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INTERANNUAL SPATIAL AND TEMPORAL SOLAR IRRADIANCE VARIABILITY IN CANADA (1995-2025)

Summary

This study assesses spatial and temporal solar irradiance variability across Canada over a 30-year period (1995-2025) using ERA5 reanalysis data on a 31×31 km grid. Both global horizontal irradiance (GHI) and beam horizontal irradiance (BHI) are analyzed, comparing interannual and monthly variability using the coefficient of variation (COV). The 2025 spatial analysis reveals a clear latitudinal gradient with the highest solar resource concentrated in the southern interior of Canada, including the Prairie provinces and southern Ontario. The completed variability assessment will provide a national scale evaluation of long-term solar resource stability to support photovoltaic planning and renewable energy development, and will include a comparison between reanalysis and satellite model variability.

Keywords: Solar resource, solar energy, irradiance, variability, Canada, interannual analysis, reanalysis, satellite

Field of application for the findings: Solar Resources and Energy Meteorology

Addressed audience: Solar resource researchers; users of solar data (industry, government, and academic).

1. Introduction

Understanding spatial and temporal trends of solar irradiance and variability is essential to the application and development of solar energy, particularly as the installed global capacity of solar photovoltaics (PV) continues to grow (Lohmann *et al*. 2016). Quantifying irradiance variability enables improved reliability and predictability of solar energy technologies, contributing to photovoltaic (PV) system planning, electrical grid stability, and storage technology sizing and dispatch (Gerald *et al*. 2016). The variability of solar irradiance is driven by many influencing factors, including meteorological conditions, natural disturbances, solar cycles influences, and varies depending on geographical location and climate patterns (Habte, A. *et al*., 2020). Irradiance variability can be quantified from a minutely timescale to a solar-cycle scale, capturing applications from grid-dynamics to global climate change (Solanki, S. *et al*., 2013).

Although national and continental-scale assessments of solar variability have been conducted in regions like Australia (Davy, R, & Troccoli, A., 2012), little research exists on the variability of solar resource in polar regions. In a 2020 study by the National Renewable Energy Laboratory (NREL), Habte *et al*. characterized GHI and direct normal irradiance (DNI) variability in the National Solar Radiation Database (NSRDB) across North America (Habte, A. *et al*., 2020). The geographical coverage of this dataset was limited to below 58°N at the time of publication and thus does not represent complete coverage of Canada. This limitation highlights the need for a comprehensive assessment of solar irradiance across Canada's full national extent, with emphasis on Arctic territories where knowledge of irradiance variability is crucial for increasing renewable energy penetration levels in remote microgrid communities. In this work, we examine interannual trends and seasonal variability of solar irradiance across Canada, focusing on a 30-year period spanning 1995 to 2025. This analysis will provide a fundamental understanding of fluctuations in solar energy generation potential, highlighting regional and climate-drive differences in irradiance variability, as well as differences between satellite and reanalysis models.

2. Methods

This study is conducted on two different weather datasets – the underlying SolarAnywhere satellite model in the Canadian Weather Energy and Engineering Datasets (CWEEDS) (NRCan, 2022) and the fifth-generation atmospheric reanalysis dataset (ERA5) produced by the European Centre for Medium-Range Weather Forecasts (Hersbach *et al*. 2023). These datasets are among the most accurate solar irradiance datasets for satellite and reanalysis models in Canada. All spatial analyses are conducted using the Canada Albers Equal Area Conic projection to ensure accurate representation across Canada's domain. Irradiance variability is calculated for GHI and BHI variables by converting hourly irradiance data to mean daily total irradiance (kWh/

m^2/day) under different temporal scales (annually and monthly). This study will examine variability in solar irradiance by evaluating long-term and seasonal trends in irradiance patterns throughout Canada over a 30-year assessment period.

2.1. Calculation of Interannual Variability in Canada's GHI & BHI (1995-2025)

The COV quantifies the temporal variability of solar irradiance in relation to the mean solar irradiance for a given location, allowing for variability to be compared consistently across different geographic regions and temporal scales. The COV is defined as:

$$COV = \frac{\sigma}{\mu} \times 100\% \qquad \text{(eq. 1)}$$

Where **σ** is the standard deviation and **μ** represents the long-term mean of the dataset across the timeseries. For each grid cell, the annual mean daily total irradiance for GHI and BHI is calculated for each year in the 30-year period, and then the long-term mean is found by averaging these annual values. The COV is computed interannually and monthly to assess temporal variability across the national domain on an annual and seasonal scale. In addition to the COV, irradiance variability will be further quantified using the mean absolute deviation, D, from the long-term average, expressed as:

$$D = \frac{\sum_{i=1995}^{2025} |x_i - \bar{x}|}{30} \qquad \text{(eq. 2)}$$

Where $\boldsymbol{x_i}$ represents the annual mean daily irradiance (GHI or BHI) for year $\boldsymbol{i}$, and $\bar{\boldsymbol{x}}$ represents the mean daily irradiance averaged over the full 30-year period (1995-2025). Equation 2 calculates the average absolute difference between each year's irradiance value and the long-term mean.

3. Results

3.1. Spatial Distribution of Irradiance for 2025

Spatial patterns of mean daily total irradiance were examined for 2025 within the ERA5 dataset. Figure 1 shows a map of GHI across Canada in 2025, while Figure 2 shows BHI. Both irradiance maps exhibit a clear south-to-north gradient, with higher values in southern regions of Canada and progressively lower values towards the north. Regions of high irradiance in Canada include the Prairies and southern Ontario. Across both GHI and BHI datasets, the provinces of Alberta and Saskatchewan have the highest irradiance, with GHI values approaching approximately 5 kWh/m^2/day and BHI values around 4 kWh/m^2/day on average.

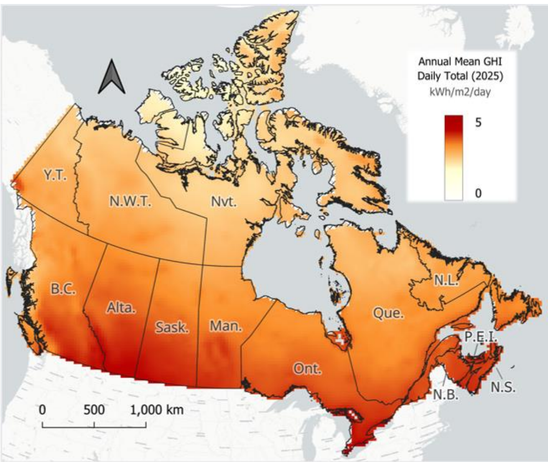

Figure 1: The annual mean daily GHI in 2025.

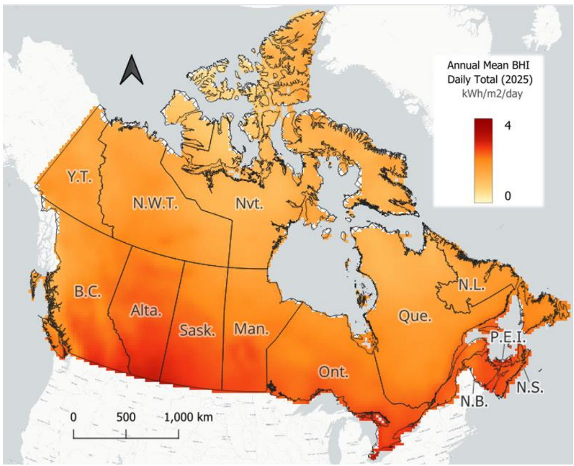

Figure 2: The annual mean daily BHI in 2025.

These spatial patterns showcase Canada's diverse climatic and daylight conditions and highlight the potential for solar energy technologies particularly in the southern interior regions of Canada. Table 1 shows the mean daily total GHI and BHI irradiance for 2025 for select cities in Canada. In 2025, Toronto, Charlottetown, and Regina had the highest recorded irradiance values, with around 3.9 kWh/m^2/day in GHI. Capital cities in Canada's northern territories received around 25% less GHI on a mean daily basis, compared to southern capital cities <60°N.

Table 1: Mean daily total irradiance for capital cities in Canada.

Capital City	Latitude (°N)	Longitude (°W)	GHI (kWh/m^2/day)	BHI (kWh/m^2/day)
Toronto, ON	43.6	79.3	3.95	2.59

Halifax, NS	44.6	63.5	3.73	2.52
Ottawa, ON	45.4	75.6	3.73	2.44
Fredericton, NB	45.9	66.6	3.71	2.37
Charlottetown, PE	46.2	63.1	3.93	2.57
Quebec City, QC	46.8	71.2	3.64	2.34
St. John's, NL	47.5	52.7	3.43	2.07
Victoria, BC	48.4	123.3	3.72	2.38
Winnipeg, MB	49.8	97.1	3.76	2.53
Regina, SK	50.4	104.6	3.86	2.56
Edmonton, AB	53.5	113.5	3.78	2.55
Whitehorse, YK	60.7	135	2.94	1.76
Yellowknife, NT	62.4	114.3	3.02	1.92
Iqaluit, NU	63.7	68.5	2.56	1.26

3.2. Interannual Irradiance Variability 1995-2025

Figure 3 and Figure 4 show the interannual COV for GHI and BHI using the ERA5 reanalysis dataset, highlighting significant regional differences in interannual irradiance. This work will be repeated using the CWEEDS satellite model, and further analyzed and compared. Monthly irradiance variability will additionally be calculated to quantify seasonal effects.

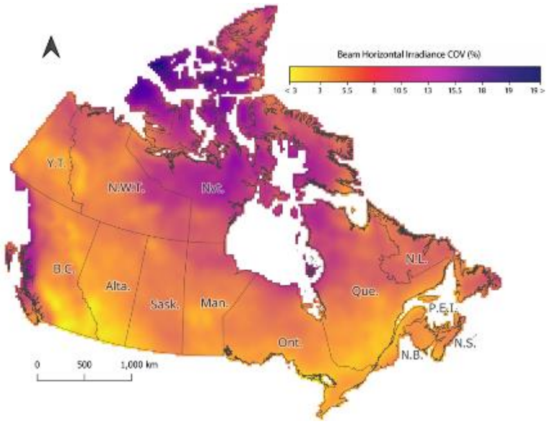

Figure 3. ERA5 interannual GHI COV from 1995-2025.

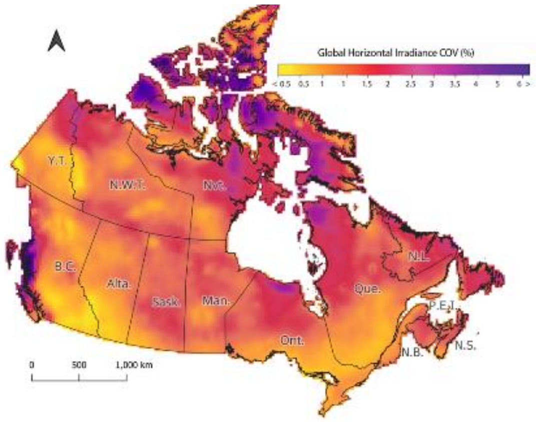

Figure 4. ERA5 interannual BHI COV from 1995-2025.

4. Conclusion

This study addresses a critical knowledge gap by quantifying interannual irradiance variability across Canada, specifically focusing on underserved regions above 58°N. Preliminary analysis of interannual COV from 1995-2025 using ERA5 data highlights regional differences in irradiance, particularly in Northern Canada. By expanding this analysis to include satellite data, the final work will provide a robust assessment of long-term solar resource variability and showcase differences in irradiance trends depending on the underlying weather dataset. These results are essential for PV system bankability, grid reliability, and de-risking renewable energy infrastructure in high-latitude environments.

5. References

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