Rooftop Solar with Net Metering: An Integrated Investment Appraisal

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Development Discussion Paper: 2023-01

ABSTRACT

This paper develops a framework for a financial, economic, and stakeholder analysis of a residential rooftop solar net-metering program. The empirical focus of the paper is the net metering program in Ontario, Canada, but the methodology is applicable to evaluating other public programs. The results highlight that without the Federal Government's subsidy for the initial investment cost, net-metered solar systems are not financially viable for representative households. Moreover, the stakeholder analysis reveals that for each additional net-metered system installed in Ontario, non-net-metered households experience financial losses of eight times the benefits to the net-metered households. The net losses to the Federal Government of

Canada and the Canadian economy are six and twelve times the benefit to the net-metered households, respectively. The only stakeholder who benefits marginally is the Government of Ontario. In terms of environmental benefits, our estimate of the cost of greenhouse gas abatement by residential net-metered solar is 413 CAD per ton of CO2e, which is significantly higher than the current (65 CAD in 2023) and future (170 CAD by 2030) social cost of carbon set by the Government of Canada.

Keywords: rooftop solar, net metering, greenhouse gas emissions, renewable energy, the social cost of carbon, Canada.

JEL Classification: D61, L94, Q42, Q48

1. Introduction

Under the 2030 Emissions Reduction Plan, Canada aims to reach an emission reduction target of 40 percent below 2005 levels by 2030 and net-zero emissions by 2050. To achieve this target, the federal and provincial governments have undertaken a range of sector-specific interventions to reduce greenhouse gas (GHG) emissions across different sectors of the economy. In the electricity sector, billions of dollars have been allocated to initiatives that promote the adoption of renewable electricity generation resources. With the substantial growth in the deployment of renewable resources, regulators and stakeholders need to investigate such interventions from two perspectives: efficiency and sustainability.

From the efficiency perspective, the up-front capital outlays tend to be a larger part of the lifecycle costs of renewable energy technologies than those of fossil-fuelled technologies, with the lifecycle costs being mostly fuel expenditures over time (Steffen 2020). Moreover, the sustainability of any project is heavily impacted by which stakeholders in the project's sphere of influence gain or lose because of it. By identifying the fiscal and stakeholder impacts of the project, it is possible to make a more realistic assessment of the implementation success of such a program and its likely sustainability over time. Any imbalances in the stakeholder impacts will put the project's long-term sustainability at risk.

A popular example of renewable energy interventions are net-metering programs that encourage the deployment of rooftop solar distributed energy resources (DERs) among grid-connected electricity consumers[2]. The heart of a net-metering program is the compensating mechanism designed to reward the solar DER owners for electricity that is self-consumed

[2] A DER is sited close to customers. It can provide all or some of their immediate electric and power needs and can also be used by the system to either reduce demand or provide supply to satisfy the energy, capacity, or ancillary service needs of the distribution grid. Examples of different types of DERs include solar photovoltaic (PV), wind, combined heat and power (CHP), energy storage, demand response (DR), electric vehicles (EVs), microgrids, and energy efficiency (EE).

and/or exported to the distribution grid[3]. The decision by electricity consumers whether to invest in a net-metered rooftop solar photovoltaic (PV) system is a direct function of how much they benefit financially in the form of savings on their existing grid-electricity bills. However, decisions being made by these prosumers create other impacts that translate into benefits or costs that impact other stakeholders. To ensure an efficient resource allocation, the main question is how well the current electricity retail rate structures interact with the net-metering compensating mechanism to reflect the actual costs and benefits of each stakeholder. In this situation, these stakeholders include the DER owners, the electric utility, non-DER owners, provincial and federal governments, the economy, and the global environment.

The concerns about the efficiency and sustainability of net-metering programs have been raised in previous studies (Brown and Sappington 2017; Gautier, Jacqmin, and Poudou 2018, 2021). This study proposes to extend the previous research by conducting a comprehensive stakeholder analysis of a net-metering program that includes all the relevant consumer groups, different levels of government, and the environmental impacts[4]. The empirical focus of the paper is the net-metering program in Ontario, Canada, but the methodology is applicable for evaluating other public programs in electricity and other sectors of the economy.

Ontario's net-metering program was introduced in 2016 to promote the deployment of renewable energy resources (solar, wind, water, and agricultural biomass) connected to the electricity distribution network. Given that the main type of net-metered installed capacity has been rooftop solar, in this study we focus on the net-metered solar systems[5]. In 2021, the

[3] Solar DER owners are also referred to as prosumers because they both produce and consume electricity.

[4] We employ the Integrated Investment Appraisal approach developed by Jenkins, Kuo, and Harberger (2019), a similar methodology used by Bahramian, Jenkins, and Milne (2021), to evaluate the wind farms in Ontario, Canada.

[5] As of 2021, solar net metering has been the most popular type of installed capacity, with more than 3,000 participants across the province, totaling 66 megawatts (MWs).

Federal Government also introduced the Greener Homes Initiative, which provides financial support for energy-efficiency-improving home retrofits such as rooftop solar panels, up to 5,000 CAD in grants and up to 40,000 CAD in interest-free loans, with a repayment term of ten years. Therefore, we start by evaluating how the investment subsidy provision would affect a household's investment decision in a net-metered solar system. An economic analysis follows that examines the resource costs and savings of such an investment. Lastly, we estimate the expected stakeholder impacts by quantifying each stakeholder group's net gains or losses at the aggregated program level.

Our results indicate that the levelized financial benefits to a representative household from a net-metered system add up to 0.13 CAD per kWh, which falls far short of the lifetime private costs of 0.21 CAD per kWh. However, government subsidies turn such investments financially viable, though economically wasteful. Moreover, non-net-metered electricity consumers lose significantly because the benefits of fuel savings from the displacement of marginal thermal power plants are insufficient to outweigh the costs to the grid of serving net-metered consumers. More specifically, for every dollar of benefit the net-metered households gain, almost 8 dollars of cost is imposed on non-net-metered consumers, who tend to be lower-income households.

The rest of the paper is structured as follows. The data and methodology employed in this paper are discussed in Section 2, followed by the empirical results in Section 3. In Section 4 we aggregate the results at the federal program level, and we conclude the paper in Section 5.

2. Methodology and data

2.1 Methodology

Our empirical model is constructed based on the Integrated Investment Appraisal (IIA) methodology developed by Jenkins, Kuo, and Harberger (2019). The IIA method evaluates benefits and costs in terms of domestic prices from both financial and economic points of view instead of carrying out these analyses separately. Based on this method, the difference between the net present value of financial cash flows and economic resource flows (both discounted at the country's economic opportunity cost of capital, EOCK) must reconcile with the present value of incremental stakeholders' impacts created by the program over its life. We use a real rate of 7 percent for the EOCK for Canada, which is estimated by Jenkins and Kuo (2007) and has been recommended by the Treasury Board for the cost-benefit analysis of regulatory proposals in Canada (TBCS, 2022).

In the following subsections, we first explain how we measure the net impact of the net-metering program on each stakeholder. We then describe the relationship that must hold between the economic outcome (society's perspective), the financial outcome (prosumers' perspective), and the expected distributional impacts on stakeholders (stakeholders' perspective). Our empirical results in Section 4 are based on the outcome of the equations developed in the following subsections. Table 1 lists the description of the variables used in the equations.

2.1.1 Prosumers (net-metered households)

From the prosumers' perspective, the trade-off is between the present value of electricity bill savings from their net-metered system and the present value of the system's capital and operating expenditures. A typical electricity bill includes energy, delivery, and regulatory charges, with delivery and regulatory charges having both variable and fixed components. The final payable bill is the summation of all these charges, subject to sales tax and rebates on electricity bills. To appraise the feasibility of investing in a net-metered solar system, we compare the changes in electricity bills without ($E_{t,without}^{prosumer}$) and with ($E_{t,with}^{prosumer}$) the net-metering program.

Table 1: Description of variables used in the equations

Variable	Description
Indices	
t	year, $t \in T$ (i.e. lifetime of solar PV system, T=25 years)
Prices	
$p^{c}_{t,grid}$	Electricity price for consumption from utility grid (CAD/kWh)
$p^{e}_{t,grid}$	Electricity price for exports to utility grid (CAD/kWh)
d_t	Variable portion of delivery charges of grid electricity (CAD/kWh)
r_t	Variable portion of regulatory charges of grid electricity (CAD/kWh)
p^{gas}_{t}	Dawn Hub natural gas price (CAD/million BTU)
SCC^{CAD}_{t}	Social cost of carbon (CAD/tonne of CO_2)
Quantities	
Q^{c}_{t}	Quantity of electricity consumed from grid (kWh)
Q^{s}_{t}	Quantity of electricity generated by net-metered solar PV system (kWh)
Q^{e}_{t}	Quantity of electricity exported to grid (kWh)
Solar PV system	
$C_{t,opex}$	Annual operating expenditures for solar PV system (CAD)
$C_{t,capex}$	Investment cost for installing solar PV system (CAD)
Federal subsidy	
G_t	Grant received from the Greener Homes Initiative (CAD)
L_t	Interest-free loan provided by the Greener Homes Initiative (CAD)
A_t	Annual loan repayment (CAD)
Electric network	
TD_t	Transmission and distribution losses as a percentage of generation output
HR_t	Heat rate of electricity generation source (BTU/MWh)
Emission variables	
NG^{d}_{t}	Annual quantity of natural gas displaced by solar net-metered systems (million BTU)
F^{CO2}_{t}	Natural gas CO_2 emission coefficient (kg CO_2 /million BTU)
Other parameters	
$EOCK$	Economic opportunity cost of capital
s_t	Sales tax (i.e. 13 percent)
s^{ON}_{t}	Portion of the sales tax going the Government of Ontario (i.e. 8 percent)
s^{FG}_{t}	Portion of the sales tax going the Federal Government (i.e. 5 percent)
OER_t	Annual rebates for electricity charges
R^{AL}_{t}	Royalty rate collected by the Alberta Government for natural gas sales

Without the net-metered solar, a representative prosumer draws $Q^{c}_{t,without}$ units of electricity from the local grid over year *t*. For every kWh, the prosumer must pay the retail price ($p^{c}_{t,grid}$), delivery charge ($d_{t,grid}$), and regulatory charge ($r_{t,grid}$). Afterwards, the fixed delivery and regulatory charges are added to the bill ($D_{t,grid}$ and $R_{t,grid}$, respectively), and the sales tax (s_t) will be applied on top of the total grid-consumption charges. The final payable bill includes the rebate provided by the Ontario Government (Ontario Electricity Rebate, OER), which covers a certain percentage of total pre-sales-tax grid-consumption charges. Eq. 1 shows how a representative prosumer's electricity bill without net metering is calculated.

After installing the net-metered solar PV, a total of $Q^{s}_{t,with}$ units of electricity will be generated by the system over the year. The portion of solar PV output that coincides with the prosumer's hourly consumption pattern will be consumed on-site, resulting in an overall lower quantity of electricity drawn from the grid by the prosumer ($Q^{c}_{t,with} < Q^{c}_{t,without}$). The prosumer receives per-kWh compensation ($p^{e}_{t,grid} = p^{c}_{t,grid}$) for all the energy exports (i.e. $Q^{e}_{t,with} = Q^{s}_{t,with} - Q^{c}_{t,with}$) to the grid, variable delivery, and regulatory charges, which is identical to what they pay to purchase from the grid. The benefits obtained by the prosumers are outlined in Eq. 3.

$$E^{prosumer}_{t,without} = \left[Q^{c}_{t,without}\left(p^{c}_{t,grid} + d_{t,grid} + r_{t,grid}\right) + D_{t,grid} + R_{t,grid}\right](1 + s_t) - OER_{t,without} \quad (1)$$

$$E^{prosumer}_{t,with} = \left\{\left[Q^{c}_{t,with}\left(p^{c}_{t,grid} + d_{t,grid} + r_{t,grid}\right) + D_{t,grid} + R_{t,grid}\right](1 + s_t) - OER_{t,with}\right\} - Q^{e}_{t,with}\left(p^{e}_{t,grid} + d_{t,grid} + r_{t,grid}\right) \quad (2)$$

$$B^{prosumers}_{t} = \underbrace{\left[\Delta Q^{c}_{t}\left(p^{c}_{t,grid} + d_{t,grid} + r_{t,grid}\right)(1 + s_t)\right]}_{Value\ of\ self-consumption} + \underbrace{\left[Q^{e}_{t}\left(p^{e}_{t,grid} + d_{t,grid} + r_{t,grid}\right)\right]}_{Value\ of\ excess\ credits} + \Delta OER_t \quad (3)$$

As shown in Eq. 4, the investment cost ($C_{t,capex}$) is financed by the Federal Government's grant (G_t) and interest-free loan (L_t). Thus, from the prosumers' point of view, the incremental costs are mainly the annual loan repayments (A_t) and the installed system's operation and maintenance costs ($C_{t,opex}$).

$$C_t^{prosumers} = [C_{t,capex} \times (1 + s_t) + G_t + (L_t - A_t)] + C_{t,opex} \quad (4)$$

After developing the incremental annual benefits and costs to prosumers, the net present value from the prosumers' perspective can be stated as shown in Eq. 5.

$$NPV_{t=0}^{prosumers} = \sum_t^T \frac{B_t^{prosumers} - C_t^{prosumers}}{(1 + EOCK)^t}. \quad (5)$$

2.1.2 Canadian economy

The only economic benefit of the net-metered solar capacity that accrues to the Canadian economy (B_t^{econ}) is the present value of natural gas purchases avoided due to displaced electricity generation by gas-powered plants during the solar operating hours. To quantify these benefits, we measure the annual quantity of natural gas purchases avoided by mid-day peaking natural gas plants (NG_t^d) and multiply those quantities by the average price of natural gas in that year (p_t^g). It should also be noted here that the Alberta Government will experience a reduction in royalty revenues on natural gas production, given that most natural gas imports to Ontario are sourced from Alberta. Therefore, we must subtract the forgone royalty revenues from the economic benefits to arrive at the net economic benefits (see Eq. 6).

The outcome of Eq. 6 provides us with the value of the natural gas purchases avoided by gas-powered plants. The first component in Eq. 7 is an adjustment for avoided transmission and distribution losses (TD_t) that no longer occur when the supply source is the local net-metered solar PV system. The second component calculates the weighted average heat rate by Ontario's gas-fuelled generation fleet, where w_{ij} represents the weight of electricity generation by each plant's technology and HR_{ij} represents the corresponding heat rate of each technology.

$$B_t^{econ} = p_t^{gas}(1 - R_t^{AL}) \times NG_t^d \quad (6)$$

$$NG_t^d = \underbrace{\frac{Q_{t,with}^s}{(1 - TD_t)}}_{Adjusting\ for\ avoided\ TD\ losses} \times \underbrace{\sum_{ij} w_{ij} HR_{ij}}_{Weighted\ average\ of\ heat\ rates} \quad (7)$$

On the economic cost side, three categories of costs must be accounted for: (i) the resources spent on capital expenditures of the installed net-metered solar PV systems ($C_{t,capex}$); (ii) the resources spent on the operating expenditures of those systems ($C_{t,opex}$); and (iii) the additional costs to the Canadian economy of integrating these systems into the grid ($C_{t,int}$). Thus, the economic resource outflows and the present value of the net impact can be expressed as

$$C_t^{econ} = C_{t,capex} + C_{t,opex} + C_{t,int} \quad (8)$$

$$NPV_{t=0}^{econ} = \sum_t^T \frac{B_t^{econ} - C_t^{econ}}{(1 + EOCK)^t} \quad (9)$$

In addition to evaluating the economic impacts that directly affect Canada, we must evaluate the incremental global environmental impacts of the net-metering system because there is certainly a reduction in global GHG emissions. This benefit is allocated as a global economic benefit in the stakeholder analysis rather than a direct benefit to Canadian residents. From the global environment's perspective, because of the relatively small population of Canada compared to that of the world, the value of the incremental environmental benefit accruing to Canadian residents is expected to be insignificant.

The nature of this intervention in the electricity system creates several impacts on other stakeholders in the system. The following is a framework for evaluating each of these impacts.

2.1.3 Non-prosumers (non-net-metered households)

A revenue-neutral electricity distribution company shifts the incremental benefits and costs of serving net-metered consumers to its remaining consumer base. On the benefit side, the solar electricity generated by prosumers during the daytime will reduce the generation by natural gas plants as they are generally the marginal generation source when solar panels produce electricity. This results in savings in natural gas purchases to generate electricity (see Eq. 10). On the cost side, the present value of the reduction in the electricity bills of the net-metered consumers from savings in each component of the electricity bill (except sales tax and rebates) will be passed on to non-net-metered consumers (the first component of Eq. 11). Additionally, solar-to-grid integration costs ($C_{t,int}$ in Eq. 8) will be borne by non-net-metered consumers (the second component of Eq. 11).

Consequently, the net impact is determined by the present value difference between benefits from fuel savings ($B_t^{consumers}$ in Eq. 10), and the costs that will be shifted from prosumers to consumers ($B_t^{prosumers}$ in Eq. 3).

$$B_t^{consumers} = p_t^{gas} NG_t^d \tag{10}$$

$$C_t^{consumers} = \underbrace{\Delta Q_t^c\left(p_{t,grid}^c + d_{t,grid} + r_{t,grid}\right) + Q_t^e\left(p_{t,grid}^c + d_{t,grid} + r_{t,grid}\right)}_{Benefits\ to\ prosumers\ shifted\ as\ costs\ to\ other\ consumers} + C_{t,int} \tag{11}$$

$$PV_{t=0}^{consumers} = \sum_{t}^{T} \frac{B_t^{consumers} - C_t^{consumers}}{(1 + EOCK)^t}. \tag{12}$$

2.1.4 Federal Government

A less explored impact of the net-metering program is its fiscal impact on the provincial and federal governments. When prosumers invest in a solar PV system and start generating and consuming their own electricity, there will be fiscal impacts on the Federal Government. On the one hand, there will be incremental inflows from the Federal Government's point of view. First, the government collects incremental sales tax revenues from the sales of solar PV systems. Second, there is the present value of the loan repayments A_t (principle only).

On the other hand, as prosumers cut back their grid consumption due to the self-consumption of solar-generated electricity, they pay fewer sales taxes because of their reduced payments to the grid. Moreover, at the federal level, the government incurs substantial costs for providing financial support in the forms of grants (G_t) and interest-free loans (L_t) to those who invest in a net-metered solar PV system, i.e. an incremental financial cost from the perspective of Canada (taxpayers).

The present value of the net impact on the Federal Government (FG) is estimated using the following equations.

$$B_t^{FG} = \left(s_t^{FG} \times C_{capex}\right) + A_t \tag{13}$$

$$C_t^{FG} = [s_t^F \times \underbrace{\Delta Q_t^c\left(p_{t,grid}^c + d_{t,grid} + r_{t,grid}\right)}_{Value\ of\ self-consumption\ by\ prosumers} + G_t + L_t \tag{14}$$

$$PV_{t=0}^{FG} = \sum_{t=0}^{T} \frac{B_t^{FG} - C_t^{FG}}{(1 + EOCK)^t} \tag{15}$$

2.1.5 Government of Ontario

From the Ontario Government point of view, there are two incremental benefits (B_t^{ON}): (i) the sales tax collected on the installed solar PV systems; and (ii) the savings in OER payments (OER_t) due to the reduction in the prosumers' total grid-electricity charges. A part of these benefits will be offset by the opportunity cost of forgone sales tax revenues due to a reduction in the prosumers' total grid-electricity charges. Similar to the Federal Government's point of view, the present value of the net impact on the Ontario Government is estimated by discounting the net benefits at the opportunity cost of capital for Canada (Eq. 16–18).

$$B_t^{ON} = \left(s_t^{ON} \times C_{t,capex}\right) + OER_t \tag{16}$$

$$C_t^{ON} = s_t^{ON} \times \underbrace{\Delta Q_t^c \left(p_{t,grid}^c + d_{t,grid} + r_{t,grid}\right)}_{Value\ of\ self-consumption\ by\ prosumers} \tag{17}$$

$$PV_{t=0}^{ON} = \sum_t^T \frac{B_t^{ON} - C_t^{ON}}{(1 + EOCK)^t} \tag{18}$$

2.1.6 Government of Alberta

We must also adjust the gains from the natural gas purchases avoided by the amount the Alberta Government loses in royalty revenues. The present value of forgone royalty revenues, a transfer from taxpayers in Alberta to those in Ontario, is estimated as follows.

$$PV_{t=0}^{AL} = \sum_t^T \frac{p_t^{gas} \times NG_t^d \times R_t^{AL}}{(1 + EOCK)^t} \tag{19}$$

2.1.7 Global environment

Reduced emissions of GHGs are another quantifiable benefit of solar net-metered systems. A key policy objective of the governments of Ontario and Canada is to reduce CO_2 emissions by displacing fossil-fuel electricity generation (i.e. natural gas in Ontario). The benefits realized are a function of the type of generation being displaced, its carbon emission rates, and the proposed values for the social cost of CO_2 abatement.

As mentioned earlier in the paper, the solar PV output will avoid carbon emissions from gas-powered plants, the economic value of which can be estimated by the social cost of carbon (SCC_t). To calculated this, we first need to calculate the quantity of natural gas displaced by net-metered systems (NG_t^d) and then use the average emission factor of the natural gas fleet in Ontario (F_t^{C02}) to estimate how many kilograms of CO_2-equivalent emissions will be avoided[6]. After estimating the associated levels of emissions, we assign a cost to the CO_2 emitted

[6] CO_2 is not the only GHG; others include methane, nitrous oxide, and hydrofluorocarbons. However, the conventional approach is to convert the non-CO_2 GHG emissions into CO_2-equivalent units.

following the federal carbon pricing policy. The carbon price has been set to 40 CAD per tonne of CO_2 equivalent in 2021 and will increase by 15 CAD per tonne per year until it reaches 170 CAD per tonne in 2030 (Government of Canada 2021). The present value of avoided CO_2 emissions that is attributable to solar net-metered capacity is estimated as follows.

$$PV_{t=0}^{environment} = \sum_{t}^{T} \frac{SCC_t(NG_t^d \times F_t^{C02})}{(1+EOCK)^t} \tag{20}$$

2.1.8 Reconciliation of financial, economic, and stakeholder outcomes

The economic value, whether from Canada's perspective or from a global perspective, can be expressed as the sum of its financial value and the values of the stakeholder impacts outlined above. The net present value of net economic resource flows at year zero from Canada's perspective ($NPV_{t=0}^{economic}$), i.e. 2021 in our analysis, is evaluated using Eq. 21. It reconciles the net present value of net financial cash flows ($NPV_{t=0}^{financial}$) plus the summation of the present value of net economic impacts borne by each stakeholder within Canada ($\sum_i PV_{t=0,i}^{externality}$). The common discount rate used is the real economic opportunity cost of capital (EOCK).

$$NPV_{t=0}^{economic} = NPV_{t=0}^{financial} + \sum_{i} PV_{t=0,i}^{externality} \tag{21}$$

The stakeholders in our study are prosumers (net-metered electricity consumers), consumers (non-net-metered consumers), the Federal Government of Canada, Ontario Government, and Alberta Government. We arrive at Eq. 22 after re-writing Eq. 21 to include all the stakeholders.

$$NPV_{t=0}^{Canadian\ econ.} = \underbrace{NPV_{t=0}^{prosumers}}_{Financial} + \underbrace{PV_{t=0}^{consumers} + PV_{t=0}^{FG} + PV_{t=0}^{ON} + PV_{t=0}^{AL}}_{Externalities}. \tag{22}$$

where FG, ON, and AL represent the federal, Ontario, and Alberta governments, respectively.

The net present value from a global perspective ($NPV_{t=0}^{Global\ economy}$) is derived by adding the environmental benefit from the reduction in GHG emissions (Eq. 20) to the economic net present value from Canada's perspective to arrive at Eq. 23.

$$NPV_{t=0}^{Global\ economy} = \underbrace{NPV_{t=0}^{prosumers} + PV_{t=0}^{consumers} + PV_{t=0}^{FG} + PV_{t=0}^{ON} + PV_{t=0}^{AL}}_{Canadian\ Economy} + \underbrace{PV_{t=0}^{environment}}_{Environmental\ Externality} \tag{23}$$

In the following subsections, we discuss the determinants of the net present values from each stakeholder's perspective.

2.2 Data

During days of full sunshine, the amount of electricity generated by the installed solar panels not only satisfies the household's power needs (coinciding with sunny hours), but also provides the household with an excess amount of electricity (henceforth "excess solar") that can be injected into the local distribution grid. However, at night or on cloudy days, the installed panels generate no (or insufficient) electricity, so the net-metered household must use the grid-supplied electricity for its power needs. Each net-metered household has two meters: (i) the consumption meter, recording the household's consumption from the grid; and (ii) the generation meter, recording the excess generated electricity injected into the grid by the net-metered household.

The analysis begins by constructing consumption and generation profiles of a representative residential consumer in Ontario. For grid-consumption profiles, we employ the actual hourly smart-meter data (aggregated at the census division level) provided by Ontario's Independent Electricity System Operator (IESO). The IESO's data contains the kWh of electricity consumed by large samples of residential premises in each census division.

After estimating the pattern and quantity of electricity consumption for a representative net-metered household, the next step is to determine the optimal system size. The conventional approach taken by solar system installers is followed. The size of the system needed by a household is a function of its annual electricity consumption and the PV potential at its location. Therefore, installers divide the kWhs of electricity consumed by the household over the year by the annual kWh of electricity that can be potentially generated per kW of the installed solar system at the household's location[7]. The optimal size equals 8 kW after considering an average rate of system degradation and modest growth in electricity consumption by the household over time.

Using the system size, the hourly output of a residential rooftop solar PV installation is calculated using the System Advisor Model (SAM), developed by the United States National Renewable Energy Laboratory (NREL). SAM utilizes the hourly meteorological data and technical specifics of the installed solar system to simulate the system's hourly output at designated locations[8]. Following the common technical specifics of the solar systems installed across Canada (Doluweera et al. 2020), we define a DC to AC ratio of 1.15, an inverter efficiency of 96 percent, and system performance losses (due to soiling, shading, snow, etc.) of 15 percent. Given that the purpose of this study is to evaluate the impacts of the net-metering program on stakeholders rather than to examine results that are technology-specific or which arise from modifications to system design, we do not adjust performance specifications beyond the suggested settings provided in SAM.

Table 2, column 1 provides for one year of the energy consumption by month (kWh) that a representative Ontario household consumer would purchase from the grid without the solar system. In column 2, the values of the simulation are reported for what the same consumer

[7] Different references are available for the potential PV yield by location. We use the potential PV yield data at the municipality level. This database is publicly available on the Ministry of Natural Resources website and is developed by the Canadian Forest Service (Great Lakes Forestry Centre) in collaboration with the CanmetENERGY Renewable Energy Integration group and the Federal Geospatial Platform.

[8] The typical-year methodology analyzes multi-year datasets to construct the most representative weather data.

would purchase from the grid with the solar system. In practice, these values are recorded by the household's consumption meter. Column 3 reports the surplus that the household's solar system exports to the grid. These are the amounts of electricity generated that are more than those coincidentally consumed by the household when the solar system is generating electricity. These are the values that are measured by the household's generation meter. The focus of this research is the financial, economic, and stakeholder impacts arising from the change in costs caused by the change in the technology used and the pattern of generation of electricity over the year, as reported in Table 2.

Table 2: Monthly meter readings without and with net metering

Month*	Without net metering	With net metering	
	Consumption meter Consumption from the grid (kWh) (1)	Consumption meter Net consumption from the grid (kWh) (2)	Generation meter Excess generation exported to the grid (kWh) (3)
Mar	751	460	650
Apr	628	373	512
May	586	317	607
Jun	637	319	801
Jul	978	504	706
Aug	801	421	764
Sep	602	352	508
Oct	596	394	484
Nov	698	501	258
Dec	782	601	180
Jan	849	611	308
Feb	746	490	396
Annual	**8,655**	**5,344**	**6,174**

Notes:
* The annual estimations in this study are all based on March as the first month because of the common practice of installing the solar panels when there is sufficient sunshine for excess generation credits to offset grid charges. Also, at least in the case of Ontario, cold weather and snowfall make it challenging to install a rooftop solar system in January or February.

The prosumer receives a per-kWh compensation for all the energy exports (Table 2, column 3) to the grid, variable delivery, and regulatory charges, which is identical to what they pay to purchase from the grid. The compensation shows up as credits in the electricity bill and will be used to offset the remaining grid-electricity charges. The monthly electricity bills of net-metered customers are calculated based on the net difference between the kWh used from the local grid and the cumulated credits received for any excess electricity currently or previously sent to the local grid. Any cumulated credits can be carried forward for up to 12 calendar months.

To estimate the electricity bills without the net-metering program, the hourly grid-electricity charges are simulated on an hourly basis by applying Ontario's time-of-use price periods. Price periods are different within the day and across seasons[9]. Additionally, we model hourly grid-electricity charges with the net-metering program. Once a consumer turns into a prosumer, the local distribution company takes them off the time-of-use tariff and puts them under the tiered tariff[10].

3. Empirical results

3.1 Prosumers' perspective (the investment decision)

Table 3 also lists the breakdown of changes in the annual electricity bill without and with net metering. Delivery and regulatory charges both have fixed and variable components. The fixed components are payable regardless of the net-metering status (Table 3, rows 2 and 4), whereas prosumers save on the variable portion of delivery and regulatory charges for each kWh of displaced grid-supplied electricity (Table 3, rows 3 and 5). The sales tax on grid-electricity consumption is 13 percent, broken down as 8 percent going to the Ontario Government and the remaining 5 percent to the Federal Government. Given that the grid-electricity consumption net of solar-generated electricity decreases for the net-metered households, savings in sales tax payments also turn into a saving. However, the amount households receive in the form of the OER payment is less than what they would have received

[9] There are three price periods: off-peak, mid-peak, and on-peak. The off-peak hours are identical in summer and winter, 7pm–7am, and weekends and holidays are always off-peak periods. However, the mid-peak hours in summer are 7–11am and 5–7pm, whereas they change to 11–5pm in winter. Moreover, the on-peak hours in summer are 11am–5pm, while they are spread between 7–11am and 5–7pm during the wintertime.

[10] With tiered pricing, consumers use a certain amount of electricity each month at a lower price. Once that limit is exceeded, a higher price applies. As of 2022 in Ontario, the lower tier threshold is 600 kWh in summer and 1,000 kWh in winter.

without net metering[11]. Therefore, the change in the OER counts as a loss for net-metered households.

Table 3: Annual savings in electricity bills by component (CAD, 2021 prices)

	Electricity bill component	Without net-metering	With net-metering	Difference
1	Annual grid-electricity charges	923	524	400
2	Fixed delivery charge (per month)	420	420	-
3	Variable delivery charge (per kWh)	178	110	68
4	Fixed regulatory charge (per month)	3	3	-
5	Variable regulatory charge (per kWh)	34	21	13
6	Sales tax on grid-electricity charges – Ontario	125	86	38
7	Sales tax on grid-electricity charges – Federal	78	54	24
8	OER (17% of total charges excl. sales taxes)	265	183	(82)
9	Annual grid-electricity bill	1,496	1,034	461
10	Total generation credits	-	764	764
11	**Annual savings (row 9 + row 10)**			**1,225**

For a representative net-metered household in our model, the annual savings in electricity bills amount to 1,225 CAD, the outcome of Eq. 3 (Table 3, row 11). Thirty-nine percent of the annual savings (461 CAD) originates from the coincidental displacement of grid electricity by solar generation, i.e. self-consumed solar (Table 3, row 9), while 61 percent (764 CAD) is made up of credits earned from excess generation sent to the local grid (Table 3, row 10).

An 8-kW system potentially generates 9,484 kWhs in its first year of operation, and this amount degrades by 0.5 percent every year over its 25-year economic life. This translates into a present value of lifetime output of 105 MWh. The present value of annual bill savings to

[11] Since 2019, the OER has replaced the 8 percent Provincial Rebate on consumers' bills. The rebate offsets a determined proportion of total charges pre-HST. It was set at 31.80 percent in 2019, and was subsequently changed to 33.20 percent in 2020 and to 17 percent in 2021.

prosumers ($B_t^{prosumers}$) over 25 years is 15,215 CAD (Table 4, row 2). Also, the present value of lifetime costs (investment and operating costs) equals 24,001 CAD (Table 4, column 3, row 4). Therefore, with the Federal Government's financial support of a 5,000 CAD grant ($G_t = 5{,}000$ in Eq. 4) and an interest-free loan equal to 17,600 CAD ($A_t = 17{,}600$ in Eq. 4), the net present value for an 8-kW net-metered system (Eq. 5) becomes a positive 1,563 CAD (Table 4, row 9).

Table 4: Prosumer's financial perspective (present values over 25 years, @EOCK=7%)

	Financial cash flow statement (1)		With federal subsidy ($G_t + A_t = C_{t,capex}$) (2)		Without federal subsidy ($G_t = 0$ & $A_t = 0$) (3)
1	Cash inflows	37,815		15,215	
2	Annual bill savings		15,215		15,215
3	Grant & loan		22,600		-
4	Cash outflows	36,253		24,001	
5	Investment cost		22,600		22,600
6	O&M expenditures		1,401		1,401
7	Loan repayment		12,252		-
8					
9	**Financial NPV**	**1,563**		**− 8,785**	

The picture changes without the federal subsidy. The present value of the benefits received by the prosumer before receiving the subsidies from the Federal Government is 15,215 CAD (Table 4, column 3, row 1). As shown in Table 4, column 3, the present value of the benefits of the system is not sufficient to break even, given the investment and operating costs. Indeed, such an investment is doomed to be infeasible in the absence of subsidies, with a net present value of −8,785 CAD (Table 4, column 3, row 9). Once we measure the levelized cost of the representative net-metered solar PV system, it appears that the rooftop solar PV has a levelized cost of 0.21 CAD per kWh as of 2021. However, the levelized savings in electricity bills with a net-metered system add up to only 0.13 CAD per kWh.

3.2 Canadian economy's perspective

Table 5 reports the values of the incremental economic resource flow, benefits, and costs created by a net-metered system (Eq. 6 and 7). The main benefit from the whole society's perspective is the savings in natural gas purchases during the operating hours of the net-metered solar PV system. Each kWh of solar-generated electricity displaces 1 kWh of electricity generation in a natural gas power plant. After adjusting the output of the net-metered system for transmission and distribution ($TD_t = 3\%$) and the weighted average of displaced natural gas plants (the second component of Eq. 6), the present value of avoided natural gas purchases is 3,220 CAD.

Table 5: Economic outcome of a representative net-metered solar in Ontario

Resource flows statement	Present value @EOCK = 7% (CAD, 2021 prices)	
1.Economic resource inflows	3,220	
• Fuel savings (natural gas savings)		3,220
2. Economic resource outflows	21,701	
• Investment cost (exclusive of sales tax)		20,000
• Operating and maintenance (O&M)		1,401
• Solar-to-grid integration cost		300
3. Net economic resource flows	**−18,480**	

Not all the cost of the avoided natural gas purchases translates into resource savings for Canada because for each unit of natural gas avoided, the Government of Alberta loses royalty revenues ($R_t^{AL} = 8\%$). The present value of forgone royalty revenues due to the displacement of gas power plants by solar adds up to 259 CAD over 25 years. We will assign the value of forgone royalty revenues as a loss to the Government of Alberta later in the stakeholder analysis.

Table 5, row 3 reports that the net economic cost per prosumer is −18,480 CAD. Comparing this value to the present value of the resource cost of each system, we find that from Canada's point of view, 85 percent of the resources spent are wasted. When comparing this cost to the net financial benefits received by the prosumer of 1,563 CAD (including the subsidies), the net economic cost to Canada is 12 times the private benefit to those who install the rooftop solar systems. This might be an unprecedented waste of economic resources by a government-incentivized program.

3.3 Non-prosumers' perspective

Those electricity consumers who do not make investments in net-metered systems will be the first on the list of stakeholders when it comes to the negative impacts. The impacts borne by non-net-metered consumers are linked to the local distribution companies' (LDC) losses and gains (Eq. 10, 11, and 12). From the LDC's perspective, the trade-off is between the incremental costs to the grid of connecting prosumers and the avoided costs from not having to supply the energy generated by prosumers. The incremental costs are comprised of lost revenues due to reductions in prosumers' bills and solar-to-grid integration costs. On the other hand, the avoided costs reflect the fuel savings for the displaced marginal resource. Whatever the net impact turns out to be, it will be passed on to consumers.

As shown in Table 6, an 8-kW net-metered solar system imposes a net cost of 12,286 CAD to non-net-metered consumers (the outcome of Eq. 12). Using the annual average natural gas prices over the evaluation period, the present value of savings in natural gas purchases ($B_t^{consumers}$ in Eq. 10) amounts to 3,479 CAD for each representative net-metered system[12]. These figures imply that the net loss to other electricity consumers is 12,286 CAD (Table 6, row 1), almost 8 times the benefits received by the net-metered prosumers.

Table 6: Stakeholder impacts of a representative net-metered solar PV system in Ontario

Stakeholder	Present values @EOCK=7% (CAD, 2021 prices)	
1. Ontario's non-net-metered electricity consumers	**−12,286**	
a. Savings in natural gas purchases		3,479
b. Forgone utility revenues due to reductions in prosumers' bills		−15,466
c. Solar-to-grid integration cost by net-metering program		−300
2. Federal Government	**−9,661**	
a. Subsidies		
Canada Greener Homes Grant Initiative		−5,000
Canada Greener Homes interest-free loan		−17,600
Interest-free loan repayment by prosumers		12,252
b. Tax revenues		
HST revenues from installed net-metered capacity		1,000
Forgone HST revenues on grid-electricity charges by prosumers		−313
3. Ontario Government	**2,163**	
a. Subsidies		
Saving in OER payments to prosumers		1,064
b. Tax revenues		
HST revenues from the installed net-metered capacity		1,600
Forgone HST revenues on grid-electricity charges by prosumers		−501
4. Alberta Government	**−259**	
a. Royalty revenues		
Forgone royalty revenues from natural gas production		−259
5. All stakeholders within Canadian economy (1+2+3+4)	**−20,043**	
6. Global environment (CO_2 emission reduction)	**4,266**	

[12] We use the natural gas price forecasts used by the OEB in the Ontario Wholesale Electricity Market Price Forecast report (OEB, 2021). The average Dawn/Union hub natural gas market price is 4.11, 5.05, and 5.10 CAD/MMBtu for 2021, 2022, and 2023–2045, respectively.

Such a significant cost-to-benefit ratio occurs because prosumers are compensated for their exports to the grid at the same rate at which they purchase electricity from the grid. However, the only savings from the grid's perspective are the avoided variable fuel costs of marginal generation capacity during the time when the effective capacity of solar systems coincides with the system peak. The generation capacity cannot be deferred or avoided due to the installation of distributed solar PVs because it is unlikely that solar will provide capacity at times when it is needed (Astier, Rajagopal, and Wolak 2021).

Indeed, the electric utility will incur additional integration costs ($C_{t,int}$) to manage the net-metered capacity that is connected to the distribution grid. The integration costs include various required investments ranging from upgrading transformers to the procurement of additional ancillary services such as reserves and fast-ramping resources due to the intermittency of solar output. With a conservative assumption of 2.65 CAD per MWh of net-metered installed capacity for integration costs, the present value of integration costs is 300 CAD.

3.4 Federal Government's perspective

The stakeholder impacts of the net-metering program are not limited to the electricity market. The net impact on the Federal Government materializes through the subsidies provided by the Greener Homes Grant Initiative and taxes earned/forgone with the introduction of net-metered systems. (Eq. 13, 14, and 15) The Federal Government pays 5,000 CAD in grants (G_t) and 17,600 CAD in loans (A_t) to finance an 8-kW net-metered solar system. The loans will be repaid by prosumers over ten years, with a present value of 12,252 CAD. Thus, the net cost of the federal subsidy is 10,348 CAD. This subsidy to the prosumer is equivalent to 0.10 CAD per kWh over the system's lifetime.

The Federal Government also experiences changes in tax revenues per unit of installed net-metered capacity. The first impact is incremental tax revenue through the sales taxes charged when a household installs a solar PV system. The value of sale tax revenues from installed net-metered capacity adds up to 1,000 CAD ($s_t^{FG} \times C_{capex}$ in Eq. 13). However, as prosumers reduce their electricity bills, there will be some forgone sales tax revenues for the Federal Government, with a present value of 313 CAD over 25 years. The net impact on the Federal Government is a loss of 9,961 CAD (Table 6, row 2). The fiscal loss is equal to six times the net present value of the benefits received by the prosumers.

3.5 Government of Ontario's perspective

Provincial governments also experience some fiscal impacts. The Ontario Government is the only stakeholder, along with prosumers, that does not end up with a net loss due to the negative impacts created by the additional net-metered solar capacity (Eq. 18). Increased sales tax revenues from the sales of solar PV systems and savings in the OER rebates to prosumers are the two main incremental revenues from the Ontario Government's perspective, while forgone sales tax revenues from prosumers due to reduced grid-electricity consumption offset about 17 percent of the incremental revenues. For each 8-kW net-metered system installed, although the Government of Ontario experiences a loss of sales tax revenues amounting to 501 CAD (in present value terms over 25 years), it benefits from 1,600 CAD of incremental tax revenues from the solar PV system sales, and 1,064 CAD of savings in OER payments. Therefore, a representative solar net-metered system improves the Ontario Government's fiscal expenditures by 2,163 CAD in present value terms (Table 6, row 3).

3.6 Government of Alberta's perspective

The Government of Alberta loses the royalty revenues from the avoided natural gas purchases by Ontario (Eq. 19). The present value of forgone royalty revenues per 8-kW solar PV system installation is estimated at 259 CAD.

3.7 Global environment's perspective

Each 8-kW net-metered solar installation promoted by the Greener Homes Initiative reduces CO_2 emissions over its lifetime by a present value of 45 metric tonnes. According to the federal carbon pricing benchmark in Canada, the carbon price is scheduled to increase by 15 CAD per year, starting from 65 CAD/tonne CO_2e in 2023 to 170 CAD in 2030 and staying at 170 CAD thereafter (Government of Canada 2021)[13]. The product of reduced CO_2 emissions and carbon pricing schedule over 20 years results in a present value of global environmental benefits of 4,266 CAD (the outcome of Eq. 20)[14]. These savings are only 20 percent of the economic costs incurred to accommodate the solar net-metered capacity[15].

From Eq. 23, the economic perspective is expressed as the sum of the economic analysis from the point of view of Canada plus the social savings (valued at the social price of carbon set by the Government of Canada) from the reduction in GHG emissions. With a net economic cost of 18,480 CAD from the perspective of the residents of Canada, there is a need to add the global savings of 4,266 CAD from the reduction in GHGs to arrive at an economic net present value from a global perspective. The net result of this program, from a global perspective, is a loss of 14,214 CAD. Moreover, the results from this analysis show that the levelized cost of carbon abatement by net-metered solar systems will be 413 CAD per ton of abated CO_2,

[13] The Federal Government's carbon prices reflect its maximum willingness to pay to reduce GHG emissions rather than reflecting the monetary values of the averted damage to residents of Canada due to the reduction in CO_2 emissions. Therefore, these shadow prices are used in the cost-benefit analysis of interventions that will have an impact on GHG emissions to determine whether the economic benefits from an intervention exceed the economic resources spent by the intervention.

[14] It is worthwhile mentioning here that the intermittent nature of solar power requires additional backup power from natural gas plants. If Ontario experiences a surplus of base-load generating capacity, further additions to base-load in the form of solar power may require removing a nuclear plant from operation and replacing it with a combination of renewable and gas-fired generation, yielding a net increase in emissions (see McKitrick (2013)).

[15] This finding is comparable with those of Bahramian, Jenkins, and Milne (2021), who found that the environmental benefits of Ontario's wind power generation are only 11 percent of the net economic losses created by wind generation.

significantly higher than the proposed current (65 CAD in 2023) and future (170 CAD by 2030 and thereafter) social cost of carbon by the Federal Government of Canada.

In sum, Table 6 represents the magnitude and direction of impacts on each group of stakeholders other than prosumers. As a result of adding a net-metered solar PV, Ontario's non-net-metered electricity consumers, the Federal Government, and the Alberta Government incur economically significant losses, whereas the global environment and the Government of Ontario gain, albeit proportionally at lower levels. In terms of impact magnitude, non-net-metered electricity consumers bear the highest burden of losses.

3.8 Reconciliation of financial, economic, and stakeholder analyses

Table 7 shows the reconciliation of the financial, stakeholder, and economic outcomes. The financial NPV, present value of stakeholder impacts and economic NPV are obtained from Tables 4, 5, and 6, respectively. The fact that the summation of financial NPV (1,563 CAD) and stakeholder impacts (−19,535 CAD) equals the economic NPV (−18,524) confirms that the analysis is performed consistently.

Table 7: Reconciliation of financial, economic, and stakeholder outcomes (present values, 2021 CAD)

Impact	Economic	Prosumers	Non-prosumers	Federal Government	Provincial governments	Global environment
A. Net impact (Canada perspective)	−18,480	1,563	−12,286	−9,661	1,904	-
B. Net impact (Global perspective)	−14,214	1,563	−12,286	−9,661	1,904	4,266

From the results in Table 7, it appears that in contrast with prosumers and the global environment, non-prosumers and the Federal Government are big losers. There is a "shadow value" for the reduction of GHG emissions of 4,266 CAD per prosumer, but this is far below the economic cost to the country of this investment.

4. Aggregated impacts at the Greener Homes Initiative program level

A total of 2.6 CAD billion in grants and 4.4 CAD billion in interest-free loans are allocated in the Federal Government's budget for the Greener Homes Initiative for a period of seven years, starting from 2021. If only 20 percent of the loans (880 CAD million) are taken by Ontarian households to install a solar net-metered system, the aggregated capacity encouraged by this generous subsidy program approximates to 400 MW (about 50,000 new prosumers). Our previous findings for a representative prosumer's investment enable us to aggregate the combined impact of the Federal Greener Homes Initiative and Ontario's net-metering program.

Table 8: Aggregated impact (present values discounted @EOCK = 7%, million CAD)

Impact	Canadian economy	Prosumers	Non-prosumers	Federal government	Provincial governments	Global environment
A. Net impact (Canada perspective)	− 924	78	− 614	− 483	95	-
B. Net impact (global perspective)	− 711	78	− 614	− 483	95	213

As shown in Table 8, the net economic losses will rise to 924 CAD million, compared with a financial gain of 78 CAD million for new prosumers. Additionally, households that are not prosumers will incur a financially significant burden of 614 CAD million. The aggregated impacts highlight the significance of resource waste from the Canadian and global economies perspectives.

5. Conclusion

The results of this analysis allow us to conclude that residential rooftop solar with net metering is currently an economically inefficient and unsustainable program in Ontario, Canada. A representative household would lose financially if they were to invest in net-metered rooftop solar without the Federal Government's investment subsidy. Moreover, the stakeholder analysis reveals that the net financial loss borne by non-net-metered households per net-metered solar system installed in Ontario is eight times the benefits received by the net-metered households. The impacts of Ontario's net-metering program on the Federal Government and the Canadian economy are net losses, amounting to six and twelve times the net present value of the benefits received by the net-metered households, respectively. The only stakeholder that benefits marginally is the Government of Ontario.

Over the last decade, Ontario's electricity consumers have been experiencing unnecessarily high electricity prices, partly because of fixed-price 20-year contracts for solar and wind energy resources. The incremental cost of these contracts has been reflected in the Global Adjustment payments to electricity generators and eventually reflected in electricity consumers' electricity bills. With solar and wind contracts making up more than 30 percent of the Global Adjustment, promoting another inefficient program (at least at the residential level), such as net metering, will result in nothing but higher costs to Ontario residents, disproportionately from low-income households. Extending the Federal Government's subsidy coverage only worsens the inequity and inefficiency issues of the net-metering program. Borenstein (2022) suggests that if policymakers believe that rooftop solar should continue to be given special support, the extra funds should be financed primarily by progressive income taxes.

Provided that the objective is to address the threat of global warming by reducing GHG emissions, major capital-intensive expenditures will need to be made in many cost-effective interventions. The private and public capital resources needed to bring about this major societal transformation are limited. Hence, inefficient incentive programs are a backward step, financing expensive unproductive "green energy resources" for some better-off households.

This study clearly shows that the net impact of these programs is to waste scarce financing that could be used for financing more cost-effective interventions in the energy sector.

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