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# Harnessing the Sun: Reviewing the potential of solar photovoltaics in Canada

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ABSTRACT

Over the past decade, a number of jurisdictions have taken significant steps to encourage the diffusion of solar photovoltaic technology (PV). Supportive policy frameworks have been widely adopted, spurring deployment and driving down the cost of PV components. The increased competitiveness of this technology presents a promising opportunity for meeting energy needs in a low-carbon fashion. Indeed, a growing body of research suggests that PV could produce significant quantities of energy. However, the diffusion of PV in Canada has been comparatively slow and GHG emissions in this jurisdiction are on an upward trajectory. As a result, we explore the potential of PV in Canada in regards to: (1) the scale of possible contributions to energy supply and GHG abatement, and (2) the particular functional roles and niches this technology could occupy looking out to 2050. In doing so, this study reviews the current status of knowledge on PV potential in Canada and argues that estimates which revolve around technical parameters such as solar irradiance, module efficiency, and land area (and even those that include some reference to current prices), are limited in their ability to understand the place this technology might actually occupy in Canada in coming decades. While technical potential is an important consideration, the interrelated economic, socio-political, and environmental influences need to be taken into account. This paper discusses the nature of these influences and explores PV potential in the context of key features of possible low-carbon pathways for Canada.



**Contents**



## 1. Introduction

Over the past decade, solar photovoltaic technology (PV) has received increasing interest as a promising low-carbon energy option. Policymakers in many countries have attempted to encourage the development and diffusion of PV by implementing supportive policies such as the Feed-in Tariff (FiT) [1]. With this

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aggressive support, global PV capacity has risen from 1.4 gigawatts (GW) in 2000 to over 100 GW in 2012 [2], and PV module prices have dropped from $4 per watt in 2008 to under $1 per watt in 2012 [3]. The increased competitiveness of PV offers new opportunities with respect to its potential contributions to energy supply and GHG abatement. A number of studies have begun to consider the appropriate place of this technology in longer term energy system evolution, suggesting that PV may have a sizeable role to play in the transition to low-carbon emission energy systems [4–8].

Despite the international trend, in Canada PV has been comparatively slow to emerge as an option for transforming electricity networks and broader energy systems. The low-carbon transition will necessitate substantial adjustments to electricity production and consumption. Notwithstanding the high proportion of hydroelectricity in Canada's existing generation mix (roughly 60% of electricity output), in 2012 the sector accounted for 88.3 megatonnes of $CO_2$ equivalent or 13% of Canada's total GHG emissions [9]. Moreover, the broader decarbonization of energy systems will necessitate radical changes to the way society provides those energy services which are not now generally powered by electricity, including transportation and space-heating. At present, Canadian GHG emissions remain on an upward trajectory and even the country's modest 2020 target of reducing emissions 17% below 2005 levels will be out of reach without more vigorous intervention [10]. This is to say nothing of attaining the more ambitious GHG reduction goals that are likely for 2030 or 2050. It is within this context that PV may offer a number of promising opportunities for energy provision and GHG emission abatement in Canada.

In this paper we approach PV potential in Canada from two angles, enquiring about both (1) the scale of the contribution PV could make to energy provision and GHG abatement, and (2) the particular functional roles or niches that PV might occupy looking forward to 2050. To gain traction on these interrelated questions, we review the current status of knowledge on PV potential in Canada. We argue that estimates which revolve around technical parameters such as solar irradiance, module efficiency, and land area (and even those that include some reference to current prices), are limited in their ability to understand the place this technology might actually occupy in Canada in coming decades. While technical potential is an important consideration, it sheds little light on the interrelated economic, socio-political, and environmental influences that will shape future energy trajectories [11]. The paper discusses the nature of these influences and explores PV potential in the context of key features of possible low-carbon pathways for Canada.

The paper starts with an overview of the current policy and market context for PV in Canada, and considers estimates of the solar resource, as well as features of PV technologies and their applications. It moves from estimates of PV energy output and potential GHG emissions reductions to offer an assessment of important constraining and enabling factors. The analysis concludes by identifying some features of possible low-carbon pathways in Canada and their implications for the potential role of PV.

## 2. Policy and market context for PV deployment in Canada

In Canada, electricity-related decisions fall primarily under provincial jurisdiction, with regional governments playing the largest role in terms of policy engagement around PV. As a result of this fragmented policy environment, each province offers different rates for electricity generated by PV systems under a variety of policy and regulatory conditions. Most provinces provide net-metering options for PV generation, whereby electricity from a PV system net of consumption is exported to the grid at the retail electricity price or some other established rate [12]. Some jurisdictions (e.g., The Northwest Territories) provide direct subsidies for a portion of the system costs. Canada's largest province of Ontario is unique in that it offers premium rates for electricity generated by grid-connected PV systems under 20 year power purchase agreements as part of a provincial FiT program (2009–ongoing). Current FiT rates for PV vary by installation size and application as reflected in Table 1. As the capital costs and long-term risks associated with installing PV can be a significant barrier, a FiT helps to mitigate uncertainty by providing a stable return on investment. The substantial FiT rate offered for PV in Ontario has attracted sizeable private investment (but also opposition from those complaining about upward pressure on utility rates).

**Table 1**
Ontario Power Authority past and present price schedule for PV.

| Renewable technology | Capacity | FiT version 1 (October 2009) $/kW h | FiT version 2 (April 2012) $/kW h | FiT version 3 (August 2013) $/kW h |
|---|---|---|---|---|
| **Solar PV** | | | | |
| Rooftop | ≤ 10 kW | 0.802 | 0.549 | 0.396 |
| | > 10 kW ≤ 100 kW | 0.713 | 0.548 | 0.345 |
| | > 100 kW ≤ 500 kW | 0.635 | 0.539 | 0.329 |
| | > 500 kW | 0.539 | 0.487 | N/A |
| Ground-mounted | ≤ 10 kW | 0.642 | 0.445 | 0.291 |
| | > 10 kW ≤ 500 kW | 0.443 | 0.388 | 0.288 |
| | > 500 kW ≤ 5 MW | 0.443 | 0.350 | N/A |
| | > 5 MW | 0.443 | 0.347 | N/A |

The policy regime surrounding renewable energy technologies in Ontario has made the province a prominent location for the deployment of PV. Other Canadian regions have seen only limited diffusion in comparison. As of 2012, Ontario was the site of 99% of PV installed capacity nationwide [12]. The latest figures (see Fig. 1) place cumulative installed capacity for PV in the province of Ontario at 1019 megawatts (MW) as of the end of 2013, with an additional 1120 MW under development for completion by 2017 [13].

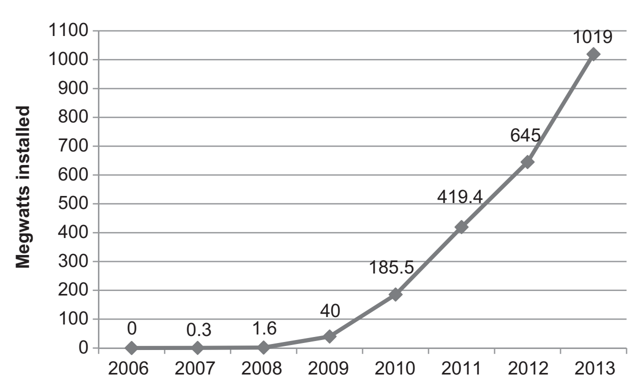


**Fig. 1.** PV deployment in Ontario, Canada. *Note*: Data was drawn from the Ontario Power Authority's progress report [13].

This deployment context highlights the fact that the rollout of PV in Canada is currently, and will remain for some time, dependent on policy support. Even with precipitous declines in PV module prices, relatively inexpensive electricity rates (as illustrated in Fig. 2) and the lack of a national carbon pricing mechanism severely constrain the diffusion of PV [14]. Moreover, PV faces risks, high upfront costs, and competing investment priorities (e.g., energy efficiency) that suggest a strong policy role would be required for further PV deployment in Canada.

## 3. Solar resource in Canada

The solar resource is an important foundation for understanding the overall potential of PV in terms of energy production and GHG emissions abatement. Also referred to as insolation or irradiance, it determines the amount of energy a PV system can generate and influences the overall cost of energy production. A greater amount of sunlight translates into lower costs as the system cost is spread over a larger quantity of electricity generation [15].

The solar resource in Canada, as measured in kilowatt-hours (kW h) generated per kilowatt (kW) of PV installed, varies regionally and seasonally. Fig. 3 illustrates that the potential annual electricity generation from PV can range from approximately 700–1400 kW h/kW [16]. An optimally oriented PV array in the Prairie Provinces, for instance, could yield 1100–1400 kW h/kW per year. In contrast, PV systems installed in the southern portions of Ontario, Quebec, or the Maritime Provinces could generate approximately 1000–1300 kW h/kW annually. Northern Canada experiences the least annual solar insolation as a result of substantial seasonal variations in sunlight. A PV system in the Northwest Territories, for instance, can reach 200 kW h/kW in April but produce almost no electricity during winter months [16]. In contrast, monthly PV potential in southern Canada peaks at roughly 160 kW h/kW in July and can fall to 60 kW h/kW in December.

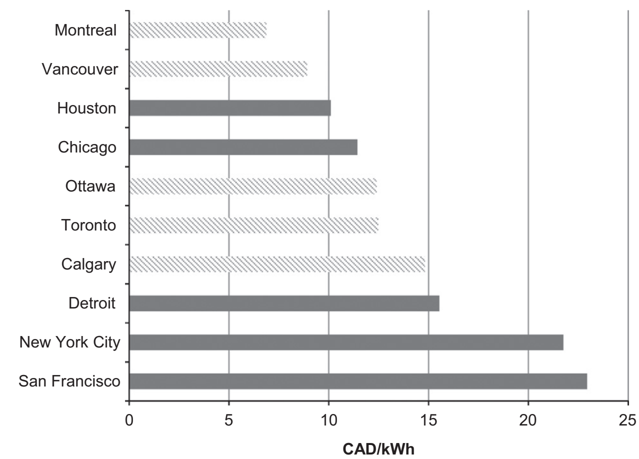


**Fig. 2.** Average residential electricity prices per kWh in CAD/kW h. *Note:* Data was drawn from Hydro Quebec's comparison of electricity prices [14].

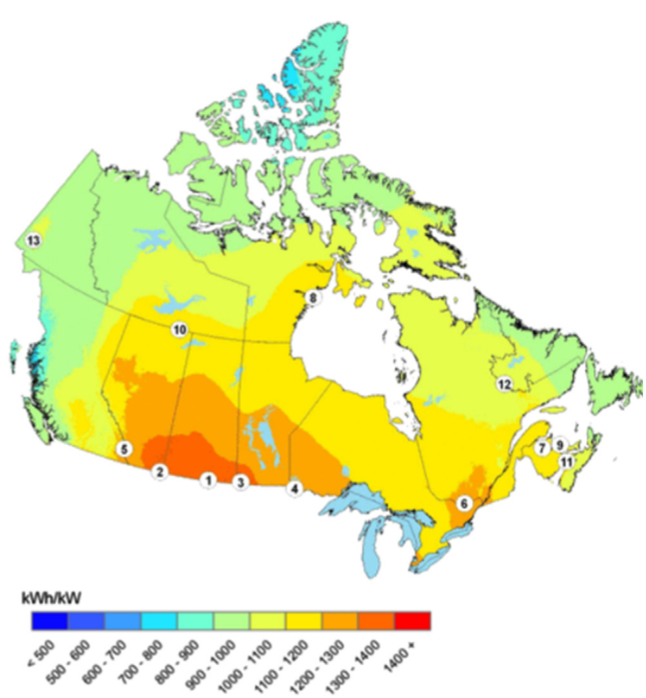


**Fig. 3.** Map of PV potential generation per kW installed. *Source:* Natural Resources Canada [16].

**Table 2**
Municipal PV potential.

| Municipality | PV potential (kW h/kW) | Municipality | PV potential (kW h/kW) |
|---|---|---|---|
| Los Angeles | 1485 | Beijing | 1148 |
| Mexico City | 1425 | Moncton, Canada | 1140 |
| Regina, Canada | 1361 | Quebec City, Canada | 1134 |
| Saskatoon, Canada | 1346 | Victoria, Canada | 1091 |
| Calgary, Canada | 1292 | Halifax, Canada | 1074 |
| Rome | 1283 | Vancouver, Canada | 1009 |
| Winnipeg, Canada | 1277 | Paris | 938 |
| Edmonton, Canada | 1245 | St. John's, Canada | 933 |
| Ottawa, Canada | 1198 | Tokyo | 885 |
| Montreal, Canada | 1185 | Berlin | 848 |
| Toronto, Canada | 1161 | London | 728 |

*Note:* Estimates of PV potential are drawn from Natural Resources Canada's solar maps [16].

As the majority of energy consumption occurs in urban centers and transmitting electricity long distances imposes infrastructure and efficiency costs, it is more useful to focus on the solar resource in and around cities. As indicated in Table 2 [16], many of Canada's municipalities experience relatively high levels of solar insolation in comparison to international jurisdictions. Canadian municipalities with some of the highest annual incidence of sunlight include Regina, Saskatoon, Calgary, Winnipeg, and Edmonton. The largest urban centers in Canada (Toronto and Montreal) also experience substantial annual solar insolation in relation to international jurisdictions like Germany (a world leader in PV).

So what does this tell us about the potential of PV? In one sense, these results reveal an abundant solar resource in Canada that could be harnessed for the purpose of energy generation through PV. Yet the daily and seasonal solar cycles pose serious challenges for this technology. To gain further insight into the role PV may play in future energy systems we must look beyond the availability of sunlight to the technical features of PV.

## 4. PV technologies and applications in Canada

PV does not encompass a single technology. Rather, it consists of a variety of different cell technologies and concepts. At present, first generation cell technologies made up of wafer-based crystalline silicon dominate global [17] and domestic markets [12]. Second generation cells comprised of thin films may still benefit from sizeable performance improvements [18] and are beginning to gain traction in global markets [17]. Third generation cells, which include a number of novel concepts (e.g., organic PV) remain largely under development. This diversity also extends to the way in which PV may be deployed. Its modular features allow for distributed or centralized applications. At present, the vast majority of PV applications in the Canadian context are grid-connected projects due to the FiT program [12].

Distributed PV systems tend to be small-scale and produce electricity at or near the point of consumption. Many of these projects take the form of roof-mounted systems. Ownership is typically residential, commercial, or institutional. Since 2011, distributed systems have accounted for just over 30% of annual installed capacity of PV in Canada [12]. Rooftop systems face several challenges linked to the additional cost and complexity of installation. Despite these drawbacks, distributed PV may have less of an impact on the stability of the electricity grid in comparison to centralized installations [19].

A number of promising distributed designs are emerging in the Canadian context. Building-integrated PV (BIPV), for instance, is garnering increasing attention as a way to reduce the environmental impact of the built environment [20]. While this application may encompass a series of designs and technologies, the basic premise is the integration of PV modules into the building envelope. Unlike standard PV applications, BIPV involves the functional, architectural, and esthetic integration of the PV units into the building structure. In this fashion, the PV system becomes an integral part of the building system and must be incorporated at the early planning stage for new construction and retrofits.

With respect to centralized applications, PV can also take the form of a utility-scale and investor-owned energy project. Centralized PV projects tend to be ground-mounted and multi-MW in scale. They are typically located further from sites of electricity consumption where land values are lower and they can take advantage of greater economies of scale. In 2011 and 2012, centralized projects accounted for over 60% of annual installed capacity for PV in Canada [12]. As opposed to distributed PV, centralized projects may face more pronounced techno-economic issues surrounding line losses, grid access, system stability, and grid congestion [19]. These projects may also encounter socio-political and environmental issues related to competing land uses and community opposition [21,22]. Recent revisions to the FiT in Ontario have attempted to mitigate concerns around the use of prime agricultural land for PV deployment.

Off-grid PV makes up less than 1% of annual capacity additions [12]. These systems are typically deployed in remote locations where grid connection may be unfeasible (e.g., isolated cottages and water pumping systems). Here PV may present opportunities for remote communities to decarbonize energy services and reduce costs associated with conventional sources (e.g., diesel generators) as fuel prices rise [23].

To reiterate, this technology does not possess a dominant design around which efforts can be concentrated. Instead, research and innovation are directed down a number of different avenues, each with differing long-term potential. Additionally, decentralized and centralized applications present different implications for system planning and policy.

## 5. PV potential in Canada

### 5.1. Technical potential

Over the past several years, research assessing the potential of PV in the Canadian context has gradually begun to emerge. Studies have explored PV potential with respect to building-integration [24] and peak-shaving [25,26]. Other research has estimated the electricity supply potential of rooftop PV regionally [27–29] and nationwide [24]. Still others have made strides to model the potential of ground-mounted applications [30]. Together, these studies provide an initial basis for evaluating the potential of PV in regards to energy supply and carbon abatement.

The medium-term potential of PV is greatly facilitated by its generation profile. PV produces electricity in a fashion that closely matches demand. Pelland and Abboud [25] reviewed electricity demand data in Toronto from 2000 to 2006 and compared this to simulated electricity generation from PV systems. Their results indicate that electricity production from PV closely follows electricity load and periods of peak consumption (which is consistent with the experience of other jurisdictions such as Germany [31]). In particular, the highest output from PV coincides with the use of carbon-intensive sources during periods of peak demand in Canada's most populous province [26]. PV shows promise as a means of reducing or completely removing building loads from the centralized grid during periods of high electricity demand. Specifically, PV is being considered as a component of “net-zero peak” housing in the Canadian context [32]. Through a combination of efficiency measures, architectural elements, behavioral changes, and PV, pressure can be taken off of the centralized grid when it is most taxed [26,32]. Consequently, PV appears to be well positioned to facilitate the decarbonization of daytime peak consumption and reducing reliance on the centralized grid [33].

With respect to total electricity production, PV may offer still larger potential. Wiginton, Nguyen, and Pearce [27] demonstrate that in Ontario distributed rooftop PV systems could supply a substantial portion of *overall* electricity consumption in addition to peak demand. They estimate the amount of roof space available for PV in south eastern Ontario and develop deployment scenarios using a variety of cell efficiency levels. In this instance, suitable roof space was estimated using fairly restrictive criteria, accounting for shading, competing uses (e.g., HVAC), orientation (only south facing roof area), and balance of system components. Their findings indicate that if high-performance PV modules (22.9%) were deployed on all suitable roof space in the selected region, PV could provide a peak power output of 5.74 GW or enough to meet roughly 24% of peak demand in the entire province. With respect to total output, rooftop PV from this region could generate 6909 gigawatt-hours (GW h), or about 5% of Ontario’s total electricity demand in 2012. If the rollout of rooftop PV systems was extended to the rest of Ontario, 30% of total electricity demand could be met. However, this would require nearly 35 GW of high efficiency rooftop PV systems. To put this in perspective, this deployment is roughly equal to the current installed capacity of Ontario's generation infrastructure.

A comparable modeling study of Guelph, Ontario found even greater potential for rooftop PV installations. McIntyre [28] leveraged GIS data to quantify the rooftop area of existing buildings, and atlas data to estimate the solar resource in the region. Their analysis employs two models in conjunction with meteorological data and compares outcomes to atlas insolation data. The models assume module efficiency levels of 20.1% and apply a performance ratio of 75% to the balance of system components. Unlike Wiginton, Nguyen, and Pearce, roof space is not regarded as restricted by competing uses, shading, and suboptimal orientation. To be sure, McIntyre acknowledges that more restrictive assumptions would be needed to capture a more realistic estimate of PV potential. That being said, even suboptimal surfaces could become candidates for electricity generation with advancements in BIPV. Employing a series of rooftop orientation scenarios, this study suggests that 1496–2950 GW h could be generated if all available roof space in the study region was covered with PV arrays. This output is equivalent to 90–200% of the annual electricity consumption of Guelph in 2005.

Hassan, Rahman, Haque, and Ali [29] examined rooftop PV potential in the Calgary community of Sandston, modeling incident insolation and the total output of PV systems. Their analysis limits roof area based on orientation, excluding all roof space that is not facing south or south west. The model incorporates module efficiency levels of 15%. While findings reveal significant seasonal variations, they suggest that 322 megawatt-hours could be generated annually under widespread deployment. This would correspond to approximately 60% of total electricity consumption in this community.

Similarly, a study by Pelland and Poissant [24] finds sizeable PV potential in regards to roof-mounted and BIPV applications across Canada. This study estimates PV generation based on the deployment of modules with 15% efficiency levels on all suitable roof space in Canada. Suitable space, in this instance, is defined as receiving at least 80% of the total annual solar insolation for a given region. This study also assumes a 75% performance ratio for PV systems, accounting for losses related to temperature, shading, and other factors. Results indicate that a total of 53 terawatt-hours could be generated per year. This figure represents approximately 35% of Canada's residential electricity demand or just under 10% of the country's total electricity demand in 2012 [9]. According to Pelland and Poissant, this would correspond to a nationwide GHG reduction of 16 megatonnes of $CO_2$ equivalent per year or 18% of Canadian GHG emissions stemming from electricity and heat production in 2012 [9,24]. If BIPV applications are taken into account, nearly 246 TW h or roughly 44% of Canada's electricity needs could in principle be met [24]. This would amount to 23 megatonnes of $CO_2$ equivalent avoided annually, or 26% of emissions from electricity and heat generation [9,24].

Research has also examined the potential of centralized ground-mounted PV deployment. Specifically, Nguyen and Pearce [30] identified suitable sites for ground-mounted PV projects in south eastern Ontario using GIS data. Suitable sites, in this case, are considered to possess good solar insolation, grid access, and limited competing land uses. Results suggest that the south eastern region of Ontario has 935,000 acres of appropriate land for large-scale PV projects. This acreage is equivalent to 850 times the land used by the largest current solar project in Canada [34]. Under this scenario, total installed capacity could reach 90 GW and annual generation could amount to 108 TW h or just over 75% of Ontario's electricity demand as of 2013 [35].

Taken together, these studies reveal that PV possesses considerable technical potential in Canada (see Table 3 for a summary of results). While the work varies in terms of assumptions and estimates, it suggests that a combination of distributed and centralized PV applications could meet all of Canada's current (and possibly future) electricity needs. A study conducted by the US National Renewable Energy Laboratory [4] reaches a parallel conclusion, estimating that rooftop and ground-mounted PV systems in urban settings could supply 3000 TW h or about 75% of the current electricity consumption of the United States. These results offer an encouraging picture of the role PV might play in reshaping electricity systems along low-carbon lines. However, raw estimates of PV potential cannot be translated into a realistic assessment of the prospects for this technology. After all, at base such estimates equate potential with cell efficiency and the abundance of land and sunlight. To further develop our understanding of PV prospects in Canada, a series of constraining and enabling factors need to be factored into the analysis.

### 5.2. Constraining and enabling factors

Foremost among these is the variability and uncertainty associated with electricity generation from PV. As discussed in Section 3, PV depends on intermittently available sunlight to produce electricity. It not only faces daily cycles, but also encounters seasonal as well as minute-to-minute fluctuations. Even though solar energy is available in vast quantities, there are limitations on when this energy is needed. In the absence of storage, generating large amounts of energy during the day (or summer) is of little use for providing energy services at night (or in the winter). As a result, PV cannot completely displace generation from fossil fuel sources in the absence of synergistic technologies and practices. Electricity storage devices (e.g., batteries, pumped hydro, and flywheels) [36], dispatchable renewable energy technologies (e.g., bioenergy) [37], detailed meteorological forecasting [38], geographic dispersion [39], and demand response mechanisms [40] are some of the options that are being considered to mitigate the variability and uncertainty of wind and solar technologies in Canada. Yet, to date, synergistic technologies remain in the early stages of development and deployment [41]. In Germany, the high penetration of PV is already leading to serious grid stability issues [42].

Economic considerations continue to influence the potential of PV. Module and system costs have fallen dramatically in Canada and internationally over the past several years (see Fig. 4), opening up new opportunities for this technology [12,17]. In Canada, module prices have dropped from \$4.31 in 2005 to \$1.15 in 2012. In regards to system prices, smaller scale systems ($\leq$ 10 kW) have declined in cost from \$10 per watt in 2005 to under \$5 per watt in 2012 [12]. Larger systems, in comparison, have decreased from \$12.60 per watt in 2005 to less than \$4 per watt in 2012. These costs are expected to decline further over the coming decade [17,43]. However, soft costs (such as installation and permitting) are now making up a larger component of total system costs, and international experience has found them to be “stickier” than module costs [17,44]. Moreover, a variety of issues outside the basic production/installation matrix can end up impacting costs. For instance, certain local distribution companies in Canada now require grid-connected micro-generation such as PV to have separate liability insurance coverage [45]. Above all, addressing the variability, storage and grid architecture issues mentioned above can add significant costs as the PV proportion of grid-supplied electricity rises, bringing to the fore the issue of how to distribute the costs of such facilitating investments.

Indeed, there is a gamut of socio-political and environmental factors impinging on PV potential. Utility-scale projects in Ontario, for instance, have encountered resistance in regards to siting and grid expansion [46–48]. PV has begun to emerge as a politically

**Table 3**
Summary of results from studies of PV potential in Canada.

| Study | Deployment location | Estimated generation | Proportion of electricity demand |
|---|---|---|---|
| ***Distributed applications*** | | | |
| Wiginton et al. [27] | South Western Ontario | 6909 GW h | 5% of demand in Ontario |
| McIntyre [28] | Guelph, Ontario | 1496–2950 GW h | 90–200% of demand in Guelph |
| Hassan et al. [29] | Sandstone, Calgary, Alberta | 0.322 GW h | 60% of demand in Sandstone |
| Pelland and Poissant [24] | Canada | 53,000 GW h | 10% of demand in Canada |
| ***Centralized applications*** | | | |
| Nguyen and Pearce [30] | South Western Ontario | 108,000 GW h | 75% of demand in Ontario |
| ***Building-integrated applications*** | | | |
| Pelland and Poissant [24] | Canada | 246,000 GW h | 44% of demand in Canada |

contentious topic in relation to its perceived impact on electricity rates [49,50]. On the positive side, PV benefits from some of the highest levels of social acceptance among energy options [51]. This high public acceptance could facilitate the deployment of PV in areas where other energy sources face strong public opposition. Moreover, there is some evidence from other jurisdictions that consumers like the idea of enhancing their energy independence vis-à-vis traditional large utility suppliers through rooftop arrays. Not surprisingly, energy system incumbents (such as centralized utilities and conventional energy supply rivals) are less enthusiastic about the rollout of PV. In the United States, a number of utilities are attempting to impose grid access charges on households that adopt PV and reduce their main electricity consumption, arguing that PV users “are avoiding paying their fair share for the electric grid they still rely on, and the long-term investments the companies have made in power plants and the delivery grid” [52]. Continued reliance on existing sources is promoted by sunk costs (and system ‘lock in'), suggesting that decisions to rollout PV (at least in a centralized fashion) may take place over longer timescales as infrastructure is replaced and/or demand rises. This raises questions about the temporal dynamics influencing PV potential.

With respect to the environment, PV is not without impacts. PV may encounter land use issues in regards to centralized applications and may suffer from higher lifecycle impacts than other low-carbon sources. While PV systems produce marginal GHG emissions during operation (some emissions stem from maintenance and inverter replacement, for instance), silicon purification and cell production are energy intensive processes that can have substantial carbon footprints depending on the local energy mix [53,54]. The lifecycle carbon impact of PV systems can be almost zero if manufactured in jurisdictions with low-carbon electricity networks. Conversely, PV systems produced in locations with carbon-intensive grids exhibit some of the highest lifecycle GHG emissions among low-carbon energy options (see Table 4). As carbon constraints tighten, the lifecycle GHG impacts of PV may increasingly be seen as problematic. In 2012, 60% of PV modules produced globally originated from manufacturers in China [55]. Although this emerging economy benefits from low production costs, it currently relies heavily on carbon-intensive fossil fuels for electricity generation [56]. In contrast, Canada has higher manufacturing costs, but possesses a relatively low-carbon electricity network that could be leveraged to produce more environmentally benign PV modules. Thus, in certain circumstances there may be a tension between PV cost reductions and environmental performance.

Above all, PV deployment will be constrained by the prospects for other (increasingly other low-carbon) energy sources. Canadian jurisdictions have an abundance of energy options, including low-carbon hydroelectricity (e.g., Manitoba, Quebec, and British Columbia), relatively inexpensive natural gas (e.g., Ontario, Alberta, and others), potential new nuclear reactors (e.g., Ontario), and growing investment in more affordable new renewables such as wind (e.g., Saskatchewan, Alberta, and Nova Scotia). The choice between technologies involves the evaluation of tradeoffs with respect to economic, political, industrial, technical, and environmental priorities. Currently, the priorities of Canada's federal government are reinforcing dependence on conventional energy rather than promoting low-carbon options like PV. But even when climate policy is taken more seriously, Canadian jurisdictions have a plethora of other low carbon options from which to choose.

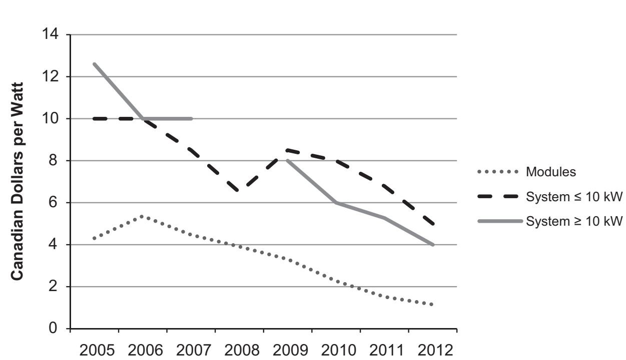


**Fig. 4.** System and module prices. *Note*: Data was drawn from Luukonen et al., [12]. System price data are taken from the high range of available data. Price data for systems ≥10 kW was unavailable for 2008.

Research has yet to address systematically the array of influences impinging on PV potential in Canada. However, several forecasts have employed economic and climate policy considerations. Based on cost models, the National Energy Board of Canada [57] projects that PV will make up less than 5.4 GW of capacity or 6% of Canada's electricity mix by 2035. Bataille, Wolinetz, Peters, Bennett, and Rivers [58], model the economic dynamics surrounding energy options based on a number of carbon reduction scenarios. Their simulations find that PV holds virtually no significant potential in Canada's energy systems in 2020. The European Renewable Energy Council and Greenpeace [59] consider three energy scenarios for Canada, projecting that PV capacity will range from 3 to 7 GW by 2050 and that total PV generation could then reach 6–12 TW h. In marked contrast, the Canadian Solar Industries Association [60] proposes that PV capacity could grow to between 9 and 15 GW by 2025. Although they are based on very different models and assumptions these estimates all illustrate that once economic and policy factors are considered the estimated PV potential in Canada becomes sharply circumscribed. Even the relatively optimistic industry association projections are far removed from estimates of technical potential.

Given the issues illustrated above it is clear that the prospects for PV hinge on more than solar insolation, land or roof area, module efficiency, and even declining component costs. Estimates of technical-economic potential serve as critical inputs for understanding the possibilities for PV. However, the next step is to consider additional economic, social, technical, and environmental factors that may promote or constrain deployment, and to assess how these factors may weaken or intensify over time. For example, land use and/or grid congestion issues may become more serious over time. In contrast, competition between PV and carbon-intensive forms of energy may subside as concern over climate change places greater pressure on existing energy production paradigms. The limits imposed by PV component costs may also

**Table 4**
Estimates of lifecycle GHG emissions for selected energy sources.

| Energy source | Grams of $CO_2$equivalent per kW h |
|---|---|
| **PV** | |
| PV: Nugent Sovacool [54] | 1–218 |
| PV: IPCC SRREN[53] | 5–217 |
| **Selected low-carbon technologies** | |
| Hydroelectricity | 0–43 |
| Geothermal | 6–79 |
| Tidal | 2–23 |
| Wind | 2–81 |
| Nuclear | 1–220 |
| Natural gas with carbon capture and storage | 65–245 |
| Coal with carbon capture and storage | 98–396 |
| **Selected carbon-intensive technologies** | |
| Natural gas | 290–930 |
| Coal | 675–1689 |

*Note:* Estimates for other technologies are drawn from the IPCC SRREN [53].

relax with cumulative efficiency improvements (although rival technologies may also benefit from improvements). Fig. 5 illustrates some of these dynamics and suggests how they may interact with the actual potential of PV in the coming decades.

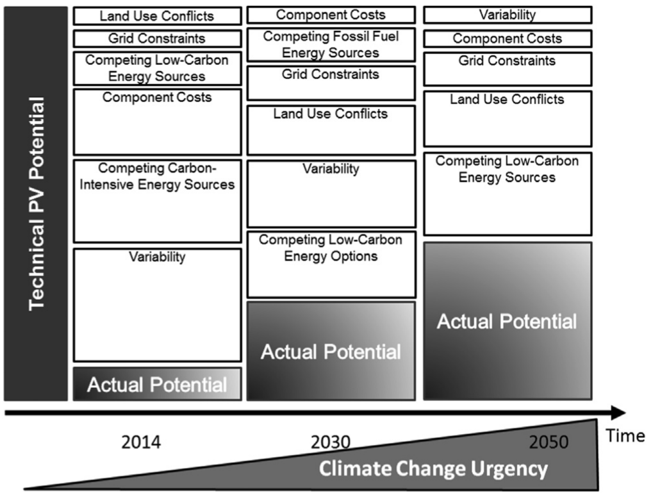


**Fig. 5.** Translating technical PV potential into actual PV potential in a carbon constrained world. *Note:* This diagram illustrates the influences on PV potential with respect to temporal dynamics and mounting concern over climate change. It is assumed that synergistic low-carbon technologies would be gradually adopted, thus mitigating variability issues over time.

### *5.3. Features of low-carbon pathways for Canada and implications for PV*

A further step in understanding the potential of PV in Canadian energy systems could be taken by developing more detailed low-carbon transition pathways and scenarios [61–63]. Such pathways would illustrate the role PV would assume in alternative energy system configurations as GHG emissions are progressively squeezed out over the longer term. Thus, the scale and nature of PV deployment would be characterized in relation to the evolution of other technologies, changing demand patterns, and the transformation of the built environment and transport. Although the exploration of such detailed pathways is beyond the scope of this paper, we can identify several critical features of such pathways in Canada and indicate some of the potential implications for PV.

First, while the low-carbon transition in Canada will be national in scope, it will also be deeply regional in character. The energy political economy of Canadian regions is quite distinct: various parts of the country have very different resource endowments, and industrial structures differ based on these endowments. Resources, electricity systems, and the associated policy and regulatory frameworks are largely controlled by the provinces, and there are marked contrasts among them: consider Alberta with its hydrocarbon extraction industries, mainly coal-based and privatized electricity system on the one hand and Quebec with its hydro-based electricity system operated by a vertically integrated crown corporation (Hydro Quebec) on the other. Such differences will almost certainly lead to a different reception for PV as existing resource and infrastructure endowments, market structures, along with political and policy priorities, feed into collective and individual decision-making.

Second, Canada already has a relatively decarbonized electricity system, with nearly 80% of supply provided by low-carbon sources (in 2012: 61% hydro, 16% nuclear, and 2% new renewables [9]). So the ‘space’ for PV expansion as a decarbonization option is to some degree constrained, particularly with respect to hydro-rich jurisdictions where relatively low cost power is flowing from already depreciated assets with very long lifetimes. Moreover, substantial untapped hydro resources remain in some regions (Quebec, Manitoba, Newfoundland and Labrador, and British Columbia). Exploiting these resources would be expensive and accompanied by major environmental impacts. Moreover, applying them to decarbonize provincial electricity systems still dependent on fossil fuels would require increased interprovincial electricity system integration, which has so far proven elusive. Still, the momentum and path dependence of established energy systems (including expertise, system architecture and infrastructure investments) suggest that further expansion of centralized hydro systems may occur. On the other hand, the prospects for low carbon nuclear (mainly concentrated in Ontario) are somewhat less clear as a number of plants will require refurbishment and/or replacement and government enthusiasm for expensive new reactors has cooled. This may open up opportunities in Ontario for PV to take up some of the slack from a declining nuclear sector. The modular characteristics of PV also make it more amenable to current infrastructure investment models in Ontario and elsewhere, which favor less capital intensive projects. Of course, PV can still fill strategic roles in hydro-based regions (e.g., relieving grid congestion in dense urban centers) or provide electricity where grid connection is unfeasible. In fossil fuel dependent regions, however, PV and synergistic innovations (e.g., conservation and efficiency, wind turbines, energy storage, smart grids, and bioenergy) could be much more central to decarbonization trajectories.

Third, the relative abundance of domestic energy options in the Canadian context further complicates the prognosis for PV. In addition to hydro and nuclear, there are other new renewable options including wind, biomass, and geothermal. PV will also have to contend with emerging technologies (e.g. tidal/wave) and other forms of solar energy including solar thermal and hot water. So, PV is likely to face heightened levels of competition now and into the future. Moreover, Canada is currently an international leader in carbon capture and storage (CCS) technology demonstration projects, with the first utility-scale pulverized coal plant equipped with CCS commencing operations at Boundary Dam in Saskatchewan. While PV has recently experienced rapid progress as compared with CCS, efforts to develop CCS and reduce costs may redouble as climate change concern exerts greater pressure on fossil fuel interests. So CCS cannot be ruled out as a part of Canadian low-carbon pathways (for example, CCS on natural gas).

Finally we should point to a number of issues which, while not particular to the Canadian context, are at least likely to assume importance here. First, PV's prospects depend on the successful development and deployment of a series of related technologies. Smart grids, electricity storage (perhaps associated with electric vehicles), and other new renewables are implicated as key supports in a future with widespread PV deployment. Mitigating variability and maintaining grid stability in a fashion that permits high levels of PV penetration will necessitate energy storage and demand response, among other possibilities. This reveals a tension between the synergistic and competitive roles of low-carbon energy technologies. An integrated and inter-reliant system of low-carbon innovations will be required to decarbonize energy services, yet technologies will also compete for limited government support and market share. This tension along with persistent unevenness in deployment and development will place limits on PV's role in Canadian as well as global energy systems. Second, another tension exists between the centralized and decentralized modes of PV deployment. If PV evolves to fill roles within a traditional utility model, centralized PV along with utility-level storage and state-of-the-art forecasting techniques may be advantaged. Conversely, new participatory models could take hold and encourage the deployment of PV in a decentralized fashion. A number of potential low-carbon pathways implicate the increasing involvement of households, businesses, and local communities through micro-generation, electric vehicle storage, demand response mechanisms, and conservation programs. This may help secure PV's position as a distributed energy option capable of facilitating deep reductions in electricity consumption. As part of this, PV may redefine itself as an energy reduction technology rather than an energy supply technology. Together, these issues play out in interaction with the three factors identified above.

## 6. Conclusion

This paper has examined the potential of PV in Canada in regards to: (1) the scale of possible contributions to energy supply and GHG abatement, and (2) the particular functional roles and niches this technology could occupy looking out to 2050. Literature on the technical potential of PV indicates that PV could decarbonize a major portion of energy services. However, research which estimates PV potential on the basis of the availability of land or roof area, solar irradiance, and system efficiency do not capture the realistic prospects of PV technology within the Canadian energy landscape. In order to better understand the potential of this technology, it is crucial to assess an array of interrelated technical, economic, socio-political, and environmental influences. Competing energy technologies, variability, component costs, land use issues, and high levels of social acceptance are some of the factors constraining and enabling the diffusion of this technology in Canadian energy systems. As carbon constraints tighten and time passes, these influences are expected to relax or intensify, modulating impacts on the potential of PV. A promising way to account for these influences and further elaborate the actual potential of PV is to devise and evaluate low-carbon pathways. Key features of such pathways for Canada include: the centrality of their foundation in the regional energy political economy [11]; the already low-carbon nature of electricity systems; and the abundance of Canadian energy options. This analysis suggests that these factors, along with the set of interrelated influences mentioned above, will shape the evolution of the role assumed by PV within Canada's future energy systems.

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