Distributed generation investment strategies for hybrid solar projects in Ontario, Canada

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1. Introduction

At present, Canada is not close to meeting their emission reduction target under the 2015 Paris Agreement (30% below 2005 levels by 2030). In 2019, the country generated the equivalent of 730 megatonnes of carbon dioxide equivalent, a much larger figure than the agreed upon target of 517 megatonnes by 2030. The largest sources of these Canadian emissions include the transportation sector, industrial processes, waste disposal, oil & gas, electricity generation, and the operation & construction of buildings. While the federal government of Canada has confirmed their intention to meet the Paris Agreement target, further specialized planning and development will be needed in order to realize this goal. [1]

Investing in the development of renewable energy technologies (such as solar, wind, hydro, and geothermal power) has long been suggested as a means of mitigating the negative impact of anthropogenic climate change. Solar power and other renewable energy sources have significant potential for development as sustainable, lower-carbon sources of power within Canada and globally. However, it is well known that the intermittent nature of renewable energy sources (e.g. solar, wind) does create problems in terms of developing a reliable power source when restricted by the natural environmental conditions of these resources (Ostovar et al. 2021; Paska et al. 2009). For example, solar power is limited by the hours of available daylight, proximity to the equator, and other environmental conditions such as cloud. Wind power is also limited by the variations in naturally occurring wind both temporally and geographically (Hoicka and Rowlands 2011; Paska et al. 2009; Wang et al. 2021).

However, solar (photovoltaics and concentrated solar power) and wind power are of particular interest to policy makers and energy developers due to several factors. First, solar and wind power are among the cheapest renewable energy technologies available, and are projected to continue to become cheaper in the future, and secondly, solar and wind power are both at commercially mature stages of development and deployment (Corrocher and Cappa 2021; Watson et al. 2019).

[1] Environment and Climate Change Canada https://www.canada.ca/en/environment-climate-change.html

1.1 Hybrid Energy

There are significant logistical questions regarding which technologies should be invested in and developed, both between and within renewable energy technologies. Thus, it is necessary for policy makers to understand which renewable energy sources represent the largest gains in terms of reducing GHG emissions, efficient land-use, energy efficiency, power reliability, integration, and cost-effectiveness. Therefore, additional research is required in order to determine optimal energy investment and development strategies for renewable energy within Canada and globally (Abdelshafy et al, 2020; Bakhtavar et al. 2020). Hybrid power plants have been identified as a potential solution to many of the problems associated with traditional single source renewable energy power plants (Bajpai and Dash 2012; Krishna and Kumar 2015; Paska et al. 2009). In particular, hybrid power plants provide greater power reliability and sustainable power generation, due to their use of multiple renewable energy sources (Bajpai and Dash 2012; Krishna and Kumar 2015; Paska et al. 2009), although the inclusion of fossil fuel-based back-up generators have traditionally helped improve power reliability. The ability to combine numerous different energy resources (e.g. wind power, solar power, hydro power, fossil fuel generators, energy storage, geothermal power, tidal power) within a single power generation plant, allows countries to customize their set-ups to take advantage of their unique environmental conditions (Bentouba and Bourouis 2016; Shezan et al. 2016).

As such, hybrid power plants can be more effective than traditional single renewable energy source power plants by ensuring sustainable power generation, providing greater power reliability, reducing excess power generated, reducing GHG emissions producing, and allowing for greater customization (Bajpai and Dash 2012; Krishna and Kumar 2015). At present, most studies have examined hybrid solar power plant designs individually, and often within very different conditions and geographic locations (Goodbody et al. 2013; Halabi et al. 2017; Hossain et al. 2017; Ma et al. 2014; Olatomiwa et al. 2015; Soria et al. 2015). Comparisons between fundamentally different hybrid power plant designs have most often been performed as reviews of different studies (Khare et al. 2016; Krishna and Kumar 2015; Zhou et al. 2010). Furthermore, most completed studies are based on the optimization of a particular set-up, often with cost as the prevailing optimization factor (Ding et al. 2019; Wibowo and Sebayang 2015). In contrast, other factors such as power reliability, renewable penetration, or reducing GHG emissions, are often secondary to the concern of cost.

This study aims to address these gaps by comparing modelling results for a variety of hybrid solar power plant designs, under the assumption of a distributed generation requirement, within the same set of conditions and geographic location (Peterborough, Ontario), and with an emphasis on evaluating the results on the basis of three equally weighted factors of analysis (cost-effectiveness, GHG emission reductions, power generation and reliability).

2. Methods

This research used hybrid modelling software (HOMER Pro) to perform a direct comparative analysis of the performance and efficacy of a series of different hybrid solar power plant designs, with the requirement to meet a typical annual load profile where the peak day demand is 2 megawatts. The study compared a variety of hybrid solar power plant designs (using solar, wind, batteries, and fossil fuel generators) on the basis of three equal factors (GHG emission reductions, power generation and reliability, and cost-effectiveness), under similar environmental conditions and location.

2.1 Hybrid Solar Power Plant Modelling

2.1.1 Geographic Location of Simulated Plants

Peterborough, Ontario was chosen as the location of the modelled hybrid solar power plants due to being representative of the environmental conditions for southern Ontario as defined by the "Climate Zones and Planting Dates for Vegetables in Ontario" (Ontario Ministry of Agriculture, Food, and Rural Affairs 2021).

2.1.2 Environmental Data Sets

Using NASA's "The Power Project" database, a full year's worth of environmental conditions and solar irradiation data was gathered for the location of Peterborough, Ontario.[2] The solar data obtained was measured as daily values of "All Sky Insolation Incident on a Horizontal Surface" (in kWh/m^2/day) for a full year (January/01/2019 - Dec/31/2019). All Sky Insolation Incident on a Horizontal Surface was confirmed to be the same value as GHI (global horizontal irradiance) by NASA Earth Data Support (from the NASA Langley Research Center (LaRC) in Hamptonton, VA (USA)). This was also independently confirmed from HOMER Energy Support Renewable Energy Engineers.[3] HOMER Pro modelling software accepts solar radiation data as monthly averages of GHI or Clearness Index. Therefore, the daily measurements were converted to a monthly average for 2019, and these values were entered into HOMER Pro to produce the environmental conditions for the simulation. Four values were removed where data was missing or could not be computed. The daily average wind speed measurements (in m/s) at heights of 10 m and 50 m were obtained for a full year (January/01/2019 - Dec/31/2019). HOMER Pro modelling software accepts wind

[2] https://power.larc.nasa.gov/
[3] Confirmed with NASA Langley ASDC User Services, e-mail message, December 18th, 2020).

speed data as monthly averages. Therefore, the daily measurements (at 10 m and 50 m) were converted into monthly averages for 2019, and these values were entered into HOMER Pro to produce the environmental conditions for the simulation. Average monthly temperature data (mean temperature in °C) was obtained for Peterborough, Ontario from the Government of Canada website. The data was obtained from separate monthly reports and compiled into a single data set. These values were entered into HOMER Pro to produce the environmental conditions for the simulation. All hybrid solar power plant modelling was performed using HOMER Pro modelling software. Studies that have used HOMER modelling software within the context of hybrid power plant simulations include Al Garni et al. (2018), Bentouba and Bourouis (2016), Gökçek (2018), Shezan et al. (2016), and Wibowo and Sebayang (2015) among many others.

2.1.3 Equipment Information and Selection Process

A systematic approach was developed and implemented to choose each specific piece of equipment used in the design of the hybrid solar power plant models. The approach was to create an extensive list of equipment options, generate an average technology rating (e.g. power capacity, storage capacity), and then refine the list based on specific criteria for each piece of equipment. The objective of this approach was to choose a piece of equipment that was representative of the average, mid-range technological capabilities available on the market.

Solar Component and Costs

The solar component (PV cells) for the hybrid solar power plants was selected via an extensive list cataloguing existing PV cells and their technical specifications that was obtained from the California Energy Commission.[4] The list was filtered in ascending order for power generation capacity (in watts) per solar panel. Subsequently. the average (289 W) and median (290 W) power capacity were calculated. These measures are in line with a review study of PV technology which capped first generation PV units at 320 W power capacity per solar panel in 2016 (Khan and Arsalan 2016). The Zytech ZT290P solar panel (290 W power capacity, polycrystalline silicon) was chosen as the solar power component within the hybrid solar power plant designs due to its close proximity to the average and median power capacity values. Obtaining pricing information was a key aspect of the equipment information being entered into HOMER pro. First, the average cost per installed watt of solar power for Ontario was obtained online, and

[4] California Energy Commission 2021 https://www.energy.ca.gov/

determined to be $2.34 - $2.59 CAD per watt generated.[5] The average of the range was taken for use, and therefore the cost of solar power per watt installed in Ontario was determined to be $2.465 CAD. As HOMER Pro accepts solar power pricing information as cost ($) per kW, this was scaled up and determined to be $2465/kW. Finally, this price was converted to U.S. currency (as of Mar/16/2021), which determines a final price of $2042.75/kW (USD). Thus, the capital and replacement costs for the ZT290P solar panel was assumed to be $2042.75/kW (USD). Furthermore, this cost is in line with the capital and replacement costs used in similar hybrid solar power plant studies using HOMER Pro (Halabi et al. 2017; Olatomiwa et al. 2015). A previous study (Hossain et al. 2017) which modeled hybrid solar power plants, listed the operation and maintenance costs as $10/kW/year per solar panel (in U.S currency). Therefore, given the recent publication and the type of study, this value was used for this solar panel unit. The operational lifetime of the ZT290P solar panel (25 years) was obtained from the default setting in HOMER Pro for this solar panel. This was also verified with Zytech Solar, as their products have a 25-year warranty.[6]

Storage Component and Costs

HOMER Pro provides an extensive list of potential battery options. This list was filtered by power storage capacity (kWh) and the average (59.4 kWh) and median (4.3 kWh) power storage capacities were calculated. The capital cost was confirmed to be $2540.15 USD per battery unit.[7] The operation and maintenance cost used in Hossain et al. (2017), ($10/year) was used to approximate these costs. The operational lifetime of the batteries was confirmed through the product website and by the manufacturer to be 10 years.[8]

Wind Component and Costs

The HOMER Pro library provides an extensive list of potential wind turbine options. From the list provided, two main power capacity classes of wind turbine were available, with ranges from approximately 0-50 kW and +200 kW respectively. A smaller class of wind turbine was chosen in order to provide greater flexibility and customization within the hybrid solar power plant designs. The Futurenergy Airforce 10 (13 kW power capacity) wind turbine was selected as the wind power component within the hybrid storage power plant designs. The capital cost was confirmed to be $83,010.32 per wind turbine and the annual service for each

[5] Energy Hub 2021 https://www.energyhub.org/
[6] Zytech Solar https://zytechsolar.co/
[7] PowerPlus Energy, e-mail message, March 16, 2021
[8] Ibid

wind turbine would be £400-500.[9] Therefore, the average of the low and high-end range (£450) was taken to provide an average representation of the operation and maintenance costs. This value was then converted to U.S. dollars (as of Mar/23/2021) which is $619.86. The operational lifetime (20 years) of the Airforce 10 wind turbine was obtained from the default setting in HOMER Pro.

Natural Gas Component and Costs

HOMER Pro provides an extensive list of natural gas generators within its library catalogue. The list was filtered by power generation capacity in ascending order and an average of (1169 kW) and median (1033 kW) power generation capacities of the natural gas generators were calculated. Due to a lack of sufficient price or emissions data for the generators on this list, a generic model 200 kW Gas Microturbine (200 kW power generation capacity) was chosen, with no combined heat and power capabilities. The HOMER Pro model for the generic 200 kW Gas Microturbine provided the capital cost ($340,000.00), replacement cost ($260,000.00), operational lifetime (40,000 hours), and the operation and maintenance cost ($4.00/operational hour) values. The fuel cost for natural gas in Ontario is determined by the Ontario Energy Board.[10] Furthermore, for the area of Peterborough, natural gas is supplied by Enbridge Gas. As of Jan/01/2021, the Ontario Energy Board designated the cost of natural gas for Peterborough at 0.104$/m^3 (Ontario Energy Board 2021a).[11] This rate was converted to U.S. currency (on Mar/23/2021) and is 0.083$/m^3.

Diesel Generator Component and Costs

HOMER Pro also provides an extensive list of diesel generators within its library catalogue. The full list filtered by power generation capacity and an average (846 kW) and median (648 kW) of the diesel generators were calculated. Two different diesel generators were selected: the 500 kW generic fixed capacity genset and the Generac 100 kW SD 100. The generic 500 kW model was chosen as it contained full price and emission data while being in close proximity to the average and median power capacities. The HOMER Pro model for the generic 500 kW fixed capacity genset provided the capital cost ($150,000.00), replacement cost ($150,000.00), operational lifetime (15,000 hours), and operation and maintenance cost ($5.00/operational hour) values. The Generac 100 kW SD 100 diesel generator was also chosen in order to provide additional flexibility in overall fossil fuel power capacity when designing the

[9] Futurenergy, e-mail message, March 18, 2021
[10] https://www.oeb.ca/consumer-information-and-protection/natural-gas-rates
[11] Current natural gas costs have risen to .177$/m^3 significantly impacting the cost of natural gas integration

hybrid solar power plants, as the large values of the 500 kW make it difficult to provide fine adjustments to the overall capacity. This smaller generator was chosen due to availability of complete emission data within the base model, in comparison to alternative models. Prices were gathered from publicly available American market websites for similar 100 kW power capacity diesel generators. The costs for five similar models were obtained and their average price was calculated in order to provide an estimate of average cost for this scale and type of generator. The average price was determined to be $25,740.00 U.S. The operational lifetime of the unit (15,000 hours) was obtained from the HOMER Pro base model information. The operation and maintenance costs were not available in the HOMER Pro base model. As such, this value was taken from a similar cost unit ($0.03/operational hour) from a similar hybrid model paper (Hossain et al. 2017). The fuel cost of diesel was determined using the location of Kingston, ON due to the lack of available data in Peterborough and its relatively close proximity. The rack-price of diesel fuel for Canada (as a weekly average) was obtained from the Petro-Canada website, and as of Mar/18/2021 was $0.7410/L (Petro-Canada 2021).[12] This value was then converted to U.S. currency, at $0.59/L.

2.1.4 Hybrid Solar Power Plant Design Overview

A total of 11 hybrid solar power plant set-ups were designed during the course of the research. Following modelling, the results of each simulation were compared and analyzed. In addition, two baseline models using solely diesel and natural gas were designed in order to provide some comparison between single resource and hybrid power plants. Each hybrid power plant model was designed in order to meet a peak load demand of approximately 2 MW. Due to the nature of renewable energy (intermittent and subject to environmental weather conditions), power generation capacity exceeding 2MW was required in order to ensure that the demand could be met at all times. Therefore, to achieve this, a total base power generation capacity of 3500 kW was assigned to all of the hybrid solar power plant models. A synthetic load profile provided by HOMER Pro of a typical residential area was used to provide the load demand that the hybrid solar power plants aimed to meet during the simulations. The load profile was scaled up to meet a peak load of approximately 2 MW (1996.5 kW), which occurred at 18:00 daily. Storage capacity (batteries) were applied (500 kWh capacity) in addition to the 3500 kW power generation capacity (where applicable). Plant designs were chosen to measure the impact of each individual energy resource (e.g. renewable energy source, fossil fuel generator source, storage technology). Specifically, the hybrid models were designed to minimize the variables changed between the models, in order to try and isolate the

[12] Current rack diesel prices (as at May 19th, 2022) have reached $1.53/L significantly impacting the economics of diesel integration.

impact of each energy resource. As such, only a single energy resource was changed between each hybrid model. Power generation resource allocation was set at a level that would allow for equal distribution between the energy generation sources. A three-resource hybrid design followed a similar distribution, but split the 50% allocated to renewable energy sources evenly between solar and wind, resulting in 25% solar, 25% wind, and 50% fossil fuels. Any two-resource hybrid plant that contained only renewable energy sources, also followed this principle and contained a 50-50 resource allocation split between the two renewable energy sources. The eleven hybrid solar power plant models are described in detail in Table 1).

2.1.5 Results Analysis Methods

The results of each model were gathered and examined to determine the efficacy and overall performance of each hybrid solar power plant in relation to each other. Three main factors (GHG emissions, cost-effectiveness, and power generation/reliability) were compared using calculations produced by HOMER Pro. For GHG emissions, HOMER Pro provides a total quantity of pollutants produced over a year (in kg/year) from the production of electricity from each individual hybrid solar power plant model, and then calculates an emission factor (kg of pollutant emitted per unit of fuel consumed) multiplied by the total annual fuel consumption. For cost-effectiveness, HOMER Pro provides measurements of levelized cost of electricity (LCOE) ($/kWh), operating cost ($/year), and total net project cost ($). For power generation and reliability, HOMER Pro provides measurements of total power produced (kWh/year), capacity shortage (%), unmet electrical load (%), excess electricity (%), renewable fraction (%), and fuel consumed

Table 1. Design layout for all modelled hybrid solar power plants, including base fossil fuel models.

Hybrid Design No./ Type	Component	Equipment Type	Equipment Quantity	Individual Power/ Storage Capacity	Ideal Resource Ratio (%)	Actualized Resource Ratio (%)	Individual Capacity (kW)	Total Resource Capacity (kW)	Total Hybrid Power Capacity (kW)
1 (PV-DG)	Photovoltaic Cells	Zytech ZT290 Solar Panel	6207 Panels	290 W (per solar panel)	50%	51.43%	1800	1800	3500
	Diesel Generator	Generic 500 kW Fixed Capacity Genset	3 Generators	500 kW (per generator)	50%	48.57%	1500	1700	
		Generac 100 kW SD 100	2 Generators	100 kW (per generator)			200		
2 (PV-Wind)	Photovoltaic Cells	Zytech ZT290 Solar Panel	6207 Panels	290 W (per solar panel)	50%	51.43%	1800	1800	3500
	Wind Turbine	Futurenergy Airforce Wind Turbine	131 Turbines	10 kW (per wind turbine)	50%	48.57%	1700	1700	
3 (PV-BAT)	Photovoltaic Cells	Zytech ZT290 Solar Panel	12069 Panels	290 W (per solar panel)	100%	100.00%	3500	3500	3500
	Lithium Ion Battery	PowerPlus Energy ECO 4840 LI Battery	125 Batteries	3.994 kWh (per battery)	N/A	N/A	500	500	
4 (PV-Wind-DG)	Photovoltaic Cells	Zytech ZT290 Solar Panel	3103 Panels	290 W (per solar panel)	25.00%	25.71%	900	900	3500
	Wind Turbine	Futurenergy Airforce Wind Turbine	69 Turbines	10 kW (per wind turbine)	25.00%	25.71%	900	900	
	Diesel Generator	Generic 500 kW Fixed Capacity Genset	3 Generators	500 kW (per generator)	50.00%	48.57%	1500	1700	

Hybrid Design No./ Type	Component	Equipment Type	Equipment Quantity	Individual Power/ Storage Capacity	Ideal Resource Ratio (%)	Actualized Resource Ratio (%)	Individual Capacity (kW)	Total Resource Capacity (kW)	Total Hybrid Power Capacity (kW)
		Generac 100kW Generator	2 Generators	100 kW (per generator)			200		
5 (PV-BAT-DG)	Photovoltaic Cells	Zytech ZT290 Solar Panel	6207 Panels	290 W (per solar panel)	50.00%	51.43%	1800	1800	3500
	Lithium Ion Battery	PowerPlus Energy ECO 4840 LI Battery	125 Batteries	3.994 kWh (per battery)	N/A	N/A	500	500	
	Diesel Generator	Generic 500 kW Fixed Capacity Genset	3 Generators	500 kW (per generator)	50.00%	48.57%	1500	1700	
		Generac 100kW Generator	2 Generators	100 kW (per generator)			200		
6 (PV-Wind-BAT)	Photovoltaic Cells	Zytech ZT290 Solar Panel	6207 Panels	290 W (per solar panel)	50.00%	51.43%	1800	1800	3500
	Wind Turbine	Futurenergy Airforce Wind Turbine	131 Turbines	10 kW (per wind turbine)	50.00%	48.57%	1700	1700	
	Lithium Ion Battery	PowerPlus Energy ECO 4840 LI Battery	125 Batteries	3.994 kWh (per battery)	N/A	N/A	500	500	
7 (PV-Wind-BAT-DG)	Photovoltaic Cells	Zytech ZT290 Solar Panel	3103 Panels	290 W (per solar panel)	25%	25.71%	900	900	3500
	Wind Turbine	Futurenergy Airforce Wind Turbine	69 Turbines	10 kW (per wind turbine)	25%	25.71%	900	900	
	Lithium Ion Battery	PowerPlus Energy ECO	125 Batteries	3.994 kWh (per battery)	N/A	N/A	500	500	

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		4840 LI Battery							
	Diesel Generator	Generic 500 kW Fixed Capacity Genset	3 Generators	500 kW (per generator)	50%	48.57%	1500	1700	
		Generac 100kW Generator	2 Generators	100 kW (per generator)			200		
8 (PV-NG)	Photovoltaic Cells	Zytech ZT290 Solar Panel	5862 Panels	290 W (per solar panel)	50%	48.57%	1700	1700	3500
	Natural Gas Generator	Generic 200kW Gas Microturbine	9 Generators	200 kW (per generator)	50%	51.43%	1800	1800	
9 (PV-Wind-NG)	Photovoltaic Cells	Zytech ZT290 Solar Panel	3103 Panels	290 W (per solar panel)	25.00%	25.71%	900	900	3500
	Wind Turbine	Futurenergy Airforce Wind Turbine	62 Turbines	10 kW (per wind turbine)	25.00%	22.86%	800	800	
	Natural Gas Generator	Generic 200kW Gas Microturbine	9 Generators	200 kW (per generator)	50.00%	51.43%	1800	1800	
10 (PV-BAT-NG)	Photovoltaic Cells	Zytech ZT290 Solar Panel	5862 Panels	290 W (per solar panel)	50.00%	48.57%	1700	1700	3500
	Lithium Ion Battery	PowerPlus Energy ECO 4840 LI Battery	125 Batteries	3.994 kWh (per battery)	N/A	N/A	500	500	
	Natural Gas Generator	Generic 200kW Gas Microturbine	9 Generators	200 kW (per generator)	50.00%	51.43%	1800	1800	
11 (PV-Wind-BAT-NG)	Photovoltaic Cells	Zytech ZT290 Solar Panel	3103 Panels	290 W (per solar panel)	25%	25.71%	900	900	3500

Hybrid Design No./ Type	Component	Equipment Type	Equipment Quantity	Individual Power/ Storage Capacity	Ideal Resource Ratio (%)	Actualized Resource Ratio (%)	Individual Capacity (kW)	Total Resource Capacity (kW)	Total Hybrid Power Capacity (kW)
	Wind Turbine	Futurenergy Airforce Wind Turbine	62 Turbines	10 kW (per wind turbine)	25%	22.86%	800	800	
	Lithium Ion Battery	PowerPlus Energy ECO 4840 LI Battery	125 Batteries	3.994 kWh (per battery)	N/A	N/A	500	500	
	Natural Gas Generator	Generic 200kW Gas Microturbine	9 Generators	200 kW (per generator)	50%	51.43%	1800	1800	
B1 (Diesel)	Diesel Generator	Generic 500 kW Fixed Capacity Genset	4 Generators	500 kW (per generator)	100%	99.95%	2000	2000	2001
	Photovoltaic Cells	Zytech ZT290 Solar Panel	4 Panels	290 W (per solar panel)	0%	0.05%	1	1	
B2 (Natural Gas)	Natural Gas Generator	Generic 200kW Gas Microturbine	10 Generators	200 kW (per generator)	100%	99.95%	2000	2000	2001
	Photovoltaic Cells	Zytech ZT290 Solar Panel	4 Panels	290 W (per solar panel)	0%	0.05%	1	1	

(L/year and m^3/year). For the purpose of this study, “power reliability” is defined as the degree to which power is consistently available to meet load demand at a given time. To account for cost implications caused by Canada’s Greenhouse Gas Pollution Pricing Act on the results from each individual design, a cost of $50/tonne of carbon dioxide equivalent in 2022, with the price increasing by $15/tonne of emissions per year (CBC 2020; Environment and Climate Change Canada 2019; The Globe and Mail 2021) was applied to the results.

3. Results

The modelling results showed that the hybrid solar power plant designs that included the use of PV, batteries and either diesel or natural gas performed best across all three primary factors of analysis, while models that added wind technology to those designs produced the lowest quantities of GHG emissions among all of the hybrid solar power plant designs. However, even with the Canadian government’s current carbon tax policy, the level of economic benefit is not sufficient to discourage the use of fossil fuel generation as part of a distributed generation design at present.

Of the eleven hybrid solar power plant models in this study, three (H2 PV-Wind, H3 PV-Bat, H6: PV-Wind-Bat) were unable to meet the 2MW load demand under the research conditions and were therefore not included in the results.

3.1 Emissions

As shown in Figure 1, Designs H7 (PV-Wind-BAT-DG) and H11 (PV-Wind-BAT-NG) produced the lowest emissions of carbon dioxide with 1486.939 t/year and 1443.495 t/year respectively. Hybrid solar power plant models H1 (PV-DG) and H8 (PV-NG) produced the largest quantity of carbon dioxide emissions with 1763.399 t/year and 1790.961 t/year. The addition of wind power to the base PV-fossil fuel models in H4 (PV-Wind-DG) and H9 (PV-Wind-NG) resulted in a 6.83% reduction in total emissions from the PV-DG hybrid model (H1), and a 5.75% decrease in total emissions from the PV-NG hybrid model (H8). The addition of batteries to the base PV-fossil fuel models in H5 (PV-BAT-DG) and H10 (PV-BAT-NG) resulted in a 10.68% reduction in total emissions from the PV-DG hybrid model (H1), and a 15.00% decrease in total emissions from the PV-NG hybrid model (H8).

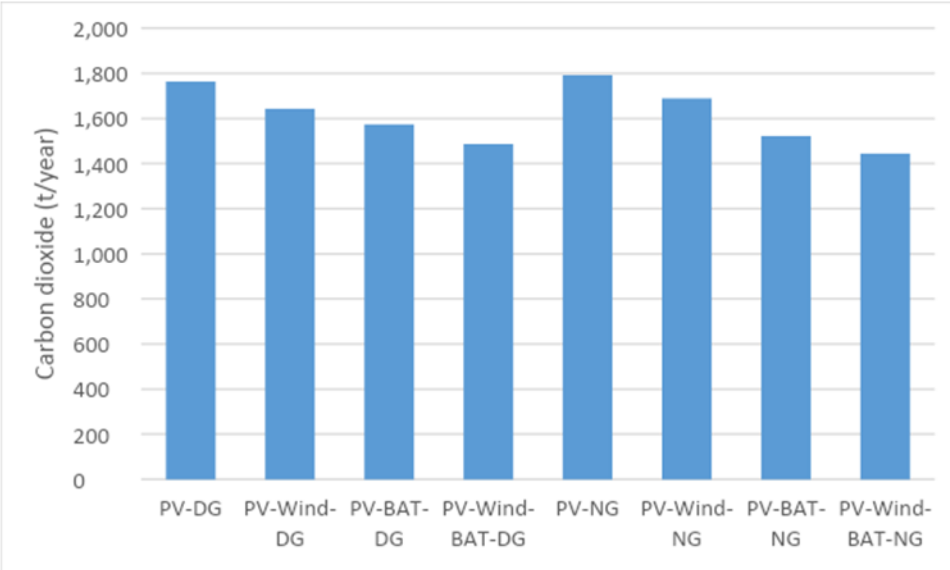

Figure 1. Total emissions (in t/year) for each of the eight modelled hybrid solar power plants. The total values include: carbon dioxide, carbon monoxide, unburned hydrocarbons, particulate matter, sulfur dioxide, and nitrogen oxides.

3.2 Power

Capacity shortage ranged from 0.0003 - 0.0773% for all eight hybrid models, with unmet electrical load across all models ranging from 0 - 0.0182%. Hybrid models H1 (PV-DG) and H8 (PV-NG) produced the largest quantities of power, with 4,624,560 kWh/year and 4,495,692 kWh/year produced respectively (see Figure 2).

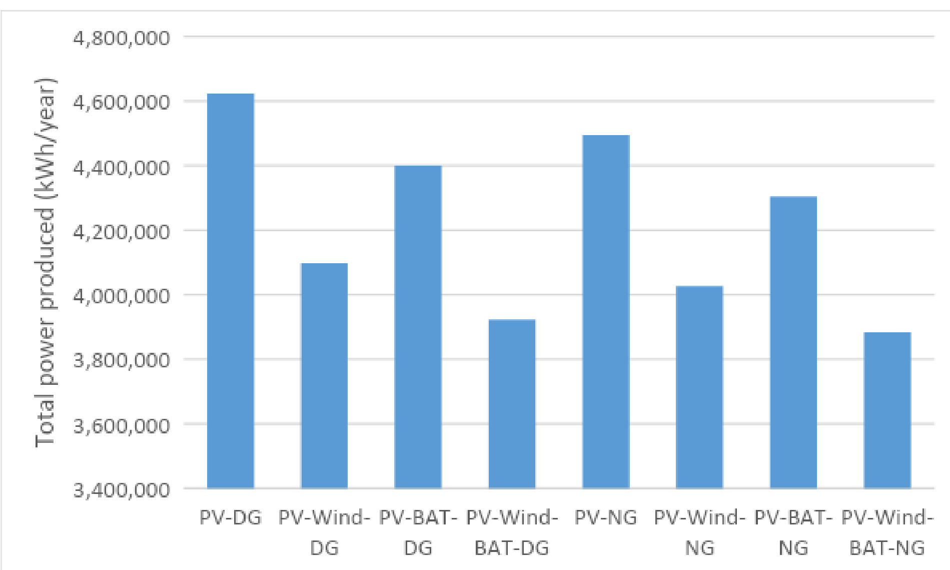

Figure 2. Total power produced (in kWh/year) for a full operating year of each of the eight modelled hybrid solar power plants.

In Figure 3, the hybrid model H1 (PV-DG) produced the highest quantity of excess electricity (24.7% of total power produced). Conversely, hybrid model H11 (PV-Wind-BAT-NG) achieved the lowest quantity of excess electricity (9.68% of total power produced). The addition of wind power to the base PV-fossil fuel models in H4 (PV-Wind-DG) and H9 (PV-Wind-NG) resulted in a 40.10% reduction in excess electricity from the H1 (PV-DG) hybrid model, and a 41.15% reduction in excess electricity from the H8 (PV-NG) hybrid model. The addition of batteries to the base PV-fossil fuel models in H5 (PV-BAT-DG) and H10 (PV-BAT-NG) resulted in a 17.00% reduction in excess electricity from the H1 (PV-DG) hybrid model, and a 17.70% reduction in excess electricity from the H8 (PV-NG) hybrid model. The addition of both wind power and batteries to the base PV-fossil fuel models in H7 (PV-Wind-BAT-DG) and hybrid model H11 (PV-Wind-BAT-NG) resulted in a 57.10% reduction in excess electricity from the H1 (PV-DG) hybrid model, and a 57.17% reduction in excess electricity from the H8 (PV-NG) hybrid model.

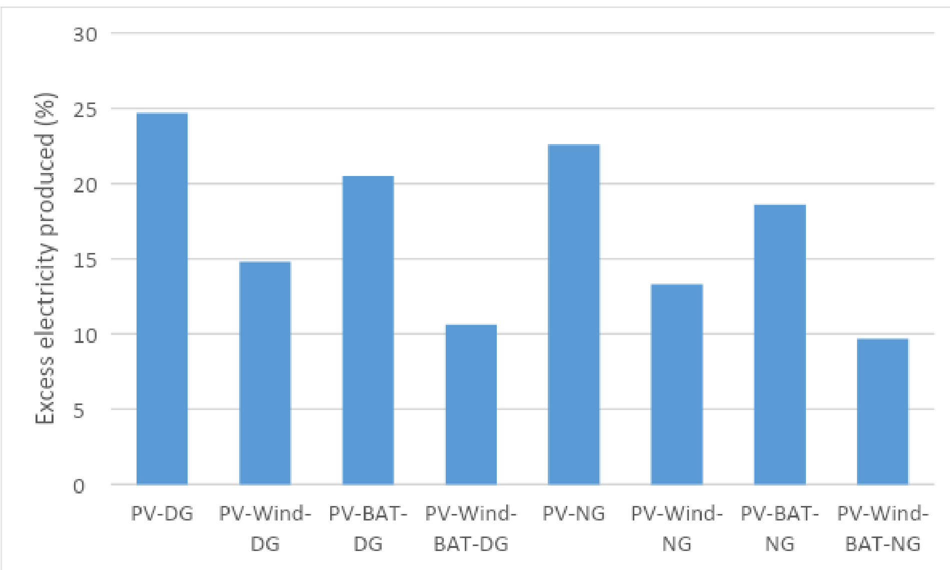

Figure3. Excess electricity produced (as a % of total annual power produced) for a full operating year for each of the eight modelled hybrid solar power plants.

Figure 4 highlights the fraction of renewable energy technology employed in each of the eight modelled hybrid solar power plants. In comparison, the power plant models for diesel (B1) and natural gas (B2) produced 3,495,228 and 3,431,065 kWh/year each, achieved 0% unmet electrical load, 0.0098% capacity shortage, 0.0% renewable fraction, and produced 1.84% and 0.0002% excess electricity respectively.

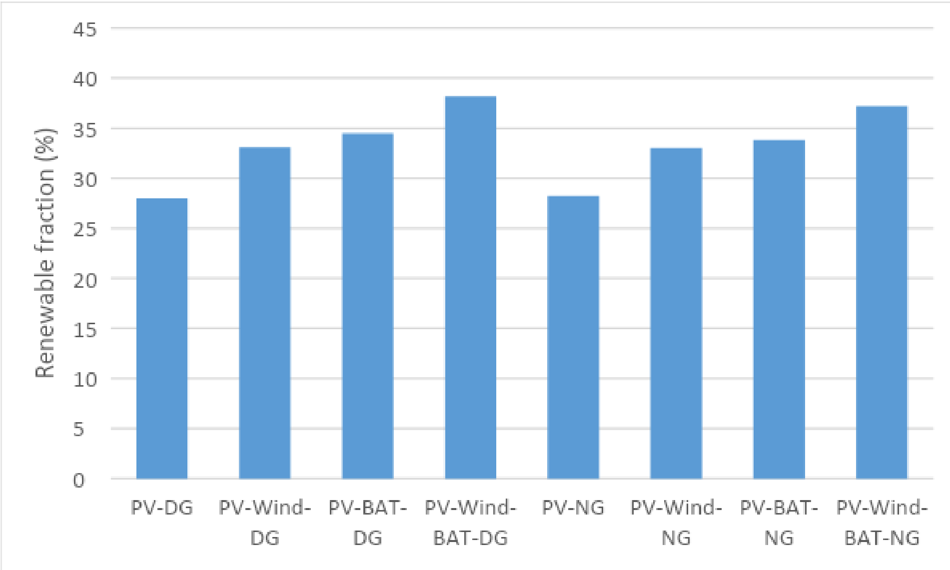

Figure 4. Renewable fraction (%) for a full operating year of each of the eight modelled hybrid solar power plants.

3.3 Cost

In terms of project cost (See Figure 5), the model H4 (PV-Wind-DG) produced the highest total net project cost at $15,808,280.00. In contrast, model H10 (PV-BAT-NG) achieved the lowest total net project cost $9,312,803.00. All hybrid models that contained wind power (H4 PV-Wind-DG, H7 PV-Wind-BAT-DG, H9 PV-Wind-NG, H11 PV-Wind-BAT-NG) were more expensive (in terms of total net project cost) than the

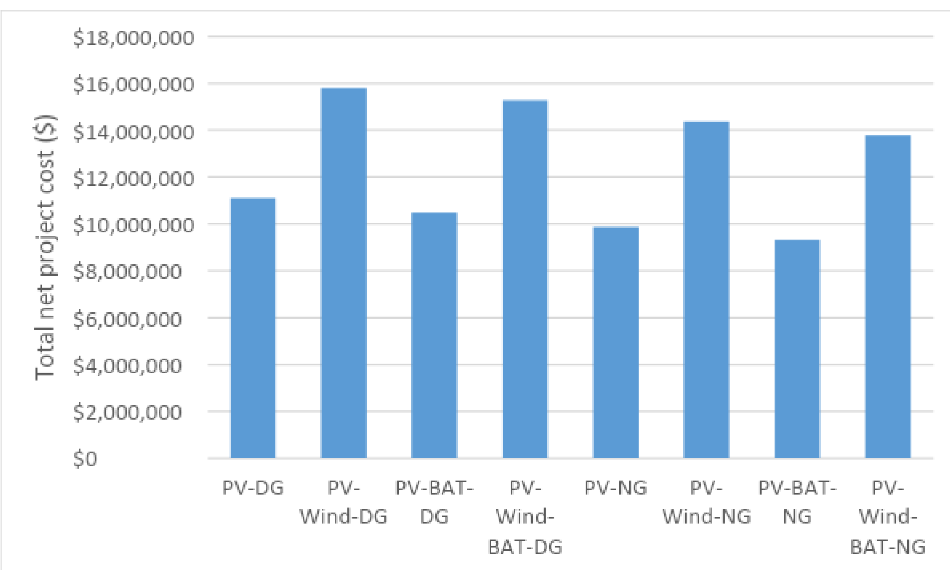

Figure5. Total net project cost (in $) for the project lifetime of each of the eight modelled hybrid solar power plants.

alternative hybrid solar power plant models. Within this metric, the cheapest wind hybrid model (H11, PV-Wind-BAT-NG) was 19.41% more costly than the most expensive non-wind hybrid model (H1, PV-DG). In comparison, models for diesel (B1) and natural gas (B2) achieved total net project costs of $9,843,765.00 and $6,905,361.00, respectively. In comparing annual operating costs, and as shown in Figure 6, the hybrid model H4 (PV-Wind-DG) produced the highest operating cost at $588,272.60 per year. Hybrid model H10 (PV-BAT-NG) produced the lowest operating cost at $177,461.80 per year. The hybrid models that incorporated natural gas produced much lower operating costs, compared to their diesel counterparts. In terms of annual operating cost, the cheapest diesel-based hybrid model (H5, PV-BAT-DG) was 27.48% more costly than the most expensive natural gas-based hybrid model (H9, PV-Wind-NG). In comparison, models for diesel (B1) and natural gas (B2) achieved operating costs of $714,779.10 per year and $270,888.40 per year, respectively.

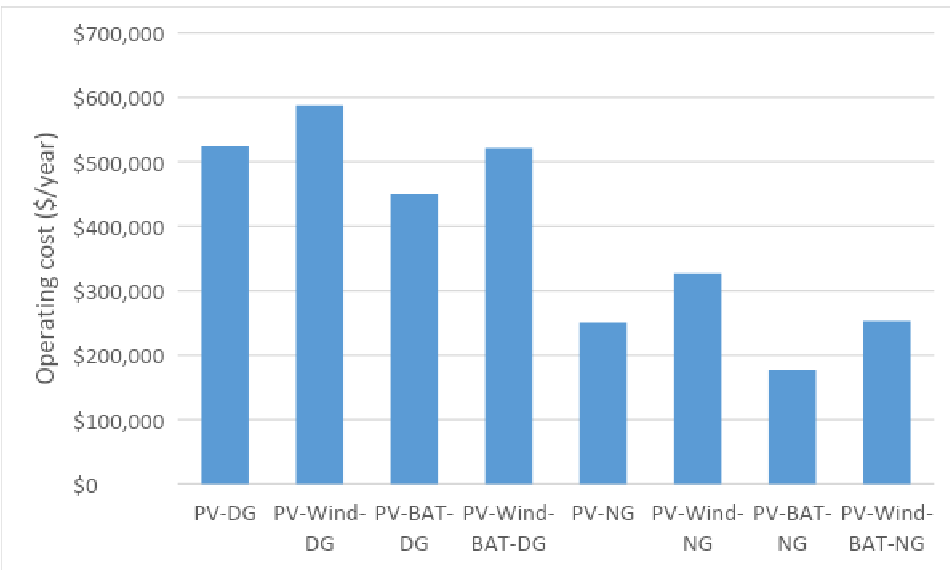

Figure 6. Operating cost (in $) for a full operating year for each of the eight modelled hybrid solar power plants.

When it came to the levelized cost of electricity (LCOE)(see Figure 7), the hybrid model H4 (PV-Wind-DG) produced the highest LCOE at 0.3565 $/kWh. Conversely, hybrid model H10 (PV-BAT-NG) achieved the lowest LCOE at 0.2100 $/kWh. In terms of the levelized cost of electricity, this represents a 41.10% reduction in cost from the most expensive to the least expensive hybrid model. Hybrid model H8 (PV-NG) achieved the second lowest LCOE at 0.2227 $/kWh. All hybrid models that contained wind power (H4 PV-Wind-DG, H7 PV-Wind-BAT-DG, H9 PV-Wind-NG, H11 PV-Wind-BAT-NG) were more expensive

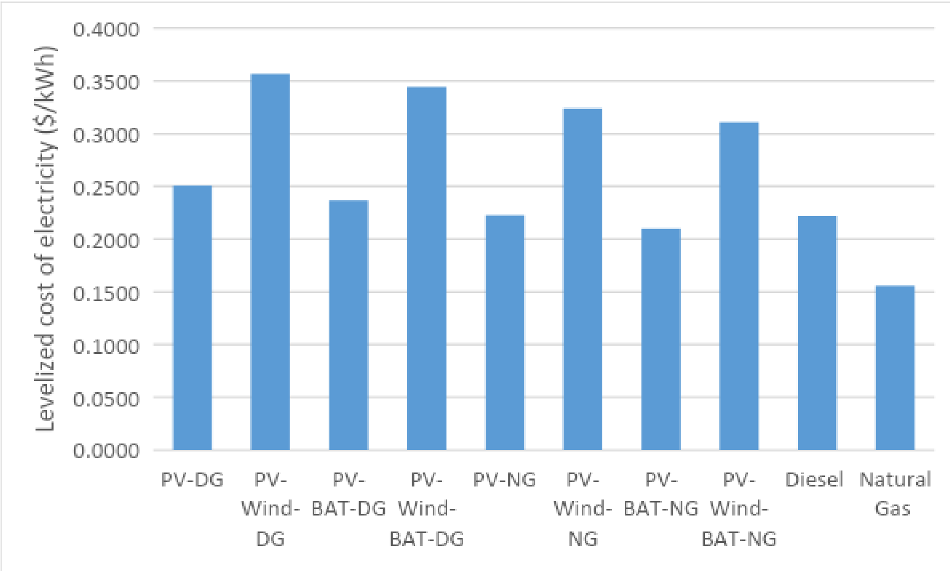

Figure 7. Levelized cost of electricity (in $/kWh) for each of the eight modelled hybrid solar power plants, and the B1 (diesel) and B2 (natural gas) baseline fossil fuel power plants.

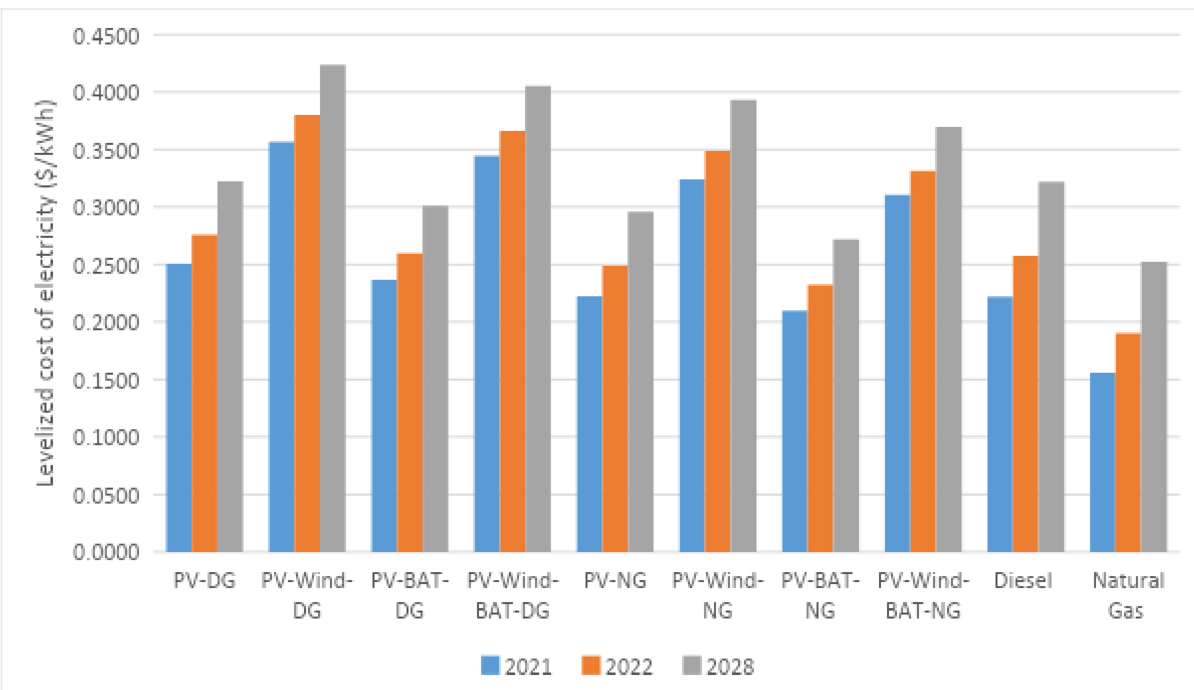

Figure 8. LCOE (in $/kWh) for 2021, 2022, and 2028, incorporating the additional carbon cost of the national greenhouse gas pollution pricing act.

than the alternative hybrid solar power plant models. Within this metric, the cheapest wind hybrid model (H11, PV-Wind-BAT-NG) was 19.40% more costly than the most expensive non-wind hybrid model (H1, PV-DG). In comparison, models for diesel (B1) and natural gas (B2) achieved LCOE values of 0.2219 and 0.1557 $/kWh respectively. Building into the LCOE analysis the effects of Canada's current carbon tax scheme results in an LCOE profile as shown in Figure 8.

4. Conclusions

Currently challenges remain for promoting distributed hybrid solar power projects in jurisdictions where pollution pricing measures remain relatively low. Power generation, reliability and cost continue to have a greater effect on the economic performance of these projects. Future policy strategy will need to recognize that greater performance at a lower cost is required for the renewable energy technology elements of a distributed hybrid power project. For now, and in the immediate future, promoting the most environmentally-friendly distributed generation project will require acceptance of higher electricity rates by the end user. Designs H10 (PV-BAT-NG) and H5 (PV-BAT-DG) performed well across most categories, providing large reductions in total emissions and low LCOE. However, these designs did produce relatively high levels of excess electricity although this does open up the viability of their use in combining hydrogen production with their operation. Based on the pressing need to reduce global GHG emissions while maintaining reliable power and economic viability, investing in the H5 (PV-BAT-DG) and H10 (PV-BAT-NG) hybrid solar power plant designs for energy resource development is logical in the short and long term for all levels of policymakers as these models provide a fair balance between cost-effectiveness, reduced GHG emissions, and providing stable sources of electricity production. Furthermore, investing in multiple plants in different geographic locations (ideally in locations with optimal environmental conditions for renewable resource power generation) would help to deal with fluctuating environmental conditions and reduce the quantities of excess electricity produced (Budischak et al. 2013; Hoicka and Rowlands 2011). Alternatively, Designs H7 (PV-Wind-BAT-DG) and H11 (PV-Wind-BAT-NG) were the most successful hybrid solar power plant designs in terms of reducing total emissions and decreasing the total quantity of excess electricity produced. However, both of these hybrid solar plant designs produced some of the highest levelized costs of electricity. Optimized versions of PV-Wind-BAT-DG/NG plants have been shown to produce levelized costs of electricity that are lower than those achieved in this study, as well as larger renewable fractions and power generation (Bentouba and Bourouis 2016; Hossain et al. 2017; Olatomiwa et al. 2015; Shezan et al. 2016; Watson et al. 2019; Wibowo and Sebayang 2015). As such, policymakers that are more concerned with long-term energy development and reliability, servicing increasing energy demands from a growing population, and maximizing the reduction of GHG emissions, should opt to invest in the H7 (PV-Wind-BAT-DG) and H11 (PV-Wind-BAT-NG) hybrid solar power plant designs.

This research has performed a regionally-contextual comparative analysis with the aim of helping to determine appropriate strategies for investment in low-carbon energy. However, achieving net-zero emissions and mitigating climate change globally will require progress in many different areas including: further reducing GHG emissions, employing carbon capture and storage to remove carbon dioxide from the atmosphere, increasing afforestation and reducing deforestation rates, reducing plastic production and consumption, halting and reversing ocean acidification, addressing biodiversity and habitat loss, creating urban density and reducing reliance on combustion engines, reducing per capita energy usage and increasing energy efficiency, developing new renewable energy technologies, and adapting to existing climate change (e.g. rising sea levels, permafrost thaw), and unparalleled cooperation within the international community.

There are several limitations to this research. First, HOMER Pro modelling software does not model all renewable energy sources such as concentrating solar power, geothermal power, or tidal power. In addition, hydro power was not incorporated into any hybrid power plant design. As such, the scope of the research was limited to PV-based set-ups as the primary renewable energy resource. Furthermore, a number of technologies related to photovoltaics were not included or examined in this study. These technologies include but are not limited to: sun-tracking systems (or rotating axis systems) for PV panels, concentrating PV, concentrating solar power, bifacial solar modules, or newer generation PV cells. However, while these technologies represent potentially higher energy efficiencies, at present they are not the most commercially available, technologically mature (ready for broad dissemination into the market), cost-effective, or widely used materials in the solar power field so this study focused on flat panel PV cells, as they are readily available, less expensive, and the most representative of immediate solutions for mitigating GHG emissions. HOMER Pro GHG emission calculations do not consider emissions related to the construction and implementation of the hybrid or traditional power. However, all modeled hybrid and baseline power plants are subject to the same limitation, thereby not favoring one design or another. Future research could conduct similar comparative analysis, but include a metric designed to account for the full quantity of life cycle GHG emissions generated from each energy resource within the hybrid design. Another limitation is that Ontario can have long and snow-laden winters. As such, the cost of removing snow from PV arrays, as well as the possibility of losing sunlight from snow-covered panels may not be adequately accounted for in this research. At present, HOMER Pro does not have any means for accounting for this potential loss. Due to the modelling software limitations this limitation must be accepted, and should be taken into consideration by policy makers in climates with heavy snowfall. Future comparative analysis research would attempt to include calculations that consider the effect of snowfall on PV array power production. These limitations may potentially reduce the accuracy of the results of this study, but the degree of accuracy is sufficient to provide a reasonable comparative analysis, given the assumptions made.

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