Comparison Between Nuclear and Solar Energy Land Use and Costs

Alex Fernandes

I. Introduction

As Ontario works towards its goal to rely completely on clean energy by 2050, it faces the difficult decision of which energy sources to invest in. Among the range of options available are solar and nuclear, two different energy sources that Ontario has had experience using, each with merits and drawbacks. This report focuses on the economic and geographical side by comparing the land use and Levelized Cost of Energy (LCOE) of solar and nuclear energy. LCOE is a standardized way of assessing energy sources by calculating the average net present cost to generate electricity over the source's lifetime. This comparison is achieved by building a hypothetical solar plant that matches the Bruce Nuclear Generating Station's energy output in 2023 and then analyzing the associated costs.

Different research papers have compared solar and nuclear energy, however, they either didn't account for land costs and grouped wind and solar together [1] or they used strictly theoretical data to develop their hypothetical solar and nuclear plants [2]. This report will directly compare a solar and nuclear plant of equal output size based on existing solar and nuclear plants (Sarnia PV Farm and Bruce Nuclear Generating Station) while including factors such as land use. Additionally, no report has compared nuclear and solar energy in the context of CANDU reactor technology, which has a unique LCOE thanks to its cheaper fuel cycle that doesn't involve enriched fuel. The aforementioned reports are also not based on Ontario but rather on Southeast Asia and Turkey, respectively. This report is based on data local to Ontario, which takes into account Ontario's unique irradiance and land costs.

This report starts with calculating the annual power output of the Bruce Nuclear Generating Station in Section II. The plant's construction, O&M, fuel, and decommissioning costs are then calculated, along with its land use. These costs are used to calculate nuclear energy's LCOE. Section III tests two different ways to calculate the amount of land needed to build a solar farm that matches the Bruce Nuclear Generating Station's output in 2023. Then, the associated costs of building, operating, and decommissioning a solar farm of that size are calculated to find solar energy's LCOE. Section IV concludes the paper by discussing results and future research opportunities.

II. Bruce Nuclear Generating Station

This section analyzes nuclear energy's land use and costs by calculating the total power output, land use, and LCOE of the Bruce Nuclear Generating Station.

A. Calculating Power Output

The Bruce Nuclear Generating Station consists of 2 plants (Plant A and Plant B) and a total of 8 reactors (4 reactors per plant). Table I shows the nameplate capacity, power output in 2023, and average annual output over the last 5 years of each unit. Summing the energy outputs of each of the units gives a total energy output of 42.34 TWh in 2023. The plant has a nameplate capacity of 57.42 TWh, giving an availability capacity factor of 74.09% for 2023.

Unit 3 and 6 have considerably lower energy outputs in 2023 because they were offline for Major Component Replacement (MCR), a part of Bruce Power's Life-Extension Program that replaces essential components of the reactor, such as calandria tubes, feeder tubes, pressure tubes, and steam generators [3]. Unit 6 had returned to being commercially operational in September 2023 after undergoing MCR in January 2020. Unit 3 began its MCR in March 2023 and is expected to return by 2026 [3]. In Table I, when calculating the average annual output over the last 5 years for Units 3 and 6, the years they underwent MCR were not included in order to get an accurate representation of each unit's average output under normal operating conditions.

The expected annual output of the Bruce Nuclear Generating Station throughout its lifespan can be seen in Figure 1. The annual output of the plant is taken from Bruce Power's Annual End of the Year reports, which gave the annual output of the reactor between 2002 and 2023 [4]. For the output before 2002 and after 2023, each unit's 5 year average output is used to approximate each unit's output.

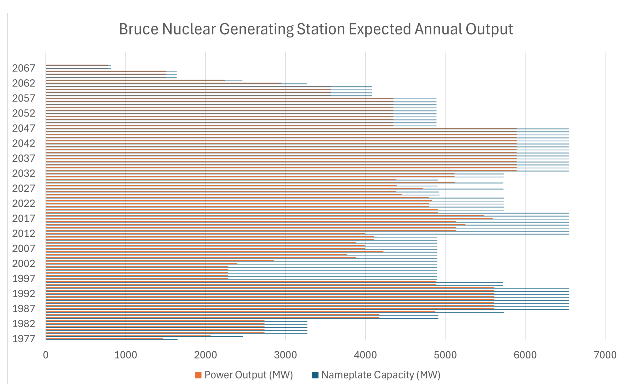

Fig. 1. Bruce Nuclear Generating Station Annual Output and Nameplate Capacity

When each unit undergoes MCR, they produce no power but experience a boost in output after completion. Based on the increase in power output of Unit 6 in 2023, the increase

TABLE I
BRUCE NUCLEAR GENERATING STATION'S UNITS POWER OUTPUT AND LIFESPAN

Plant	Unit	Nameplate Capacity (GWh)	2023 Power Output (GWh)	Average 5 Year Output (GWh)	MCR Period	Total Lifespan
A	1	7,210	7,020	6,510	1997 - 2012	1997 - 2047
	2	7,250	6,990	6,360	1995 - 2012	1977 - 2047
	3	7,150	1,150	5,200	2023 - 2025	1987 - 2061
	4	7,060	5,900	5,900	2024 - 2027	1979 - 2062
B	5	7,200	6,930	6,100	2026 - 2028	1984 - 2063
	6	7,160	2,200	6,500	2020 - 2023	1984 - 2057
	7	7,230	7,180	6,120	2028 - 2030	1986 - 2066
	8	7,160	4,960	6,480	2030 - 2032	1987 - 2068

of power output for each unit after MCR is approximated as a 5% increase in annual output for the rest of the unit's lifespan. The time period of each unit's MCR is included in Table I. MCR adds an additional 30-35 years to each unit's lifespan. The total lifespan of each unit can be seen in Table I as well.

B. Calculating Costs

1) Construction Costs: The construction of Bruce Nuclear Generating Station spanned multiple decades. Plant A was constructed from 1970 to 1979 and cost 1.8 billion dollars-of-the-year[1], which, when adjusted for inflation, would cost \$11.83 billion in 2024. Plant B was constructed from 1976 to 1987 and cost 5.9 billion dollars-of-the-year [5]. Adjusted for inflation, Plant B's construction costs would be \$14.19 billion in 2024.

2) Land Costs: Bruce Nuclear Generating Station is located in Bruce County, Ontario, and takes up around 2300 acres (9.3 km^2) of land [5]. According to the Government of Canada, an acre of land in Ontario was valued at \$19,685 in 2023 [6], resulting in the Bruce Plant having a land value of over \$45 million.

3) Refurbishment Costs: As outlined before, all of the units have undergone, or are planned to undergo, MCR to further extend their lifetime by up to 35 years. Refurbishment for Unit 1 and 2 was completed in 2012 and cost \$4.8 billion [7], which is \$6.3 billion in 2024. Unit 6 completed MCR in 2023 and totaled \$2.64 billion [8]. Refurbishment on the remaining units is predicted to cost around \$3 billion per unit. Table II shows the investment expenditures involved in the Bruce Nuclear Generating Station and over what period they occur.

4) Operation and Maintenance Costs: The operation and maintenance (O&M) costs for a CANDU reactor are approximately \$98,560/MW based on the nameplate capacity of all operating units and \$1.64/MWh based on the annual output of the plant [9].

5) Fuel Costs: Because of CANDU Reactors' unique fuel cycle that doesn't require enrichment, the fuel costs for CANDU Reactors are lower than that of other reactor designs. Fuel costs include purchasing of uranium and zirconium alloys, converting the uranium from U_3O_8 to UO_2 powder, fuel fabrication, which includes uranium pelletization, fuel rod encapsulation, and fuel bundle assembly, and transportation. Fuel costs include the costs associated with running the facilities that fabricate the fuel. In total, fuel costs are estimated at \$340.19/kg of fuel [10]. CANDU reactors require approximately 160 kg of fuel in order to produce 1 MW-year of energy [11], giving a fuel cost of \$54,430/MW-year.

[1]Dollars-of-the-year is a common method of measuring nuclear plants' construction costs by summing each year's total costs during the construction period

TABLE II
BRUCE NUCLEAR GENERATING STATION INVESTMENT EXPENDITURES

Description	Time Period	Cost
Plant A Construction	1970 - 1978	\$11.83B
Plant B Construction	1976 - 1986	\$14.19B
Unit 1 and 2 Refurbishment	1997 - 2011	\$6.3B
Unit 3 Refurbishment	2023 - 2025	\$3B
Unit 4 Refurbishment	2024 - 2027	\$3B
Unit 5 Refurbishment	2026 - 2028	\$3B
Unit 6 Refurbishment	2020 - 2023	\$2.64B
Unit 7 Refurbishment	2028 - 2030	\$3B
Unit 8 Refurbishment	2030 - 2032	\$3B

6) Decommissioning Costs: Decommissioning costs involves all the costs associated with safely removing a plant from service. Decommissioning costs are incurred at the end of the plant's life, but have to be discounted to present value (PV) using Equation 1.

$$PV = \frac{D}{(1+r)^n} \tag{1}$$

This cost then has to be annualized among the operational life of the plant using Equation 2.

$$D_t = PV \times \frac{r}{1-(1+r)^{-n}} \tag{2}$$

Plant A has a decommissioning cost (D) of \$1,096 million and a lifespan (n) of 86 years, giving a decommissioning cost (D_t) of \$0.838 million/year using a 5% discount rate (r). Using the same discount rate, Plant B has a decommissioning cost of \$1,904 million and a life span of 84 years, giving a decommissioning cost of \$0.923 million/year. All of the annual costs for the Bruce Nuclear Generating Station are listed in Table III.

7) Calculating LCOE: The LCOE is calculated using Equation 3 where I_t is investment expenditures, M_t is O&M

TABLE III
BRUCE NUCLEAR GENERATING STATION ONGOING COSTS

Description	Cost
Operation & Maintenance Fixed Costs	$98,560/MW
Operation & Maintenance Variable Costs	$1.64/MWh
Fuel Costs	$54,430/MW
Plant A Decommissioning Cost	$838,000/year
Plant B Decommissioning Cost	$923,000/year

costs, F_t is fuel costs, D_t is decommissioning costs, and E_t is the energy generated. Using the annual power output in Table I, the investment expenditures in Table II, the ongoing costs in Table III, and a discount rate of 5%, the LCOE of nuclear energy is found to be $64.17/MWh. MIT's report on the costs of nuclear energy found the LCOE to be around $110/MWh [12]. This is a higher than $64.17/MWh, however, the MIT study involved a nuclear reactor that used enriched fuel, significantly increasing fuel costs, and that had a plant life of only 40 years.

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t+M_t+F_t+D_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{3}$$

III. HYPOTHETICAL SOLAR FARM

This section analyzes the land use and costs of solar energy by building a hypothetical PV farm using two methods. The first method involves using the power output and land use of an existing PV farm in Ontario. The second method requires building a PV farm from scratch by calculating the area of all the different parts of a PV farm. Both methods include finding a surface power density and then scaling it up to get the land required to match the Bruce Nuclear Generating Station's power output in 2023. The costs associated with the result from the more accurate method is then used to calculate solar energy's LCOE.

A. Method 1: Calculating from an Existing Plant

The Sarnia Photovoltaic Solar Plant is the largest operating solar farm in Ontario. The plant has a nameplate capacity of 700,800 MWh [13] and an actual annual output of 120,000 MWh, giving an availability capacity factor of 17.12%. The plant covers 3.84 km^2, however, as Figure 2 shows, a large portion of the plant is empty space, likely due to construction complications, ecological issues, or the farm size being bigger than needed. Figure 2 makes a rough estimate of the land required purely for solar panels in blue, which gives an area of 2.87 km^2. This number is more of a minimum space required, as there is likely equipment outside of the blue area, but 2.87 km^2 is a more accurate representation of the space required than the total area of the farm.

Based on the solar panel area, the farm has a surface power density (P_d) of 41.81 kWh/m^2. However, the Sarnia PV Farm was constructed in 2010, and PV technology has progressed significantly since then, making 41.81 kWh/m^2 an outdated power density. The Sarnia plant uses First Solar modules, which, based on First Solar's product selection during the time

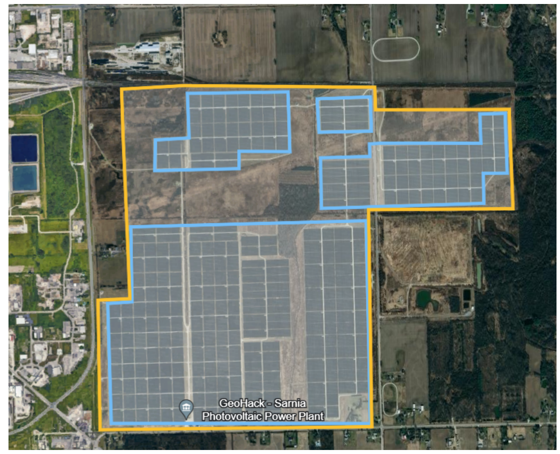

Fig. 2. Sarnia PV Farm Area. Yellow Outline - Total Farm Area. Blue Outline - Approximate Space Required

of construction and the nameplate capacity of the farm, are assumed to be the First Solar FS-270 Series 2 PV Module. These modules have a maximum power output (P_{max}) of 70 W, a length of 1.2 m, and a width of 0.6 m [14]. Using Equation 4, where G is Irradiance at STC (1000 W/m^2) and A_{mod} is the module area in m^2, the efficiency (η) of the FS-270 is 9.72%.

$$\eta = \frac{P_{max}}{A_{mod} \times G} \times 100\% \tag{4}$$

First Solar, the world's largest supplier of PV modules [15], is offering the Series 7 in 2024 for utility-scale projects, with the FS-7550-TR1 model having an efficiency of 19.9% [16]. This efficiency is 2.05$\times$ better than the Series 2, giving an updated surface power density of 85.71 kWh/m^2.

Using Equation 5, to match the Bruce Nuclear Generating Station's 2023 output (P_{Bruce}), the solar farm's area (A_{plant}) would need to be scaled up to cover an area of approximately 493.99 km^2, which is around $53\times$ larger than the Bruce Nuclear Generating Station.

$$A_{plant} = \frac{P_{Bruce}}{P_d} \tag{5}$$

B. Method 2: Calculating from Insolation

1) Number of PV Modules: Solar insolation is the energy received from the sun in the form of electromagnetic radiation per unit area. The average yearly insolation gives the amount of energy received over a year per unit area and takes into account factors such as weather, geographical location, and length of day. For solar panels in Southern Ontario, a tilt of 35° and an azimuth angle of 2° east of due south is suggested for optimal power generation [15]. At this angle, the average daily insolation (G) for major South Western Ontario cities is around 4.25 kWh/m^2/day.

Using the same PV modules as Section III-A (FS-7550-TR1), with an efficiency of 19.9% and an area of 2.8 m^2 [16], the annual output (P_{mod}) of each module can be calculated using Equation 6.

$$P_{mod} = G \times \eta \times 365 \times A_{mod} \tag{6}$$

This gives an annual energy output of 864 kWh per module. Using Equation 7, where N_{mod} is the number of modules needed, approximately 49,000,000 modules would be needed to match the Bruce Nuclear Generating Station's 2023 output of 42.34×10^9 kWh.

$$N_{mod} = \frac{P_{Bruce}}{P_{mod}} \tag{7}$$

2) Solar Panel Layout: PV farms can arrange PV modules in portrait or landscape orientation, and have them single-stacked, double-stacked, or multi-stacked. For this hypothetical farm, a double-stacked arrangement is chosen in a portrait orientation for space efficiency. The PV modules will be on a fixed tilt system at a 35° angle from the horizontal to maximize solar collection.

PV module rows must be spaced far enough from each other to prevent casting shadows on adjacent rows and allow access for maintenance. In order to calculate the minimum distance between rows (d_{min}), the height of the module is found using Equation 8, where h is the height of the two modules double-stacked, h_0 is the distance from the lower edge of the bottom module to the ground, which is typically 50 cm, l_m is the length of the module (2.3 m for the FS-7550-TR1) and θ_t is the angle of the module, as seen in Figure 3 [17].

$$h = h_0 + (2 \times l_m \times \sin(\theta_t)) \tag{8}$$

The length of the shadow (l_s) at the sun's lowest position, as seen in Figure 4, is calculated with Equation 9 using the elevation angle (α) of the sun during solar noon of the winter solstice, which is considered a worst case scenario for shadow length.

$$l_s = \frac{h}{\tan(\alpha)} \tag{9}$$

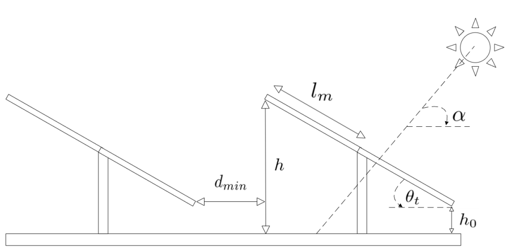

Fig. 3. PV Module Side View

Finally, Equation 10 is used to project the shadow onto the ground in the direction the panels are facing according to the panels' azimuth angle (θ_{az}) of 2° east of due south, giving a minimum row spacing of 7.42 m.

$$d_{min} = l_s \times \cos(\theta_{az})) \tag{10}$$

Each module is 2.3 m long and 1.216 m wide. There is a 10 mm spacing between adjacent modules to accommodate for possible expansion of the module frame [17]. Two modules

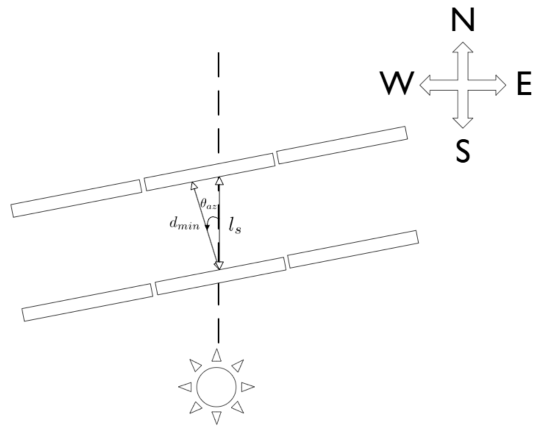

Fig. 4. Shadow Length

double-stacked with a row space of 7.42 m would take up an area of 14.74 m^2, meaning 49,000,000 modules would take up approximately 361 km^2.

3) Inverters and Transformers: The DC to AC Ratio (R_{DCtoAC}) represents the ratio of the DC power generated by the PV modules to the AC power output by the inverters. On average, DC to AC Ratios range from 1.0 to 1.6 [18]. The FS-7550-TR1 has a max power output of 550 W, giving a DC capacity (P_{DC}) of 26,950 MW. Since the average power output of the plant is expected to be much lower at 4,833 MW, a high DC to AC ratio of 1.6 can be used. By having more PV module (DC) capacity than inverter (AC) capacity, it ensures that the inverters are more likely to run at full capacity, as the PV modules are often not running at full capacity due to varying solar conditions. Using a ratio of 1.6 with Equation 11, an AC capacity (P_{AC}) of 16,900 MW for the inverters is chosen.

$$R_{DCtoAC} = \frac{P_{DC}}{P_{AC}} \tag{11}$$

Using 1000 kWac inverters (P_{inv}), 16,900 inverters will be needed. Each inverter will be able to connect to 2,910 PV modules ($N_{modperinv}$) using Equation 12, where P_{modmax} is the max output of a PV module, 550 W.

$$N_{modperinv} = \frac{P_{inv}}{P_{modmax}} \times R_{DCtoAC} \tag{12}$$

Using similarly sized transformers, each inverter can be paired with a transformer, resulting in 19,600 transformers. The inverters and transformers are stored in buildings, with each inverter transformer pair taking up 100 m^2. This requires 1.96 km^2 of land for inverters and transformers.

4) Plant Layout and Roads: Each inverter is connected to 2,910 PV Modules, which are then divided into 4 sections of 728 modules. Each section will be 52 modules wide and 14 modules long, giving a width of 63.2 m (w_{sec}) and a length of 78.3 m (l_{sec}). For accessibility for maintenance, every section is surrounded by a 3 m wide road (w_{road}). The total area needed for roads (A_{road}) is calculated using Equation 13.

$$A_{road} = N_{sec} \times (l_{sec} \times w_{road} + w_{sec} \times w_{road}) \quad (13)$$

For 78,000 sections (N_{sec}), 33.3 km^2 is required for roads. Figure 5 shows how 4 sections are layed out.

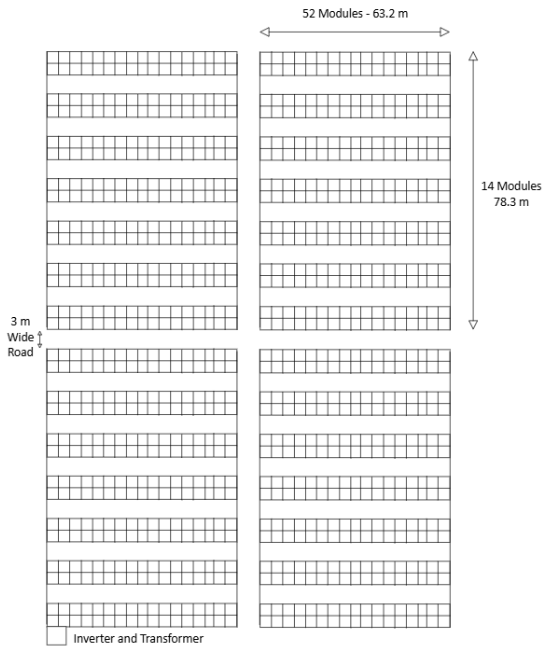

Fig. 5. Section Layout

5) Total Area and Yield: An additional 5% of the total area is needed for setback from the site's boundary to account for possible shading and miscellaneous things such as control buildings. Thus, the total amount of area required for the solar plant (A_{farm}) is found using Equation 14, where A_{inv} is the area required for inverters and A_{mod} is the total area of the PV modules, including row spacing. Equation 14 gives a total area required of 416 km^2, 45$\times$ larger than the Bruce Nuclear Generating Station.

$$A_{farm} = 1.05 \times (A_{road} + A_{inv} + A_{mod}) \quad (14)$$

C. Calculating Output and Lifespan

The farm is expected to produce a yield of 42.34 TWh in year 1 and has a nameplate capacity of 236.1 TWh, giving an availability capacity factor of 17.9%. However, the PV modules are expected to degrade over time, reducing their annual yield. The FS-7550-TR1 experiences a 0.3% annual degradation rate and has a lifetime of 30 years.

D. Calculating Costs

1) Construction Costs: The construction cost of the hypothetical solar farm is based on the National Renewable Energy Laboratory's Solar Photovoltaic System Price Analysis from 2023 [19]. The analysis uses current market trends, previous benchmarks, and supplier information to determine the prices needed to construct a 100-MW utility-scale PV system. Prices in the report are given per kWh but have been scaled to match the hypothetical plant's nameplate capacity of 26.95 GW in CAD, as seen in Table IV. The costs and land use are based on the results from Method 2, as the exact land use is less accurate in Method 1. The same land rate of $19,685 per acre is used, giving a total construction cost of $42.01 billion.

TABLE IV
PV FARM INVESTMENT EXPENDITURES

Description	Cost	NREL $ per kW
Solar Modules	$13.83B	$510
Inverters	$2.42B	$89
Electronics	$8.71B	$323
Structural	$1.12B	$41
Fieldwork	$2.27B	$84
Other	$11.64B	$429
Land	$2.02B	NA
Total	$42.01B	$1,476

2) O&M Costs: The O&M cost of running a PV Farm is also based on the NREL 2023 Price Analysis and is priced at $22,710/MW [19]. The O&M cost of running a PV farm is significantly lower than that for nuclear energy because of the simplified nature of PV farm operations. However, the O&M cost is based on the nameplate capacity of the farm, and for a PV farm to match the Bruce Nuclear Generating Station's output, the farm must have a high nameplate capacity due to the PV modules' low availability capacity factor. Because of this, the PV farm ends up having a similar average annual O&M cost to the Bruce Nuclear Generating Station.

3) Decommissioning Cost: The cost of decommissioning a PV farm in an environmentally friendly manner, which includes recycling the PV modules, would cost $697.50/kW [20], based on the nameplate capacity of the farm. Following the same method as finding the decommissioning cost of the nuclear reactor, the PV farm decommissioning cost has to be discounted to present value using Equation 1 and then annualized using Equation 2, giving an annual cost of $282.98 m/year.

4) Calculating LCOE: Using Equation 3, the investment expenditures in Table IV, and the ongoing costs in Table V, the PV farm LCOE is calculated to be $89.77/MWh. This is similar to other papers that have found the LCOE of PV farms to be around $93.51/MWh [2].

TABLE V
PV FARM ONGOING COSTS

Description	Cost
Operation & Maintenance Fixed Costs	$22,710/MW
Decommissioning Cost	$282.98 m/year

IV. CONCLUSION

This paper compares the land use and costs of nuclear and solar energy in Ontario by using data from the Bruce Nuclear Generating Station and by building a hypothetical PV farm that matches the plant's energy output in 2023.

The Bruce Nuclear Generating Station was found to span 9.3 km^2 and produced 42.34 TWh in 2023. The solar farm's area to produce the same output was calculated using two methods. The first method involved finding the area based on a previous PV farm in Ontario, the Sarnia PV Farm, and resulted in an area of 494 km^2. The second method required constructing a PV farm based on the insolation rates in Ontario, which resulted in an area of 416 km^2. A comparison of the different areas relative to the GTA can be seen in Figure 6, where the yellow area represents the area of the Bruce Nuclear Generating Station, the green area represents the PV farm area from the first method, and the blue area represents the PV farm area from the second method.

Fig. 6. Area Comparisons. Yellow - Bruce Area. Green - PV Farm Area From Sarnia Farm. Blue - PV Farm Area From Insolation

The PV farm area from the insolation method was selected as more accurate, as the area from the Sarnia plant was less accurate due to the area of the plant not fully being used and the plant being over a decade old. Using this method, the PV farm was found to have an area 45$\times$ larger than the area of the Bruce Nuclear Generating Station in order to match its output in 2023.

Using data from Bruce Power Annual Reports, along with average annual outputs to predict the plant's output for the remainder of the plant's lifetime, nuclear energy's LCOE based on the Bruce Nuclear Generating Station was found to be \$64.17/MWh. Solar energy's LCOE was found to be \$89.77/MWh, around $1.4\times$ as expensive as nuclear energy.

This paper has found nuclear energy to be both cheaper and more land efficient than solar energy. While nuclear energy was found to have a lower LCOE, its investment expenditures and ongoing costs were higher than solar energy, especially due to the fact that, unlike solar energy, nuclear energy has fuel costs. However, nuclear energy's output and lifespan were higher than solar energy, resulting in a lower LCOE. Nuclear energy's lower LCOE is certainly desirable, as it means the total cost per unit of nuclear energy is cheaper than that of solar energy, however, nuclear energy's overall higher costs should also be considered.

It's clear that nuclear energy is more space efficient than solar energy, which has environmental benefits. However, unlike nuclear energy, solar energy can be integrated into urban, residential, or farm settings, just not at the scale outlined in this report. Integration like this would also further decrease solar energy's space efficiency.

This study has found nuclear energy to be more space efficient and cheaper than solar energy. Further research is needed to look beyond the economic and geographical aspects of the two energy sources. Potential future research could compare additional energy sources using similar tests or instead compare different aspects of solar and nuclear energy, such as public safety or CO_2 emissions.

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