

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

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G-2019-100

December 2019

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CITATION ORIGINALE / ORIGINAL CITATION

E. Kuznetsova, & M. F. Anjos (2020) Challenges in energy policies for the economic integration of prosumers in electric systems: A critical survey with a focus on Ontario (Canada), *Energy Policy*, 142. <https://doi.org/10.1016/j.enpol.2020.111429>.

La publication de ces rapports de recherche est rendue possible grâce au soutien de HEC Montréal, Polytechnique Montréal, Université McGill, Université du Québec à Montréal, ainsi que du Fonds de recherche du Québec – Nature et technologies.

The publication of these research reports is made possible thanks to the support of HEC Montréal, Polytechnique Montréal, McGill University, Université du Québec à Montréal, as well as the Fonds de recherche du Québec – Nature et technologies.

Dépôt légal – Bibliothèque et Archives nationales du Québec, 2020
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Prosumers and energy pricing policies: When, where and under which conditions will prosumers emerge? A case study for Ontario, Canada

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December 2019
Les Cahiers du GERAD
G–2019–100

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Abstract: The energy landscape is marked by a rapid emergence of electricity prosumers at all levels of the grid. While energy policy seems to be more adaptive to the needs of large-scale prosumers, it may be less concerned to accommodate the needs of small-scale prosumers. While their behaviour may be disruptive for the entire grid when their number reaches a certain threshold, scepticism about the feasibility and profitability of the disconnection mode remains. This paper contributes to the exploration of these issues by analysing the impact of billing policy on the profitability of investment in prosumer schemes, such as Net Metering and Off-grid, for the case of Ontario (Canada). We conclude that fast improvement of commercial storage technologies makes it possible for prosumer to become fully electricity self-sufficient even in locations with low availability of renewable energy sources. While the profitability analysis shows that Off-grid is not profitable in 2019 and will likely remain not profitable in 10 years, it reveals some important findings. The profitability of investment in Net Metering scheme is comparable with the profitability with Off-grid scheme in 2019. For Ontario, this means that a prosumer would need to triple his investment to switch from Net Metering to the grid-disconnected mode, but the profitability of this decision will be divided by two. Critical locations where consumers are more prompt for disconnection are characterised by a high share of fixed costs in the total electricity bill. The pattern of disconnection profitability increase matches with the pattern of fixed costs share increase showing that billing policy has a direct impact on consumers decisions. The profitability of disconnection increases faster with the increase of fixed charges. By comparing the three locations of Atikokan, Hawkesbury and Espanola, it was found that a five-fold increase in variable cost (with same fixed cost) increases the Off-grid profitability by 10% while a three-fold increase in fixed cost (with same variable cost) will increase the Off-grid profitability by 26%. If the shares of variable and fixed costs are maintained the same in the future, the profitability of Off-grid mode may almost double between 2019 and 2030. Moreover, if the cost trends of recent years are maintained, i.e., decrease of variable costs and increase of fixed costs, then the profitability of Off-grid mode will push electricity consumers toward disconnection.

Keywords: Energy system, energy policy, variable and fixed costs, electricity prosumer, net metering, off-grid scheme, profitability

Acknowledgments: This research was supported by an IVADO Postdoctoral Scholarship awarded to the first author.

1 Introduction

Policies such as [feed-in-tariff \(FIT\)](#) that support the transition toward cleaner energy system promote a wide adoption of [renewable energy sources \(RES\)](#) and stimulate a fast decrease of their installation costs. [RES](#) integration is not only relevant for high- and medium-voltage grid. High electricity rates, continuously decreasing technologies cost, and increasing environmental awareness of residential electricity consumers stimulate their transformation into small-scale prosumers [23]. In Canada, the importance of end-use transition for reliable and clean energy system is also increasing. New Energy Vision for Canada includes a 2030 milestone of the majority of Canadians getting the option of becoming prosumers [27] mainly with residential and commercial building solar, district heating and distributed storage. The relevance of this milestone is supported by provincial statistics. In Alberta, the total installed capacity of micro-generators (of less than 5 MW) increased by a factor of 5.8 between 2015 and 2019 reaching 4,283 participants (prosumers) [1]. 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 [6]. British Columbia reports a six-fold increase in Net Metering participants (of less than 100 kW) between 2013 and 2019, in 2019 the prosumers number under this tariff scheme reached approximately 1,850 customers with over 14 MW of total installed capacity [7].

The electricity tariff structures in some jurisdictions not only create a financial incentive for self-consumption, but also may push prosumers toward their physical disconnection from the grid. In Australia, under current tariff and incentive arrangements for standalone systems, up to 10% of grid-connected consumers could choose to go off-grid by 2050 [19], accepting the implications for their energy reliability. High cost of environmental policies led to self-sufficiency around 16% of German companies in 2014 and another 23% of businesses announced their intention to become self-sufficient in the coming years [38]. Grid defection for residential prosumers seems to be not profitable in Germany at least until 2025 according to [53]. However a wide integration of home electric batteries reaching 100,000 installations in 2018 [10] and the emergence of commercial seasonal storage technologies [78] prepare the ground for such scenario. A similar tendency is observed in other countries, such as US, where businesses started to invest in the electricity generation installations providing them with a certain degree of self-sufficiency [88].

Since the change in behaviour (going up to disconnection) of industrial-scale prosumers would present an immediate major threat to energy system including conventional utilities, energy policies for large consumers mitigating these undesirable effects are implemented faster than for small-size residential prosumers. In this view, the industrial-scale prosumers are subject to different exemption and relief [81]. However, the continuous expansion of commercialized [RES](#) and storage options that become more affordable every year means that residential consumers could also choose a pathway of disconnection. If their number reaches a critical threshold it may also considerably impact the operation of energy system by amplifying the already noticeable effect of large consumers [57]. A famous example is a total net load in the shape of the so-called duck curve due to massive penetration of [photovoltaic \(PV\)](#) generation [15].

Different attempts, illustrated through the following bibliography sources, were made to address questions related to prosumer emergence and their energy self-sufficiency. [79] aims to analyse a self-consumption potential under different options for [PV](#)/battery installations sizing and for different European countries (Portugal, Italy, Greece, Romania, France, Denmark and UK). The simulation of residential load, [PV](#) generation and battery dispatch was done under assumption of presence of rewarding policy similar to [FIT](#). The tariff structure and the difference between electricity buying and selling rates for prosumer were pointed out to be a key driver for self-consumption [79]. It was also found that complete self-sufficiency is not realistic without excessively oversizing the [PV](#) installation. Going further, [62] reasonably concluded that the economy of scale has effect on electricity self-sufficiency, i.e., it found that in Europe it may be profitable to make self-sufficient a district of several hundreds household. [9] pursues the exploration of electricity self-sufficiency for low-population density areas in Germany and Czech Republic by relying exclusively on [PV](#) array and electric battery installations.

Based on [standard load profile \(SLP\)](#), detailed spacial maps of [PV](#) and electricity storage requirements are drawn showing that purely electrical self-sufficiency (only for electrical appliances) of single-family house may be possible in these locations under some specific installation sizes. These results were achieved for locations with high [RES](#) capacity factors [98], e.g., [PV](#) capacity factor going beyond 20%, and modest typical electricity consumption per capita [42].

This paper pursues the exploration of self-sufficiency feasibility and profitability by considering the more extreme case of Ontario (Canada) characterized by high typical electricity consumption and modest potential for [PV](#). The paper contributions are as follows:

- By pursuing the previous exploration done for European countries, we explore [PV](#) and electric battery potential for Ontario. We attach particular importance to improving model accuracy, i.e., household load is represented by taking into account its thermal sensitivity and [PV](#) power output is simulated by taking into account a variability of solar irradiation and ambient temperature. The analysis of household self-sufficiency with the unbounded increase of installation capacities leads to the conclusion that above some threshold the increase of [PV](#) capacity has a zero effect on household self-sufficiency. Instead, full autonomy can be achieved by focusing on storage solutions. Thus, we identify a prominent track for further research on the concept of complete self-sufficiency.
- By relying on recent advancements, we address the question “*Is it possible to operate in disconnected mode?*” for Ontario and introduce hydrogen-based seasonal storage in the prosumer power dispatch model. It was found that 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 [PV](#) power lost usually occurred during high solar irradiation periods. Until now this power surplus was injected in the grid [79] or curtailed [9].
- We analyse the history of Ontario pricing policy and potential changes in legislation and account for various costs (i.e., energy and power, transmission and distribution costs) to identify the profitability of investment in 100% self-sufficient installation. This analysis is done under pricing policy projections and technologies costs trends.
- By addressing the question “*When and where it is profitable to become a prosumer?*” we identify critical geographical locations in Ontario ripe for disconnection. A specific relationship between tariff structure, in particular level of variable and fixed costs, is pointed out narrowing a basis for modification of energy policies to involve small-scale prosumers in global energy management process.

2 Ontario pricing policy for households

Pricing policy defines the total electricity bill that a consumer pays each month. In Ontario, a monthly electricity bill EB_m for the electricity consumption $\sum_{t \in T} c_t$ of consumer c during month m has the following structure:

$$EB_m = Tax_y \cdot \left[\underbrace{\sum_{t \in T} c_t \cdot ER_y}_{\text{energy and power cost}} + \underbrace{\sum_{t \in T} c_t \cdot (RTSR_y^{Network} + RTSR_y^{Connection})}_{\text{transmission cost}} + \underbrace{MSC_y + \sum_{t \in T} c_t \cdot (VC_y + VCLV_y)}_{\text{distribution cost}} \right] \quad (1)$$

The bill is composed of energy and power, transmission and distribution costs. These amounts depend on the yearly charges and rates adopted by an electricity retailer (i.e., distribution company).

2.1 Energy and power cost

Energy and power cost is based on the electricity rate ER_y selected by consumer, i.e., [time-of-Use \(TOU\)](#) or tiered rates [72]. These rates are based on market electricity price ([hourly Ontario electricity price \(HOEP\)](#)) and [global adjustment \(GA\)](#) analysed in [45].

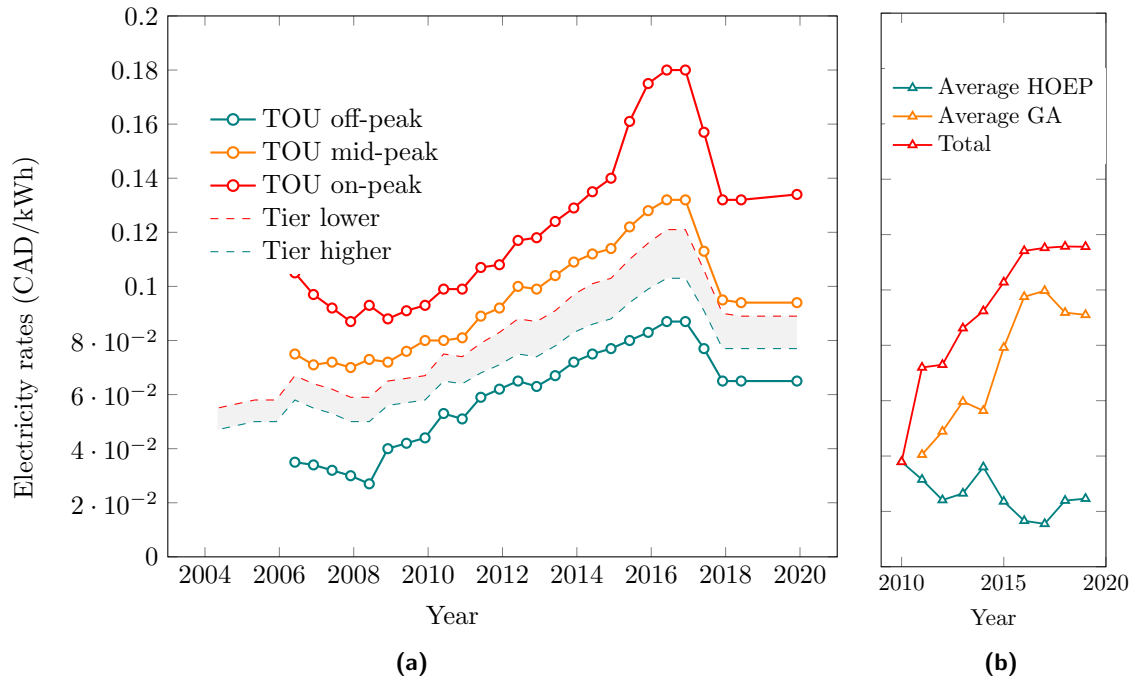


Figure 1: Historical electricity rates in Ontario: a) [TOU](#) and [Tier](#) rates [72] and b) [HOEP](#) and [GA](#) [44].

2.2 Grid fees

Grid fees are subject to the different tariff schemes adopted by over 70 different distribution companies responsible for distributing power from transmission lines to final consumers. These distribution companies usually provide power in a specific service area around a city or a community and its neighbourhood. In addition, a large power distribution provider with over 1.1 million customers covers the rest of the province and supplies electricity to low-density and remote areas. Figure 2 reports the cities, communities and districts associated with different distribution companies (and different tariff schemes). Weagamow and Matheson were selected as examples of remote and medium density areas, respectively.

2.2.1 Transmission cost

Transmission cost is the sum of two rates - network service rate $RTSR_y^{Network}$, and line and transformation connection service rate $RTSR_y^{Connection}$. On average, network service rate and connection service rate increased by 24% and 4.2%, respectively, for the last 12 years [73]. In 2018, network service rate and connection service rate were between 0.002 and 0.008 CAD/kWh depending on the consumer location.

2.2.2 Distribution cost

Distribution fees are composed of fixed service charge MSC_y (Figure 3a) and distribution volumetric rate VC_y (Figure 3b). While the transmission rates are almost the same for all residential consumers in Ontario, the delivery rates vary by different distribution companies. In addition, each company

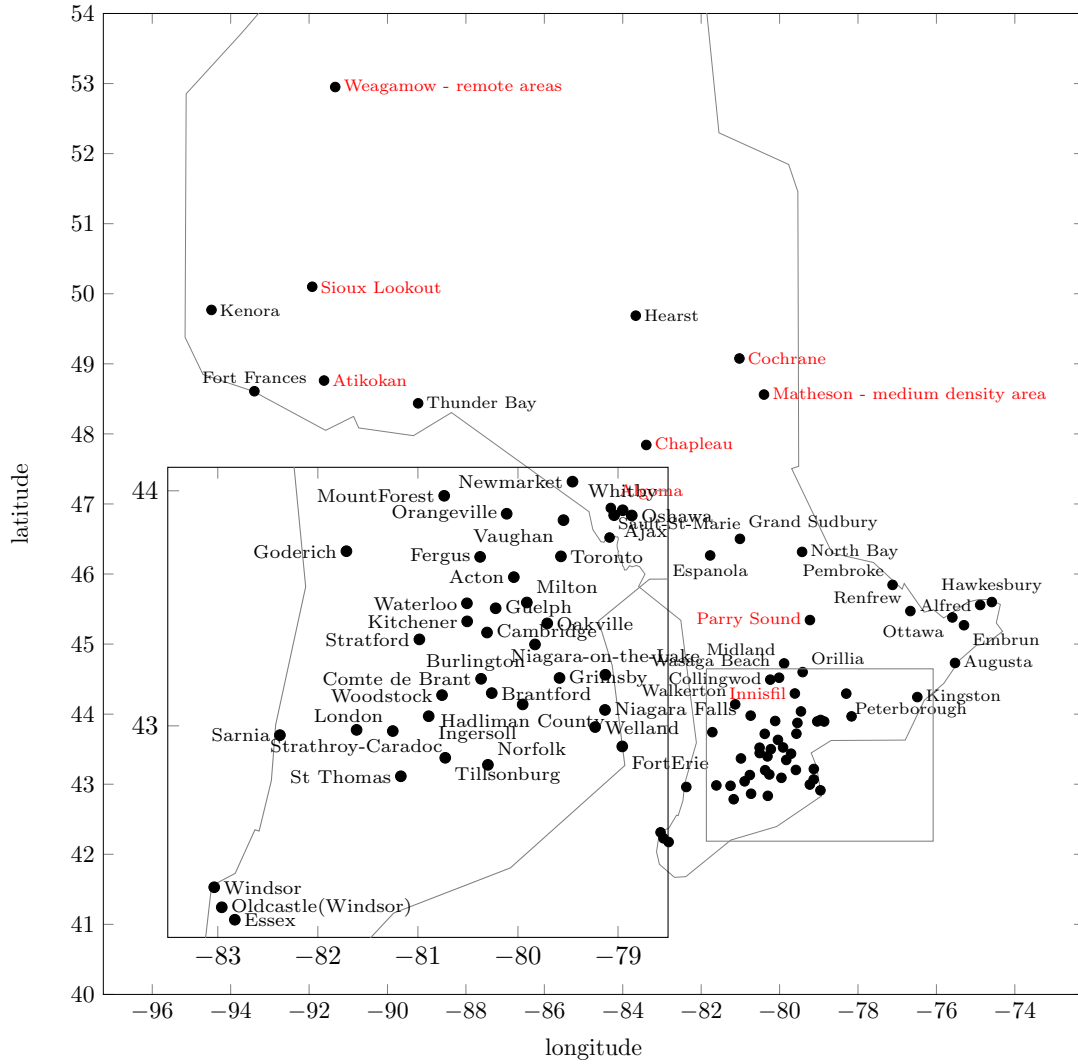


Figure 2: Cities, communities and districts associated with different electricity distribution areas for 2018.

can provide different delivery rates for locations by consumers densities (urban and suburban) and by periods of consumption (year-round and seasonal). This densities-related tariffs may be illustrated through the following households classification [39]:

- A year-round household in an urban high density zone with 3,000 or more consumers and at least 60 consumers for every km of power line used to supply the zone;
- A year-round household in a medium-density zone with 100 or more consumers and at least 15 consumers for every km of power line used to supply the zone;
- A year-round household in a low-density zone not covered by urban or medium-density zones.

Note that this classification can vary depending on the distribution company and from year to year, depending on the review of geographical location criteria.

Figure 3 presents residential average year-round rates, and several rates for medium- and low-density areas for 72 cities and communities [73]. Note that year-to-year fluctuations of fixed charges and variable rates may be due to:

- reorganization of distribution companies tariff schemes (e.g., additions of new more expensive seasonal rates or medium/low densities tariff zones and, as a consequence, reduction of residential year-round rates);
- mergers, reorganizations or acquisitions of distribution companies leading to changes in tariffs scheme;
- application of special governmental measures to the basic delivery rates in order to reduce the consumer electricity bill (their effects are noticeable in recent years, when for some tariff regions the increase in delivery rates decelerated).

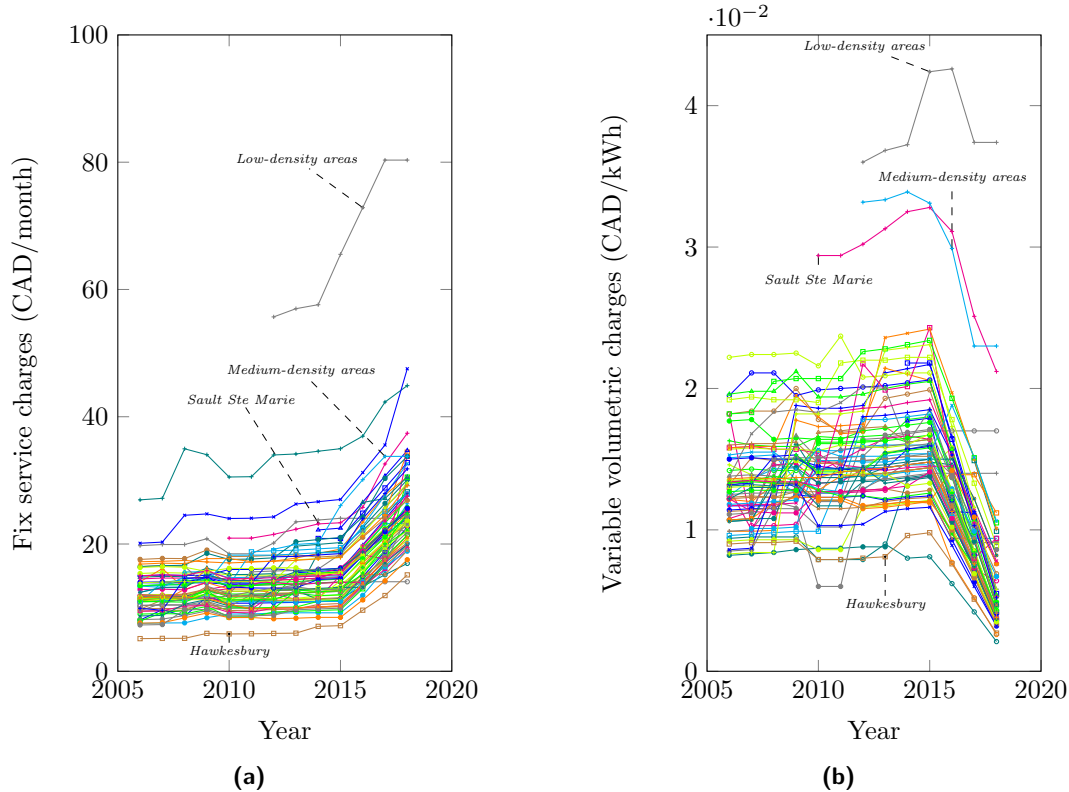


Figure 3: Historical distribution grid fees for residential consumers in 72 cities and communities of Ontario the period 2006–2018 [73] for a) monthly fixed service charges and b) variable volumetric charges.

Starting from 2015 an important change was observed in the delivery rate tariff scheme: fixed service charges start to increase while variable charges decrease. This tendency becomes pronounced after 2015. On average, during last twelve years fixed service charge gained around 40%, while variable charges decreases by 25%. Note that in 2010 an additional variable rate (low voltage rate $VCLV_y$) was added to the pricing scheme in locations characterized by low or modest variable charges. Low voltage rates vary in the range from $4 \cdot 10^{-5}$ to $5.5 \cdot 10^{-3}$ for different locations and their profiles remain almost constant between 2010 and 2018.

2.3 Distributed renewable energy sources - options for prosumer

According to the [Ontario Energy Board \(OEB\)](#), the final [FIT](#) application period was held in 2016 after which [Independent Electricity System Operator \(IESO\)](#) ceased accepting applications [46]. The remaining Net metering scheme introduced as an alternative to [FIT](#) allows to send the difference between [RES](#) generated energy and locally consumed energy back to the grid in exchange for credits that can be carried over to future bills for up to 12 months [34]. Typically 1 kWh of [PV](#) generation injected in the grid is granted a credit of 1 kWh of utility generated electricity in future bills. To

participate in this scheme residential consumers are switched from **TOU** rates to tiered rates for both kWhs generated and used from the grid (see Figure 1) [74]. Another possible pathway not framed yet with policy context, but is explored in this paper, is the Off-grid scheme or permanent disconnection from the grid.

2.4 Ad hoc changes in legislation and paper assumptions

The continuously increasing electricity rates and consequent impossibility for growing number of consumers to pay their bills make energy billing legislation part of Ontario government agenda. The major updates introduced through the Fair Hydro Plan starting from July 2017 [70] are related to:

- *Energy and power cost.* Fair Hydro Plan focuses mainly on the reduction of electricity bill by 25% on average for all residential consumers: from July 2017 to April 2018 the government subsidized the “artificial” reduction of electricity rates while the **OEB** reset electricity rates “in a way that holds increases to the rate of inflation” (the rate drop, stagnation and increase can be seen in Figure 1a compared with actual costs in Figure 1b).
- *Distribution cost.* **OEB** also aims at decelerating the increase of distribution cost under Fair Hydro Plan while accepting that distribution companies need to increase their delivery rates to maintain the existing equipment and invest in new one [70]. A credits measure depending on household location and income is introduced (participant areas are marked in red on Figure 2). The eligibility and credit amounts vary depending on the distribution companies operated in this areas: while some companies seem to provide credits only to eligible low-income customers [32] other applies relief for all their non urban consumers [40]. For the examples of Matheson and Weagamow, there is a cap of 36.86 CAD on the fixed service charge and distribution volume charge, and additional monthly credit of 60.50 CAD for rural or remote areas [40]. **OEB** set the maximum monthly base distribution charge at 36.43 CAD for the unknown duration [70]. Figure 3 does not take into account this relief.
- *Indirect relief.* Ontario government introduces also a tax credits program for seniors, low-income families and rebates for indigenous consumers [32]. The primary goal of these subsidise measures was to support the most vulnerable low-income consumers (for example, to participate in the low-income credit program household of 1 person must earn less than 28 kCAD and household of 5 person - less than 52 kCAD [68]).
- *Bill restructure.* Attempts to restructure the electricity bill are also undertaken. For example, the costs of programs funding electricity supply to rural and remote communities and providing monthly credits for low-income customers were removed from the electricity bill and funded instead through taxes [70].

Fair Hydro Plan was funded through a refinancing of a portion of **GA** cost, which in its turn will be recovered through a new adjustment on electricity bill called a Clean Energy Adjustment (to appear in 2020) [70]. It costs approximatively 4 billion CAD in borrowing costs for people in Ontario and in 2019 the new government aims to improve relief rate structure and billing transparency [33]. One of new legislative intention is to hold the average bill increase to the rate of inflation starting from May 1, 2019 [33].

The assumptions for this paper are the following:

- The paper does not provide yet advices for policies changes, i.e., **GA**, **FIT** or electricity delivery cost, to reduce pressure on the consumers (especially from the low-density regions) and to address utilities budget requirements to reward long-term contracts, guarantee infrastructure maintenance, new utilities construction etc. The paper assumes that Ontario government and **OEB** will pursue their energy policy strategy which could delay but not avoid a massive emergence of energy prosumers.

- Nevertheless it was assumed that in line with other countries Ontario exited FIT program and Net Metering is the only rewarding scheme available for prosumers.
- Legal and technological issues behind novel way of system operation are not considered. This means that it was assumed that there are no legal limitations for prosumers creation (e.g., implementation of RES, storage and smart metering technologies) and their interactions (i.e., collaboration or competition) with other system stakeholders.

3 From electricity consumer to prosumer

3.1 Household consumption and load

3.1.1 Typical household electricity consumption

The monthly electricity consumption of a typical residential customer is used by the independent regulator to illustrate the impact of different policies on a consumer electricity bill. This typical monthly consumption is defined by using data for several years previous to a revision year which includes the annual amount of consumption reported by residential users and the total number of customers each year [69]. Following this information, a standard level of electricity consumption for all Ontario was set to 1,000 kWh/month before 2009, to 800 kWh/month between 2009 and 2016 and to 750 kWh/month starting from 2016 [69]. To compare this consumption level, during this last revision a typical consumer from the Greater Toronto Area (GTA), where nearly half of all Ontario's consumers is located, uses 699 kWh/month while a typical consumer for all Ontario excluding low-density and remote regions uses 721 kWh/month [69].

Household energy consumption in Ontario by end-use and by source shows that space and water heating are major contributors for household energy consumption. However, these uses are almost excluded from typical electricity use - only 9.7% and 13% of heating water and space needs, respectively, are satisfied by electricity, with the rest using other sources (mainly natural gas). Therefore, the typical electricity consumption of 750 kWh is mainly composed of consumption from electrical appliances, lighting and space cooling, with a small part used for heating.

We therefore assume that a typical detached or semi-detached household relies on non-electrical energy sources for water and space heating. Space cooling is relevant mainly for southern locations, including GTA. For example, [55] monitored 25 homes including lighting, appliances and air conditioning systems in Milton between 2011 and 2013. The study shows an average monthly usage between 600 and 1200 kWh/month for an average home size of 225 m² [55]. For locations with colder climate and with less need of space cooling, the electrical consumption decreases considerably. For example, [28] reports different studies based on 23 Ottawa households using non-electric energy sources for heating between 2009 and 2012. The maximum annual load peak (happening in the summer due to air conditioning) does not exceed 1.1 kW for the entire household, which makes a typical consumption of less than 486 kWh/month.

3.1.2 Electricity load profile and thermal sensitivity

Household electricity load profile depends on the number and type of electrical appliances and their usage. Taking into account the difficulty of collecting large amounts of reliable information and building complex models, the top-down approach, based on chronological and detailed data collection of overall electricity demand, is used [35]. Note that the load model provides an average smooth household load profile, which will differ from the real-time measurements of the single household.

$$c_t^{el} = c^{peak} \cdot r_w^{peak} \cdot r_d^{peak} \cdot r_h^{peak}, \quad \forall c, t \quad (2)$$

The load sensitivity is translated by the increase of load with the change of temperature from the typical neutral temperature around 19 °C. While Europe shows a strong demand-temperature rela-

tionship for winter and very minor load increase in summer, North America demonstrates a strongest summer correlation with active use of cooling installations. For example, France records approximately 2,400 MW/°C load increase in winter. This represented over 40% of load increase in 2016 winter due to electric heating [83]. Contribution of air conditioning to peak load in summer was less than 1% [83]. In comparison, New York transmission zone recorded up to 10.5 MW/°C of load increase for winter and up to 63 MW/°C of load increase for summer [90]. This may correspond to more than 40% of load increase in summer due to temperature-dependent appliances [90]. Similar tendency for summer-temperature correlation is present in south of Canada, in Ontario the winter peaks becomes dominant over summer peaks for locations above around 46° of latitude (Figure 4) [71]. Note that thermal sensitivity could be observed in the households with non-electric heating and in absence of cooling system due to the power draws from the heating system auxiliaries such as furnace fans and boiler pumps [28].

This study considers a household without a cooling system (typically situated in northern Ontario) with the maximum hourly peak demand c^{peak} over a year of **1.7 kW** which corresponds to 750 kWh of average monthly electricity consumption (Figure 4).

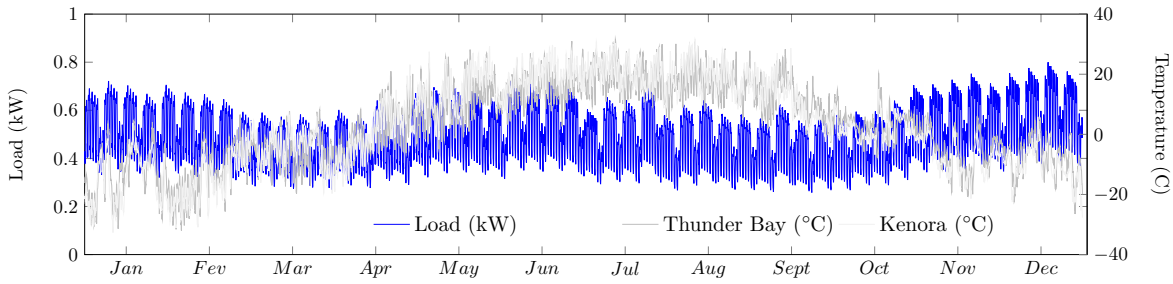


Figure 4: Load profile of typical households and examples of seasonal temperatures for several locations in the north of Ontario (year 2018).

3.2 Power dispatch model

Better performance and resilience (especially crucial in off-grid mode) are achieved with a combination of various RES in situ selected according to their potential for a specific geographic location as well as households constraints (e.g., space availability). In this view, a potential prosumer must evaluate different RES technologies available. The goal of this paper is not to propose an optimal RES generation portfolio for a given prosumer such as done in [13] for partial self-sufficiency, but to show the near-future feasibility of Off-grid mode. For simplicity and after the review of different RES options including solar and wind it was assumed that the electrical load is supplied with power generated by PV, currently the most accessible RES for residential use.

In grid-connected mode, the prosumer tends to minimize its electricity bill (Equation 1) by maximizing the avoided cost through the optimal management of its equipment. For a grid-disconnected prosumer, the objective of bill minimization is replaced by the maximization of its self-sufficiency which is expressed as the minimization of electricity shortage b_t and PV array generation surplus w_t^{PV} under forecasted hourly operational conditions.

$$\text{Minimize } \sum_{t \in T} (b_t + w_t^{PV}) \quad (3)$$

$$p_t^{PV} - c_t^{el} \geq w_t^{PV} - b_t - R_t^{disc} + R_t^{ch} \quad (4)$$

$$c_t^{el} \leq l_t^{PV} + R_t^{disc} + b_t, \quad \forall t \quad (5)$$

$$p_t^{PV} \geq R_t^{ch} + l_t^{PV} + w_t^{PV}, \quad \forall t \quad (6)$$

$$l_t^{PV} \geq 0, b_t \geq 0, w_t^{PV} \geq 0, \quad \forall t \quad (7)$$

$$R_t \leq R_{t-1} - R_t^{disc} + R_t^{ch}, \quad \forall t \quad (8)$$

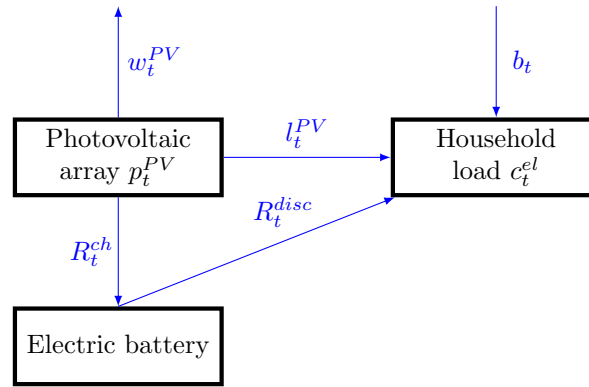
$$R_t = R_{t=0}, R^{Min} \leq R_t \leq R^{Max} \quad \forall t \quad (9)$$

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

$$\delta_t^{disc} \cdot R^{disc,Min} \leq R_t^{disc} \leq \delta_t^{disc} \cdot R^{disc,Max} \quad \forall t \quad (11)$$

$$0 \leq \delta_t^{ch} \leq 1, 0 \leq \delta_t^{disc} \leq 1, \quad \forall t \quad (12)$$

$$\delta_t^{ch} + \delta_t^{disc} \leq 1, \quad \forall t \quad (13)$$



Short-term electricity storage

Figure 5: Abstract scheme of prosumers power flows to dispatch.

The objective of the prosumer here is to maximize its self-sufficiency or, in other words, to minimize powers b_t and w_t^{PV} for a given planning horizon T (3). Prosumer equipment includes PV array coupled with the battery storage that power balance is specified by (4-5). The electrical load c_t^{el} is covered by the PV power output l_t^{PV} and power R_t^{disc} discharged from the battery. The remaining load b_t may be covered from the grid (in case if the prosumer is connected), or non-supplied (in case if the prosumer is in off-grid mode) (5). The power from PV R_t^{ch} is directed into the battery and the excess power w_t^{PV} that could be not used to cover prosumer load nor to be stored due to the battery storage limit (6). The dynamics of usable state of charge (SOC) of the battery is depicted in (8). Equation (9) provides battery initial conditions and specified its charging and discharging limits. Constraints (10) and (11) provide limits for power which can be charged and discharged to/from the battery depending on the battery type (e.g., fast speed charge). Constraints (12) and (13) stipulate that the battery cannot be charged and discharged simultaneously. The non-linearity of (10) and (11) was handled using the Big M method. Efficiency of battery and inverter were not taken into account.

3.3 Prosumer key performance indicators

Several key performance indicators (KPI) are defined in [79] to size the equipment and evaluate the performance of the power dispatch algorithm. The relative PV and battery sizes KPI [79] are used to size the power installations:

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

$$R^{bat} = \frac{R^{Max}}{\sum_{t \in T} c_t^{el}}, \left[\frac{kWh}{MWh} \right] \quad (15)$$

The **self-sufficiency rate (SSR)** and **self-consumption rate (SCR)** represent the ratio between the self-consumed energy and the total yearly energy demand, and the self-consumed energy and the total yearly **PV** production, respectively:

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

$$SCR_T = \frac{\sum_{t \in T} (l_t^{PV} + R_t^{disc})}{\sum_{t \in T} p_t^{PV}} \quad (17)$$

3.4 PV potential

3.4.1 PV capacity factor

The annual mean daily **global horizontal irradiation (GHI)**¹ is very similar in different locations in Ontario with slight larger potential in the south. It varies from 3.2 kWh/m² for northern remote areas to 3.79 kWh/m² for southern locations near Lake St. Claire [29].

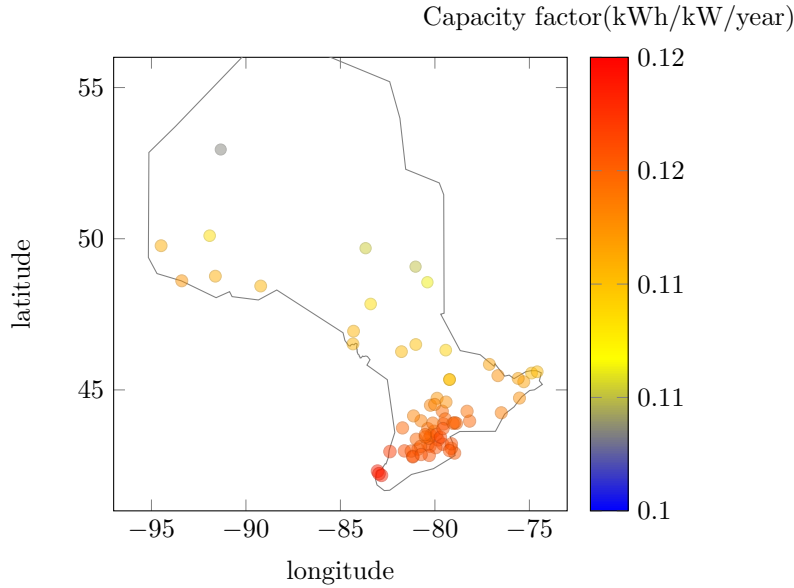


Figure 6: Capacity factor of 1 kW installation (kWh/kW/year).

The mean monthly energy output p_m^{PV} of the **PV** module is defined as:

$$p_m^{PV} = \eta \cdot GHI_m \cdot PR \quad (18)$$

The **PV capacity factor (CF)** for different locations is within the interval 0.103–0.118 kWh/kW/year. These values are in accordance with various **PV** potential maps reported by different research organizations and consulting companies such as [22] (Figure 6).

3.4.2 PV power output profile

The available **GHI** data for different locations for the period 2002 - 2008 was retrieved from [66]. The data was generated by using a semi-empirical satellite model converting a cloud index retrieved from

¹**GHI** is the total amount of radiation received from above by a horizontal surface which includes both Direct Normal Irradiation (DNI) and Diffuse Horizontal Irradiation (DHI). It is used to perform Measure Correlated Predict evaluations to estimate **PV** installation potential [3].

the satellite visible channel into a clearness index that is then applied to scale output from the clear sky model to derive a **GHI** [77]. To verify this data coherence the output from SUNY model [77] is compared with a recent widely used reference clear sky model McCLEAR [58]. The example of **GHI** comparison for Atikokan and Innisfil locations is shown on Figure 7. As it can be observed, the resulting **GHI** of SUNY model remains less than or equal the **GHI** of McCLEAR clear sky **GHI**.

The output from the **PV** array is calculated using the following mathematical model accounting for technical characteristics of panels, **GHI** and loss of module efficiency with the increase of ambient temperature [5, 61]. Hourly values of temperature in different locations in Ontario are available from [95]. We use **PV** module technical characteristics in Table 1.

$$T_t^m = T_t^a + GHI_t \cdot \left(\frac{T^{NOT} - T^{aofNOT}}{\phi} \right) \quad (19)$$

$$I_t = GHI_t \cdot \left(I^{sc} + K^I \cdot (T_t^m - T^{STC}) \right) \quad (20)$$

$$V_t = V^{oc} - K^V \cdot T_t^m \quad (21)$$

$$FF = \frac{V^{MPP} \cdot I^{MPP}}{V^{oc} \cdot I^{sc}} \quad (22)$$

$$p_t^{PV} = N \cdot FF \cdot V_t \cdot I_t \quad (23)$$

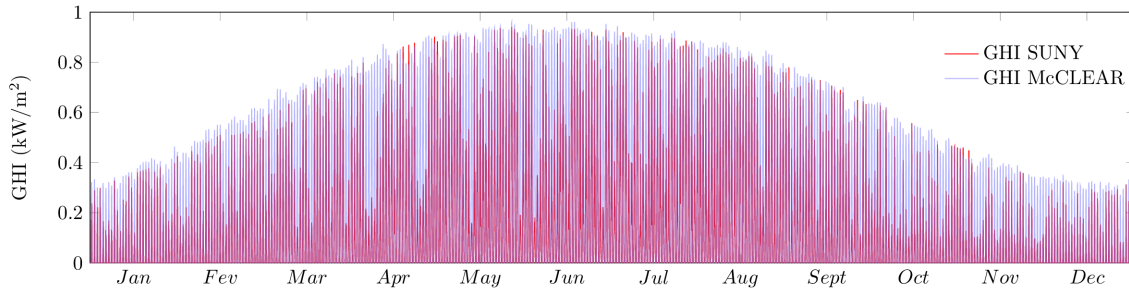
Equation (19) calculates **PV** module temperature T_t^m which helps to identify module current (20) and voltage (21). Equation (22) provides the fill factor coefficient FF based on module technical specification. Finally, (23) estimates the power output of the **PV** array.

Table 1: Technical specification of **PV module [91].**

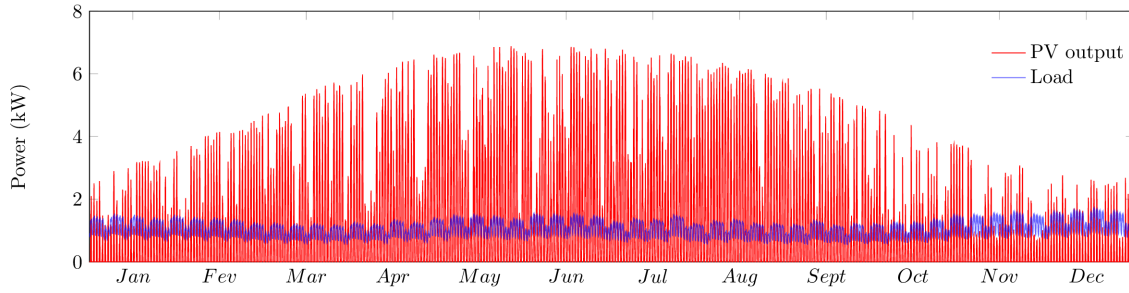
Watt peak, kW	0.3
Performance ratio	0.75
Module area, m ²	1.635
Yield, %	18.35
Open circuit voltage, V	44.71
Short circuit current, A	8.947
Voltage at maximum power, V	37.23
Current at maximum power, A	8.06
Voltage temperature coefficient, V/C	-0.152014
Current temperature coefficient, A/C	-0.0044735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

3.5 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. Figure 7b gives the example of typical household load profile and **PV** power output of 9 kW array for a household in Atikokan, a northern location with modest solar insolation selected for illustration. In this case the yearly household consumption is around 9,000 kW while yearly **PV** generation is 9,970 kW. In practice, the solar insolation hourly and seasonal variations. In the best case scenario (typically in summer), solar insolation is available only 30% of the day (see Figure 9a for the example of summer **PV** power output). This means that the electricity storage is needed to shift the excess of solar power from hours of high solar insolation to hours when the sun is down but the household load is present. Electric battery already widely available on the market (see Section 5.2) may be able to provide this shift. Figure 9a provides the example of household power dispatch in summer showing that a 10 kWh battery of rapid charge (less than 6h) may perfectly accomplish this task. At the same time, a considerable amount of electricity which can be used neither to cover household consumption nor to store in the battery is lost due the limited battery capacity (Figure 8). For illustration, the total amount of energy lost per year simulated for a typical household in Atikokan reaches 3,340 kWh or 34% of the total **PV** generation.



(a) GHI.



(b) Household load and PV power output.

Figure 7: PV installation potential in Atikokan: a) Solar insolation modelled by SUNY with cloud index [77] and insolation at perfect conditions calculated with McCLEAR [58] (year 2008), and b) typical household load profile and PV output for 9kW array.

The most challenging issue is related to the seasonality of solar insolation because solar availability considerably decreases during Fall and Winter. During these periods, PV power output is lower and available only for few hours during the day (see Figure 9b for the example of winter PV power output). The available PV generation barely meets 25% of daily household demand, the battery is almost not used, and no PV energy is lost. During these periods, the electricity shortage is particularly important (Figure 8). For illustration, the total amount of unmet energy demand per year simulated for a typical household in Atikokan reaches 3,280 kWh or 36.6% of total yearly demand.

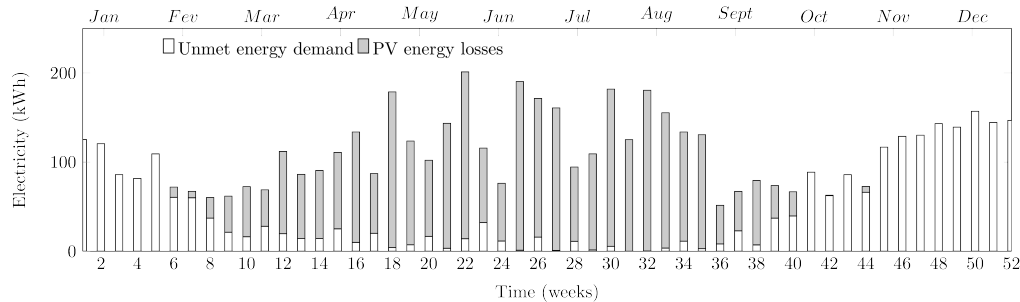


Figure 8: PV energy losses and unmet energy demand per week for typical household in Atikokan with 9 kW PV array and 10 kWh battery.

We reproduced the exercise done in [79] showing the influence of the battery R^{bat} and PV array R^{PV} sizes on SSR and complemented with the impact of installations on SCR (Figure 10a,b). The

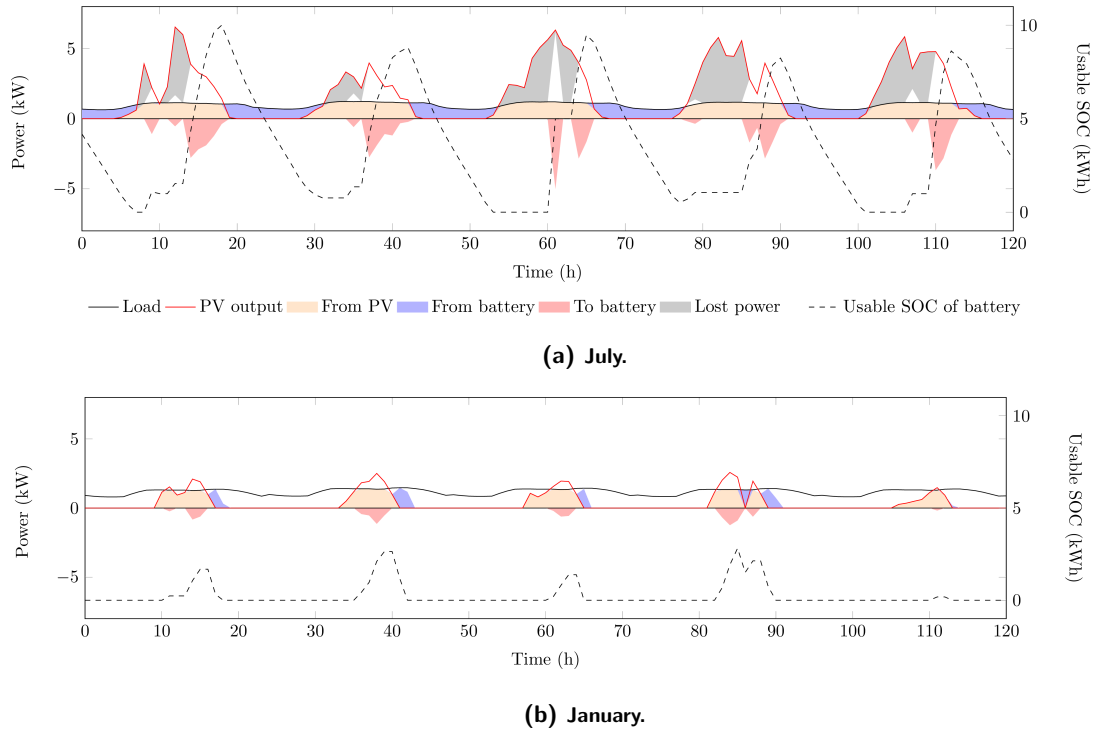


Figure 9: Example of power dispatch for household of typical consumption, **PV** array of 9 kW capacity and electric battery of 10 kWh capacity (allowing fast charge/discharge of 2h), situated in Atikokan: a) 5 days in July and b) 5 days in January.

increase of R^{bat} and R^{PV} stimulates the increase of electricity self-sufficiency. However, this increase has diminishing returns on the SSR , i.e., with every additional kW for **PV** and kWh for battery the SSR gain decreases. At the same time, the increase of installed capacity increases the **PV** energy losses (Figure 10a).

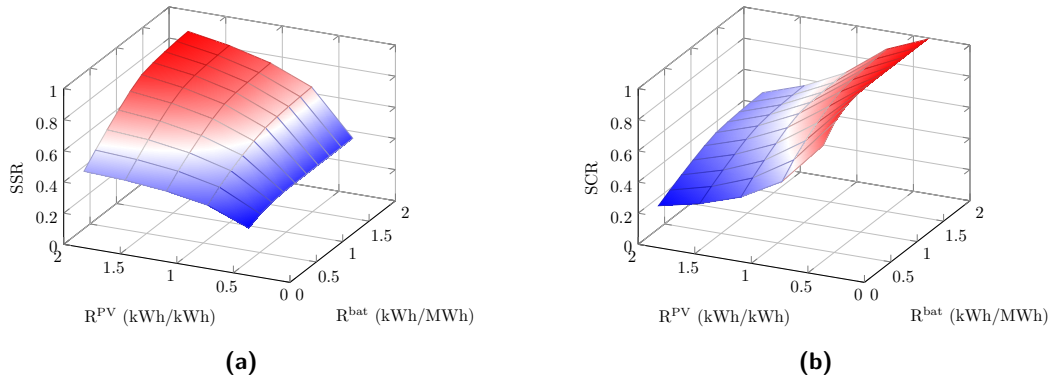


Figure 10: SSR and SCR depending on relative battery and **PV** sizes for a household in Atikokan.

In our analysis, we went further in providing more details about installation capacities for full household self-sufficiency. Figure 11 provides two extreme cases of the unbounded increase of battery and **PV** array capacities. Figure 11a shows that a sufficient increase of storage capacity allows sufficient shifting of electricity from months of **PV** surplus to months of previously unmet demand (Figure 8) to achieve complete electricity self-sufficiency. For this purpose, a storage solution of more than 2 MWh is required for a household in Atikokan of typical consumption of 750 kWh/month. At the same time, only increasing **PV** generation will not lead to complete self-sufficiency in northern locations, where

solar insolation can be extremely low or nil for several days in a row. The SSR stagnates at 0.9 showing that seasonal storage is essential to ensure electricity self-sufficiency.

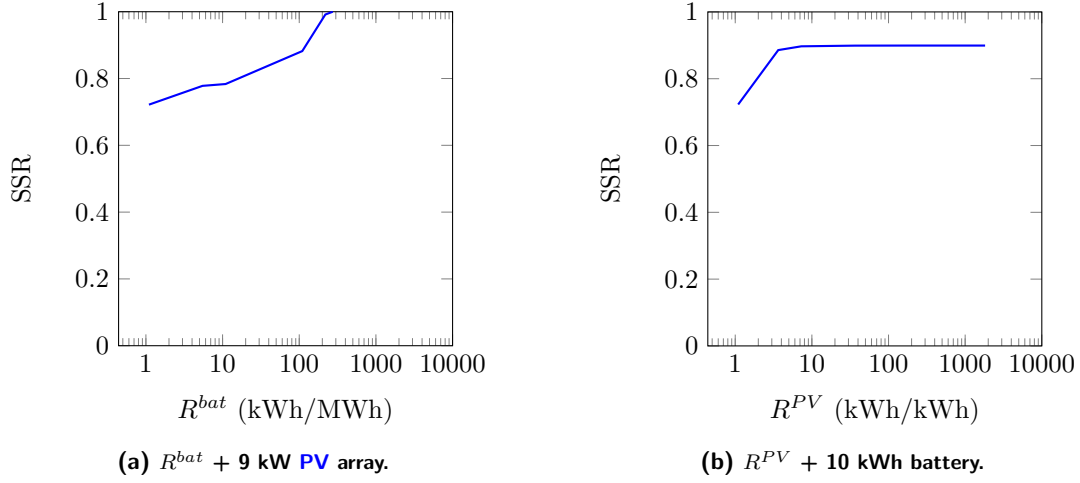


Figure 11: Complete self-sufficiency for Atikokan household for two extreme cases: a) increase of battery capacity with constant PV capacity and b) increase of PV array capacity with constant battery capacity.

4 Is it possible to operate in disconnected mode?

4.1 Seasonal storage: Closing the loop of PV power losses

We have seen that the two key ingredients to operate off-grid are 1) the selection of an adequate seasonal energy storage technology, and 2) the sufficient sizing of household on-site equipment in relation to household demand and environmental conditions. Given the scale of storage necessary, a potential technology to consider is hydrogen storage with power-to-gas and gas-to-power solutions (Figure 12). In the following text we refer to this technology as hybrid hydrogen storage.

Hybrid hydrogen storage are no longer investigated purely for large-scale and industrial applications, but integrated in studies for microgrids and smart home designs [89]. Ontario has underground storage potential for hydrogen that could be coupled with renewable and conventional power sources to balance seasonal energy demands [59]. The Ontario Smart Home Roadmap considers hydrogen technologies to be integrated by 2030 [43].

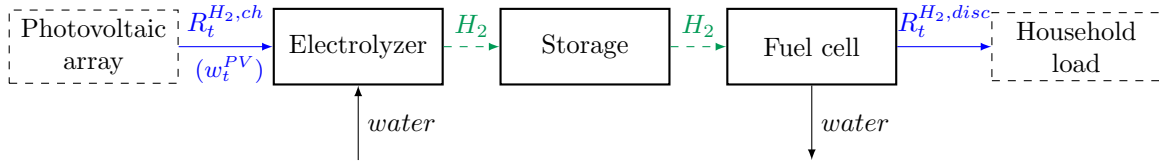


Figure 12: Abstract scheme of hybrid hydrogen storage: power-to-gas, hydrogen storage and gas-to-power.

The major challenges of hybrid hydrogen storage illustrated in Figure 12 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 3.5) and compatible with the context of residential households with minimum maintenance and space requirement. For example, to make 2 MWh available for use in Fall and Winter and assuming a fuel cell efficiency of 60% (Table 2), a household must store around 85 kg of hydrogen. At 25°C and atmospheric pressure this hydrogen storage will occupy around 1,040 m³ posing an impassable barrier of storage size. The established technologies for hydrogen storage allow reducing the storage size rising new challenges related to equipment efficiency and security for

non-industrial applications. To decrease the storage space by 99% it will be sufficient to compress hydrogen up to at least 100 bar at 25°C [12]. However, this requires a compression module associated using reciprocating and rotating machinery associated sealing problems, therefore their small-scale residential application were rare and careful [94].

As a consequence, operations research studies on residential energy management mainly consider hydrogen as a RES using tanks with already compressed gas (e.g., hydrogen vehicle). These solutions ensure only a short- and middle-term storage. For example, a hydrogen fuel cell electric vehicle was used as short-term storage (between vehicle trips) and as the power source, together with PV array, it allows to reach around 70% of energy self-sufficiency [82]. It can provide a constant power output (the excess of power is drawn back to the grid) or operate in load following mode. Under good solar and wind potential, complete off-grid operation was achieved by using a combination of PV array, wind turbine, electric battery, fuel cell, and possible load shifting [4]. [60] and [52] introduce in their hybrid hydrogen storage a compressor module, but use it as a support for stand-alone RES to power residential districts situated at some reasonable distance. It was showed a possibility for complete self-sufficiency for a small residential area of typical daily load of 15 kW with PV panels and hybrid hydrogen storage, and 8 days autonomy in the absence of solar insolation. A study [8] is a rare attempt to integrate hybrid hydrogen storage as a proper seasonal storage considers the self-sufficient operation of an independent living and working capsule with a 200 kWh (5.3 kg of hydrogen) storage used to contribute to its complete self-sufficiency. The hydrogen storage and fuel cell complemented the PV array and electric battery and allowed to reduce the PV power lost, which remained however almost half of the annual PV generation.

During last several years novel hydrogen storage and compression technologies are becoming commercially available for household real-life applications [94]. Among them is a chemical storage based on low temperature metal hybrids (when metal powder absorb hydrogen and release it with a moderate temperature increase) developed for a household demonstrator of 14 days of fully autonomy alpine chalet [80]. The established technologies also improve. A seasonal storage with compressed hydrogen (300 bar) and total usable capacity of up to 6,000 kWh (which could be further scaled up) is already on the market [37, 24]. Using this technology a complete self-sufficient house appeared in Bavaria in 2019 [78].

This paper considers this latter technology to explore potential electricity self-sufficiency for prosumers in Ontario. To include hydrogen technology in the analysis the model (3)–(13) was extended with an abstract battery model (by analogy with the electric battery) describing hydrogen-based technology operation (illustrated on Figure 12) in the context of residential prosumer. The following model reasons in terms of energy content which is agnostic to technology evolution.

$$R_t^{H_2} \leq R_{t-1}^{H_2} - \frac{R_t^{H_2, disc}}{\eta_{FC}} + \eta^{Mod} \cdot \eta^{El} \cdot R_t^{H_2, ch}, \quad \forall t \quad (24)$$

$$R_t^{H_2} = R_{t=0}^{H_2}, R^{H_2, Min} \leq R_t^{H_2} \leq R^{H_2, Max} \quad \forall t \quad (25)$$

$$\delta_t^{H_2, ch} \cdot R^{H_2, ch, Min} \leq \eta^{Mod} \cdot \eta^{El} \cdot R_t^{H_2, ch} \leq \delta_t^{ch} \cdot R^{ch, Max} \quad \forall t \quad (26)$$

$$\delta_t^{H_2, disch} \cdot R^{H_2, disch, Min} \leq \frac{R_t^{H_2, disc}}{\eta_{FC}} \leq \delta_t^{H_2, disch} \cdot R^{H_2, disch, Max} \quad \forall t \quad (27)$$

$$0 \leq \delta_t^{H_2, ch} \leq 1, 0 \leq \delta_t^{H_2, disch} \leq 1, \quad \forall t \quad (28)$$

$$\delta_t^{H_2, ch} + \delta_t^{H_2, disch} \leq 1, \quad \forall t \quad (29)$$

The right sides of (4)–(5) include hybrid hydrogen storage discharging power $R_t^{H_2, disc}$ and charging power $R_t^{H_2, ch}$.

Table 2: Characteristics of hydrogen-based technology.

Characteristic	Electrolyzer [85]	Compression, storage and dispensing module [67]	Fuel cell ¹ [63]
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. The consideration of thermal potential would increase fuel cell efficiency from 40–60% (reported in Table 2) to up to 90% [63] and may potentially ensure fully energy (thermal and electricity) self-sufficiency for an Ontario household.

4.2 Case study analysis

Several locations in Ontario were tested and it was found that on average a prosumer will need a 15 kW PV array and a 2.6 MWh capacity hybrid hydrogen storage. The seasonal storage is charged during the period of high PV generation and mainly used to cover the load during Fall and Winter. The rest of load is covered directly from PV. With the selected sizing of equipment, a household can reach a complete electricity self-sufficiency. The electric battery capacity has been reduced to 2 kWh to handle short-term load variations. Figure 13 provides the illustration of energy flows dispatch in the presence of hydrogen-based seasonal storage (one year selected from a 3-year simulation).

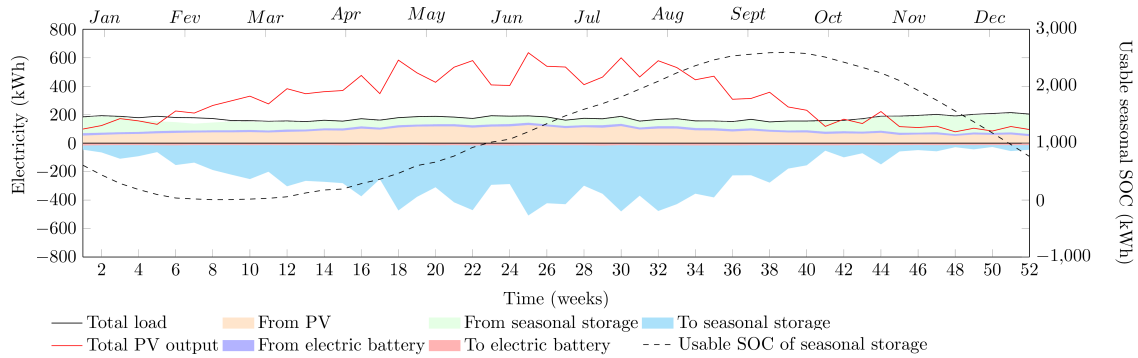


Figure 13: Example of yearly power dispatch for a household in Atikokan of typical consumption with 15 kW of PV, electric battery of 2 kWh (allowing fast charge/discharge of 2h) and hybrid hydrogen seasonal storage of 2.6 MWh.

4.3 Major observations

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

- Unlimited increase of generator capacity relying on a modest resource (here PV capacity increase under a modest insolation) is not sufficient to achieve complete self-sufficiency. This remains the case even with increased efficiency due to technological development, as illustrated on Figure 11b. Self-sufficiency may be achieved only with the development of medium- and long-term seasonal storage. A potential alternative option for self-sufficiency is a combination of different RES with different seasonality, but we do not consider it here.
- Seasonal storage with hydrogen-based technology is able in principle to close the energy loop of summer PV energy losses and winter unmet demand. However, the operational model used to simulate hydrogen-based technology dispatch may need to be refined in collaboration with hydrogen experts to ensure its representativeness. Moreover, in addition to hydrogen seasonal storage, the household would require an electric battery to compensate short-term load fluctuations. A prosumer dispatch model must integrate both a refined model of hydrogen storage and electric battery to identify prosumers' storage needs.

- The optimal sizing and matching of household load, **PV**, electric battery and seasonal storage capacities under given environmental conditions remain a key issue. It will allow to fully profit from the use of **RES** generation as a main power source for prosumers and enable them to become self-sufficient at an acceptable investment cost.

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

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

5.1 Profitability of investment

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

$$PI_c = \sum_{y \in Y} \frac{1}{(1+r)^y} \cdot \frac{C_y^{avoided}}{CAPEX_y} \quad (30)$$

Net Metering allows for the consumer to receive a non-cash credit for the surplus generation. This credit is applied towards variable kWh and kW charges, but it cannot be applied towards the fixed charges, taxes, or other charges that are not kWh or kW based [41]. Moreover, Ontario Net Metering requires that the consumer switch from **TOU** rates to tiered rates for both kWh generated and used from the grid (see Figure 1a). Basically this means that its 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 the 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: Yearly cash flows.

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

5.2 Market RES technologies and their cost trends

In order to perform the economic analysis it is important to differentiate two type of costs: *technology* cost (sometimes also called Global price index) and *installed* cost [51]. The technology cost is associated to the technology (product) cost at factory gate while the installed cost is associated with costs paid by the by final purchaser of technology. The installed cost may include transportation cost, import levies (if the technology is shipped from abroad), expenses related to preparation of installation (e.g., site preparation, grid connection and auxiliary equipment), and working capital. The installed cost is more difficult to track because it can vary widely within individual countries and regions, maturity of domestic markets, labour costs, and incentives. For illustration, the installed cost of a **PV** module was 6 times higher than technology cost in countries such as Italy, Spain, Portugal and USA, with relatively well developed solar markets in 2011 [48]. In this analysis we try to account for the installed cost.

5.2.1 **PV** panels

Figure 14 reports the evolution of the thin film a-Si/u-Si a Global price index (technology cost) and installed cost for US markets (as the market closest to Ontario) [51]. Overall the installed cost of

residential solar PV globally follows constant reduction trends with a decline of 47 - 78% between 2007 and 2017 depending on the country [51]. The level of installed cost varies widely depending on the market, e.g. California has become the most expensive residential solar PV market where the installed cost is double that in Germany [51].

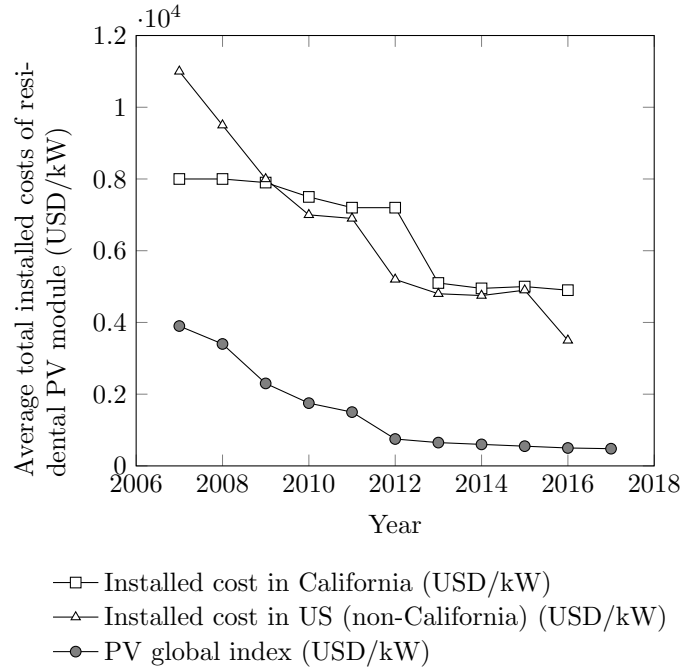


Figure 14: PV global index (manufacturer cost) and installed cost.

One recent study revealed that material cost is no longer a major contributor to the spectacular reduction of PV module cost [54]. Technical performance and economy of scale are now the dominating factors. This means that with the recent increase of efficiency and material usage, and the growth of PV installed capacity, PV costs will continue to decrease supported by market-stimulating policies and R&D programs [54]. Multiple sources support these conclusion and predict that PV costs will continue to drop. Notably [49] predicts that the levelised cost of electricity generation (which includes not only the installed cost, but also yearly operation and maintenance) of large capacity 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 between 2,595 CAD/kW and 2,252 CAD/kW in an optimistic scenario (representing a cost reduction of approximately 19 - 30%) [30]. At the same time, [30] states that residential PV installation cost in provinces with experience in solar installation (such as southern Ontario) is already equal to the installed cost of an optimistic scenario. This is confirmed by [21], which recorded the lowest installed costs in Ontario among all Canada's provinces in 2019 situated in the range 2,280–2,780 CAD/kW. Therefore, if this decrease tendency is maintained, we may assume that PV installed cost for residential use in Ontario may reach the cost level 1,596–1,946 CAD/kW in 2030.

5.2.2 Short-term storage: Electric battery

The batteries used for residential electricity storage are mainly lithium-ion batteries similar to those used in electrical vehicles. The information about electric battery installation cost available in the US in 2018 is summarized in Table 4.

Detailed predictions regarding battery cost decrease are more careful and usually done under the assumption of new policies that may motivate this decrease [76]. Due to the greater availability of

Table 4: Installed cost of residential electric batteries in 2018 [65, 20].

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, 70% after	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, 80% after	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 a nominal capacity multiplied by the maximum depth of discharge.

data, most estimations are done for large-scale industrial storage installations [18], however, at the same time, large-scale battery manufacturers such as Tesla provide batteries for residential usage. Table 4 includes residential batteries sold by car manufacturers. [64] reports that the global yearly deployment of “behind the meter” storage capacity almost tripled from 2017 to 2018 overcoming the speed of grid-scale storage deployment. Lithium-ion batteries represent the waste majority in this deployment.

As in the case of PV, the battery CAPEX is subject to factors such as efficiency and economies of scale. In fact, it was found that the **learning rate (LR)** of lithium-ion technology cost (LR for battery was 19% in 2017 [11]) is comparable with the LR of PV (LR for PV was 28.5% in 2018 [92]), i.e., both costs per kW for PV and per kWh for battery decrease with every doubling of capacity. The deployment rate is expect to continue increasing. According to different estimates, storage capacity must at least increase by 50% [16] and at most triple [50] between 2017 and 2030. Following the most optimistic trend, the battery installation cost for electric battery may decrease by approximatively 35% between 2019 and 2030 [50]. It was assumed that these factors may decrease the average battery cost for Canada’s application from **1,560 CAD/kWh** in **2019** to **1,016 CAD/kWh** in **2030**.

5.2.3 Seasonal storage: Hybrid hydrogen storage

Hydrogen-based technologies for non-industrial applications observed a spectacular rise in recent years led by the transportation sector with the largest hydrogen bus fleet operating in Aberdeen, Scotland [97] and the first hydrogen train entering service in Germany in 2018 [2]. The global fuel cell private vehicle stock of 11 200 units at the end of 2018 is expected to reach up to 2.5 million of units in 2030 [25]. As in the case of electric battery, fast development of transportation applications stimulate the use of hydrogen-based technologies in power sector, most importantly for 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. A demonstrator system for an off-grid alpine chalet based on solid state metal hybrid hydrogen storage is developed since 2017 [80]. Another hybrid storage solution is commercialized for the equivalent of 87,780 CAD for the installation of total usable capacity (electricity plus thermal) up to 6 MWh since 2018 [14].

Experts estimate that the increase of R&D investment may reduce hydrogen electrolysis CAPEX by 24% while the economy of scale also may have an impact of 17 - 30% CAPEX reduction for different electrolysis technologies by 2030 [85]. The cost will also tend to decrease for other technologies, e.g., the LR for fuel cell could reach 18% from 2015 and 2025 [84]. Taking into account the hydrogen storage electric efficiency reported in Table 2 makes the technology price to be around **22,000 CAD/MWh** in **2019**. By assuming that the technology cost will decrease of 30%, hybrid hydrogen storage cost may be as low as **15,400 CAD/MWh** in **2030**.

5.3 Investment conditions

As discussed in Section 2.4, Ontario's government is attending to decelerate bill increase since 2017. However, no coherent policy plan for restructuring grid fees has yet been proposed: temporary or indirect relief for distribution cost has been introduced to the total grid fees without specific actions on fixed or variable charges and remained in effect until changed. In general, it was promised that the annual bill increase will be no more than the inflation rate. However, if average increase/decrease rates for grid fees, illustrated in Section 2, are maintained, the annual average total bill increase in different cities and communities will be around 2.94%. This number is comparable with Ontario's annual inflation rates which have fluctuated around 2% per year during the last twenty years [47]. The OECD long-term forecast suggests that the inflation rate for Canada will be maintained at the same level for the foreseeable future [75].

Therefore, in the absence of a clear policy plan regarding bill restructuring, it is assumed that it will increase according to an inflation rate of 2% per year. It is also assumed that the proportion of fixed and variable costs in the bill remains the same for different cities and communities. For capital investment, it was assumed that the market costs discussed in Section 5.2 already account for inflation rate.

The discount rate was set to 2.5% [31].

5.4 Case study

This section provides numerical results about the profitability to become an electricity prosumer in Ontario.

Figure 15 presents the examples of yearly avoided cost for household prosumer under pricing conditions of year 2019 for Net Metering and Off-grid options. In both cases, a 15 kW PV installation was considered. The effect of application of consumer relief adopted for medium density areas and low-density areas is shown here at the examples of Weagamow and Matheson, respectively. However, this relief is regarded as a temporary measure and were not considered for further profitability analysis.

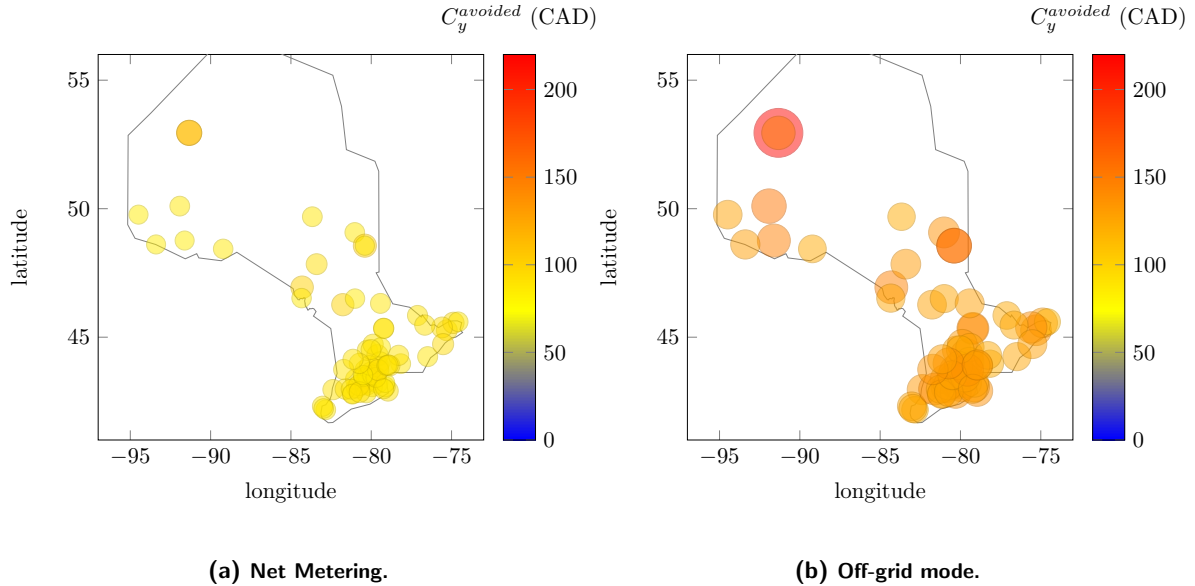


Figure 15: Monthly avoided cost for Ontario household prosumer for year 2019 under a) Net Metering and b) grid-disconnected scheme.

The avoided cost for Net Metering is related only to variable rates before application of taxes and its amount will be almost the same for all locations in Ontario with potential decrease for low-density and remote areas due to application of fixed relief. The application of the total distribution bill cap for medium-density areas makes the avoided cost slightly less. In the case of Off-grid, the avoided cost will be equal to the total electricity bill in different locations. For medium-density locations and a typical 750 kWh/month consumption, the total distribution will be less than suggested cap, so the avoided cost in 2019 will be the same. For remote and low-density areas the avoided cost decreases with the application of fixed relief.

PI_c was calculated for investment done in 2019 and 2030 with a project duration of **15 years** (which corresponds to a minimum lifespan for PV [49] and major parts of storage installations [20, 52]). The Net Metering scheme includes a 15 kW PV array with installation cost of 34,200 CAD. As defined in Section 4, the Off-grid scheme includes a 15 kW PV array, a 2 kWh electric battery and a 2.6 MWh hydrogen storage. The total installation cost was estimated to be 73,353 CAD.

Figure 16a,b shows that currently it is not profitable to become a prosumer under either Net Metering and Off-grid schemes. For the Net Metering the average PI_c is 0.51 while for the Off-grid scheme, the average PI_c 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 triple its investments, but the profitability of this decision will be only divided by two. Note that both schemes will require additional regular payments. Under Net Metering scheme the prosumer pays the remaining bill: consumption from the grid and fixed charges which can be up to 40% of the typical electricity bill. In addition, the prosumer will be exposed to potential changes in legislation increasing these fixed costs. In Off-grid mode the prosumer covers expenses related to maintenance.

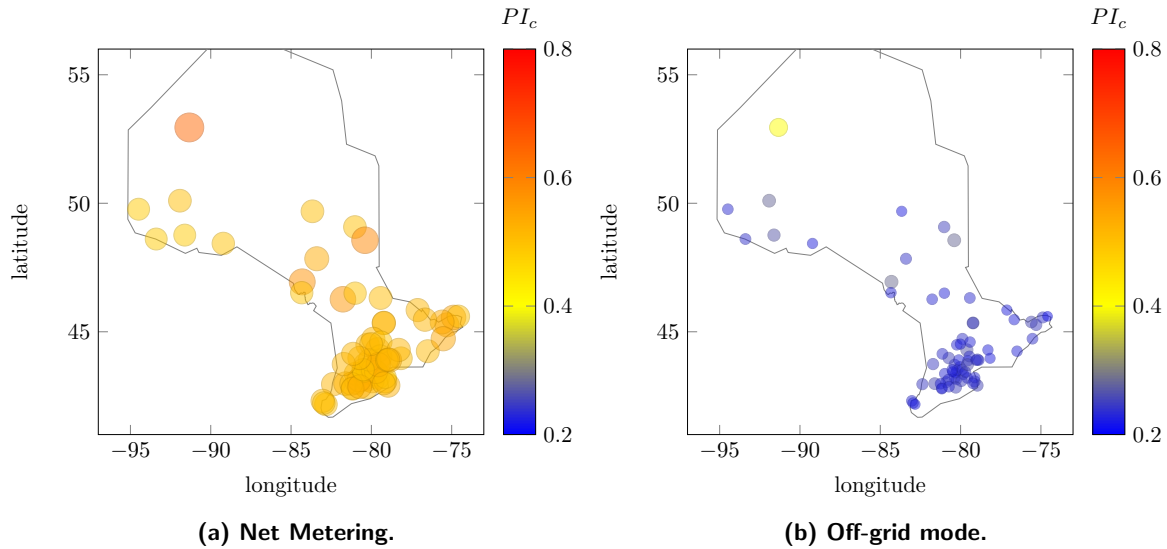


Figure 16: PI_c of investment in 2019 under prospects for Ontario energy pricing policies in a) Net Metering and b) Off-grid prosumer scheme.

The profitability analysis reveals the following important findings. Figure 18 shows the distribution of profitability index for 2019 mapped as a function of fixed monthly cost (CAD) and variable distribution cost (CAD/kWh). As it can be noticed, the profitability index for disconnection increase faster in the presence of higher fixed service charges while the increase of variable charges has a minor influence on the decision to disconnect. For example, Espanola and Hawkesbury have similar fixed cost of 14.07 and 15.15 CAD/month, respectively, but Espanola consumers pay five times higher variable distribution rate than Hawkesbury. The profitability for disconnection in Espanola is only 10%

higher than in Hawkesbury. At the same time, Atikokan has similar variable distribution charges of 0.0038 CAD/kWh than in Hawkesbury, but three time higher fixed monthly cost. The profitability for disconnection for Atikokan's household is 26% higher than in Hawkesbury.

The fact that the dominating reason pushing consumers to disconnect is high fixed service charges is confirmed by Figure 17. It shows the distribution of fixed cost in the total 2019 electricity bill mapped as a function of fixed monthly cost (CAD) and variable distribution cost (CAD/kWh). The fixed cost share distribution for different locations on Figure 17 almost exactly coincides with distribution of profitability index on Figure 18. In general, critical locations where consumers are more prompt for disconnection are characterised by high a proportion of fixed cost in the total electricity bill. Table 5 provides results ranked by the profitability of Off-grid scheme. Locations with highest profitability of disconnection are in top twenty of highest fixed cost among all Ontario locations.

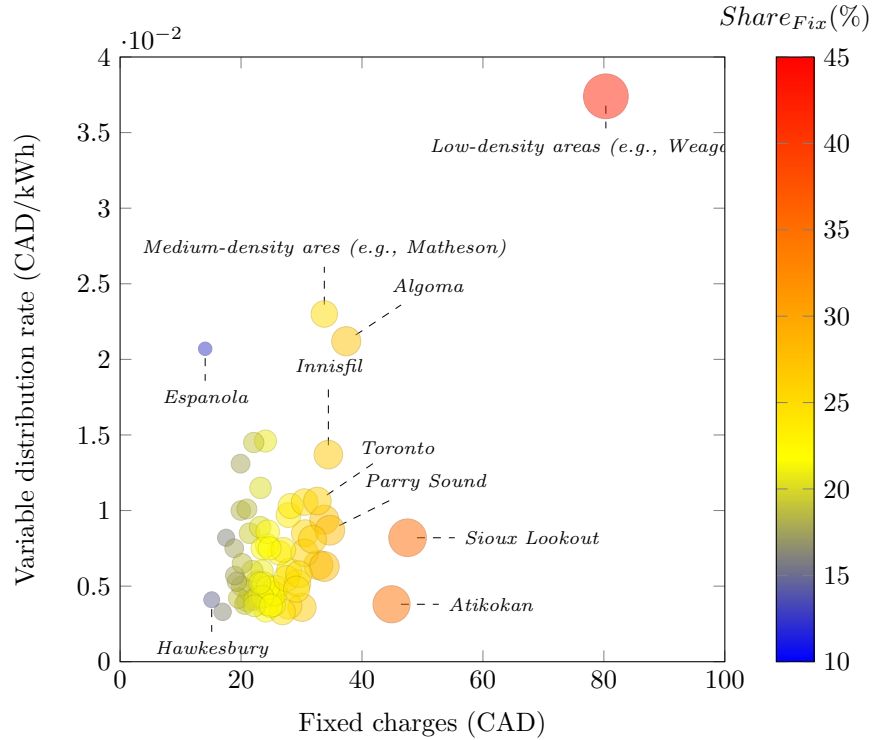


Figure 17: Share of fixed cost in the total electricity bill depending on the fixed and variable distribution costs for year 2019.

The profitability of disconnected scheme may become considerably more attractive in the near future due to the decrease of installations costs. Figure 19 shows PI_c in case of investment done in 10 years (in 2030) under conditions of technologies costs drop assumed in Section 5.2. Here the same assumption is made that consumers will see the general trends regarding Ontario energy pricing policy to be maintained, i.e. and the proportion of fixed and variable costs in the electricity bill, and monthly typical consumption for the next years will remain unchanged in comparison with 2019. The profitability of Off-Grid scheme will almost double between 2019 and 2030 (Table 5).

5.5 Major observations

It is not yet profitable, and it will remain unprofitable (under assumed conditions, i.e. capital investment, tariff policy and project duration) in 2030, to disconnect from the grid in Ontario. However, this balance is delicate. The profitability analysis involves multiple factors and requires different assumptions. Changes to these assumptions may drive electricity consumers rapidly to disconnection. The following observations are made:

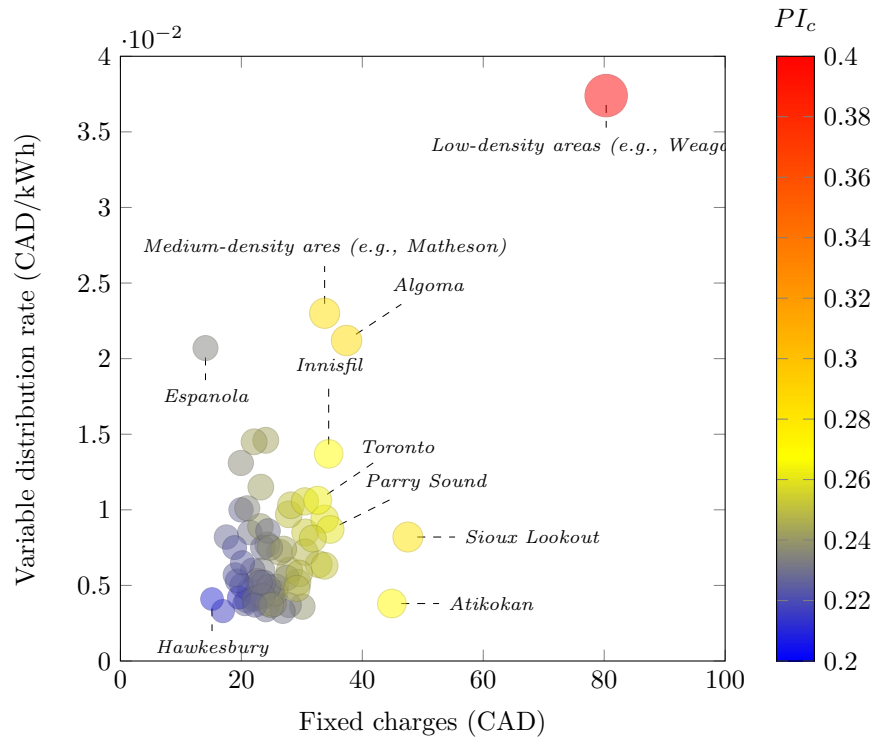


Figure 18: PI_c depending on the fixed and variable distribution costs (relief as a temporal measure was not considered).

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 The location labelled in red in Figure 2 are currently subject to relief (Section 2.4) which is considered as a temporary measure and not taken into account in this analysis.

² Year 2018/2019.

- Several locations in Ontario have been found to be particularly close a disconnection decision: Sioux Lookout and Atikokan in North West Region, Algoma and Parry Sound in North-East Region and Innisfil near GTA. The same applies to same medium-density areas such as Matheson and low-density areas such as Weagamow (Table 5). Consumers in these locations are currently subsidised with temporary rate relief to maintain their costs at the average provincial level.
- Most of the critical locations are spread along the Ontario-USA border. This geographical area is characterised by a decent PV potential of around 1,000 kWh per kW of installed capacity per

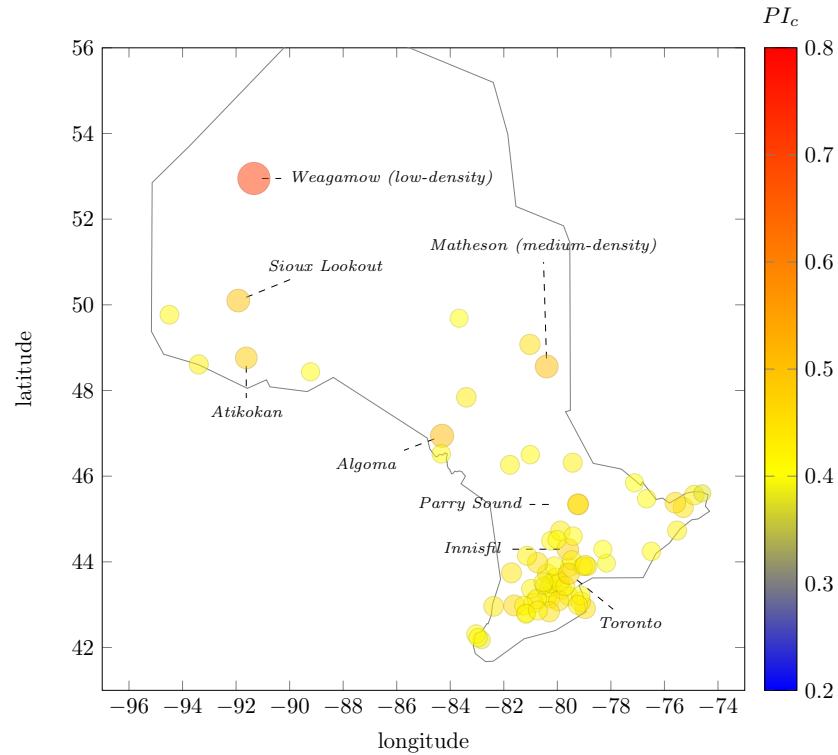


Figure 19: PI_c of investment in 2030 under prospective for Ontario energy pricing policies.

year. This potential can be further increased by a choice of optimal installation parameters (e.g., facing, tilt) for PV panels.

- Another advantage of their geographical positions lies in the proximity of booming solar and storage technologies markets in USA. According to a recent report summarized in [96] the installed capacity of residential storage recorded a 9-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 USA states but rebounded in 2018 with 7% growth [86]. This may facilitate the adoption of these technologies in Ontario.
- In general, a prosumer in Off-grid mode will increasingly be a challenge throughout Ontario. If the provincial energy pricing policy is unchanged and equipment costs continue to decrease, already in 10 years (in 2030) an average profitability index for the whole of Ontario may double. A minor push may be sufficient to bridge the gap toward disconnection. This analysis considers the same portion of fixed and variable charges in future electricity bills. Should the government decide to maintain current trends of increasing fixed charges increase and decreasing variable rate, this will not only accelerate the increase of profitability for disconnection, but may also increase people awareness of conventional energy system challenges.

6 What is the impact for the grid?

The decrease or elimination of FIT makes possible the implementation of RES technologies costs only under Net Metering scheme. The continuous decrease in PV installation cost shapes total net load resulting in a so-called duck curve. This phenomenon discovered ten years ago by a team at NREL [15] is characterised by an important fall of net load during times of high PV generation and ramp effects bordering this period. The duck curve effect is not confined to California [87] where it was first observed. The high penetration of distributed PV may also lead to a pronounced duck curve in other

jurisdictions, such as Australia [93] and China [36]. An important outcome of the duck curve is the increase of hourly electricity prices during peaks rewarding the ability of some conventional generators to increase output on command [17]. With the increase of ramp effects and, as a consequence, of hourly electricity prices, the interest of investment in Net Metering may decelerate. In this view, prosumers may judge that it will be more attractive to take advantage of PV generation immediately rather than to save Net Metering credits to cover future bills. This interest matches well with the grid actions to promote storage technologies, and coupling PV panels with battery storage may become a logical next step for prosumers. This step towards increased autonomy is also supported by the importance of environmental motives to increase share of RES generation [26]. However, if the level of fixed charges (independent from the consumption level and mode) in the electricity bill is maintained and no alternative policy to Net Metering exists, prosumers may be pushed to disconnection in a snowball effect. The process may start at critical locations, pointed out by the analysis in Section 5.1, where a gradual disconnection of prosumers may influence local tariff policy applying more pressure on still-connected consumers and pushing them to reconsider their choice of staying connected. Without an adequate tariff policy promoting RES and storage integration and, at the same time, actively involving prosumers in the global energy management process, the practice of disconnection may rapidly propagate to the entire jurisdiction.

The share of residential customers in different distribution areas varies between 83% and 99.7% of total consumers. Therefore, distribution areas almost exclusively composed of residential customers may be most sensitive to prosumer emergence. For example, this is the case of Algoma where 99.7% of customers are residential and are no large electricity consumers [71].

7 Conclusions and policy implications

This paper continues the exploration of pricing policy impact on prosumers initiated in [56] and analyses feasibility and profitability of prosumer schemes, i.e., Net Metering and Off-grid, at the example of Ontario (Canada) characterized by high typical electricity consumption and modest RES potential. It reveals that it may be possible to operate in fully self-sufficient mode by relying on PV array and seasonal hydrogen-based storage even in northern Ontario. The explored configuration allows to reach 100% of self-consumption by closing a loop of PV power usually lost during high solar irradiation periods. The analysis of prosumer profitability is done under current projections of pricing policy and technology costs, and shows that currently both schemes are not profitable, and in 10 years Off-grid scheme is more likely to remain not profitable. However, this balance is delicate. The profitability analysis involves multiple factors and requires different assumptions. Changes in these assumptions may drive electricity consumers straight to disconnection over a (very) short time period. The analysis reveals critical geographical locations in Ontario ripe to disconnection. A specific relationship between tariff structure, in particular the levels of variable and fixed costs, can serve as the basis for modification of energy policies to involve small-scale prosumers in global energy management process.

Current work involves the development of a computational framework helping integration of high number of small-scale prosumers in a large electricity grid under various operational uncertainties. The goal of this tool is to test the optimality of different energy policies for different jurisdictions prior to implementation.

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