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Experiences from seasonal Arctic solar photovoltaics (PV) generation- An empirical data analysis from a research infrastructure in Northern Finland

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ABSTRACT

The European Union's highly anticipated "solar strategy" to equip the new and existing building stocks with solar PV panels displays a promising trend in the solar PV industry. However, from Finland's perspective, generating solar PV energy in an Arctic setting is characterised by a few common ambiguities, further lowering the motivation. There are several methodologies for identifying and bridging the gaps to provide accurate conclusions. This article employs the observational and empirical approach in presenting the solar PV energy generation data from the research infrastructure in Oulu, a North Finland city. Empirical evidence from a solar PV system from an Arctic background with a macro to micro-level analysis and documentation is expected to bridge the gap between uncertainties and reality and improve the understanding of the region's seasonal, monthly and annual solar PV generation. Spring was the best period for generating solar PV energy, and autumn was the least favourable for generating solar PV energy in the Arctic. Rooftop inclined solar PV have a better potential during spring and summer, and vertical PV quantitatively generate more energy in autumn and winter. Lower tilt angles proved optimal, as these angles eminently capture the spring and summer irradiation.

1. Introduction

The European Union (EU) is aspiring to ensure all the new buildings are "solar ready" and is urging the member states to ensure access to solar energy to energy-poor and vulnerable consumers and support building-integrated solar PV panels for both new and existing building stocks. According to European Solar Rooftops Initiative, rooftop installations will be mandatory for all new and future public and commercial buildings with a functional floor area larger than 250 m^2 by 2027 and 2026, respectively, and all new residential buildings by 2029 [1]. An estimated country-aggregated rooftop solar photovoltaic (PV) provides 25% of the EU's electricity consumption, more significant than the current share of natural gas [2]. These ambitious initiatives increase the dependency on solar prediction and simulation models.

Finland generated 298 GWh of electricity from solar in 2021. It installed 98 MW of distributed solar capacity in 2020, taking the cumulative capacity to 313 MW [3]. Solar PV accounted for around one per mil of total energy consumption in 2020 [4]. Utility-scale ground-mounted solar power plants have been on the rise lately. Interests have grown recently in utilising abandoned peat lands to install large-scale ground-mounted solar power plants in the country [5]. A technical electricity potential analysis of rooftop PV installations in Finland also predicts a growth between 4000 GWh/year to 5000 GWh/year [2]. However, extreme weather and climatic conditions, significant variations in the day lengths leading to polar nights and days, sub-zero temperatures, snow, and significant seasonal temperature variations characterise the Arctic and subarctic regions. These predefined characteristics of the Arctic and Subarctic tend to reduce the potentiality of solar PV generation in the region and provide sufficient conditions for solar PV generation. The data on seasonal variability, the effect of frost and snow, albedo, the PV system's lifecycle after operating under sub-zero temperatures, and optimal tilt angle and azimuth for the region annually and seasonally provides accurate insights for future investments and improved predictability of the solar simulations. Comprehension increases with improved solar energy prediction models that accurately predict the losses in a solar PV system and advanced climate and weather predictions. It can also advance by analysing empirical evidence collected by the solar PV equipment operating under natural conditions in a specified region. With an increased understanding of solar PV operations in the Finnish Arctic conditions, the solar industry's future could be more efficient.

This article will focus on presenting the verifiable observed and analysed solar PV data throughout four seasons in two years from the

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Abbreviations

EU	European Union
FMI	Finnish Meteorological Institute
GWh	Giga-Watt hour
kWh	Kilo-Watt hour
MW	Mega-Watt
PV	Photovoltaics
Si	Silicon
Wh	Watt-hour

experimental setup installed in Oulu in Northern Finland. The paper's objective is to provide empirical data on the observations on seasonal variation in solar PV generation, the impact of snow on energy generation, the potentiality of different mounting setups across the months and seasons, and a recommendation on improving the energy generation potential of a solar PV system in the high North.

2. Background

2.1. Location

Oulu is a region in Northern Ostrobothnia, North Finland, situated at 65.0121° N and 25.4651° E, 170 km South of the Arctic circle, stationed in the transitional zone between the Arctic and the subarctic regions (see Fig. 1). The Arctic and subarctic terms have different interpretations, depending on their context. Geographically, a common periphery that defines the Arctic is the area above the Arctic circle (66° 33′ 44″ N). The Arctic circle outlines the latitude above which two phenomena are evident concerning the daylight period. The sun does not set or rise on or about the 21st of June and the 21st of December [6]. Part of Northern Europe, Asia, and North America lies above the Arctic Circle. Thermally, the Arctic is the region with an average temperature for the warmest month below 10 °C.

Geographically, the subarctic region is the transitional zone amidst the core Arctic and humid continental regions [7]. Differentiation of the Earth according to surface, latitude, and height forms the transitional zones at the boundaries of the core areas. The Arctic and temperate latitudes' air influences the subarctic regions' climate [8]. Iceland, Norway, Sweden, Finland, Russia, Canada, central Siberia, and Alaska land mass falls under subarctic regions [9]. Thermally, the subarctic is a region with an average temperature recorded for the year, except for four months, below 10 °C. However, due to the social and economic impacts, subarctic regions are integrated within the Arctic [6]. To eliminate any confusion from the location perspective, geographically and thermally, it is safe to consider that the results exhibited in this article from the research infrastructure in Oulu are justifiable from both the Finnish Arctic and subarctic viewpoint.

2.2. Climate and meteorology

Maritime and continental climatic conditions are typical climates in the Finnish and subarctic. Seasonal variability influences solar irradiation levels in the region [10]. Solar irradiation in the summer is higher than that during the winter. The imbalance in radiation levels results in low temperatures, and redistribution of heat occurs from the southern temperate latitudes and ocean currents. Low air temperatures characterise this region [9]. The interior Finnish Arctic experiences a continental climate with relatively lesser precipitation and substantial differences between winter and summer conditions.

The direction of airflow decides the climatic condition. From the statistics observed by the Finnish Meteorological Institute (FMI) from 1961 until 2020, the annual mean temperature in the study area is 3.1 °C. The annual mean temperature ranges between 1.48 °C and 6.73 °C from North to South of Finland [11]. Compared with most other areas in these latitudes, the mean temperature is relatively higher because of the Baltic Sea, inland waters and warmer airflows from the North Atlantic Ocean through the Gulf streams [10]. February is the coldest month, and July is the hottest month, with a mean temperature of −8.7 °C and 16.7 °C, respectively, recorded in the area under study.

Overall, Finland experiences plenteous cloud cover during autumn and winter. During the spring and summer, the skies are comparatively cloudless. First snowfall events commence by the end of September in a few regions in the North of Finland. However, the permanent snow cover typically starts by the end of October. Snow depth varies between 14 cm in the South to 94 cm in the North. The Northern Ostrobothnia province's snow cover depth is between 50 cm and 54 cm (Fig. 2), significantly less than that measured in the Lapland region [12].

Further, radiation energy from the sun, temporal fluctuations, and distribution determine a region's climate [13]. In Finland, the level of radiation is proportional to the seasons and varies considerably from South to North. In addition, the irregularity in the daylight hours is another notable characteristic of the region. The region experiences the maximum sunlight hours following the Vernal Equinox until the Autumnal Equinox. The length of the days begins to reduce from the summer solstice and starts to gain from the winter solstice. The global horizontal irradiation measured in kWh/m^2/day varies between 2.26 kWh/m^2/day to 2.70 kWh/m^2/day in Finland. The area under study receives an average of 2.37 kWh/m^2/day, summing to an annual average of 863.83 kWh/m^2 [14]. Fig. 3 depicts the provinces in Finland with their respective annual average global solar radiation measured in kWh/m^2/day.

2.3. Seasons

Meteorologically, the Finnish Arctic observes vast dissimilarities between the seasons. From the temperature and solar radiation perspective, the winter season combines cold, dark, and snowy days. Following this, the spring season combines cold, bright, and snowy days. The temperature through these seasons is comparable as the temperature remains below sub-zero levels. The temperatures exceed sub-zero levels in different circumstances, like summer and autumn. However, the magnitude of change in temperature between the snowy days and the snow-less days is significant. Other significant divergences are about the position of the sun on the horizon and the air mass values in the atmosphere through the seasons. The Arctic and its surrounding subarctic regions experience comparable seasons. However, the seasons are not identical concerning the number of days. There are divergent ways of categorising the seasons in these regions. The types of distinctions for defining the Arctic and subarctic seasons are mainly astronomical and thermal.

Mean daily temperatures define the thermal seasons. Winter starts when the daily mean temperature falls below 0 °C. The daily mean temperature falling below +10 °C marks the start of the autumn season. The spring season starts when the daily mean temperature increases from 0 °C to +10 °C. The summer season of the Arctic starts when the daily mean temperature is above +10 °C. This method calculates the cumulative sum of the daily mean temperatures and considers the point where a certain threshold exceeds and subceed. This seasonal distinction results in two months each of spring and autumn, three months of summer and six months of winter for the region.

On the other hand, astronomical seasons are according to the timing of Equinoxes and Solstices. The Vernal and Autumnal Equinoxes occur when the Earth's tilt is neither away nor towards the sun, resulting in nearly proportionate daylight and darkness at all the latitudes [15]. Alternatively, the winter and summer solstices occur when the Earth's tilt is farthest and closest to the sun. A seasonal distinction based on this distributes nearly equal days across all seasons, with three months of spring, autumn, winter, and summer. The Vernal Equinox marks the

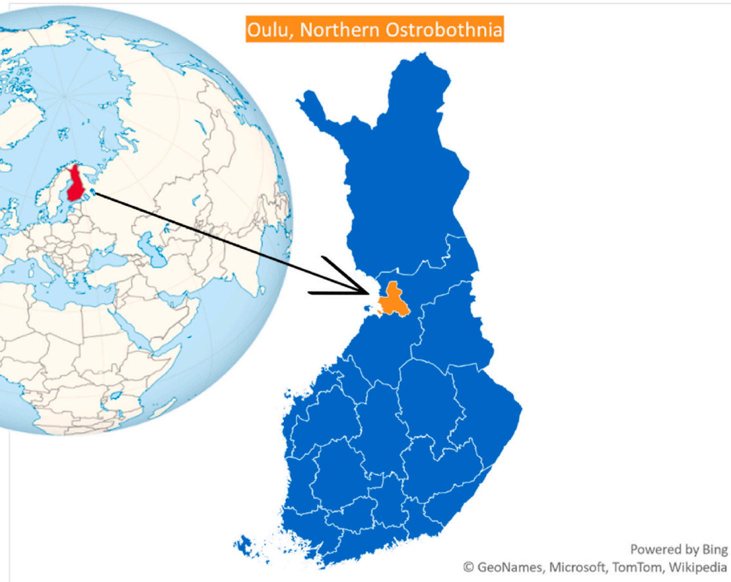

Fig. 1. Finland (the region marked in red on the globe) and Oulu (the orange-filled region on the map) is the capital of Northern Ostrobothnia province in Finland.

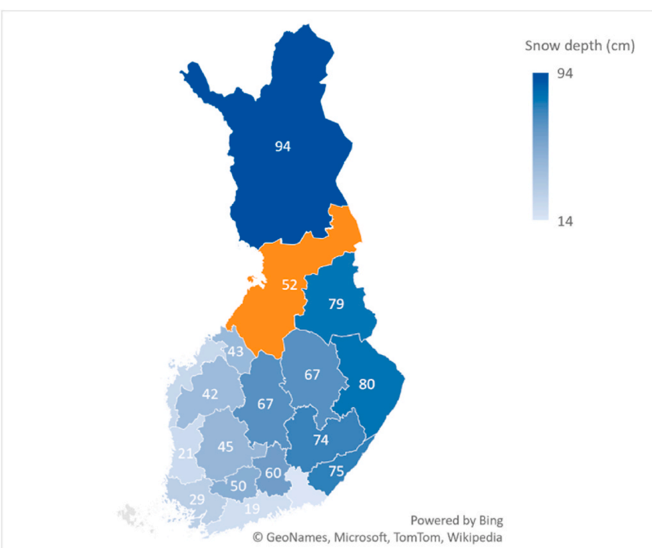

Fig. 2. Provinces of Finland with recorded snow cover depths measured in centimetres.

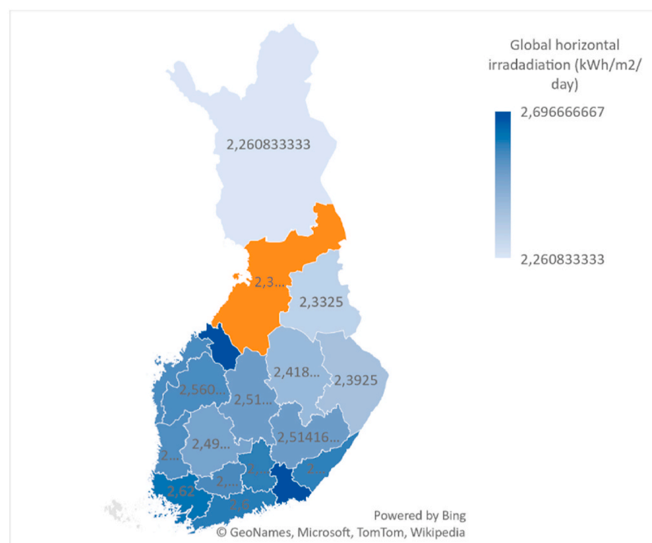

Fig. 3. Provinces of Finland with their annual average global solar radiation in kWh/m2/day.

start of the spring season, from the 21st of March until the 21st of June. The Summer Solstice on the 21st of June marks the start of the summer season until the 22nd of September. The autumn season gets underway from the 23rd of September, the Autumnal Equinox, to the 21st of December. The winter solstice marks the start of the winter season until the forthcoming Vernal Equinox.

As the Astronomical distinction of the seasons is according to the movement of the Earth relative to the sun, illustrating the solar PV energy generation data in conjunction with relative sunlight hours allows a better representation of seasonal variations of solar PV energy generated in higher latitudes. Hence, this article does not consider the Thermal distinctions of the seasons to maintain consistency in the data analysis and future discussion. Table 1 represents the astronomical seasonal distinctions and the daylight and sunlight hours, respectively.

Table 1
Astronomical seasonal distinctions include the number of days in the region and their respective average daylight and sunlight hours.

Seasons	Astronomical distinction			
	Period	Number of Days	Average Daylight hours	Average sunlight hours
Autumn	23rd September - 21st December	90	07 h 29 min	02 h 16 min
Winter	22nd December- 20th March	89	07 h 22 min	02 h 31 min
Spring	21st March- 20th June	92	17 h 22 min	08 h 50 min
Summer	21st June- 22nd September	94	17 h 52 min	09 h 20 min

3. Materials and methodology

3.1. Solar PV and monitoring platform

The research infrastructure comprises 24 solar PV panels. Twelve solar PV panels are mounted on the wall at an angle of 90° inclinations. In addition, twelve solar PV panels are placed on the flat roof of a 3-storey building in the foreground of the vertical solar PV panels. The solar PV panels on the roof are at inclinations of 23°, 28°, 37°, 41°, 42° and 46°. All the solar PV panels are at an azimuth of 180°; in other words, facing South. Six solar PV panels feature differing physical properties and characteristics among the twelve rooftop inclined solar PV panels. The remaining six solar PV panels are identical to one another. The twelve vertical solar PV panels' power output is symmetrical. Data from six identical solar PV panels, each from the roof and wall, are analysed to achieve homogeneity and narrow down the variables. Fig. 4 shows the research infrastructure consisting of 24 solar PV panels.

The six identical solar PV panels on the roof are inclined at various angles to study the impact of inclinations on solar PV energy generation. The rooftop features panel R1.2.4 is at the angle of 23° followed by R1.2.2 at 28°, R1.2.6 at 37°, R1.2.1 at 41°, R1.2.7 at 42°, and R1.2.12 at 46°. Fig. 5 represents the nomenclature used for referring to the solar PV panels of the research infrastructure. The solar PV panels are not affected by any external shadows; however, snow buries the panels fully during the peak snowy days. Fig. 6 shows the solar PV panels under the influence of snow.

The fore solar PV panels also cast a small percentage of shadow on the rear panel during the low-lying Sun periods. The six vertical solar PV panels V1.1.2, V1.1.3, V1.1.5, V1.1.6, V1.1.7, and V1.1.9 are at an inclination of 90°, and an azimuth of 180° are free from any shadowing from the adjacent structures. Vertical solar PV panels are unaffected by the snow, unlike rooftop inclined solar PV panels. All the solar PV panels are 60-cell monocrystalline-Si with a power output of 275 W and an efficiency of 18%. The solar PV panels' length, width and thickness are 1650 mm, 992 mm, and 35 mm, respectively. Table 2 represents the characteristics of solar PV panels under analysis.

SolarEdge is an energy generation monitoring platform which allows us to read and examine the solar PV energy generation data from the research infrastructure. This platform allows the user to analyse parameters like current, energy, module voltage, optimiser voltage, and power of the selected solar PV panels. The research infrastructure also features on-site sensors, which allow for studying the direct irradiance, ambient temperature, and module temperature.

Fig. 4. The research infrastructure comprises 12 vertical solar PV panels and 12 rooftop inclined solar PV panels.

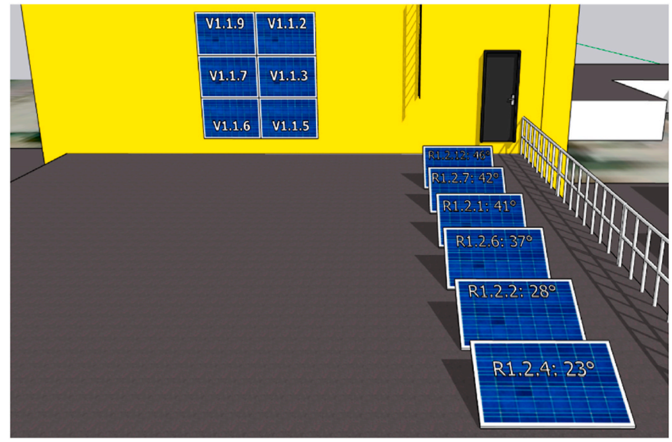

Fig. 5. Representation of the research infrastructure with vertical and rooftop inclined solar PV panels using SketchUp and Skelion

Fig. 6. Solar PV research infrastructure under the blanket of snow (Photographed on 22nd of February 2021).

3.2. Data collection and analysis

The data from SolarEdge continues to collect solar PV energy generation data in watt-hour (Wh). Data is available in the time intervals of 5 min and can be visualised in 5 min, 15 min, 60 min, and 1440 min for two years. The cloud hosts the data collected from the research infrastructure. It is retrievable at any point in time. To explicitly present the results, the data is further categorised multitudinously.

3.2.1. Seasonal evaluation and optimisation of solar PV generation

Seasonal categorisation evaluates the solar PV energy generation data from vertical and rooftop inclined solar PV panels in all seasons. The variables for this analysis are the energy in Wh from vertical and rooftop inclined solar PV panels and astronomically distinguished seasons. At 24-h intervals, the data is collected for two years continuously. The daily generation profile (kWh/day) is aggregated into the monthly profile (kWh/month), subsequently ascertaining each season's best-performing panel installation type. In addition to the comparative analysis of vertical and rooftop inclined solar PV panels, as the latter comprises six solar PV panels at various angles of inclination, the outcome of the analysis will represent the ideal inclination angle for rooftop solar PV panels in the Arctic for all four seasons and annual generation. Although the solar PV energy generation and weather data were collected and analysed for two years, an initial investigation and visualisation of the anomaly of the solar generation across the four seasons in the Arctic led to an improved comprehension of short-term

Table 2
Characteristics of solar PV panels in the research infrastructure.

Solar Panel Type	Power (W)	Efficiency (%)	Length (mm)	Width (mm)	Thickness (mm)	Weight (kg)
Monocrystalline-Si	275	18	1650	992	35	18.6

optimisation of the solar PV systems. This analysis incorporates the research infrastructure's annual solar PV energy generation profile alongside the seasonal solar PV energy generation profile.

4. Results

This section presents the empirical results from the research infrastructure that substantiates the significant impact of seasonal variability on solar PV generation from vertical and rooftop-inclined perspectives.

4.1. Monthly solar PV generation profile

In 2021, the best-performing solar PV panels from both the mounting setups, rooftop inclined and vertical, generated 246.28 kWh and 229.27 kWh of energy annually, respectively. Similarly, the same PV panels generated 224.12 kWh and 241.64 kWh of energy the following year. Table 3 represents the annual solar energy generated by monocrystalline-Si solar PV panels mounted at two distinct tilt angles at 28° and 90°.

Fig. 7 represents the monthly solar energy generation profiles of the two solar PV mounting systems. The reference, however, is from the two best-performing solar PV panels, V1.1.6 and R1.1.2.

4.2. Seasonal rooftop inclined and vertical solar PV generation profile

Table 4 represents the solar PV generation from the research infrastructure across the four seasons for two years. In autumn, vertical solar PVs generated 30.25% more energy than rooftop inclined solar PV panels. In winter, the same pattern as in autumn was observed, where vertical solar PV panels generated 98.36% more energy than rooftop inclined solar PV panels. A yearly distinction in Table 3 further explains the differences observed in 2021 and 2022. Further, in spring and summer, rooftop inclined solar PV panels generated significantly higher than vertical solar PV panels, with a percentage increase of 20.0% and 30.4%, respectively.

Table 3
Monthly solar PV generation in the region's two types of solar PV mounting systems.

Month	2021		2022	
	Vertical solar PV generation (kWh)	**Rooftop inclined solar PV generation (kWh)**	**Vertical solar PV generation (kWh)**	**Rooftop inclined solar PV generation (kWh)**
	V1.1.6	**R1.2.2**	**V1.1.6**	**R1.2.2**
January	0.69	0	2.18	0
February	17.81	0.01	10.98	0
March	34.1	8	32.81	7.44
April	33.93	37.17	32.19	32.59
May	25.6	39.43	29.43	45.45
June	30.59	50.2	30.11	48.68
July	31.9	50.15	25.89	42.21
August	24.69	33.4	28.84	37.49
September	19.7	21.5	15.97	18.67
October	6.5	5.75	13.34	8.38
November	3.48	0.67	2.25	0.73
December	0.28	0	0.13	0
Annual	**229.27**	**246.28**	**224.12**	**241.64**

4.3. Solar PV generation under snow

Table 5 represents the solar PV energy generated by vertical and rooftop inclined solar PV panels during the snowy period. The vertical solar PV panels produced 244.0 kWh and 187.2 kWh of energy during the snowy period, between the first week of November and the first week of May (averaged for the previous five years, 2017–2022), whereas the rooftop inclined solar PV panels produced 4.6 kWh and 1.5 kWh during the same period.

A monthly evaluation of solar PV generation indicates that vertical solar PV panels generated quantitatively more energy during January, October, November, and December than rooftop solar PV panels. However, they generated qualitatively more solar PV energy for February and March than the rooftop solar PV panels. In addition, it should also be noted that the snow meltdown is faster on the roofs compared to the ground. Fig. 8 represents the solar PV generation in kWh for both mounting types during the snowy period.

4.4. Solar PV generation under snow and shading

The rooftop inclined solar PV panels, with a tilt ranging from 23° to 46°, are placed in 6 individual rows in the ascending order of their tilt angles. R1.2.4, positioned at the first row of the setup, generated relatively higher solar PV energy during March. R1.2.4 solar PV panel did not have any obstructions from the fore panel, as the panel is mounted at an angle of 23°. Further, the R1.2.7 generated relatively lower energy with 6.59 kWh and 0.66 kWh in the two consecutive winters. Table 6 represents the influence of mutual shading and snow on the rooftop inclined solar PV panels during March.

4.5. Optimal tilt angle for improving the annual solar PV generation potential

Table 7 represents the annual solar PV energy generated by the rooftop inclined solar PV panels at tilt angles of 23°, 28°, 37°, 41° and 46° in 2021 and 2022.

Fig. 9(a) represents the annual kWh solar PV generation for the experimented tilt angles. R1.2.2 at a tilt of 28° generated 244 kWh of annual solar PV energy. It outperformed the rest of the solar PV panels in May, June, July, and August with the advantages of more extended daylight and the absence of snow. The subsequent optimal tilts for the region, if ranked according to the annual solar PV energy generation, they are 23°, 37°, 41°, and 46°. Fig. 9(b) represents the months in a year when the 28° tilted solar PV panel generated higher than the rest. R1.2.4 generated 240.7 kWh of annual energy, followed by R1.2.6 with 240.5 kWh, R1.2.1 with 239.8 kWh, and R1.2.12 generating the least energy with 231.6 kWh.

5. Discussion

5.1. Monthly solar PV generation profile of the Arctic

On average, from April until September, the Arctic region receives 17 h and 37 min of daylight hours and 09 h and 05 min of sunlight hours. The solar PV profiles for these months display the region's best solar energy generation potential. However, as the weather in September shifts to colder, cloudier and rainy conditions, the potentiality of solar PV generation drops. In March and April, with increased sunlight hours and snow, the potentiality of solar PV generation from the vertical solar PV panel increased significantly due to albedo and supporting colder

Table 4
Seasonal differences in solar PV generation (kWh) by vertical and rooftop inclined solar PV panels. (The green highlighted numbers represent the best-performing figures, and the red highlighted numbers represent the opposite.).

Seasons		Vertical solar PV generation (kWh)		Rooftop inclined solar PV generation (kWh)		Percentage increase in generation (%)	
Panel		V1.1.6		R1.2.2		V1.1.6	R1.2.2
Panel angle		90°		28°			
		2021	2022	2021	2022		
Autumn	23rd – 30th September	4.84	4.88	4.64	4.67	4.22	
	October	6.50	13.34	5.75	8.38	28.78	
	November	3.48	2.25	0.67	0.73	75.75	
	1st – 21st December	0.28	0.12	0	0	100	
	Seasonal total	**15.1**	**20.6**	**11.1**	**13.8**	**30.25**	
Winter	22nd – 31st December	0.0045	0.0052	0	0	100	
	January	0.69	2.18	0	0	100	
	February	17.81	10.98	0.01	0	99.97	
	1st – 20th March	22.19	18.55	0.92	0.1	97.50	
	Seasonal total	**40.7**	**31.8**	**0.9**	**0.1**	**98.36**	
Spring	21st – 31st March	11.91	14.26	7.08	7.34		44.90
	April	33.93	32.19	37.17	32.59		5.22
	May	25.60	29.43	39.43	45.45		35.17
	1st – 20th June	20.41	18.76	33.21	31.46		39.43
	Seasonal total	**91.9**	**94.6**	**116.9**	**116.8**		**20.2**
Summer	21st – 30th June	10.18	11.35	16.99	17.22		37.07
	July	31.90	25.89	50.15	42.21		37.43
	August	24.69	28.84	33.40	37.49		24.49
	1st – 22nd September	14.86	11.09	16.86	14.00		15.91
	Seasonal total	**81.6**	**77.2**	**117.4**	**110.9**		**30.44**

Table 5
Vertical and Rooftop inclined solar PV generation in kWh during the two winter seasons.

Vertical solar PV generation (kWh)		Rooftop inclined solar PV generation (kWh)	
2020–21	**2021–22**	**2020–21**	**2021–22**
244.0	187.2	4.6	1.5

operating conditions for solar PV. June is the region's most optimum month for generating solar PV energy. As seen in Fig. 7, in the peak snow-roofed months of December, January, and February, the rooftop inclined solar PV panel fails to generate any energy mainly due to snow on the PV panels. The minimum availability of sunlight hours during these months also aids in zero energy generation from the rooftop-inclined solar PV panels. The vertical solar PV panels outperform the rooftop inclined solar PV panels quantitatively in September, October, November, December and January. It continued to outperform the rooftop inclined solar PV panels in February, March, and April

Table 6
Rooftop inclined solar PV generation (kWh) shows the influence of mutual shading and snow in March.

Rooftop inclined solar PV generation (kWh) in March.						
Solar PV	**R1.2.12**	**R1.2.7**	**R1.2.1**	**R1.2.6**	**R1.2.2**	**R1.2.4**
Tilt	**46**	**42**	**41**	**37**	**28**	**23**
2021	7.80	6.59	7.44	7.14	7.93	8.17
2022	10.01	0.66	10.27	7.92	7.48	10.47

Table 7
Annual solar PV generation (kWh) by various tilt angles in the inclined rooftop setup.

Solar PV	**R1.2.12**	**R1.2.1**	**R1.2.6**	**R1.2.2**	**R1.2.4**
Tilt	**46**	**41**	**37**	**28**	**23**
Annual generation (kWh)- 2021	231.6	239.8	240.5	244.0	240.7
Annual generation (kWh)- 2022	231.7	239.7	240.7	241.7	240.1

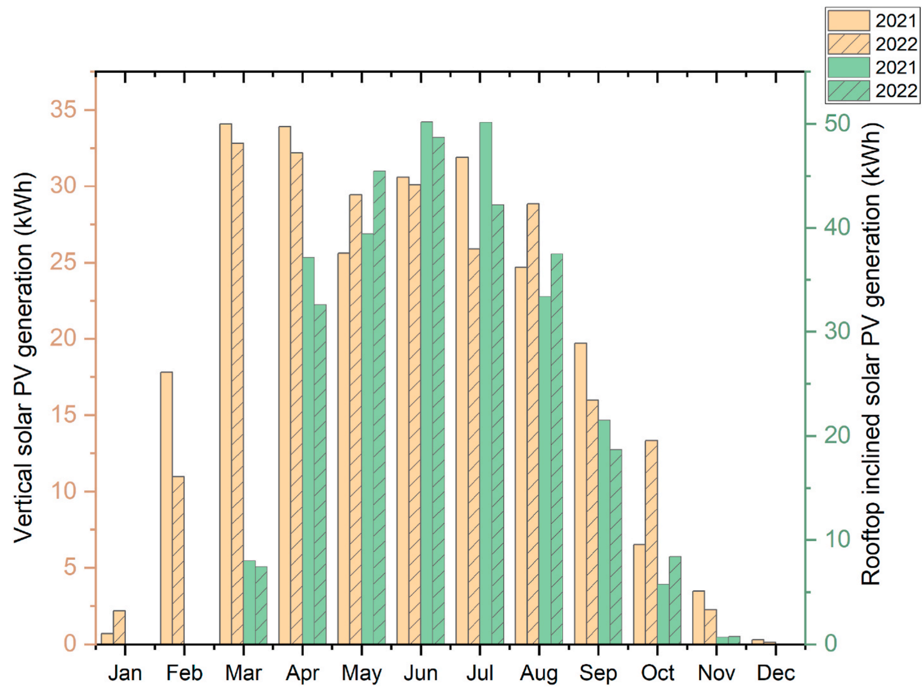

Fig. 7. A comparison between monthly solar energy generation profiles of the two mounting PV systems for two years (2021 and 2022).

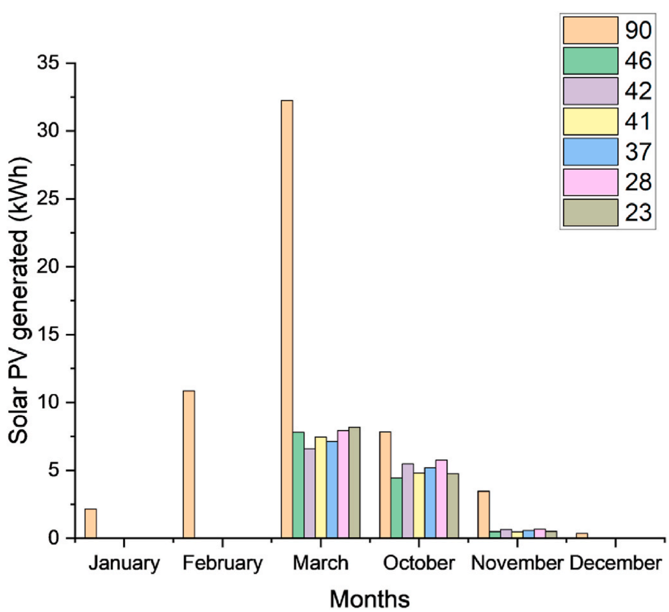

Fig. 8. Comparison of solar PV energy from the Vertical (90°) and Rooftop inclined (46°, 42°, 41°, 37°, 28°, 23°) solar PV panels during the snowy period from October to March.

qualitatively. Overall, vertical solar PV panels generated higher energy annually than rooftop inclined solar PV panels for nine months. The remaining three months allowed the latter to generate higher solar PV energy and prove its superior annual potential over the former mounting setup.

Another critical observation from Table 3 shows the irregular generation pattern from the same solar PV panels for two consecutive years. The discrepancies in the generation pattern from the same solar PV panels for the two considered consecutive years were due to differences in the monthly average global solar irradiance due to climatic conditions: cloud cover and the differently persistent presence of snow coverage. The global solar radiance values observed for the region prove higher in February, June, July, September, November, and December in 2021, whereas in January, March, April, May, August, and October in 2022. The evidence from the sunshine duration data correlated with the cloud cover values further confirmed the basis for the irregular pattern observed in two consecutive years.

However, for April, the global solar radiation values were mismatched with the generation profiles of R1.2.2. Further, the sunshine duration for April matched the generation profile of the PV panel. In the pursuit to eliminate any inconsistency, an extended investigation proved that, for R1.2.2, this correlation error resulted from snow. The snow accumulation on R1.2.2 and shading from R1.2.4 resulted in comparatively slightly extended snow accumulation periods on the panels in 2022 than in 2021 and 2023.

5.2. Seasonal solar PV generation profile of the Arctic

Spring and summer are the most suitable seasons for supporting the region's solar PV generation. Autumn is the region's minor favourable season for generating solar PV energy. In 2021, solar PV panel R1.2.2 generated 11.1 kWh in autumn, 0.9 kWh in winter, 116.9 kWh in spring and 117.4 kWh in summer. The following year, it generated 13.8 kWh in autumn, 0.1 kWh in winter, 116.8 kWh in spring and 110.9 kWh in summer. Similarly, vertical solar PV panel V1.1.6 generated 15.1 kWh in autumn, 40.7 kWh in winter, 91.9 kWh in spring and 81.6 kWh in summer in 2021, following which generated 20.6 kWh in autumn, 31.8 kWh in winter, 94.6 kWh in spring and 77.2 kWh in summer in 2022. The additional energy gain in spring was from the vertical solar PV panels, which generated 11–19% more PV energy than in summer due to favourable tilt angle during the season. The reduced generation potential of vertical solar PV panels in spring and summer is mainly due to the less favourable tilt angle of 90° for the corresponding sun angle for the season. The meteorological characteristics of the autumn season, with a higher percentage of overcast and rainy days, lead to reduced potentiality.

On the contrary, a relatively higher percentage of clear and sunny days in the spring increases the potentiality of solar PV energy generation. The additional factor, like the presence of snow during the season,

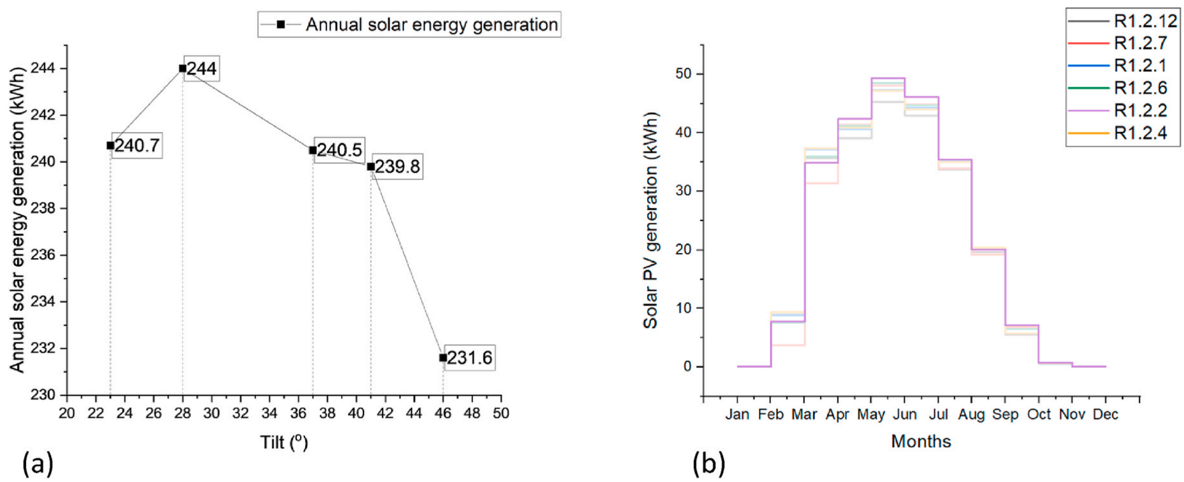

Fig. 9. (a) A line graph representing the optimal tilt angle for the region derived from the observations; 9(b) A vertical step graph representing R1.2.2's annual generation compared with the rest of the solar PV panels.

can also potentially increase energy generation through albedo, which is not the case during autumn. In addition, as represented in Table 1, the vast difference in the average sunlight hours in both seasons entails the respective potentiality. The region's average sunlight hours during spring is 8 h and 50 min compared to 2 h and 16 min in autumn.

5.3. Impact of snow on rooftop inclined and vertical solar PV generation

Snow is one of the significant meteorological elements affecting solar PV energy generation in the northern latitudes. The first snowfall event conventionally occurs at the end of October, followed by a few snowless days. The fluctuating freezing and thawing temperatures during the night and day affect snow melting and sleet formation. The period between early November to early May is the typical snowy period in the region, meaning, from the seasonal perspective, the snowy period commences in the mid of autumn and ends in the mid-spring. During the snowy period, the rooftop inclined solar PV panels are entirely under the layers of snow, leading them to produce a few kWh of energy. However, vertical solar PV panels contribute significantly more quantitatively than rooftop inclined solar panels in the same period. However, the observations on the site confirm the snow clearance much earlier than the typical snow clearance from the ground, improving the potentiality of rooftop inclined solar PV panels starting mid-March.

In the absence of any external shading elements, considering the research infrastructure installation on a three-storey high building roof and the roof material capturing and retaining the heat, snow clearance days are distinctive to the ground. The partial snow clearance commenced in late February, allowing the panels to generate minor energy. From both years of observation, it is worth noting that 98.7% of the energy generated by the rooftop inclined solar PV panels during the snowy period was at the end of February when the snow partially melted, which furthered the energy generation. The permanent snow layering on the ground typically starts at the end of November or early December. The snow remains on the ground until the end of April. However, most snow melts in mid-March and early April as the monthly mean temperature is above sub-zero with cloudless skies [13]. Typically, in the last couple of years' observation from the research infrastructure, the snow melts down the solar panels before the Astronomical spring season.

5.4 Impact of snow and shading on the rooftop inclined solar PV generation.

To find additional evidence on the influence of snow coupled with shading losses from panels at higher panel angles, a further investigation of the data described in Table 6 provided convincing conclusions. The rooftop inclined solar PV panels explicitly positioned for determining the effect of snow, optimal tilt angle, and mutual shading in real-time yielded conclusive results. A combination of the sun's lower angle during March in the region, near-to-zero mutual shading losses observed by the solar PV panels and the higher rate of the snow-melting phenomenon on and around the solar PV panels improved the energy generation potential of R1.2.4. Similar to the observations from discussion 5.1, the values observed from the two consecutive years for March are due to differences in the snow accumulation and melting rate and global solar radiation values. In 2022, the global solar radiance value was 5.47% more than in 2021. In 2022, the sunshine duration in March averaged 2.92 h/day in 2021 to 3.20 h/day in 2022. Furthermore, the snow melting rate was relatively faster in 2022, helping the same panel produce higher energy than in 2021.

On the other hand, the R1.2.7 solar PV panel at a tilt angle of 42° on the fifth row from the front and behind the R1.2.1 solar PV panel at a tilt angle of 41° generated the least energy during March. As both the solar PV panels have a minor tilt difference, based on the pitch, energy generation losses in the R1.2.7 are higher due to the shading cast from the R1.2.1. Additionally, during March, with a combination of sun and snow, the shading cast from the fore panel extended the snow-melting phenomenon, allowing for snow to remain on and around the panel for more days comparatively. This analysis proves the negative impact of snow on the rooftop inclined panels, especially during months with a combination of sun and snow. Further, it proves the importance of pitch, the distance between the panels, in reducing the mutual shading and preventing extended snow-accumulated periods between the solar PV panels.

5.4. Lower tilt angle approach for improving the annual solar PV generation potential

The theoretical optimal angle for the region calculated using the PVGIS simulation corresponds to 46° [16]. The theoretical calculations depend on the latitude information, the sun's path and the angle normalised for a year. The experimental values change regardless of the latitude but are affected by climate factors and external and mutual shading. The 28° tilted solar PV panel performed more efficiently than other solar PV panels observed from the two years of data. The differences between the theoretical and the observed values prove the practical limitations experienced on-site. The mutual shading losses for solar PV panels at a higher tilt are comparatively higher than the lower angles between 26° and 30° (illustrated in Fig. 9(a)). In addition, the lower rate of snow clearance as a factor of increased mutual shading further hinders solar PV energy generation for higher tilt angles in regions under the influence of snow. This conclusion stands valid for solar PV panel setups on a flat roof and a ground-mounted solar PV system. As the potentiality of solar PV energy generation is higher during the spring and summer seasons in the Arctic, positioning the solar PV panels at an optimum azimuth and inclining it at an optimum angle for these seasons results in higher yields. The results from the observations prove that R1.2.2 generated 3% more than the other solar PV panels during the spring and summer seasons.

6. Conclusion

The seasonal solar PV generation analysis featuring the twelve solar PV panels, six vertical and six rooftop inclined solar PV panels with a specification of 275 W power output and 18% efficiency showed that the best season for generating solar PV energy in the Finnish Arctic is the spring season and the best month for generating solar PV energy are June and July. For a vertical PV system, February, March, and April proved to be the best months for generating solar PV energy.

Further, data analysis by distinguishing the results from the vertical and rooftop inclined PV panel setups confirms the better potentiality of vertical solar PV panels during the autumn and winter seasons. Vertical solar PV panel, V1.1.6, generated 30.25% and 98.36% more than rooftop inclined R1.2.2 solar PV panels during these seasons. The rooftop inclined R1.2.2 solar PV panels performed finer during the spring and summer, generating 20.2% and 30.44% more than the vertical V1.1.6 solar PV panels. Moreover, it is worth noticing that the higher percentages of vertical solar PV panels during the autumn and winter seasons are not qualitatively comparable with the rooftop solar PV generation during the spring and summer seasons. Emphasising the influence of snow on solar PV panels from the generation perspective indicates the importance of spacing the solar PV panels. The more the spacing/pitch between the solar PV panels, the quicker the snow clearance from the panel and the foreground during the late winter and early spring seasons. As derived from the results, the solar PV panel, R1.2.7, under the influence of snow and mutual shading from the fore panel, R1.2.1, generated 41% of the energy. The results coincide with the observations conducted on another solar PV panel, R1.2.4, which had zero influence of mutual shading, helping it to generate higher energy.

The high potential window for generating solar PV energy in the Arctic is narrow. Utilising the spring and summer to their fullest could yield better. A low tilt-angle strategy, retaining the solar panel's tilt angle at a lower angle, 28°, as identified from the research infrastructure, proves an optimal solution for increasing the solar energy potential in the Arctic region throughout the year. The macro-level evaluation of the empirical data proves that the solar panel, at a tilt angle of 28°, generated 3% more energy annually compared to the rest of the solar panels at tilt angles varying from 23° to 46°. It proved the increased potentiality of solar PV panel at this tilt angle to capture the maximum irradiation during the spring and summer seasons. The additional advantages of retaining lower tilt angles in the Arctic are the lesser mutual shading losses when the solar panels are in multiple rows, one behind another, allowing snow clearance at much faster rates. The empirical evidence proves that the higher tilt angles, as recommended by simulations and theoretical calculations, are less efficient for generating solar PV energy in Arctic conditions annually. Considering the high potential spring and summer seasons, the sun's relative angle, and the optimal operating temperature during these seasons, the optimal tilt angles for the Arctic could follow the lower tilt angle approach, where the solar PV panel can be at lower angles throughout the year.

With growing global interest in renewable energy, especially solar PV energy, addressing the experience from the Arctic's perspective is significant. To establish the EU's "solar ready" buildings for the future from the Arctic's perspective, insights on seasonal generation profiles of solar PV systems and optimal tilt angle recommendations for the Finnish Arctic region alongside the generation profiles of the two main mounting systems prove essential. With its wide heterogeneity of challenges, research pushes the limits to transpose the challenges to advantages. The research infrastructure in Oulu is one such platform, and this research is one of the begets for turning the challenges into assets. The results from this empirical study show the way to a precise understanding of the potentiality of solar PV generation in Arctic weather conditions.

Data availability

Datasets related to this article can be found at Shekar, Vinay (2023), "Empirical solar PV generation data from a research infrastructure in Northern Finland.", University of Oulu, V1, https://doi.org/10.17632/cpxyw3789v.1, an open-source online data repository hosted by Mendeley Data.

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CRediT authorship contribution statement

Vinay Shekar: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Antonio Caló:** Conceptualization, Validation, Writing – review & editing, Supervision. **Eva Pongrácz:** Conceptualization, Methodology, Validation, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2023.119162.

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