Journal of Benefit-Cost Analysis (2024), 1–26
doi:10.1017/bca.2024.9

CAMBRIDGE UNIVERSITY PRESS

ARTICLE

Renewable Energy Support Through Feed-in Tariffs: A Retrospective Stakeholder Analysis

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Keywords: benefit–cost analysis; Canada; distributed energy resources; feed-in tariff; Ontario; renewable energy subsidy; stakeholder analysis

JEL Codes: D61; Q48; Q42; Q51

Abstract
This study develops a generalized evaluation framework that can be used to quantify the financial, economic, stakeholder, and environmental impacts of renewable energy support programs. The application of this framework is demonstrated by evaluating the feed-in tariff (FIT) program for solar distributed energy resources (DER) in Ontario, Canada. Our analysis reveals that Ontario's FIT program has successfully promoted the adoption of solar DER across communities. However, the program has caused inequitable societal outcomes through a cross-subsidization with a present value of 9 CAD billion, paid for by the electricity consumer base for the benefit of only the 0.06 percent of electricity consumers who could install solar systems. The cost imposed on the Canadian economy ranges from 2.86 to 5.37 CAD billion, depending on the discount rate applied. The sensitivity analysis results indicate that the burden of this program on the Canadian economy would have been reduced by 50 percent if the program had been delayed and implemented in 2016 instead of 2010 due to the declining trend in solar system investment costs. The lessons from this analysis provide insights for designing future environmental and emission reduction policies.

1. Introduction

With national and subnational governments increasingly designing programs to promote investments in renewable energy resources, an important policy question is how the benefits and costs of these programs are allocated among the stakeholders after the program implementation. The answer to this question will provide key insights to enable decision-makers to reform existing programs to the extent possible and improve the design of similar programs in the future. This study aims to formalize an ex-post evaluation framework for estimating the magnitude of the impacts created by a renewable energy support program. As a case study, we apply the framework to assess the feed-in tariff (FIT) program for distribution-connected solar photovoltaic (PV) systems in Ontario, Canada, over the decade following its implementation in 2010.

The FIT program is one of the most widely adopted programs worldwide. As of 2022, more than 90 national and subnational governments had implemented some form of FIT program (REN21, 2022). In Canada, the Ontario Green Energy and Green Economy Act (herein the Green Act) was introduced in 2009 to accelerate the addition of renewable energy resources into Ontario's electricity generation mix. Ontario's FIT program was established in the Green Act, providing long-term fixed-price power purchase agreements (PPAs) for renewable energy generators, including on-shore wind, solar PV, renewable biomass, hydropower, biogas, and landfill gas.

We begin our analysis by identifying all stakeholders involved in the FIT program: (1) FIT participants, (2) other electricity consumers in Ontario (nonparticipants), (3) provincial and federal governments, and (4) the global environment. We then develop a series of equations describing how the benefits and costs to each of these stakeholders are measured throughout the program's life. The evaluation period is set from 2010 to 2038, but all the estimates are from the perspective of the year 2023 and are therefore expressed in 2023 prices.

Our results indicate that the program successfully attracted participants because the expected financial rates of return were above the participants' opportunity cost of capital. The financial return for FIT participants has an average of 15 percent (net of inflation), above the opportunity cost of capital of 7 percent used in our analysis. We also observe that rooftop systems were financially more attractive than ground-mount systems in the earlier years, mainly because of more generous PPA prices for rooftop systems. However, this pattern was reversed in later years due to the adjustments to the PPA prices for rooftop systems.

Despite the financial profitability of such investments for the participants, we estimate a significant cross-subsidization from the current and future residents of Ontario to the FIT participants: the present value of the financial burden imposed by the FIT participants between 2010 and 2038 (when the last contract expires) adds up to 9.23 CAD billion in 2023 prices. In the earlier years of the program, the shifted cost was recovered from the electricity consumer base through adjustments in electricity bills, but after the introduction of the Renewable Cost Shift program in 2021, the cost recovery was switched from the consumer base to the taxpayer base in Ontario. In other words, during the time that the costs were being recovered by increases in electricity bills, a total of 3,073 Ontario electricity consumers who were able to join the program between 2010 and 2019 benefited from the FIT program, while the remaining 5 million nonparticipating electricity consumers were required to compensate them.

We also quantify to what extent the output from solar PV systems displaces the electricity generation by the peaking power plants (natural gas-fired plants in the case of Ontario) and hence reduces the amount of carbon dioxide (CO_2) emissions in the province.[1] We see that for every dollar of global benefit from reducing CO_2 emissions, the economic cost to Canada is somewhere between three and eight dollars, depending on whether we employ the social

[1] In Ontario, nuclear and hydropower are the baseload resources, and natural gas power plants are the peaking dispatchable resources. Given that Ontario's system is a summer-peaking system and most of the solar output is generated during summer peak demand hours, the marginal displaced resource is typically a natural gas-fired power plant. Therefore, solar-generated electricity is considered a peak load generation resource because almost all its energy is supplied during the peak demand period.

https://doi.org/10.1017/bca.2024.9 Published online by Cambridge University Press

cost of carbon (SCC) estimated by the Government of Canada or the Federal Government's carbon pollution price, respectively.[2]

Moreover, we estimate the levelized cost of carbon abatement (LCCA) by solar PV systems under the FIT program. Ontario's solar FIT program has had an LLCA of 444 CAD per abated tonne of CO_2 (2023 prices), which is significantly greater than the value assigned to CO_2 abatement by carbon pollution pricing benchmarks in Canada (i.e. the national carbon pollution prices and the SCC estimates). As of 2023, the national carbon pollution price is 65 CAD, and the estimated SCC is 290 CAD per tonne of abated CO_2. Therefore, although the Ontario FIT program has significantly contributed to the emission reduction in the electricity sector, it has not been a cost-effective carbon abatement program.

In the final part of our analysis, we ask how the estimated impacts would have changed if the program had been implemented a few years later than its original implementation. The rationale behind this "what-if" analysis is that there was a consensus among industry experts around the time this program was implemented that the cost of solar PV systems was experiencing a rapidly declining trend. In such an environment, postponing the program implementation until the investment costs had become stable could potentially have resulted in substantial cost savings. Our analysis documents that if the program had been implemented in 2016 instead of 2010, the magnitude of the economic loss to the Canadian economy would have been 53 percent lower than the original estimated impact.

Our findings contribute to the literature on the role of benefit–cost analysis in the design of climate policies. As Bureau *et al.* (2021) argue, benefit–cost analysis has played a minor role in the design of climate policies. With heterogeneous abatement costs across and within sectors and across and within countries, an integrated benefit–cost analysis that deals with the efficiency and distributive impacts of climate policies is essential for achieving net zero emissions at a reasonable cost. The framework we develop in this paper provides a practical tool for policymakers to evaluate climate policies from the efficiency and equity perspectives.

The rest of the paper is structured as follows. Section 2 describes the design of Ontario's FIT program and reviews the concerns raised by the studies that analyzed this program in its early years. In Section 3, we provide a step-by-step description of the methodology and data sources we employ in this paper. Finally, we present our empirical results in Section 4 and conclude the paper by listing the conclusion and policy implications in Section 5.

2. Ontario's FIT program

The solar FIT program was designed with two streams: (1) micro-FIT stream for projects under 10 kW; and (2) FIT stream for projects over 10 kW. As of 2023, a total of 1,756 MW is procured under the micro-FIT (259 MW) and FIT (1,497 MW) streams, accounting for 55 percent of the total solar installations across Ontario (see Table 1).[3] Out of the 3,081 installed systems under the FIT stream, only eight are transmission-connected (80 MW),

[2] In this study, we estimate the annual societal benefits from the reduction in CO_2 emissions using two benchmarks: (i) the national carbon pollution price (starting from 20 CAD in 2010 and increasing to 170 CAD in 2038) and (ii) the social cost of carbon (starting from 35.4 CAD in 2010 and increasing to 368 CAD in 2038).

[3] These figures represent the installed capacity under the solar FIT program and not the actual energy output of these systems. While installed capacity represents the maximum amount of electricity that the installed system can supply at any given time, the actual amount of energy produced by solar panels varies due to weather conditions.

Table 1. *Ontario's installed solar capacity by contract type*

Contract type	Number of contracts	Contracted capacity (MW)	% of total solar capacity
Feed–in–tariff (FIT)			
FIT (>10 kW)	3,081	1,497	55%
Distribution–connected	3,073	1,417	52%
Transmission–connected	8	80	3%
Micro–FIT (≤ 10 kW)	30,067	259	9%
Net–metering (as of 2022)	3,124	66	2%
Other programs (GEIA, LRP, and RESOP)	83	894	33%
All contracts	36,355	2,716	100%

Source: Independent Electricity System Operator's report on contracted electricity supply, October 2022.
GEIA, Green Energy Investment Agreement Power Purchase; LRP, Large Renewable Procurement Program; RESOP, Renewable Energy Standard Offer Program.

while the rest are distribution-connected (1,417 MW). This study focuses on the distribution-connected systems under the FIT stream.[4]

It took only a few years for Ontario to become the leading jurisdiction for wind and solar energy in Canada. This dramatic increase in the share of total capacity installed was mainly due to relatively high rates of return and preferred access to transmission and distribution under the FIT program (Yatchew & Baziliauskas, 2011). However, the program's pricing model generated many controversies from the beginning because it offered renewable electricity producers a guaranteed rate far above the average electricity price, leading to substantial real increases in electricity bills for households and businesses (Auditor General of Ontario, 2011).

Proponents of the FIT program have argued that although the program has been costly, it has resulted in a "learning-by-doing" benefit, reducing the future costs of adoption due to technological and supply chain improvements. Nonetheless, Beck *et al.* (2018) show that even after assuming moderately high learning effects, the support rates offered by Ontario's FIT program cannot be justified. Some studies in the early years of program implementation raised concerns about the costs of supporting renewable electricity over the course of the FIT program (Dachis & Carr, 2011; Pirnia *et al.,* 2011), as well as the potential for a net increase in air emissions due to the backup requirements for solar and wind resources (McKitrick, 2013).

Eventually, the program limited the acceptance of new applications. On February 24, 2017, in his speech at the Economic Club of Canada in Ottawa, Ontario's Energy Minister, Glenn Thibeault, admitted that the FIT program had led to "suboptimal outcomes" for consumers and increased prices in electricity for families and businesses in Ontario.[5]

[4] The electricity generated by the FIT solar PV systems is injected into the electricity grid at either the transmission level or the distribution level. Transmission-connected generators are large-scale facilities connected to the high-voltage IESO-controlled grid, whereas distributed-connected generators (also known as embedded generators) are small-scale generators located within local distribution companies' territories.

[5] Global News, February 24, 2017. https://globalnews.ca/news/3272095/ontario-energy-minister-admits-mistake-with-green-energy-program.

https://doi.org/10.1017/bca.2024.9 Published online by Cambridge University Press

3. Methodology and data

3.1 Methodology

Our analysis is conducted in three parts. First, we develop an integrated investment appraisal (IIA) framework that enables us to estimate the FIT program's impacts on each stakeholder affected by this program. Second, we evaluate the cost-effectiveness of abating greenhouse gas (GHG) emissions by the FIT program by estimating the LCCA. Third, we ask how the findings from the first and second parts of the analysis would have changed if the implementation of the FIT program had been postponed by 6 years. In the following subsections, we describe each of the components.

3.1.1 IIA framework

The IIA method evaluates the benefits and costs in terms of domestic prices from both financial and economic points of view rather than carrying out these analyses separately. Based on this method, the summation of the net present value of net financial cash flows ($NPV_t^{financial}$) and the present value of stakeholders' impacts ($PV_{i,t}^{stakeholder}$) created by the program should be equal to the net present value of economic resource flows ($NPV_t^{economic}$) over its life. This relationship is expressed in Equation 1.

$$NPV_t^{economic} = NPV_t^{financial} + \sum_i PV_{i,t}^{stakeholder} \tag{1}$$

The rate at which financial, economic, and stakeholder impacts are discounted should be the economic opportunity cost of capital (EOCK). The EOCK is the measure of the real opportunity cost of funds used to finance investments that are drawn out of the country's pool of capital (both private and public). For Canada, the EOCK is estimated to be 7 percent (Jenkins & Kuo, 2007; TBCS, 2022).[6]

We now describe how we adopt this framework to evaluate Ontario's FIT program for solar PV systems. Those electricity consumers who joined the FIT program by installing solar PV systems are the financial beneficiaries. From their perspective, the decision to join solely depended on the net financial impact of the investment over the PPA contract term (i.e. 20 years). However, there will also be some economy-wide benefits and costs that do not flow to the FIT participants, such as cost savings from avoided fossil-fuel-based electricity generation or the costs of integrating solar PV systems into the electricity network. While these items do not show up in the financial cash flow statements, the economic resource flow statement captures these impacts, eventually reflected in the net present value of economic impact ($NPV_t^{economic}$).

If the economic and financial analyses are done correctly, the difference between the two will be a series of distributional impacts that can be identified and measured. In addition to the private investors, four other stakeholders within the Canadian economy are affected by

[6] According to Jenkins and Kuo (2007), when a public intervention requires funds that are extracted from the capital markets, the funds are drawn from three sources: funds that would have been invested in alternative investment opportunities, domestic savings, and foreign capital inflows. EOCK is the weighted average cost of the three funding sources: the rate of return on alternative postponed investment, the rate of interest (net of tax) on domestic savings, and the marginal cost of additional foreign capital inflows. Therefore, it is the appropriate economic discount rate when evaluating interventions from the societal perspective.

the FIT program: (1) Ontarian electricity consumers who did not join the FIT program; (2) the Government of Ontario; (3) the Government of Alberta; and (4) the Federal Government of Canada.[7] Given that the FIT program's objective is to reduce GHG emissions in the electricity sector, we also consider the global environment as another stakeholder from the global perspective (i.e. the Canadian economy plus other economies).

Equation 2 specifies the general relationship shown in Equation 1 for Ontario's solar FIT program.

$$NPV_t^{Canadian\ Economy} = NPV_t^{FIT\ Participants} + \underbrace{PV_t^{ON\ electricty\ consumers} + PV_t^{FG} + PV_t^{ON} + PV_t^{AL}}_{\text{Stakeholder impacts}} \tag{2}$$

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

The present value of the net impact from a global perspective ($PV^{Global\ economy}$) is derived by adding the environmental benefit from the reduction in GHG emissions to the present value of net economic impact from Canada's perspective to arrive at Equation 3.

$$NPV_t^{Global\ economy} = NPV_t^{Canadian\ Economy} + \underbrace{PV_t^{GHG\ emission\ reduction}}_{\text{Global Environment}} \tag{3}$$

It should be mentioned here that our analysis is retrospective, given that the FIT program has been in place since 2010, that is, for 13 years at the time of this study. Therefore, when we estimate the present values, we make a series of adjustments to ensure that the values represent the current year's perspective ($t = t_n$). In other words, the opportunity cost of net cash or resource flows realized in the earlier years of the program (between t_0 and t_n) must be compounded to the current year (i.e. the year 2023 in this analysis). On the other hand, the flows that will be realized in future periods must be discounted back to the current year. Equation 4 formalizes the framework employed in our methodology to estimate the present value of cash and resource flows, where NCF_t and $EOCK$ denote net cash/resource flows in time t and EOCK, respectively.

$$PV_{t_n} = \sum_{t=t_0}^{t=t_n} NCF_t (1 + EOCK)^{t_n - t} + \sum_{t=t_{n+1}}^{t=t_e} \frac{NCF_t}{(1 + EOCK)^{t_e - t}} \tag{4}$$

In the following subsections, we explain how we measure the net impact of the FIT program on each of the stakeholders listed in Equation 3.

3.1.1.1 FIT participants. From each participant's perspective, the decision to invest in a FIT solar system depends on whether the present value of the payments under the PPA outweighs the present value of the solar PV system's investment cost, maintenance cost, and income taxes. The annual inflow of a FIT project is the gross-of-tax revenues for the total MWhs of electricity generated in that year. Consequently, the first step in evaluating the

[7] The solar FIT program was implemented in Ontario, but the stakeholder impacts of this program extend beyond the Province of Ontario due to the indirect incremental fiscal impacts in the form of forgone royalty revenues and income tax revenues on the Government of Alberta and the Federal Government of Canada, respectively. Section 3.1.1.4 describes these impacts in detail.

https://doi.org/10.1017/bca.2024.9 Published online by Cambridge University Press

participation decision is to estimate the annual solar-generated electricity by participant i in year t ($q_{i,t}$), which is the product of installed capacity (k_i) and solar potential yield (i.e. kWhs of solar electricity per kW of installed capacity) at the participant's location (θ_i). The output must be adjusted for efficiency losses over the system's economic life at an annual rate of α.

$$q_{i,t} = k_i \times \theta_i \times (1 - \alpha)^t \tag{5}$$

Next, the local electricity distribution company purchases the solar system's output from the participant at the pre-determined PPA price (p_{FIT_t}). Equation 6 demonstrates how the yearly nominal revenues ($r_{i,t}$) for a representative participant are projected.

$$r_{i,t} = q_{i,t} \times p_{FIT_t} \tag{6}$$

As shown in Equation 7, the cash outflows have three components: (1) the upfront capital expenditures at year 0; (2) the operating and maintenance expenditures of the installed system, that is, mainly the cost of replacing the inverter after 12 years of operation,[8] and (3) the income tax payable on the income from FIT payments after deductions.

$$c_{i,t}^{FIT\,participant} = \underbrace{c_{i,capex}}_{\text{capital expenditures}} + \underbrace{c_{i,t,opex}}_{\text{operating expenditures}} + \underbrace{TI_{i,t} \times CIT}_{\text{income tax expense}} \tag{7}$$

While the capital and operating expenditures can be estimated by the system size, the taxable income varies over the 20-year evaluation period. Thus, to calculate the taxable income, the following items must be deducted from the revenues: operating and maintenance costs, capital cost allowance (CCA), and the interest paid on debt. The only operating and maintenance cost over the system's economic life is the cost of replacing the inverter after 12 years of operation ($OM_{i,t}$). Under the Income Tax Regulations, the capital costs of solar PV systems are eligible for a 50 percent accelerated CCA on a declining balance basis. Finally, the investment is often financed by a mix of debt and equity, so the annual interest paid on the debt (denoted by $IE_{i,t}$) is deductible from gross revenues. Thus, the taxable income ($TI_{i,t}$) is calculated by subtracting all the deductibles from the gross revenues, as expressed in Equation 8. For the years in which taxable income is negative, the losses are not carried forward but are used to offset taxable income from other business activities.

$$TI_{i,t} = r_{i,t} - c_{i,t,opex} - CCA_{i,t} - IE_{i,t} \tag{8}$$

We use Equations 6–8 to project the benefits and costs to a representative FIT participant over the 20 years of the FIT contract.

3.1.1.2 Canadian economy. The Canadian economy benefits in the form of avoided purchases of natural gas by the displaced gas-fueled electricity generation plants in Ontario and the health benefits due to the relative reduction in emitted pollutants from these plants.[9]

[8] Inverters are one of the most important components of solar photovoltaic systems. Their primary function is to transform a solar photovoltaic system's variable direct current output to usable alternating current that can be fed into the electrical grid or utilized on-site by the system owner. The inverter must be replaced after 12 years, unlike all other system components, which have an expected life of 20 years. Hence, we estimate the present value of purchasing a new inverter in 12 years and add it to the upfront investment in the cash flow statement.

[9] According to Ontario's electricity system operator, the IESO, more than 80 percent of total electricity output has been supplied by nuclear and hydropower baseload generators over the 2010–2022 period. For peak demand, Ontario has historically relied on natural gas-fired power plants and renewable energy generators (wind and solar

https://doi.org/10.1017/bca.2024.9 Published online by Cambridge University Press

To quantify the economic benefits from savings in natural gas purchases in year t (B_t^{econ}), we measure the annual quantity of natural gas purchases avoided by displaced natural gas plants (NG_t^d) and multiply those quantities by the average price of natural gas in that year (p_t^g).

The equation for estimating the quantity of avoided natural gas has two components (Equation 9): (1) the total quantity of solar-generated electricity by all FIT participants in any given year ($Q_t = \sum q_{i,t}$) and (2) the weighted average of heat rates ($w_{j,t}HR_j$), that is, the rate at which gas-fueled plants would turn one unit of natural gas into one unit of electricity.[10] The first component must be adjusted for the avoided transmission losses (TL_t) that no longer occur because of the proximity of the electricity supply source to end-use consumers. Also, the second component needs to be adjusted for the annual reduction in the heat rates ($l_{j,t}$) to reflect the loss in technical efficiency of Ontario's gas-fueled fleet over their operating lives.

$$NG_t^d = \underbrace{\sum_t \frac{Q_t}{(1 - TL_t)}}_{\text{Solar}-\text{generated electricity}} \times \underbrace{\sum_{j,t} w_{j,t} HR_j \left(1 - l_j\right)^t}_{\text{Weighted average of heat rates}} \tag{9}$$

It should be noted here that most of the natural gas used in Ontario comes from Alberta. For each unit of avoided natural gas in Ontario's electricity generation, the Government of Alberta loses the royalty revenue (r_t^{AL}) that it would have collected from selling that unit to Ontario.[11] Therefore, we consider the forgone value of royalty revenues to Alberta by adjusting the natural gas price when estimating the net economic benefits in Equation 10.

$$B_t^{avoided\,gas\,purchases} = p_t^{gas}\left(1 - r_t^{AL}\right) \times NG_t^d \tag{10}$$

Conducting an in-depth assessment of the air quality impacts of Ontario's FIT program is out of the scope of this study. We employ a reduced-form screening method developed by the Environmental Protection Agency (EPA), known as benefit-per-tonne (BPT), to approximate the health benefit (B_t^{health}) associated with reducing a tonne of a given air pollutant from a particular source. As illustrated in Equation (11), the health benefits are the product of the

mainly) after the complete phase-out of coal power plants in the early 2010s. Therefore, we assume the output of solar PV systems displaces the natural gas-fired power plants, that is, the only source of direct emissions in Ontario's electricity system. An overview of the IESO's reports supports this assumption, given that the marginal emission factor in Ontario is closely aligned with how often natural gas plants are on the margin (IESO, 2021). Additionally, IESO hourly generation output reveals that there are always natural gas plants operating during the time the solar PV generates in Ontario.

[10] The heat and emission rates may vary across Ontario's installed natural gas fleet. To factor this heterogeneity in our model, we consider the four types of natural gas plants that exist in Ontario: combined cycle (CC), combined heat and power (CHP), simple cycle (SC), and steam turbine, constituting 70, 29, 0.35, and 0.65 percent of the total gas-fired capacity, respectively. With 99 percent of the natural gas plants being the highly efficient types of CC and CHP, the impact of less efficient marginal generators (SC or steam turbine) on our estimates of the displaced quantity of natural gas would be insignificant.

[11] Alberta will eventually sell Ontario's displaced natural gas exports to another importer at some point in time. The net fiscal impact on the Government of Alberta will be the present value of the royalty revenues collected from a substitute importer and the revenues that would have been paid on the gas if sold to the Ontario electricity generators. It is out of the scope of our study to estimate the net fiscal impact on the Government of Alberta. However, we must exclude the forgone royalty revenues from the economic benefits of avoided natural purchases in Ontario (see Equation 10) to ensure we do not overestimate those benefits.

quantity of displaced natural gas (NG_t^d), each pollutant's emission factor per unit of natural gas ($f^{pollutant}$), and the BPT for reduced emission of each pollutant ($BPT^{pollutant}$).

$$B_t^{health} = NG_t^d \times f^{pollutant} \times BPT^{pollutant} \quad (11)$$

On the economic cost side, three categories of costs must be accounted for: (1) the capital expenditures of the installed solar PV systems under the FIT program ($C_{t,capex} = \sum_i c_{i,capex}$), (2) the resources spent on the operating expenditures of those systems ($C_{t,opex} = \sum_i c_{i,opex}$), and (3) 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 follows:

$$C_t^{econ} = C_{t,capex} + C_{t,opex} + C_{t,int} \quad (12)$$

$$NPV^{econ} = \sum_t^T \frac{B_t^{econ} - C_t^{econ}}{(1 + EOCK)^t} \quad (13)$$

In addition to evaluating the economic impacts that directly affect Canada, we must evaluate the incremental global environmental impacts of the FIT program 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 as a direct benefit to Canadian residents.

3.1.1.3 Electricity consumers in Ontario. One of the main challenges associated with FIT programs is that the compensation offered to the FIT system owners can lead to cost shifting onto nonparticipants. Ontario's Independent Electricity System Operator (IESO) is a revenue-neutral electricity system operator; therefore, it shifts the incremental benefits and costs of the FIT PPA to its remaining consumer base. On the benefit side, the solar electricity generated by the FIT systems 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. On the cost side, the present value of the FIT contract payments (i.e. summation of all participants' revenues, $\sum_{i,t} r_{i,t}$) will be passed on to all electricity consumers in Ontario.

Additionally, solar energy production under the FIT program is mostly located within the electrical distribution systems, and the electricity distribution companies will incur incremental integration costs to host the FIT capacity in their distribution network.[12] The integration costs include various required investments ranging from upgrading transformers

[12] This contrasts with what distributed-generation advocates claim about the avoided investments in the distribution network because of solar DERs. There are two reasons why we believe their impact on the distribution network is an incremental cost. First, the empirical evidence suggests that solar DERs have an insignificant to no impact on reducing the required investments in distribution networks (Astier *et al.,* 2023). Second, a review of Ontario Energy Board reports on the issues related to the connection of embedded generation facilities demonstrates that distribution companies have raised concerns about the cost responsibility of upstream upgrades in their distribution networks as the penetration rate of solar DER increases (OEB, 2012).

to the procurement of additional ancillary services such as reserves and fast-ramping resources due to the intermittency of solar output.[13]

Consequently, the net incremental impact on Ontario electricity consumers is the present value of the difference between the benefits from savings in natural gas purchases for electricity generation ($B_t^{ON\ electricity\ consumers}$) and the costs that will be passed on to all electricity consumers across Ontario ($C_t^{ON\ electricity\ consumers}$).

$$B_t^{ON\ electricity\ consumers} = p_t^{gas} NG_t^d \tag{14}$$

$$C_t^{ON\ electricity\ consumers} = \sum_{i,t} r_{i,t} + C_{t,int} \tag{15}$$

$$PV^{ON\ electricity\ consumers} = \sum_t^T \frac{B_t^{ON\ electricity\ consumers} - C_t^{ON\ electricity\ consumers}}{(1 + EOCK)^t} \tag{16}$$

3.1.1.4 Government (federal and provincial levels). The introduction of the FIT program has also created fiscal impacts on both the Federal and Provincial Governments in the form of changes in the expected tax revenues. Business income tax regulation had considered an accelerated CCA for investments in clean energy generation equipment such as solar PV systems. Therefore, both government levels have experienced some level of forgone corporate income tax revenues as a result of having accelerated rather than regular capital cost deduction rates (50 percent vs. 30 percent annual deduction allowance). In other words, the CCA creates a tax shelter for businesses by shifting investments toward clean energy generation equipment, but those benefits for businesses translate into forgone tax revenues for the government. Equation 16 shows that the cost to the government at year t (C_t^{Gov}) is estimated by multiplying the change in taxable income at that year ($\Delta TI_{i,t}$) by the corporate income tax rate (CIT^{Gov}).

$$C_t^{Gov} = \Delta TI_{i,t} \times CIT^{Gov} \tag{17}$$

The present value of the net impact on government levels is estimated as shown in Equation 18.

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

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:

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

[13] The natural gas-fired generation in Ontario has played the main role in providing backup reliability services to the grid. As of December 2022, natural gas generation provides 28 percent of the electricity system's installed capacity, whereas the actual amount of energy produced by natural gas plants accounts for only 8.6 percent of the total amount of energy produced.

https://doi.org/10.1017/bca.2024.9 Published online by Cambridge University Press

3.1.1.5 Global environment. Reduced GHG emissions 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 carbon pollution price.

To calculate the value of environmental benefits, we first need to project the quantity of natural gas displaced by net-metered systems (NG_t^d) and then use the weighted average emission factor of the natural gas fleet in Ontario (F_t^{CO2}) to estimate how many megatons of CO_2-equivalent emissions will be avoided.[14] After estimating the associated levels of emissions, we assign a price to the CO_2 emitted to quantify the global environmental benefits. The present value of avoided CO_2 emissions that is attributable to the installed solar FIT capacity is estimated as follows:

$$PV^{environment} = \sum_t^T \frac{p_t^{carbon}\left(NG_t^d \times F_t^{C02}\right)}{(1+EOCK)^t} \tag{20}$$

3.1.2 The LCCA

The LCCA for a given technology is the carbon price (in real terms) that would equate the present value of economic benefits from the avoided GHG emissions by the solar-generated electricity ($NG_t^d \times F_t^{C02}$ from Equation 20) with the present value of net economic costs of that technology over its economic life ($\frac{C_t^{econ}}{(1+EOCK)^t}$) from Equation (13).

$$\sum_t^T \left[\frac{NG_t^d \times F_t^{C02} \times LCCA}{(1+EOCK)^t}\right] = \sum_t^T \frac{B_t^{econ} - C_t^{econ}}{(1+EOCK)^t} \tag{21}$$

After rearranging Equation 21, the LCCA for FIT systems can be estimated by dividing the present value of FIT systems' costs by the present value of total electricity generated by those systems, as expressed in Equation 22.

$$LCCA = \frac{\sum_t^T \frac{B_t^{econ} - C_t^{econ}}{(1+EOCK)^t}}{\sum_t^T \frac{NG_t^d \times F_t^{C02}}{(1+EOCK)^t}} \tag{22}$$

3.1.3 Timing of investments

One of the most important steps in the process of project preparation and implementation is to decide on the appropriate time at which the project should start. The determination of the correct timing of investment projects will be a function of how it is anticipated that future benefits and costs will move in relation to their present values. In the case of solar PV systems, the expectations were that technological breakthroughs would reduce the investment costs for solar PVs. Hence, the question that arises here is how the financial, economic, and stakeholder impacts would have differed had the FIT program been implemented later

[14] 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.

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than its original start. If investment costs are expected to fall in the future, the optimal option would be for the program to be implemented later than if investment costs remained constant or rose over time. We will test this prediction for Ontario's solar FIT program. Given that this analysis is retrospective, the lessons learned from this analysis will be critical input for decision-makers when evaluating similar investments in the future.

3.2 Data

3.2.1 Solar PV costs and PPA prices

Panels A and B of Figure 1 show the trends in the average (nominal) prices of solar PV systems in Canada by technology type (rooftop or ground-mount) next to the PPA prices offered to the FIT program's participants based on the year they joined the program. Over the time that the program accepted new applications, the PPA prices were frequently adjusted to reflect the reductions in the cost of solar PV systems. The cost of a grid-connected rooftop system ranged from 5.27 CAD per watt in 2010 to 1.80 CAD per watt in 2019. Meanwhile, ground-mount installations tend to have larger system sizes and, therefore, reduced per-watt cost through economies of scale. Over 2010–2019, ground-mount systems had lower relative prices than rooftop systems. Additionally, with the declining trend in system costs over the period 2010–2019, those FIT participants who joined the program in the earlier years had investment costs of multiple times those of systems installed in later years.

Figure 2 shows the number of FIT contracts by the year of installation and the technology type on the left vertical axis, and the cumulative capacity on the right vertical axis. Although rooftop systems make up most FIT contracts, the cumulative capacity of ground-mount installations is almost twice the capacity of rooftop systems. In fact, the maximum rooftop system has a size of 0.5 MW, whereas the ground-mount systems have up to 10 MW of capacity.

The IESO contracted a total of 3,081 solar FIT contracts between 2010 and 2019, aggregating to 1,497 MW. In this study, we focus on distribution-connected systems with a total capacity of 1,407 MW. As shown in Figure 3, the first group of FIT contracts started feeding the distribution grids in 2010 with a 1.45 MW capacity. The generation capacity accumulated as new systems were connected to the distribution systems over the period 2010–2019. Starting in 2030, there will be annual reductions in the total capacity as the contract end-dates approach. The last year with an active PPA under the FIT program will be 2038, when the contracted FIT capacity of 2019 will reach its 20-year operation year (see Figure 3).

3.2.2 Solar PV yield by location

The FIT systems are installed across the municipalities of Ontario. Because we observe the municipality in which each system is installed in the dataset, we match the annual yields provided by Natural Resources Canada with each system's municipality. Annual yields have a mean value of 1,165 MWh/MW and a standard deviation of 21 MWh/MW, with a minimum and maximum of 1,131 MWh/MW and 1,268 MWh/MW. The low standard deviation in the annual yield values allows us to assume an average annual yield of 1,165 MWh/MW for all the systems under the FIT program.

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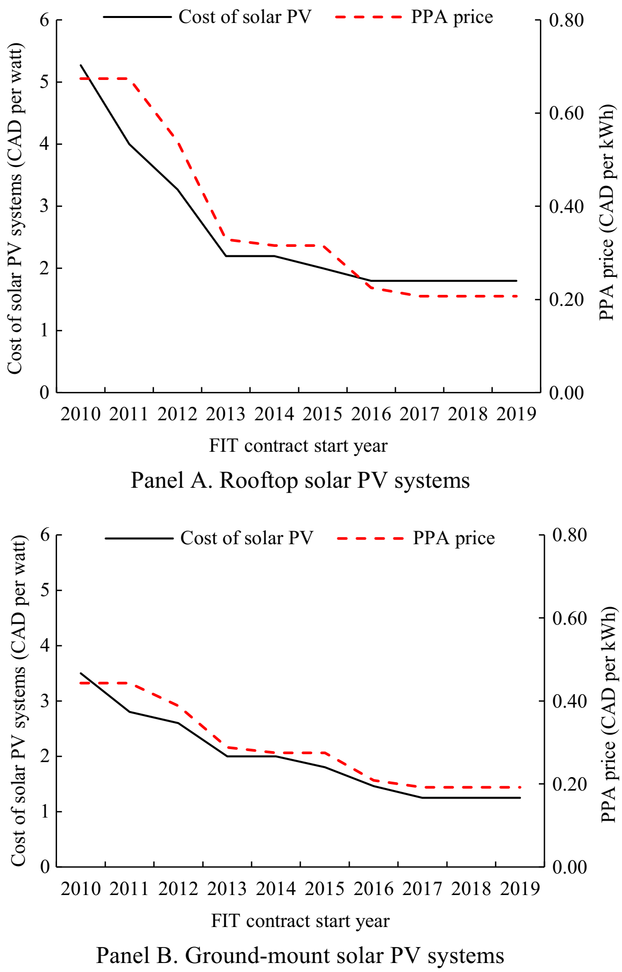

Figure 1. *The trend in solar PV investment costs over time.*
Note*: The costs of installing solar PV systems are taken from the 2019 National Survey Report of PV Power Applications in Canada published by the International Energy Agency PV Power Systems Program (IEA PVPS). The prices include all the system costs, such as the mounting materials, inverter, and installation costs. The offered PPA prices are extracted from the annual price schedules for the FIT program by Ontario's IESO.*

3.2.3 Inputs for environmental impact analysis

To quantify the reductions in CO_2 emissions from natural gas-fired power plants displaced by the solar FIT systems, we use an emission factor of 52 kg of CO_2e per MMBtu of natural gas, that is, the same emission factor used in Ontario Energy Board's reports (OEB, 2023). Then, we use two benchmarks to estimate the monetary value of these emission reductions: (1) the federal carbon pricing in Canada and (2) the estimates of the SCC published by the Government of Canada.

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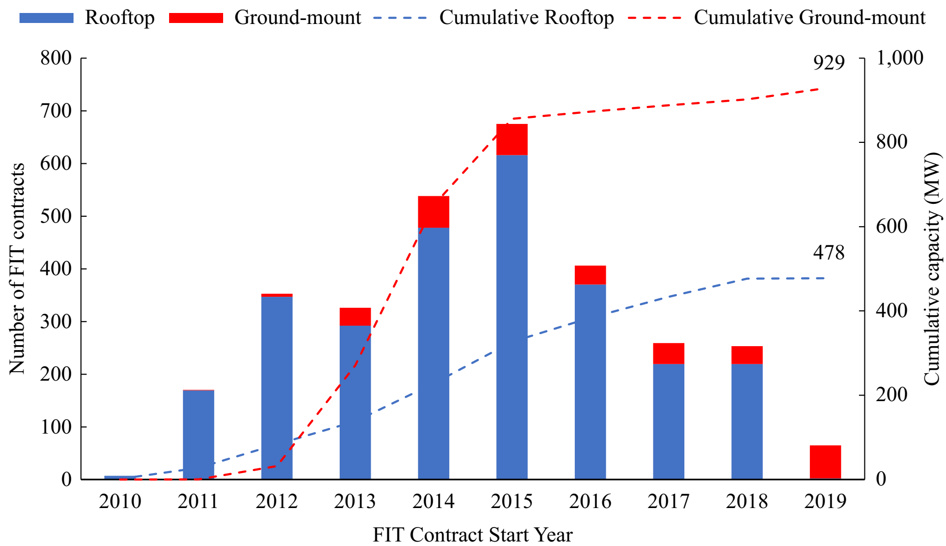

Figure 2. *Number of solar PV FIT contracts by the contract start year.*

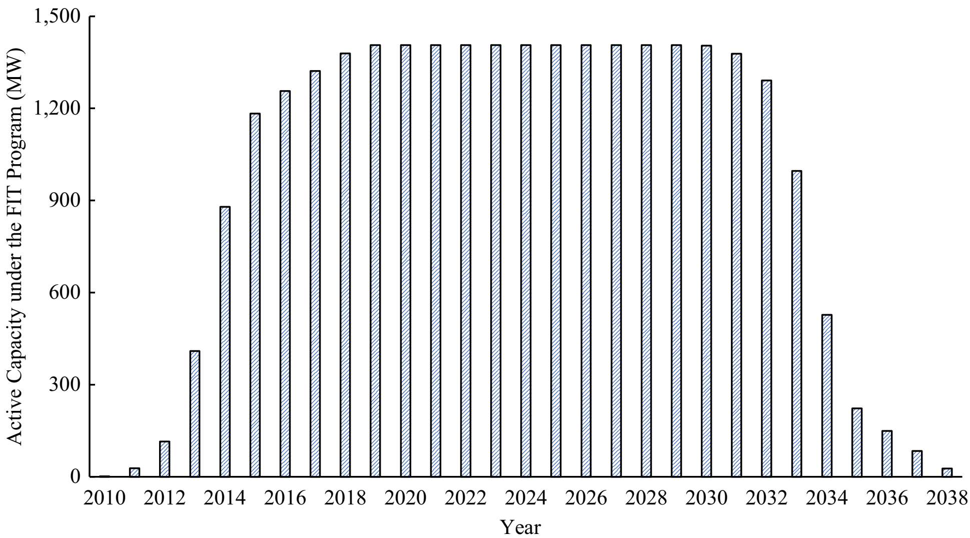

Figure 3. *Active solar feed-in tariff (FIT) contracts.*

The federal carbon pricing schedule was enacted in 2019. Starting with 20 CAD/tonne CO_2e in 2019, the carbon price increased by 10 CAD per year until 2022 and is scheduled to increase by 15 CAD per year from 2023 to 2030. Eventually, the carbon price will reach 170 CAD/tonne CO_2e in 2030 and stay at 170 CAD thereafter (Government of Canada, 2021). Given that our evaluation period for the FIT program is spread over the period 2010–2038, we need a carbon price for the years before 2019. We assume a price of 20 CAD/tonne CO_2e for the years between 2010 and 2019. Additionally, Environment and Climate Change

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Table 2. *Emission factor and benefits-per-tonne of reduction by pollutant*

Air pollutant	Emission factor (kg per MMBtu) (1)	Benefits-per-tonne (2023 CAD per tonne) (2)
NO_x	0.12	5,930
VOC	0.002	2,800
PM	0.003	460,000

Canada regularly updates the recommended SCC values for cost–benefit analyses of public projects and policies. Table A1 in Appendix A shows the recommended SCC estimates over our evaluation period (2010–2038).

For the impact of the FIT program on the emitted air pollutants, we extracted the emission factors of relevant pollutants from the US EPA documents. According to EPA (2023), the main pollutants from gas-fired power plants are nitrogen oxide (NO_x), volatile organic compounds, particulate matter, carbon monoxide (CO), and traces of sulfur dioxide (SO_2). We use the estimated BPT values by Health Canada (2022) to calculate the monetary value of health benefits associated with reducing per tonne of these pollutants (see Table 2). Our analysis excludes CO and SO_2 because BPT for CO reduction is not estimated at the time of our study, and SO_2 emissions are insignificant.

4. Results

4.1 Financial impact

The PPAs have starting years between 2010 and 2019, and they expire after 20 years of operation. With changes in solar PV investment costs and the offered rate under the FIT program over the years, the financial feasibility of a representative system would depend on the year the PPA contract started. Therefore, we start by building financial cash flow statements for 1 MW of installed capacity under the FIT program from the perspective of successive years, with all the cash flows indexed to 2023 prices. This approach is important for evaluating the FIT program because the FIT contract prices and the solar PV systems' costs have changed significantly over the period in which the program accepted applications. Table 3 lists the inputs used for constructing the financial cash flow statement from the FIT participant's perspective.

Panels A and B in Figure 4 show the outcome of financial analysis by technology type and the year in which participants joined the program. It appears that both technology types were expected to yield a positive NPV and higher-than-discount-rate internal rate of return for participants. Therefore, it is not surprising that the FIT program could successfully promote the adoption of solar PV systems in Ontario. Nonetheless, it should be mentioned that the gains on investments in the earlier years are relatively greater than those in later years due to more generous PPA rates in those years.

Our financial analysis result is consistent with the 2011 Annual Report of Ontario's Auditor General in terms of the profitability of investments under the solar FIT program. The Ontario Power Authority (merged with IESO in 2015) intended a minimum guaranteed rate of return of 11 percent when designing the FIT program. However, the initial offered rates

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were set even higher, resulting in overcompensation for private developers of renewable energy projects (Auditor General of Ontario, 2011; Rivers, 2015).

4.2 Economic impact

Canadian economy benefits from the reduction in the dispatch of gas-fired generators during the operating hours of the solar PV systems and the avoided transmission losses due to the proximity of these distribution-connected systems to final consumers. With a one-to-one displacement rate of the natural gas power plants with the FIT systems' output and a 3 percent avoided transmission loss, the projected reduction in the purchase of gas-fueled electricity by local distribution companies would be 31 terawatt-hours (TWhs) over the FIT program's life. To put this number into perspective, the solar FIT output in our projection would result in avoided electricity generation of 1.62 TWhs in 2022, the year in which the total output of natural gas plants in Ontario was 12 TWhs.

The electricity generation avoided due to the installed capacity under the FIT program translates into economic resource savings in the form of avoided natural gas use by electricity generation plants and health benefits due to reduced emission of air pollutants from these plants. Our model estimates a present value of 1.11 CAD billion of avoided natural gas use and 0.49 CAD billion of health benefits over the life of the FIT program. The

Table 3. *Summary of inputs for the financial analysis*

Parameter	Input	Source
Solar PV technical features		
Annual yield	1,165 MWh per MW	Natural Resources Canada
Annual output degradation	0.50% per year	National Renewable Energy Laboratory (NREL)
Inverter replacement cost after 12 years of operation	15% of the system cost	National Renewable Energy Laboratory (NREL)
Investment cost	Investment cost changes based on the start year of the FIT contract (see Figure 2)	National Survey Report of PV Power Applications in Canada
Financing	60% debt, 40% equity Interest rate: 5% fixed Loan tenure: 10 years	
Depreciation		
Accelerated capital cost allowance	50% per year on a declining balance, with only half of the deduction allowed in the year of acquisition	Class 43.2 of the Tax Regulations, Government of Canada
Taxation		
Corporate income tax	26.50%	Government of Canada
Federal	15.00%	
Ontario	11.50%	

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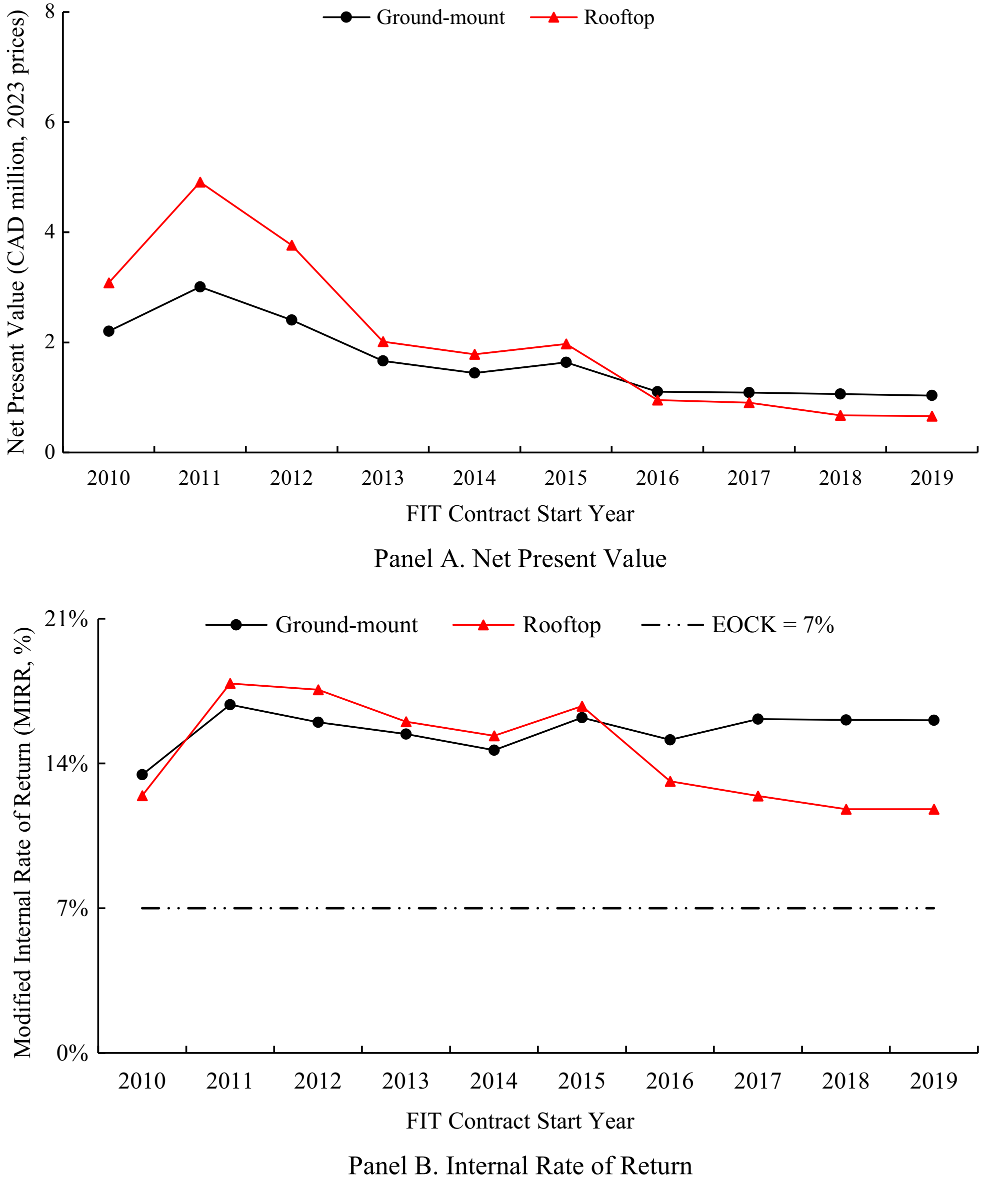

Figure 4. *Financial feasibility per MW of installed capacity.*

avoided natural gas includes the royalty collected by the Government of Alberta; therefore, the net economic benefit is 1.03 CAD billion.

From the perspective of Ontario electricity consumers, the financial benefit of the avoided natural gas purchases is the delivered price of the natural gas from Alberta, which includes the commodity price plus an 8 percent royalty collected by the Alberta Government. The forgone royalty revenues are a transfer within the economy, not an economic benefit.

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Therefore, we only consider 1.03 CAD billion of net economic benefits and will assign the value of forgone royalty revenues, 0.09 CAD billion, as a transfer from Alberta residents to Ontario electricity consumers later in the stakeholder impact analysis in Section 4.3.

The economic benefits from the FIT program come at a substantial economic cost. The incremental economic resource outflows due to investment and maintenance costs of solar PV systems have a present value of 6.80 CAD billion. Moreover, with a conservative assumption of 2.65 CAD per MW of installed solar capacity for integration costs, the present value of integration costs is 0.08 CAD billion. The net economic impact is a loss of 5.37 CAD billion to the Canadian economy (see Table 4), with the economic benefits offsetting only 22 percent of the economic costs.

4.3 Stakeholder impact

In this section, we discuss the sign and magnitude of impacts on each stakeholder. The difference between the financial gain by FIT participants and the economic loss is the aggregate impact on all stakeholders (see Equation 2). To aggregate the financial impact on all the FIT participants, we multiply our per-MW estimates from Section 4.1 by the total MW of installed capacity each year and then add them up throughout the evaluation period. Our results indicate that the owners of solar FIT systems are made better off by 3.86 CAD billion (2023 prices) through implementing Ontario's FIT program, which is the difference between the present value of PPA payments received by them (10.52 CAD billion) and the present value of their costs (6.66 CAD billion).[15] Given our estimate of the economic impact in Section 4.2, the aggregate impact on stakeholders of Ontario's solar FIT program is a loss of 9.23 CAD billion (in present value terms) distributed among the stakeholders within the Canadian economy (see Table 5).

The present value of the net impact on the electricity consumer base in Ontario of procuring solar FIT contracts amounts to 9 CAD billion. This burden fell initially on electricity ratepayers in the form of higher electricity bills until the Ontario Government introduced the Renewable Cost Shift program in 2021. The objective of this subsidy program is to shift most of the cost of electricity generation from renewable energy contracts (approximately 85 percent) from Ontario's electricity consumers to taxpayers. According to the estimates of Ontario's Financial Accountability Office, the Renewable Cost Shift will cost the province a total of 38.6 CAD billion (FAO, 2022) over the 20 years from 2021 to 2040. With 34 percent of the contracted renewable capacity in Ontario being the solar FIT contracts evaluated in this analysis, the Ontario Government will have to allocate 13 CAD billion (in nominal prices) toward these contracts.

The Ontario Government and the Federal Government of Canada also experienced losses of 0.06 and 0.08 CAD billion, respectively, in the form of forgone corporate income tax due to accelerated CCA for solar PV systems. Additionally, the Government of Alberta loses the projected royalty revenues from the expected natural gas purchases by the gas-fired power plants in Ontario. The present value of forgone royalty revenues is estimated at 0.09 CAD billion.

[15] The FIT contracts have different start and end dates, and therefore the benefits and costs of the FIT systems have been and will be realized across different years. To make the numbers comparable, all items on the cash flow statements are indexed to 2023 prices.

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Table 4. The impact of Ontario's solar FIT program on the Canadian economy

Resource flows statement	Present value @EOCK = 7% (CAD billion, 2023 prices)
1. Economic resource inflows	1.52
• Savings in natural gas for electricity generation	1.03
• Health benefits from reduced emission of air pollutants	0.49
2. Economic resource outflows	6.89
• Investment cost	6.48
• Operating and maintenance (O&M)	0.32
• Solar-to-grid integration cost	0.08
3. Net economic resource flows	−5.37

Table 5. *Allocation of stakeholder impacts for Ontario's solar FIT program*

Stakeholder	Present value at EOCK = 7% (CAD billion, 2023 prices)
1. Ontario electricity consumers	−9.00
Savings in natural gas purchases for gas–fired power plants	1.11
Health benefits from reduced emission of air pollutants	0.49
Payments to FIT participants	−10.52
Solar–to–grid integration cost by FIT program	−0.08
2. Federal government	−0.08
Incremental corporate income tax revenues from the FIT participants	−0.08
3. Ontario government	−0.06
Incremental corporate income tax revenues from the FIT participants	−0.06
4. Alberta government	−0.09
Forgone royalty revenues from natural gas production	−0.09
5. Total impacts on the stakeholders within the Canadian economy	−9.23

4.4 Environmental impact

From the global environmental perspective, our estimates indicate that the solar FIT program reduces CO_2 emissions by 11.43 megatons (Mt).[16] The product of reduced CO_2 emissions each year and the determined carbon price for that year project the yearly social value of the reduction in carbon emissions. The present value of savings in emissions from the program start year up to the year that the last contract expires adds up to 0.71 CAD and 2.24 CAD

[16] To put this number into perspective, Ontario's electricity sector emitted 5.4 Mt of CO_2 in 2020 (IESO, 2021).

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Table 6. *Reconciliation of impacts for Ontario's solar FIT program (CAD billion, 2023 prices)*

				Environmental	
Point of view	Economic	Financial	Stakeholders	Carbon price	SCC
Canadian economy	−5.37	3.86	−9.23		
Canadian economy + Global	−4.66	3.86	−9.23	0.71	
environment	−3.13	3.86	−9.23		2.24

Table 7. *Timing of Ontario's solar FIT program implementation*

Analysis outcome	Original start in 2010	If started in 2016	% change in impacts
Present value of impacts from the perspective of 2023			
a. Economic	−5.37	−2.53	−53%
b. Stakeholders	−9.23	−4.59	−50%

billion, respectively, using the federal carbon price and the SCC estimates. Table 6 shows the reconciliation of financial, economic, stakeholder, and environmental appraisals.

In terms of cost-effectiveness, the LCCA by Ontario's solar program has been 444 CAD per abated tonne of CO_2 (2023 prices). This estimate implies that the FIT program for solar PV systems in Ontario does not pass the cost-effectiveness criteria. More specifically, this program has cost almost seven times higher than the 2023 national carbon pollution price of 65 CAD and 1.5 times higher than the 2023 SCC estimate of 290 CAD per tonne of CO_2.

4.5 Sensitivity analysis

We reevaluate the FIT program by switching the program start year in our model from 2010 to 2016. The idea here is to see how the program impacts would change if the implementation had been postponed to later years when the trend in solar PV costs flattened (see Figure 1). We assume that the last year of new capacity added will remain the year 2019. To keep the total installed capacity constant between the counterfactual and the postponed program, we equally distributed the original installations before 2016 over the years 2016–2019. Also, we evaluate the program from the perspective of the year 2023, and all prices are indexed to 2023 prices, as in the original analysis.

It appears that the net economic costs of the FIT program would have been lower by almost 50 percent (changing from −5.37 to −2.53 CAD billion) over the FIT program life. This significant reduction in economic costs is mainly due to the reduction in the PPA payments to FIT participants due to lower system costs.

Therefore, postponing the implementation of the FIT program would have yielded a net gain of 2.84 CAD billion to the Canadian economy. This gain is the difference between the

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Table 8. *Sensitivity analysis to the choice of discount rate (CAD billion, 2023 prices)*

		Canadian economy + global environment	
Discount rate	Canadian economy	Carbon price	SCC
a. Base case = 7%	−5.37	−4.66	−3.13
b. 3%	−3.57	−3.26	−1.63
c. 3% 2010–2019 and 2% 2019–2038	−3.56	−3.23	−1.56
d. 2%	−3.20	−2.87	−1.20
e. 1.5%	−3.03	−2.68	−0.99
f. 1%	−2.86	−2.49	−0.79

forgone economic benefits from natural gas savings, the associated health benefits and emissions avoided, and the economic resource savings because of the reductions in solar PV investment costs. This finding highlights the importance of the decision on the appropriate time at which a program should start.

The discount rate we used in our analysis is the real rate of 7 percent recommended by the Treasury Board of Canada Secretariat for the cost–benefit analysis of regulatory proposals. However, some departments and governments across Canada consider a real rate of 3 percent when certain human health and environmental concerns are associated with a program (Government of Canada, 2023a). Lower discount rates have also become common in the literature (Nesje *et al.,* 2022; Rennert *et al.,* 2022). Therefore, we test the sensitivity of our findings to a range of discount rates. The results indicate that while a lower discount rate improves the FIT program's economic efficiency criteria, the negative impacts on the Canadian economy and stakeholders are still significant (see Table 8).

5. Conclusion and policy implications

This paper develops a framework for integrating all the criteria of cost–benefit analysis, including optimal timing, economic resource efficiency, environmental cost-effectiveness, and distributional impacts, when evaluating renewable energy support programs. We apply this framework to analyze the financial, economic, and stakeholder impacts of Ontario's FIT program for solar DERs over the decade following its implementation in 2010. The program has successfully stimulated the installation of solar DER across Ontario, and those electricity consumers who joined the program derived a substantial net benefit from their investments. However, these benefits that accrued to a few well-off institutions have come at a tremendous cost to the lower-income electricity consumers of Ontario, given the documented distributional disparities in solar PV system adoptions (Reames, 2020; Crago *et al.,* 2023).

Our findings show that the economic cost imposed on the Canadian economy ranges from 2.86 to 5.37 CAD billion, depending on the discount rate applied. Moreover, the program has caused inequitable societal outcomes through a cross-subsidization with a present value of 9.23 CAD billion, paid for by the electricity consumer base, for the benefit of only the 0.06 percent of electricity consumers who were able to install solar PVs between 2010 and

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2019. Furthermore, the displacement of gas-powered electricity generators has yielded fuel savings of a value that is less than 10 percent of the costs imposed by the FIT systems on Ontario electricity consumers. Moreover, the ratio of the environmental benefits from CO_2 emission reduction to the net cost to the Canadian economy is 0.42, using the SCC estimates.

The sensitivity analysis confirms that the loss to the Canadian economy and stakeholders could have been reduced substantially if the Government of Ontario had delayed the implementation by a few years. This finding has policy implications for jurisdictions such as Ontario, with a relatively low-emission electricity sector. Instead of rushing to administratively set high compensation rates for solar output to increase private investment in renewable energy projects, decision-makers can prioritize cost-effective alternatives and postpone those with expected real cost reductions in the near future. Otherwise, scarce public funds with high opportunity costs will maximize returns to a small group of beneficiaries at the expense of millions of residents.

Our findings highlight the importance of conducting a detailed appraisal of renewable energy programs and advising the stakeholders involved of the expected cost impacts before the implementation. According to the report of the Auditor General of Ontario (2011), several consumer surveys conducted by the government in 2010 indicated that although consumers generally supported renewable energy, they were unaware of its impact on prices. Therefore, a transparent reporting of the results of an ex ante IIA that quantifies the financial and economic outcomes and the likely impacts on all the stakeholders is essential for designing sustainable programs to address GHG emissions.

Acknowledgements. The authors would like to thank anonymous reviewers for their valuable comments on our original manuscript and Jennifer Winter and the participants of the Canadian Resource and Environmental Economics Association (CREEA) for their valuable comments on earlier versions of this paper. Financial support for this research was provided through a Mitacs Accelerate-PDF Fellowship (Application Ref. IT23436).

Nomenclature

Time indices

t_0	Program start year
t_n	Current year
t_e	Program end year

Prices

p_{FIT_t}	Guaranteed price for the power purchase agreement starting in year t (CAD/kWh)
p_t^{gas}	Dawn Hub natural gas price (CAD/million BTU)
p_t^{carbon}	Carbon pollution price in year t (CAD/tonne CO_2e)

Quantities

$q_{i,t}$	Electricity generated by a representative FIT participant i in year t
$Q_{i,t}$	Total electricity generated by all FIT participants in year t

Solar photovoltaic system

k_i	Capacity of solar PV system installed by participant i (kW)
θ_i	Solar PV's potential yield (kWh per kW)
α	Annual degradation rate of the installed solar PV system (%)
$C_{i,capex}$	Capital expenditures of installing a solar PV system (CAD)

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$C_{i,t,opex}$	Operating and maintenance expenditures for a solar PV system at year t (CAD)
$r_{i,t}$	Annual revenues for a representative solar system owner (CAD)
$OM_{i,t}$	Annual operating and maintenance cost (CAD)
$CCA_{i,t}$	Annual accelerated capital cost allowance (%)
	Solar photovoltaic system
$IE_{i,t}$	Annual interest paid on debt (CAD)

Ontario electricity system

TL_t	Electricity transmission losses as a percentage of generation output (%)
HR_j	Heat rate of gas-fueled generation plant j (btu/MWh)
$l_{j,t}$	Technical efficiency loss of gas-fueled generation plant j at year t (%)
$w_{j,t}$	Weight of gas plant j (% of total gas-powered generation capacity) at time t (%)
NG_t^d	Quantity of natural gas displaced by solar-generated electricity at year t (MMBtu)
F_t^{CO2}	Natural gas CO_2 emission coefficient at year t (kg CO_2 /million BTU)
$f^{pollutant}$	Air pollutant emission factor (kg/MMBtu)
$BPT^{pollutant}$	Benefit per tonne of emission reduction (CAD per tonne)
$C_{t,int}$	Annual solar-to-grid integration cost (CAD)

Taxes & Royalty

$TI_{i,t}$	Taxable income of FIT participant i at year t (CAD)
CIT^{Gov}	Corporate income tax rate by government level (%)
r_t^{AL}	Royalty rare collected by the Government of Alberta on natural gas sales (%)

Abbreviations

AL	Alberta
CAD	Canadian Dollar
CCA	Capital Cost Allowance
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_{2e}	Carbon Dioxide Equivalent
DER	Distributed Energy Resources
EIA	Energy Information Administration
EOCK	Economic Opportunity Cost of Capital
EPA	Environmental Protection Agency
FAO	Financial Accountability Office
FIT	Feed-In Tariff
GEIA	Green Energy Investment Agreement
GHG	Greenhouse Gas
IESO	Independent Electricity System Operator
IIA	Integrated Investment Appraisal
kW	Kilowatt
kWh	Kilowatt-hour
LCCA	Levelized Cost of Carbon Abatement
LRP	Large Renewable Procurement

Mt	Megaton
MW	Megawatt
MWh	Megawatt-hour
NCF	Net Cash Flow
NOx	Nitrogen Oxides
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
OEB	Ontario Energy Board
O&M	Operating and Maintenance
ON	Ontario
PM	Particulate Matter
PPA	Power Purchase Agreement
PV	Photovoltaic
PV	Present Value
RESOP	Renewable Energy Standard Offer Program
SCC	Social Cost of Carbon
SO_2	Sulfur Dioxide
TWh	Terawatt-hour
VOC	Volatile Organic Compound

Competing interest. The authors declare none.

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Appendix A. The Estimates of Social Cost of Carbon in Canada

Table A1. *Government of Canada estimates of social cost of carbon*

Year	Social cost of carbon (2012 CAD, discount rate 3%)	Year	Social cost of carbon (2021 CAD, discount rate 2%)
2010	34.1	2020	247.0
2011	34.1	2021	252.0
2012	34.1	2022	256.0
2013	37.4	2023	261.0
2014	37.4	2024	266.0
2015	39.6	2025	271.0
2016	40.7	2026	275.0
2017	40.7	2027	280.0
2018	40.7	2028	285.0
2019	40.7	2029	289.0
		2030	294.0
		2031	299.0
		2032	303.0
		2033	308.0
		2034	313.0
		2035	317.0
		2036	322.0
		2037	327.0
		2038	331.0

Source: Government of Canada (2023b).

Cite this article: Hashemi, Majid, Glenn Jenkins, and Frank Milne. 2024. "Renewable Energy Support Through Feed-in Tariffs: A Retrospective Stakeholder Analysis." *Journal of Benefit-Cost Analysis*, doi:10.1017/bca.2024.9