity self-sufficiency for prosumers in Ontario. We extend the model (2) – (12) with an abstract battery model (by analogy with the electric battery) that describes the HHS operation in the context of residential prosumer. The following model reasons in terms of energy content which is agnostic to technology evolution:

$$R_t^{H_2} \leq R_{t-1}^{H_2} - \frac{R_t^{H_2, disc}}{\eta^{FC}} + \eta^{Mod} \cdot \eta^{El} \cdot R_t^{H_2, ch}, \forall t \quad (22)$$

$$R_t^{H_2} = R_{t=0}^{H_2}, R^{H_2, Min} \leq R_t^{H_2} \leq R^{H_2, Max} \forall t \quad (23)$$

$$\delta_t^{H_2, ch} \cdot R^{H_2, ch, Min} \leq \eta^{Mod} \cdot \eta^{El} \cdot R_t^{H_2, ch} \leq \delta_t^{ch} \cdot R^{ch, Max} \forall t \quad (24)$$

$$\delta_t^{H_2, disch} \cdot R^{H_2, disch, Min} \leq \frac{R_t^{H_2, disc}}{\eta^{FC}} \leq \delta_t^{H_2, disch} \cdot R^{H_2, disch, Max} \forall t \quad (25)$$

$$0 \leq \delta_t^{H_2, ch} \leq 1, 0 \leq \delta_t^{H_2, disch} \leq 1, \forall t \quad (26)$$

$$\delta_t^{H_2, ch} + \delta_t^{H_2, disch} \leq 1, \forall t \quad (27)$$

The right-hand sides of (3) and (4) include the HHS discharging power $R_t^{H_2, disc}$ and charging power $R_t^{H_2, ch}$.

Table 2: Characteristics of hydrogen-based technology

Characteristic	Electrolyzer [43]	Compression, storage and dispensing module [44]	Fuel cell ¹ [45]
Conversion efficiency	64 – 80%	65%	40 – 60%

¹ Because the focus of this study is on electricity, the thermal potential of hydrogen storage is omitted. Taking it into account would increase the fuel cell efficiency to up to 90% [45], potentially leading to full energy (thermal and electricity) self-sufficiency for an Ontario household.

3.2 Case study

We tested several locations in Ontario and found that on average a prosumer will need a 15 kW PV array and an HHS with a capacity of 2.6 MWh. The seasonal storage is charged during periods of high PV generation and mainly used to cover the load during fall and winter. The remaining load is covered directly from the PV. Given the specified equipment, a household can reach complete electricity self-sufficiency. We reduce the electric battery capacity to 2 kWh to handle short-term load variations. Figure 8 shows the energy flows dispatch in the presence of HHS (one year selected from a three-year simulation).

Figure 8: Example of annual power dispatch for a typical Atikokan household with 15 kW of PV, an electric battery of 2 kWh (allowing fast charge/discharge) and HHS of 2.6 MWh.

3.3 Major observations

Our results suggest that it is possible to become self-sufficient and to disconnect from the grid subject to the following observations:

- An unlimited increase in generator capacity relying on a modest resource (here PV capacity increase under a modest insolation) will not lead to complete self-sufficiency. This remains the case even with increased efficiency due to technological development, as Figure 6b shows. Self-sufficiency may be achieved only with the development of medium- and long-term seasonal storage. Another option for self-sufficiency is a combination of different RESs with different seasonality features, but that is beyond the scope of the paper.
- Seasonal storage with HHS technology can in principle close the energy loop of summer PV energy loss and unmet winter demand. However, the operational model used to simulate HHS dispatch may need to be refined in collaboration with hydrogen experts to ensure its accuracy. Moreover, in addition to seasonal HHS, the household would require an electric battery to compensate for short-term load fluctuations. A dispatch model must integrate refined models of both HHS and the electric battery to determine prosumers' storage needs.

- The optimal sizing and matching of household load, PV, electric battery and seasonal storage capacity under given environmental conditions are key issues. The goals of the prosumer are to fully profit from RES generation as a main power source and become self-sufficient at an acceptable investment cost.

4 When and where it is profitable to become a prosumer?

To become a prosumer, an electricity consumer may select one of the following options: (i) participation in an available scheme (e.g., Net Metering) or (ii) to scale its installations for a permanent off-grid mode.

4.1 Profitability of investment

The pricing policy determines the consumer's electricity bill. In Ontario, the monthly bill EB_m for the consumption $\sum_{t \in T} c_t$ of consumer c during month m has the following structure:

$$EB_m = Tax_y \cdot \left[\underbrace{\sum_{t \in T} c_t \cdot ER_y}_{\text{energy and power cost}} + \underbrace{\sum_{t \in T} c_t \cdot (RTSR_y^{Network} + RTSR_y^{Connection})}_{\text{transmission cost}} \right] + \underbrace{MSC_y + \sum_{t \in T} c_t \cdot (VC_y + VCLV_y)}_{\text{distribution cost}} \quad (28)$$

The bill is composed of energy and power, transmission, and distribution costs. These amounts depend on the annual charges and variable rates of the retailer (i.e., the distribution company).

The profitability of investment in different equipment (e.g., PV and battery storage) may be evaluated through a profitability index (PI) defined as the fraction of the sum of discounted future avoided annual cash flows and an initial capital investment:

$$PI_c = \sum_{y \in Y} \frac{1}{(1+r)^y} \cdot \frac{C_y^{avoided}}{CAPEX_y} \quad (29)$$

Net Metering gives the consumer a non-cash credit for surplus generation. This credit can be applied to variable kWh and kW charges but not to fixed charges, taxes, or other fees that are not kWh- or kW-based [46]. Moreover, currently Ontario Net Metering requires the consumer to switch from time-of-use (TOU) rates to tiered rates for the electricity generated as well as that used from the grid. This means that the total bill over a long-term horizon (of several years) may be reduced by the RES generation p_t^{PV} multiplied by the variable rates and charges (see Table 3). If PV generation is greater than consumption for year y , this excess may be carried over to the next year. In grid-disconnected mode, the avoided cost is equal to the total electricity bill.

Table 3: Annual cash flows

Prosumer option	$C_y^{avoided}$
Net metering	$\sum_{T \in y} \left[\sum_{t \in T} p_t^{PV} \cdot (ER_y + VC_y + VCLV_y + RTSR_y^{Network} + \right.$
Off-grid mode	$\left. RTSR_y^{Connection} \right)$ $\sum_{T \in y} EB_m$

4.2 Market RES technologies and their cost trends

For the economic analysis it is important to differentiate two types of costs: *technology* cost (sometimes called the global price index) and *installed* cost [47]. The technology cost is the technology (product) cost at the factory gate, while the installed cost is the cost paid by the by final purchaser and may include transportation costs, expenses for site preparation, and others expenses. In this analysis we consider the installed cost.

4.2.1 PV panels

Figure 9 shows the global price index evolution of the thin film a-Si/u-Si and the installed cost for US markets (as the market closest to Ontario) [47]. Overall, the installed cost of residential solar PV panels has a constant reduction trend with a decline of 47 – 78% between 2007 and 2017 depending on the country [47].

Figure 9: Technology and installed costs evolution of PV panels.

A recent study has revealed that the cost reduction is driven primary by technical performance and economies of scale rather than material costs [48]. Multiple sources support this conclusion and predict that PV costs will continue to drop, e.g., [49] predicts that the levelized cost of electricity generation (which includes not only the installed cost, but also annual operational and maintenance costs) of large solar PV installations will be reduced by 59% between 2015 and 2025.

The Government of Canada reports that the cost of residential PV installation in Canada was 3,197 CAD/kW in 2019 and may decrease within ten years to 2,252 CAD/kW in an optimistic scenario (a cost reduction of approximately 30%) [50]. Furthermore, [50] states that the residential PV installation cost in provinces with experience in solar installations (such as Ontario) is already equal to the installed cost of an optimistic scenario. This is confirmed by [51], which records that in **2019** Ontario had the lowest installed costs of any Canadian province: **2,280 – 2,780 CAD/kW**. If this trend continues, PV installed costs for residential use in Ontario may reduce to **1,596 – 1,946 CAD/kW** in **2030**.

4.2.2 Electric battery

The batteries used for residential storage are mainly lithium-ion batteries similar to those used in electric vehicles. Table 4 summarizes battery installation costs available in the US in 2018.

Table 4: Installed cost of residential electric batteries in the US in 2018 [52, 53]

Model	Total capacity (kWh)	Usable capacity ¹ (kWh or %)	Battery cost (USD)	Inventor cost (if not included) (USD)	Additional installation cost (USD)	Average cost (USD/kWh)
Tesla Powerwall 2.0	14	90% for 10 years, then 70%	6,700	1,100	2,000 – 8,000	800
LG Chem RESU	NA	9.3	6,000 – 7,000	2,000 – 3,000	1,500 – 3,000	1,020
Mercedes Vivint	2.5 – 20	90% for 10 years, then 80%	5,000 – 13,000	–	NA	830
Sonnen Eco	5 – 15	90%	10,000 – 23,000	–	NA	1800
ElectrIQ Power IQ	13.5	11.4	15,000	–	NA	1,400
Sunverge	11.6 – 19.4	9.9 – 16.5	8,000 – 20,000	–	NA	1,010
Pika Energy Harbor Smart Battery	14.4 – 17.1	90%	12,000 – 20,000	–	NA	1,430

¹ Defined as nominal capacity multiplied by maximum depth of discharge.

Detailed predictions of battery cost decrease are done more carefully and usually done under an assumption of new policies that may motivate the decrease [54]. Because of the greater availability of data, most predictions are done for large-scale industrial storage installations [55], however, at the same time, large-scale batteries manufacturers, such as Tesla, provide batteries for residential usage. [56] reports that the global annual deployment of "behind the meter" storage capacity almost tripled from 2017 to 2018, overtaking grid-scale storage deployment.

As for PV, the battery CAPEX may benefit from efficiency and economies of scale. In fact, the learning rate (LR) of lithium-ion batteries cost (19% in 2017 [57]) is comparable with the LR of PV (28.5% in 2018 [58]). Both costs decrease with every doubling of the installed capacity. Storage capacity is expected to increase by at least 50% [59] or at most 200% [60] between 2017 and 2030. Following the most optimistic trend, the battery installation cost may decrease by approximately 35% between 2019 and 2030 [60]. We assumed that these factors may decrease the average battery cost from **1,560 CAD/kWh** in **2019** to **1,016 CAD/kWh** in **2030**.

4.2.3 Hybrid hydrogen storage

Hydrogen-based technologies for non-industrial applications showed a spectacular rise in recent years, led by the transportation sector. The largest hydrogen bus fleet operates in Aberdeen, Scotland [61], and the first hydrogen train entered service in Germany in 2018 [62]. The global stock of fuel cell-powered private vehicle of 11,200 units at the end of 2018 is expected to reach up to 2.5 million units in 2030 [63]. As for batteries, the rapid development of transportation applications has stimulated the use of hydrogen-based technologies in the power sector, including a long-term energy storage. Germany is a leader in the provision of integrated hydrogen solutions for the supply of electric power to small isolated sites or islands. Since 2018, a residential HHS has been commercialized for the equivalent of 87,780 CAD; it provides a total usable capacity (electricity plus thermal) of up to 6 MWh [64].

Experts estimate that increases R&D investment may reduce the hydrogen electrolysis CAPEX by 24%, and economy of scale may have an impact of 17 – 30% by 2030 [43]. The cost of other technologies is also likely to decrease, e.g., the LR for fuel cells could reach 18% between 2015 and 2025 [65]. Given the hydrogen storage electric efficiency reported in Table 2, the technology cost is around **22,000 CAD/MWh** in **2019**. If we assume that this cost will decrease by 30%, the HHS cost may be as low as **15,400 CAD/MWh** in **2030**.

4.3 Investment conditions

The Ontario government has been aiming to limit bill increases since 2017. However, no coherent policy for restructuring grid fees has been proposed: there has been temporary or indirect relief for distribution costs but no specific action on fixed or variable charges. The government promised that the annual bill would increase by no more than inflation rate, which has fluctuated around 2% per year for the last twenty years [66] and is forecasted to continue at the same level in the future [67].

We assume that the proportion of fixed and variable costs in the bill remains constant for different cities and communities. For capital investment, we assume that the market costs discussed in Section 4.2 already account for inflation.

We set the discount rate to 2.5% [68].

4.4 Case study

We calculated PI_c for investment in 2019 and 2030 with a project duration of **15 years** (which corresponds to a minimum lifespan for PV [49] and the major components of storage installations [38, 53]). The Net Metering scheme includes a 15 kW PV array with an installation cost of 34,200 CAD.

As defined in Section 3, the Off-grid scheme includes a 15kW PV array, a 2kWh electric battery and a 2.6MWh HHS. The total installation cost was estimated to be 73,353 CAD.

Figure 10: PI_c of investment in 2019 under projection for Ontario energy pricing policies in a) Net Metering and b) Off-grid prosumer scheme.

Figure 10 shows that it is not yet profitable to become a prosumer under either the Net Metering or Off-grid scheme. For Net Metering the average PI_c is 0.51, and for Off-grid the value is 0.24. While Net Metering is more advantageous than Off-grid scheme, indicators for both schemes remain comparable. A prosumer switching from Net Metering to Off-grid would need to increase the investment threefold but the profitability of this decision would be only decreased by a factor of two. Note that both schemes require additional regular payments. For Net Metering the prosumer pays the remaining bill: the consumption from the grid and the fixed charges; the latter are up to 40% of the typical electricity bill. In addition, the prosumer will remain exposed to potential changes in legislation which may increase these fixed costs. In Off-grid mode the prosumer covers the maintenance and replacement costs.

Figure 11 shows the distribution of the profitability index for 2019 as a function of the fixed monthly cost (CAD) and variable distribution cost (CAD/kWh). The profitability index for disconnection is strongly influenced by the fixed service charges and only weakly by the variable charges. For example, Espanola and Hawkesbury have similar fixed costs of 14.07 and 15.15 CAD/month, respectively. In Espanola the variable distribution rate is five times higher, but the profitability for disconnection is only 10% higher. Atikokan and Hawkesbury have similar variable distribution charges (0.0038 CAD/kWh). In Atikokan the fixed costs are three times higher, and the profitability

for disconnection is 26% higher. In general, critical locations where disconnection is more attractive are characterized by a high proportion of fixed costs in the total electricity bill. Table 5 ranks the results by the profitability of the Off-grid scheme. The locations with the highest profitability of disconnection are in top twenty of the locations with highest fixed costs in Ontario.

Figure 11: PI for different fixed and variable distribution costs (relief as a temporal measure was not considered).

Disconnection may become considerably more attractive in the near future because of decreased installation costs. Figure 12 shows PI_c for investment in 2030 given the installation costs decreases assumed in Section 4.2. Here the same assumption is made that the general trends of Ontario's energy pricing policy are maintained, i.e, the proportion of fixed and variable costs in the electricity bill, and the typical monthly consumption will remain unchanged. The profitability of the Off-grid scheme will almost double between 2019 and 2030 (Table 5).

Table 5: PI_c for geographical locations of interest.

Location ¹	Year 2019		Year 2030
	$Share_{Fix}, \%$	Off-Grid PI_c	Off-Grid PI_c
Low-density and remote areas (Weagamow)	42	0.4	0.71
Algoma	27	0.285	0.51
Medium-density areas (Matheson)	25	0.28	0.5
Sioux Lookout	35	0.28	0.5
Atikokan	35	0.27	0.48
Innisfil	27	0.27	0.477
Toronto	26	0.26	0.47
Parry Sound	28	0.26	0.46
...			
Espanola	13	0.23	0.42
Hawkesbury (base case)	15	0.21	0.38

¹ Some locations are currently subject to relief, which is considered a temporary measure and not taken into account in this analysis.

² Year 2018/2019.

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Figure 12: Forecast PI_c of investment for Ontario.

4.5 Major observations

The Off-grid mode in Ontario is not yet profitable, and it will remain unprofitable under the assumed conditions. However, the balance is delicate. The profitability analysis involves multiple factors and various assumptions. Adjustments to the assumptions may rapidly lead to a disconnection scenario. We make the following observations:

- Several locations in Ontario are close to a disconnection scenario: Sioux Lookout and Atikokan in the North West, Algoma and Parry Sound in the North East and Innisfil near the GTA, as well as medium-density areas such as Matheson and low-density areas such as Weagamow (Table 5). Consumers in these locations are currently subsidized with temporary rate relief to keep their costs at the average provincial level.
- Most of the critical locations are spread along the Ontario USA border. This geographical area is characterized by a decent PV potential of around 1,000 kWh per kW of installed capacity per year. This potential can be further increased by a choice of optimal installation parameters (e.g., facing, tilt) for the PV panels.
- Another advantage of these locations is the proximity of booming solar and storage technology markets in the US. According to a report summarized in [69], the installed capacity of residential storage in the US recorded a nine-fold growth in the first quarter of 2018 in comparison with the same period in 2017. As for the residential PV, after years of 50% annual growth the market slowed in 2017 in several leading states, but it rebounded in 2018 with 7% growth [70]. This may facilitate the adoption of these technologies in Ontario.
- The number of disconnected prosumers is likely to grow. In the last twelve years in Ontario, the fixed charges gained around 40%, while variable rates decreased by 25% [71]. If the pricing policy is unchanged and equipment costs continue to decrease, the average profitability index for Ontario may double by 2030. A minor push may be suffice to bridge the gap toward disconnection. We have assumed the same proportion of fixed and variable charges in future electricity bills. If the proportion of fixed charges continues to increase, disconnection will become increasingly attractive and public awareness of conventional energy system challenges will grow.

5 Conclusions and policy implications

We have continued the exploration of the impact of pricing policy on prosumers (initiated in [72]) and analyzed the feasibility and profitability of prosumer schemes, i.e., Net Metering and Off-grid. We have focused on Ontario (Canada), which is characterized by high electricity consumption and modest RES potential. The analysis revealed that it may be possible to operate in fully self-sufficient mode via a PV array and seasonal HHS even in northern Ontario. The reduction in or elimination of FIT makes possible the implementation of RES technologies only under the Net Metering scheme. If the share of fixed charges (independent of the consumption level and mode) in the electricity bill is maintained and no alternative to Net Metering exists, disconnection may snowball. The process may start at critical locations, as pointed out in Section 4.1. A gradual disconnection of prosumers may influence local pricing policy, resulting in more pressure on still-connected consumers and pushing them to reconsider their choice of staying connected. In the absence of an adequate tariff policy

promoting RES and storage integration and, at the same time, actively involving prosumers in the global energy management process, the disconnection may rapidly propagate to other distribution areas. In Ontario the share of residential customers in the different distribution areas varies between 83% and 99.7% of the total consumers. The areas that are almost exclusively composed of residential customers (in Algoma the figure is 99.7% [26]) may be the most sensitive to prosumer emergence.

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