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Sustainable Integration of Photovoltaic Systems Globally – A financial and Environmental assessment

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Abstract

The current work investigates the integration of a 6 MW grid-connected photovoltaic system on a continental level. The considered locations are: Washington, Ottawa, Brasilia, Berlin, Cairo, Beijing, and Canberra. As the locations spread throughout the world, they have a large variation in their irradiation level and climate conditions. The integrated PV system is simulated under real weather data imported from the NASA (National Aeronautics and Space Administration) website. The simulations have been done on RETScreen. It assesses the system energy production potential and different financial indicators, such as payback, net present value, and internal rate of return. Payback period is used as an indicator of the financial viability of the project integration. Payback period is the lowest in Brasilia (8.5 years) and the highest in Berlin (17.7 years). The rest of considered locations show a payback period that is in between both locations. The proposed project mitigates greenhouse gas emissions annually by 82 tons in Brasilia and 39.9 tons in Berlin. Sensitivity analysis reported the effect of changing parameters like initial cost and debt term on the financial feasibility of the project. It is shown that an increase in the initial cost is most likely to cause the project to be infeasible in lower irradiance locations.

Index-words: *Solar, Photovoltaic, Financial Assessment, Environmental Impact, Payback.*

I. Nomenclature

Term	Meaning
C_{capa}	annual capacity saving
C_{ener}	Annual energy savings
C_{fuel}	Annual fuel cost
C_{GHG}	GHG reduction income
$C_{in,n}$	Project cash inflow
$\widetilde{C_n}$	After tax cash flow
C_n	Pre-tax cash flow
$C_{out,n}$	Project cash outflow
$C_{O\&M}$	Yearly operation and maintenance costs
C_{per}	periodic cost
C_{RE}	annual renewable energy credit
D	annual debt payment
F_R	collector heat removal factor
G	global incident solar radiation on the collector
IRR	Internal rate of return
NPV	Net present value
PV	Photovoltaic
Q_{coll}	energy collected per unit collector area per unit time
r_e	energy cost escalation rate
r_{GHG}	GHG credit escalation rate
r_i	inflation rate
r_{RE}	renewable energy credit escalation rate
T_n	Taxes
U_L	The overall heat loss coefficient of the collector

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II. Introduction & Literature review

Sustainability has been an emerging global effort due to the rising global warming threats. There needs to be a shift from reliance on conventional fossil fuels. Solar energy has a great renewable energy potential to harness. Figure 1 shows the solar potential throughout the globe. The legend shows a variation of more than three times between high irradiation and low irradiation places. Irradiation is typically higher in the places that are located near the equator and vice versa. High irradiation is dominant in Africa, Australia, and portions of South America. Moderate irradiation is present in Asia and Europe. Europe and North America have locations of low solar irradiation. This makes the performance of a PV system completely different when installed in different locations.

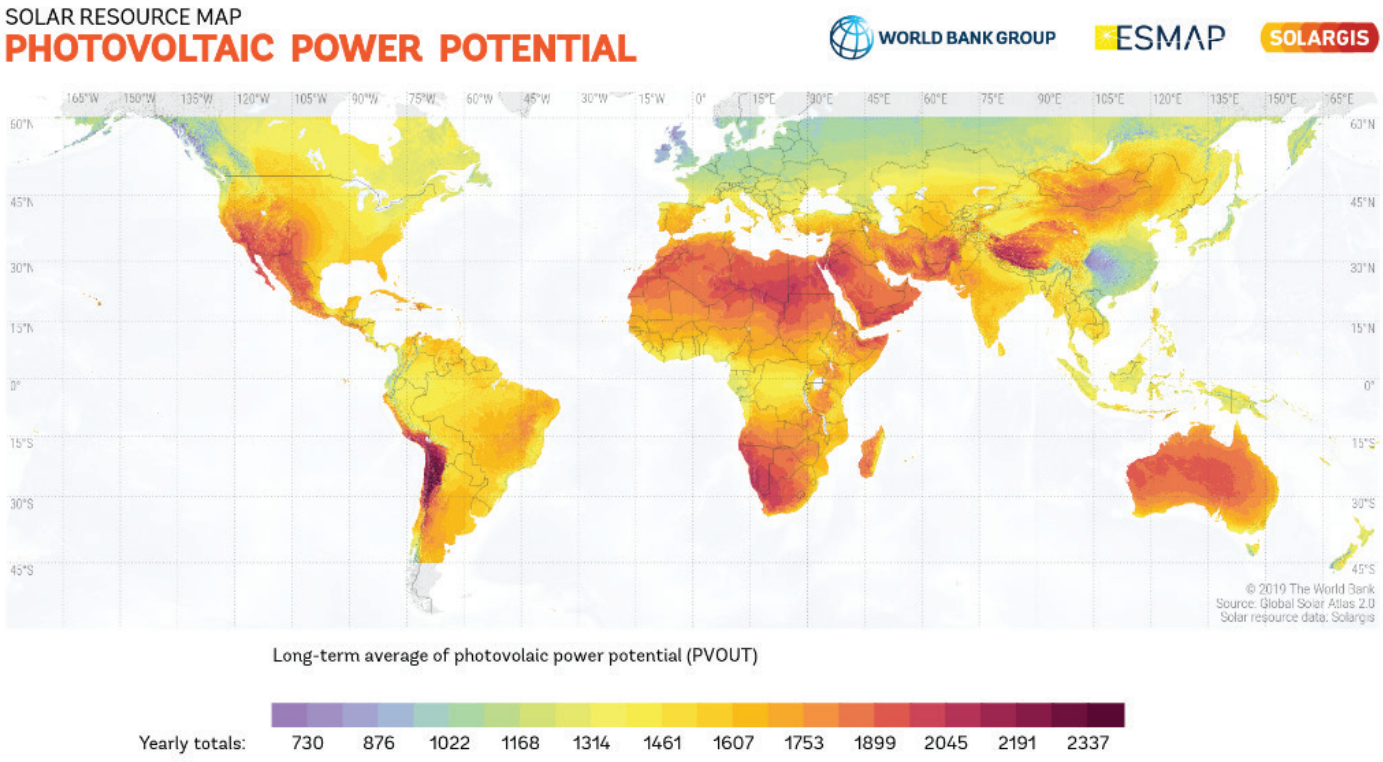


Figure 1: World solar resources map [1].

In Africa, there have been several research works reported on photovoltaic system feasibility in different regions. Sohani et al. [2] presented a comprehensive review of building-integrated photovoltaic/thermal technologies. They focused on the current status and future trends for PV systems integration in the Middle Eastern and North African countries. They provided a statistical analysis of the existing work in the area. They compared it to the rest of the world. They highlighted the technologies, heat transfer media, and integration of storage systems. They performed a critical analysis of the reported work from the technical, environmental, and financial perspectives. Geh et al. [3] investigated the potential of photovoltaic system integration in advancing the sustainability in the public universities sector. They analyzed performance assessment surveys and found that direct benefits are the main ways to advance photovoltaic system integration. They include: better university reputation, reduced energy cost, and fitting in the Sustainable Development Goals. They also found out that the detrimental impact of low government funding is the main hindrance to PV widespread integration. Alrawi and Al-Ghamdi [4] investigated the economic viability of rooftop PV units in North Africa and the Middle East. They reported a performance comparison of the PV system in the ten most populated cities in the region. The findings were intended to guide the policy makers to better understand the feasibility of rooftop PV integration in the region. Takyi and Laryea [5] performed a comparison between different PV module technologies installed in

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Ghana's sub-Saharan African weather. The comparison was between polycrystalline silicon, thin film silicon, and heterojunction PV modules. They found that the best performance was for heterojunction PV modules under the considered climatic conditions. Patchali et al. [6] studied the generation of meteorological year for PV system assessment under weather conditions of Togo, West Africa. They developed the model for five cities in the country and considered the performance of 72 photovoltaic modules. They reported slight variations in the estimated PV energy using the developed model. They recommended that the results be implemented in energy-efficient studies.

In the Asian context, a review was presented by Park et al. [7]. It included the drivers of future changes in PV systems integration in East Asia. They based their analysis on an accurate fine-resolution climate model. They found that the near-surface air temperature increase has a negative effect on PV potential. The number of rainy days projection is crucial for a realistic prediction. Wind effect was found to be insignificant on PV potential. Chandel et al. [8] presented a new rooftop grid-connected PV system in India. They highlighted the important intervention parameters in the policy that advance such integration. They are mainly: solar tariff, energy subsidy pattern, release methodology, and benchmark cost. Yu et al. [9] studied the potential of distributed and centralized PV systems in China. They highlighted that selection factors differ for both system types. For distributed systems, it included: roof type, presence of obstacles, and time of illumination. For centralized systems, the factors are: economy, environment, and terrain. Uddin et al. [10] investigated the potential energy conservation by integrating PV in a window system in Bangladesh. They simulated three different window configurations. They found out that a cadmium telluride (CdTe) building-integrated PV system was the most efficient. It saved around 31-60% of electricity consumption compared to the conventional system. Bunda et al. [11] modeled the process of adopting PV panels by residential sectors in the Philippines. They highlighted the knowledge and financial hurdles that need to be addressed. They recommended a focus on incentives for selling excess energy and a feasible return on investment to encourage PV adoption in households.

Europe has been leading in its pathway towards sustainability. There is plenty of research reported in the area of PV applications. Zsiboracs et al. [12] considered the assessment of the reliability of scheduling PV generation in seventeen countries. They reported huge differences in prediction accuracy between different countries. This necessitates improving single algorithms for different countries. Arantegui and Jäger-Waldau [13] presented an analysis of PV status in the European Union after the Paris agreement. They mentioned that the installed PV capacity had increased 50 times in 2015 compared to 2005. In order to reach the 2030 target, triple the current capacity is needed. Osseweijer [14] presented a comparative review of building-integrated PV in selected European countries. Different factors need to be included in the assessment. They are: policy, stakeholders, and markets. They need to be considered on an international level, not only nationally. Kougias [15] presented the role of PV in the European Green Deal and Recovery Plan. They focused on the needed policies after COVID-19. To cope with the desired targets, an unprecedented increase in PV integration is needed in the coming decade. Zsiboracs et al. [16] considered the integration of energy storage into a PV system. Lithium-ion and sodium sulfur storage systems were found to be effective in grid balancing under the Belgian and Hungarian climates.

In Latin America, Zhang et al. [17] investigated the total factor efficiency of implementing renewables, including photovoltaics. It was found to be 80.8%, and it has an upward trend. This is mainly attributed to adopting new technologies and adequate policies. Ottonelli et al. [18] presented the prospects of the Paris agreement and how they affect PV prevalence in Latin America. They reported that there are only twenty-five clean development mechanism projects despite the high solar irradiation in the region. Lack of incentives and regulations is the main hindrance to the advancement of PV integration. Gil et al. [19] compared the current state of the PV market in eight countries of South America. They found out that Chile has the highest penetration of PV with the strictest criteria in place. They emphasized the need for more research to advance solar integration on the continent. Miravet-Sánchez et al. [20] presented an analysis of PV integration in rural and remote communities. They presented an electrifying case study of 216 houses in nine communities. It resulted in an annual reduction of carbon dioxide emissions of 2164 tons. This is a promising result, but there needs to be more incentives to advance the technology. Saccardo et al. [21] studied the feasibility of PV integration

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in Brazil to mitigate GHG emissions. Their model quantified that fossil fuel replacement by PV can guarantee about 37% reduction in emissions. This can facilitate reaching the Brazil 2030 target set by the Paris agreement.

Numerous studies were conducted on the potential advancement of PV integration in Australia. Alim et al. [22] presented a comprehensive review of the building-integrated photovoltaic implementation in Australia. Buildings constitute 20% of total energy consumption. Although Australia has high solar irradiation, there is not enough integration of PV technology. Payback and return on investment are promising for the Australian climate. Mahmoudi et al. [23] presented an economic and environmental assessment of end-of-life photovoltaic panels. A few thousand annual tons of harmful emissions can be mitigated. However, this potential is fulfilled under certain economic parameters. Tax incentives are recommended to advance PV integration in the region. Dodd and Nelson [24] studied PV adoption for hardship and non-hardship customers. They mentioned that if society offered sufficient incentives to hardship customers, annual electricity consumption could drop by 40% in 15 years span. Tam et al. [25] presented an empirical study for the regenerative usage of PV in residential dwellings. They considered eight major cities in the analysis. They proved the feasibility of the PV system in all of them. They found a higher life cost saving corresponding to the larger capacity of the PV system. Ramos et al. [26] presented data-driven analysis and machine learning for the prediction of the energy of a distributed PV generation plant located in Queensland. They found that the model results agree with the experimental data. The most robust model was the gradient boosting-based model, as its error is low.

In North America, there is plenty of research on PV system integration. Jackson and Gunda [27] presented an analysis to evaluate the extreme weather effect on the performance of utility-scale PV in the United States. They found that the snow has the most detrimental effect on performance, followed by hurricanes and storms. Tervo et al. [28] presented an economic analysis of residential PV in the United States where lithium-ion battery storage is integrated. They found that the battery-integrated PV system is more financially sound compared to the standalone PV system. The appropriate sizing of the battery is crucial for the benefit to be attained. In the Canadian climate, Hasan et al. [29] investigated the building-integrated PV system added to an air source heat pump system of a mid-rise building. Arrays placed on the south, east, and west facades can supply the whole power needed for the compressor during the spring months. They can also provide up to 50% of the power needed in the winter months. Teamah et al. [30-33] presented numerous works on PV systems, building-integrated PV systems, and storage-integrated solar systems. They found out the promising potential of such a system under different climatic conditions. They also reported that the thermal storage is very effective in shifting the PV system operation to off-peak periods. This reduces the utility bills and mitigates greenhouse gas emissions.

Numerous works have been done on the findings within the United Nations Sustainable Development Goals. In particular, those related to affordable and clean energy, industry innovation, and infrastructure and climate action [34-35]. In addition, there has been a lot of research effort that has been done to enhance the performance of photovoltaic systems either by nano-fluids or fins [36-37]. The better the heat transfer in the PV system, the more the utilization of its potential [38-39]. Several other works have been reported in different climates [40-43]. The conclusions highlighted the effectiveness of PV integration towards the 2030 Sustainable Development Goals.

The literature review has shown some investigations on the viability of PV integration in different continents. The majority of countries consider it a promising way to mitigate greenhouse gas emissions. However, there needs to be more confidence in financial feasibility to promote the widespread integration. The majority of studies compared different cities in the same country or generally cities in the same climate zone. The comparison of system performance in different climate zones is missing in the recent literature. This motivates the current analysis to investigate the integration of PV on a continental level. The simulations include real climatic conditions. To the author's knowledge, such a comparison is novel compared to what was presented in the literature.

The main sub-objectives of the current research are as follows:

- Investigating PV systems' performance under realistic climatic conditions on a continental level.

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- Performing an economic analysis for project financial feasibility on a continental level.
- Highlighting the effect of different financial parameters on project viability at different locations.

III. Methodology & Numerical model

The current study investigates the feasibility of a PV project on a continental level. Cities from the six main continents were selected. They were chosen to span across different climate zones in the world to assess the system's viability under a large variation of climate conditions. Table 1 presents the detailed data of the seven selected cities. As the cities are dispersed all over the world, they span a wide range of latitude and longitude. The cities have a vast variation of heating and cooling temperatures as the climate is different across the globe. The table also includes the heating and cooling degree days. They are representative of days where there is a need for heating or cooling for a building, relative to the balance point temperature. Heating degree days are very high in Ottawa due to the harsh winters. It is followed by Berlin and Beijing. Washington and Canberra are intermediate. Cairo and Brasilia have very low heating degree days due to their warm weather. On the other hand, cooling degree days are the opposite. They are the highest for Brasilia and Cairo, as the warm weather necessitates more cooling in the summer months. They are followed by Washington, Beijing, and Canberra. The least are Ottawa and Berlin due to the colder weather.

Table 1: Climate conditions of the considered cities in the study

Location	Washington, US	Ottawa, Canada	Brasilia, Brazil	Berlin, Germany	Cairo, Egypt	Beijing, China	Canberra, Australia
Latitude	38.9	45.3	-16.2	52.5	30.1	39.9	-33.7
Longitude	-77	-75.7	-44.4	13.4	31.3	116.3	117.6
Heating design temperature (°C)	-6.5	-21.8	16	-9.2	7	-9.1	3.2
Cooling design temperature (°C)	33.2	28.9	32.9	28	34.7	33.1	34
Heating degree days	2116	4560	0	3092	461	2982	1221
Cooling degree days	2345	1073	4894	1042	4305	2161	2008

Solar irradiance is a crucial metric to compare different locations. Average solar radiation on the horizontal is shown for the considered cities in Table 2. It is the highest in Brasilia, followed by Cairo, as they have the warmest climate. Canberra, Beijing, and Washington are intermediate. The lowest are in Ottawa and Berlin, as they have the coldest climate of the considered cities. Monthly daily solar irradiation is shown in Figure 2. The highest levels of irradiation are in summer, noting that the months are flipped in the southern hemisphere compared to the Northern hemisphere.

Table 2: Average solar radiation per year for the considered locations

Location	Washington, US	Ottawa, Canada	Brasilia, Brazil	Berlin, Germany	Cairo, Egypt	Beijing, China	Canberra, Australia
Average annual solar radiation ($kWh/m^2/day$)	3.9	3.6	5.6	2.7	5.3	3.7	4.8

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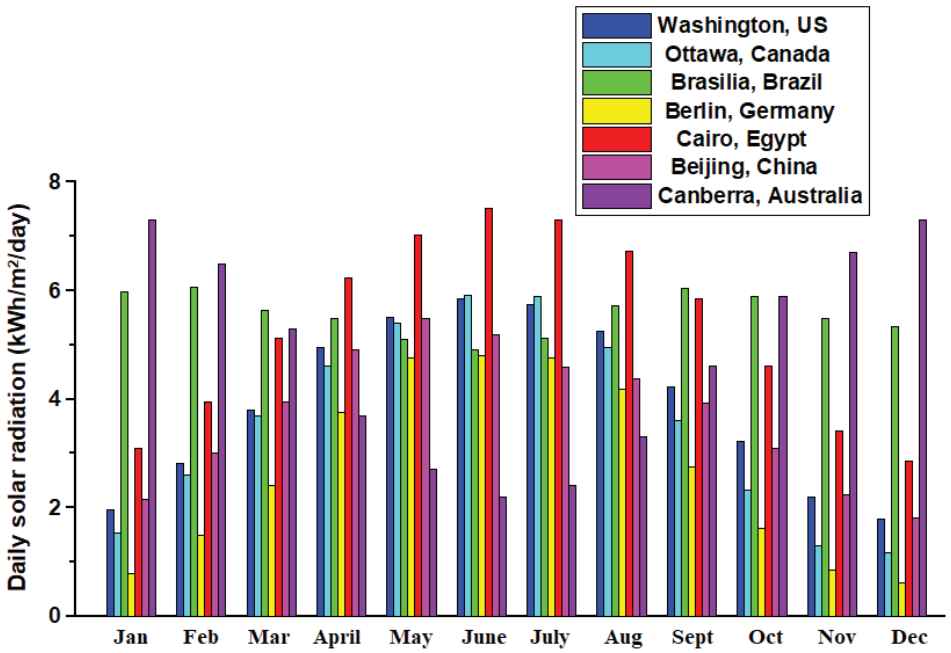


Figure 2: Monthly daily solar radiation in the considered cities.

Table 3 includes the parameters of the components of the PV system. The capacity considered is 6 MW. It is fulfilled through 20,000 modules, each of which has an output power of 300 W. The modules are of monocrystalline silicon material, as it is more efficient than the other types. They are supplied by Greenpower Company. To capture the highest solar incident irradiation, the modules face the south direction. The tilt angle is 45 ° from the horizontal. It is recommended to tilt solar panels at a degree that is equal to the latitude of the location, or a few degrees less or more. The 45 ° was chosen as it is very near the latitude of both Ottawa and Berlin, which are the lowest irradiance locations. The authors are following a conservative comparison approach by choosing more favorable conditions for the low-irradiance cities. Digital Luminous inverter of rating 10 kVA/180V and efficiency 95% is used.

Table 3: Parameters of the considered PV system

Property	Value
Solar module type	Monocrystalline silicon
Total capacity	6 MW
Module number	20,000
Temperature coefficient	0.4%/°C
Nominal temperature of operation	45 °C
Inverter type	Digital Luminous
Inverter rating	10 kVA/180V
Inverter efficiency	95%
Inverter clipping	1% per year
System performance degradation	0.5 % per year
PV project lifetime	25 years

RETscreen was used to conduct the simulations. It is a robust numerical tool developed by Natural Resources Canada. Realistic climate data from the NASA website is considered. The authors acknowledge that the spatial variation and site-specific data will yield more accurate results. However, the data from NASA is appropriate for comparison.

RETScreen uses the following equation to estimate the solar PV panels' potential:

$$Q_{coll} = F_R(\zeta\alpha)G - F_R\,U_L\boldsymbol{\Delta T} \quad (1)$$

Where Q_{coll} is the energy collected per unit collector area per unit time, F_R is the collector heat removal factor, ζ is the transmittance of the cover, α is the shortwave absorptivity of the absorber, G is the global incident solar radiation on the collector, U_L is the overall heat loss coefficient of the collector, and $\boldsymbol{\Delta T}$ is the temperature differential between the temperature of entering working fluid to the collector and outside. The generic values $F_R(\zeta\alpha) = 0.68$ and $F_R\,U_L = 4.9\left(\frac{W}{m2\,K}\right)$ of were considered in the simulations.

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RETScreen performs a financial feasibility study for the project. The following terms and equations are used in the model:

- **Project cash outflow:** it considers operation and maintenance costs, fuel costs, and debt parameters. It is given by:

$$C_{out,n} = C_{O\&M}(1+r_i)^n + C_{fuel}(1+r_e)^n + D + C_{per}(1+r_i)^n \quad (2)$$

Where n is the year, $C_{O\&M}$ is the yearly operation and maintenance costs, r_i is the inflation rate, C_{fuel} is the annual cost of fuel or electricity, r_e is the energy cost escalation rate, D is the annual debt payment, and C_{per} is the periodic cost and credits.

- **Project cash inflow:** it considers annual energy saving, annual capital savings, and credits for renewable energy and GHG emission reduction. It is given by:

$$C_{in,n} = C_{ener}(1+r_e)^n + C_{capa}(1+r_i)^n + C_{RE}(1+r_{RE})^n + C_{GHG}(1+r_{GHG})^n \quad (3)$$

Where n is the year, C_{ener} is the annual energy savings, C_{Capa} is the annual capacity saving, C_{RE} is the annual renewable energy credit, r_{RE} is the renewable energy credit escalation rate, C_{GHG} is the GHG reduction income, and r_{GHG} is the GHG credit escalation rate.

- **After tax cash flow:** It is the result of subtracting taxes from pre-tax cash flow as follows:

$$\widetilde{C_n} = C_n - T_n \quad (4)$$

Where C_n is the net cash flow, and T_n is the yearly taxes.

- Simple payback is the time required to recover the initial cost of an investment through annual cash inflows. In other words, it is the period in years taken by the project to become financially sound. It is calculated based on the following formula:

$$Payback = \frac{C_n}{(C_{ener} + C_{capa} + C_{RE} + C_{GHG}) - (C_{O\&M} + C_{fuel})} \quad (5)$$

- Internal rate of return (IRR) is a financial metric used to evaluate investment profitability, representing the annualized effective compound rate of return that makes the net present value (NPV) of all cash flows (positive and negative) equal to zero. It is given by:

$$0 = \sum_{n=0}^{N} \frac{C_n}{(1+IRR)^n} \quad (6)$$

- Net present value (NPV) is a financial metric that determines the value of an investment by subtracting the present value of cash outflows (costs) from the present value of cash inflows (returns) over time. By discounting future cash flows to today's dollars, a positive NPV indicates a profitable project. It is calculated as follows:

$$NPV = \sum_{n=0}^{N} \frac{\tilde{C}_n}{(1+r)^n} \quad (7)$$

RETScreen provides a quantification for the environmental impact of the project. The greenhouse gas emissions factor is calculated according to the following equation:

$$e = e_{CO_2} GWP_{CO_2} + e_{CH_4} GWP_{CH_4} + e_{N_2O} GWP_{N_2O} \quad (8)$$

Where e_{CO_2}, e_{CH_4}, and e_{N_2O} are the emission factors of carbon dioxide, methane, and nitrous oxide, respectively. GWP_{CO_2}, GWP_{CH_4}, and GWP_{N_2O} are the global warming potentials for carbon dioxide, methane, and nitrous oxide. In RETScreen, $GWP_{CO_2} = 1$, $GWP_{CH_4} = 21$, *and* $GWP_{N_2O} = 310$.

IV. Results & Discussion

In this section, simulation results are discussed. Table 4 includes the annual exported energy in the different locations. It also includes the capacity factor. The higher capacity factor manifests in better performance. The highest capacity factors are shown in Brasilia and Cairo, as they have the highest irradiation. It is followed by Canberra,

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Washington, and Beijing. The least are for Ottawa and Berlin because of the cold weather. The capacity factor in Brasilia is 9.8% higher than in Berlin. The annual exported energy to the grid follows the same trend as well. The highest export is for Brasilia, and the lowest is for Berlin.

Table 4: Annual exported energy for the considered locations

Location	Capacity factor	Annual exported energy MWh
Washington, US	18.2	12,012
Ottawa, Canada	16.8	11,088
Brasilia, Brazil	22.4	15,329
Berlin, Germany	12.6	9,198
Cairo, Egypt	20.8	14,786
Beijing, China	17.2	11,396
Canberra, Australia	19.2	13,768

To assess the project's economic feasibility, the financial parameters in Table 5 are considered in the model. We acknowledge that those parameters vary between different regions. However, we tried to assume unified values for the sake of comparison. The table includes average values for inflation, discount, and fuel escalation rates as the prices are increasing on an annual basis. It also includes different debt parameters with an interest rate that is applicable to the current economic situation after COVID-19. It also includes the initial, operation, and maintenance costs of the project.

Table 5: RETSreen model financial parameters

Fuel escalation rate	3%
Inflation rate	3%
Discount rate	5%
Reinvestment rate	8%
Debt ratio	50%
Debt interest rate	7%
Debt term	10 years
Initial cost	$ 9,000,000
Operation and maintenance cost	$ 246,000

To assess the project performance in the different locations, cash flow graphs are an important criterion. Yearly cash flows take into account the difference between the cash outflow and the cash inflow into the project. Brasilia and Berlin were considered as they have shown the best and the worst performance, respectively. Figure 3 shows the yearly cash flows in Brasilia, and Figure 4 shows the yearly cash flows in Berlin. Both start with a negative value that represents the project's initial cost. After that, when the project operates, positive yearly cash flows start to appear. Their magnitudes are a lot higher in Brasilia compared to Berlin due to the favorable climate conditions for Brasilia.

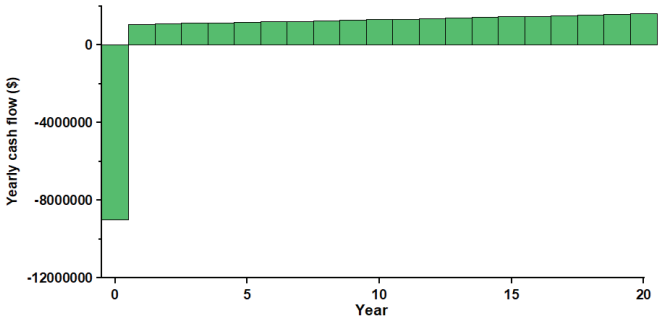


Figure 3: Yearly cash flow in Brasilia.

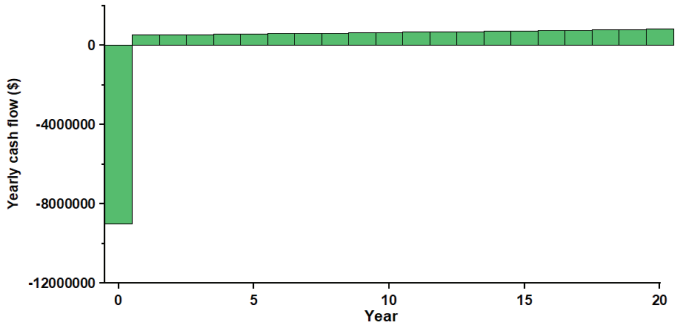


Figure 4: Yearly cash flow in Berlin.

Figure 5 shows the cumulative cash flows in Brasilia and Berlin. It includes a summation to date for the yearly cash flows. It starts in both locations with a negative value that represents the project's initial cost. As years progress, cumulative cash flow increases. The slope differs between the two locations. It is higher in Brasilia compared to Berlin. A cumulative payback of Zero means that the yearly cash flows have covered the initial cost of the project (i.e., the project has paid back). This happens at 8.5 years in Brasilia and 17.7 years in Berlin. This is more than double the duration for the project in Berlin compared to Brasilia. This highlights the major influence of the climatic conditions on project feasibility.

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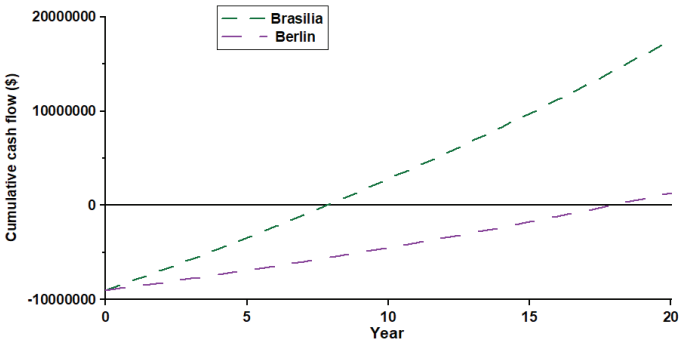


Figure 5: Cumulative cash flow in Brasilia and Berlin.

Figure 6 shows the payback period of the project in the considered locations. As seen previously from the cumulative cash flow graph, it is 8.5 years in Brasilia and 17.7 years in Berlin. The payback periods in Cairo and Canberra are less than 10 years. Ottawa, Beijing, and Washington have payback periods in between. A payback period of more than 15 years is considered long, which makes the project in Berlin not appealing from a financial perspective. Typically, a payback of more than 12 years is not considered favorable for PV projects [33]. Table 6 includes the internal rate of return for the project in different locations. The trend shows that the highest rate of return is found in Brasilia and the lowest is in Berlin. This confirms the conclusions from payback period analysis.

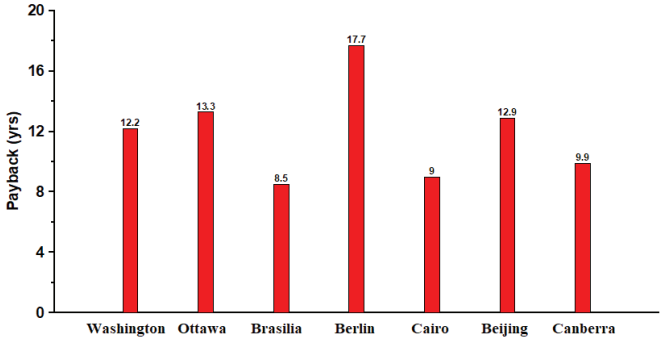


Figure 6: Payback period of the project in the considered locations.

Table 6: Internal rate of return for the project in different locations.

Location	Washington	Ottawa	Brasilia	Berlin	Cairo	Beijing	Canberra
IRR(%)	10.4	6.8	14.2	4.9	13.4	9.2	12.9

Photovoltaics are considered a clean source of energy. They reduce GHG emissions. Figure 7 includes the annual potential reduction in GHG emissions in the considered locations. It is 39.9 tons of CO_2 in Berlin and 82 tons in Brasilia. The rest of the locations are in between. It can be visualized by the hectares of forests that absorb carbon dioxide. It is 354 hectares in Berlin and 734 hectares in Brasilia, and the rest are in between.

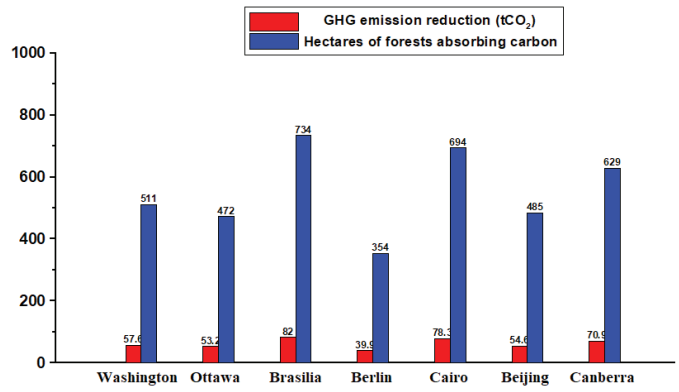


Figure 7: GHG emission reduction potential in the considered locations.

Sensitivity analysis is a great way to point out the dominant parameters that govern the project's financial viability. Table 7 shows the effect of changing the initial cost and debt term on the payback of the project in Brasilia. The values are chosen to represent typical debt terms in different PV projects. The base case presented previously is shown in bold. If the debt term decreased to half and the initial cost decreased to half its value, the payback decreases from 8.5 years to 6.2 years. Higher debt term and initial cost increase the payback period. The same trend is shown in Table 8 for the project in Berlin. However, the increase in initial cost has a very adverse effect on the payback period. It can reach higher than 25 years, which is not financially feasible.

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Table 7: Effect of debt term and initial cost on payback of the project in Brasilia.

Debt term (yr)	Initial cost ($)				
	4,500,000	6,750,000	9,000,000	11,250,000	13,500,000
5	6.2	7	7.6	9.15	10.8
8	6.4	7.2	8	9.7	11.5
10	6.5	7.45	**8.5**	10.2	12.15
12	6.6	7.7	8.85	10.8	12.9
15	6.78	7.95	9.45	11.5	13.7

Table 8: Effect of debt term and initial cost on payback of the project in Berlin.

Debt term (yr)	Initial cost ($)				
	4,500,000	6,750,000	9,000,000	11,250,000	13,500,000
5	13	14.7	15.9	19.2	22.7
8	13.4	15.1	16.8	20.4	24.15
10	13.65	15.6	**17.7**	21.4	25.5
12	13.86	16.17	18.6	22.7	27
15	14.2	16.7	19.8	24.15	28.8

Figure 8 shows the effect of changing initial cost on project payback period when the debt term is kept at 10 years. The change was mainly to cover a wide range of more optimistic or conservative values to assess the project's feasibility. Decreasing the initial cost translates to a lower payback and vice versa. The more adverse change is for the locations with lower solar irradiation, especially for Ottawa and Berlin. This is not observed for high irradiation cities like Brasilia and Cairo. This shows that the financial parameters have a major influence on whether the project is feasible or not.

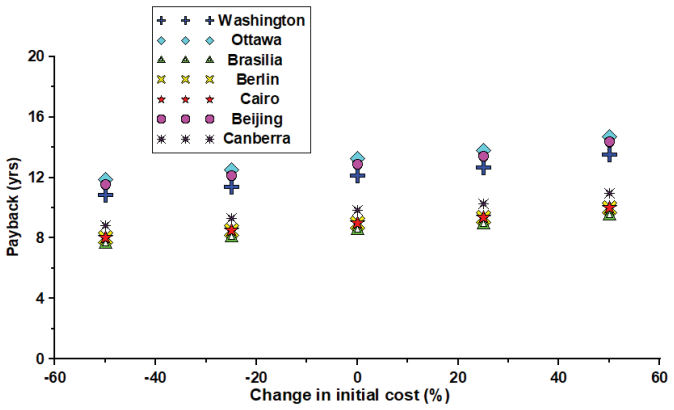


Figure 8: The effect of changing initial cost on project payback in the considered locations.

RETScreen performs a Monte Carlo analysis to quantify the relative impact of different parameters on the system performance. Figures 9 and 10 show this for Brasilia and Berlin, respectively. The parameters that have major effects on project feasibility are: electricity exported to the grid, initial cost, operation and maintenance cost, and debt interest rate. Parameters like debt term, debt ratio, and electricity export rate have minor effects on the performance. The magnitudes of those impacts are higher in Berlin compared to Brasilia due to the harsh climate conditions of Berlin.

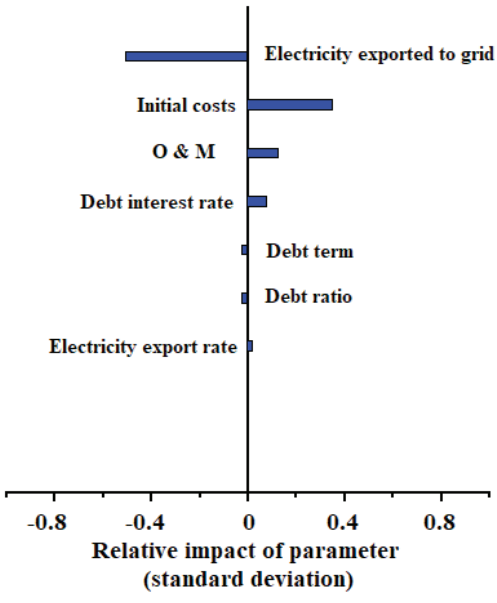


Figure 9: Brasilia impact graph.

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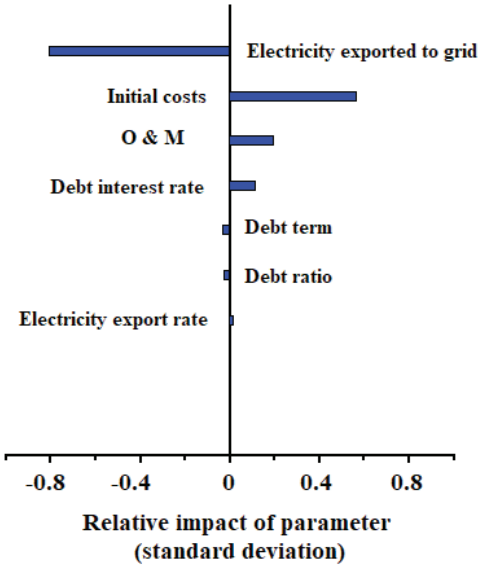


Figure 10: Berlin impact graph.

V. Conclusion

The present work investigated the feasibility of integrating a 6 MW grid-connected PV system globally. To assess that, seven cities were considered. The cities are: Washington, Ottawa, Brasilia, Berlin, Cairo, Beijing, and Canberra. They have large variations in the climate conditions. RETScreen has been used to simulate the system under real climate conditions. Financial analysis was conducted to evaluate the project's viability. The main conclusions are:

- The payback period varies greatly between the locations. It is as short as 8.5 years in Brasilia and as long as 17.7 years in Berlin. The payback in Cairo and Canberra is 9 years and 9.9 years, respectively. Ottawa, Beijing, and Washington have payback periods in between. A payback of more than 15 years is not considered appealing and can hinder the project's feasibility.
- PV systems were able to attain a significant reduction in greenhouse gas emissions. The mitigation potential is 39.9 tons of CO_2 in Berlin and 82 tons in Brasilia. This is equivalent to 354 hectares of carbon absorption in Berlin and 734 hectares in Brasilia.
- Sensitivity analysis was reported to point out the major parameters that influence project feasibility. For example, if the debt term decreased to half and the initial cost decreased to half its value, the payback decreases from 8.5 years to 6.2 years in Brasilia. It also decreases from 17.7 years to 13 years in Berlin. The higher initial cost and debt term increase the payback period, which can be detrimental in low irradiation locations such as Berlin.
- Monte Carlo analysis was carried out to quantify the relative impact of different parameters on the system performance. The parameters that have major effects on project feasibility are: electricity exported to the grid, initial cost, operation and maintenance cost, and debt interest rate. Parameters like debt term, debt ratio, and electricity export rate have minor effects on the performance. The magnitudes of those impacts are higher in Berlin compared to Brasilia due to the harsh climate conditions of Berlin.

The paper highlighted that the higher solar irradiance locations have great potential and revenue from the PV integration. This has been shown for the considered cities in South America, Africa, and Australia. In the rest of the considered cities in the other continents, there is a lower potential that is sensitive to the project's financial parameters. However, if the financial conditions are favorable, the PV integration in such locations is still appealing.

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