

A new optimal PV installation angle model in high-latitude cold regions based on historical weather big data

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HIGHLIGHTS

- Snow effects are included in the new model for PV tilt angle calculation.
- An improvement of 5% could be achieved compared with traditional methods.
- Snow conditions can lead to a change of tilt angle by up to 8.5°.
- Annual PV generation decreased by an average of 17.6% more than predicted.
- Snow removal agents improve PV performance by up to 4%.

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ABSTRACT

PV technologies are regarded as one of the most promising renewable options for the transition towards Net Zero. Despite the rapid development of PV systems in recent years, achieving the necessary goals requires more than a threefold increase in annual capacity deployment by 2030. However, current PV systems often fall short of optimal performance due to improper installation angles. In high-latitude cold regions, the actual PV generation capacity is frequently overestimated due to the omission of snow conditions. This study introduces a novel model designed for high-latitude regions to predict local optimal PV installation angle that maximizes PV power generation, utilizing historical weather big data, including snowfall and melting effects. A case study is presented within a Swedish context to demonstrate the implementation of these methods. The results highlight the crucial role snow conditions play in determining PV performance, resulting in an average reduction of 14.7% in annual PV power generation. Optimal installation angle could yield approximately a 4.8% improvement compared to common installation angles. The study also explores the application of snow removal agents, which could potentially increase PV generation by 0.1–2.3%. Additionally, the new PV installation angle successfully captures the impact of the local weather changes on PV power generation, potentially serving as a bridge between climate change adaptation and future PV power generation endeavors.

1. Introduction

To achieve the Paris agreement goal of **limiting global warming** to well below 2 °C [1], reducing fossil fuel consumption and increasing the proportion of low and zero carbon energy are crucial actions [2]. In this context, renewable energy technologies that offer abundant resources and have low negative impacts on the environmental and global warming are gaining increasing attention worldwide [3,4]. Solar photovoltaic (PV) technology, due to its abundant resource availability and technical maturity, is recognized as a significant pathway towards a

fossil-free society. Between 2010 and 2020, the levelized cost of electricity for PV plants declined by 85% to 0.057 USD/kWh, surpassing even traditional fossil fuel-based power generation systems. The total installed capacity also surged 16-fold to 707 GW [5,6] during this period. In the future, The growth trajectory of the PV industry is projected to further accelerate, aligning with the global Net Zero roadmap by 2050 [5,6]. Sweden has set a target of sourcing 100% of its electricity from renewable energy by 2040 [7]. Despite this ambitious plan and the rapid expansion of PV projects, only 10% of total electricity came from combustion-based sources and a mere 0.4% from solar power by 2019. These figures fall far short of the predicted range of 5% to 10% [8].

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Nomenclature		<i>GHI</i>	global horizontal irradiation [W/m ²]
Abbreviations		<i>G_{max}</i>	maximum global available irradiation [W/m ²]
PV	Photovoltaic	<i>G_{STC}</i>	global irradiation (STC) [W/m ²]
SPYM	snow-PV yield model	<i>h</i>	solar elevation
STC	standard test conditions	<i>i</i>	the <i>i</i> -th hour
Symbols		<i>opti_{angle}</i>	optimal tilt angle [degree]
<i>a_r</i>	angular loss coefficient	<i>P</i>	PV power output [W]
<i>B/ DNI</i>	solar beam (direct normal irradiation) [W/m ²]	<i>P_{max}</i>	maximum power (STC) [W]
<i>c₁</i>	fitting parameter of angular loss calculation	<i>r</i>	melting rate [mm/h]
<i>c₂</i>	fitting parameter of angular loss calculation	<i>R</i>	albedo irradiation [W/m ²]
<i>C_m</i>	melting rate factor [mm/°C/day]	<i>SD</i>	snow depth [cm]
<i>D</i>	diffuse irradiation [W/m ²]	<i>SF</i>	snow factor (for measuring snow accumulation)
<i>D^I</i>	isotropic diffuse irradiation [W/m ²]	<i>T</i>	temperature [°C]
<i>DHI</i>	diffuse horizontal irradiation [W/m ²]	<i>T_{stc}</i>	temperature of standard test conditions [°C]
<i>f_b</i>	angular loss factor of direct radiation	Greek	
<i>f_d</i>	angular loss factor of diffuse radiation	<i>α_T</i>	temperature coefficient
<i>f_{loss}</i>	loss factor due to snow cover	<i>β</i>	tilt angle [degree]
<i>f_r</i>	angular loss factor of reflected radiation	<i>θ_s</i>	incident angle [degree]
<i>G</i>	global available irradiation [W/m ²]	<i>ρ</i>	reflectivity ratio
<i>G(angle)</i>	global available irradiation with tilt angle “angle” [W/m ²]	<i>η</i>	PV efficiency

Consequently, PV markets in Sweden are attracting more public interests, leading to a rapid increase in PV installation in recent years [9]. In addition, due to growing population density and land resource constraints, decentralized PV is expected to experience substantial growth in the future [10,11].

Until now, the majority of installed PV systems employ non-tracking configurations with fixed installation angles due to their cost effectiveness [12,13]. The PV installation angle typically refers to the locally optimal installation angle based on the geometric calculations accounting for the geographic location, or the commercial angle, which is globally standardized. However, the performance of PV systems is also greatly influenced by local weather conditions, extending beyond geographical conditions. Under the above-mentioned installation angles, PV panels may fail to achieve maximum annual power generation, particularly in high-latitude regions. High-latitude regions encounter several challenges that affect PV power generation. First, solar irradiation may not contribute to power generation during optimal seasons with long day length, as the sun only illuminates the backside of PV panel before 6:00 AM and after 18:00 PM solar time [14]. Second, these regions frequently experience cold weather and *persistent snow* cover during winter, coinciding with peak electrical demand. Snow accumulation on solar panels can substantially hamper electricity production by obstructing solar irradiation from reaching the PV cells. In Sweden, snow covers the ground for an average of over 135 days per year, with maximum snow depth reaching 55 cm or higher [15]. Third, global climate model simulations indicate an increasing trend of extreme snowfall across vast areas of the Northern Hemisphere, including high latitudes, attributed to intensified hydrological cycles resulting from global warming [16]. Collectively, these factors complicate the determination of the optimal PV tilt angle in high-latitude areas. In addition, existing installation angles may yield PV system performance significantly below its optimal potential, leading to resources wastage, including land, PV panels, material, and labor. Consequently, developing a novel model that predicts the local optimal PV installation angle while comprehensively evaluating weather conditions to maximize PV power generation becomes crucial.

Previous literature has addressed the calculation of optimal PV tilt angle across low or mid latitudes [17–21], cold regions [17–25], and globally [22,23,26]. However, studies considering the impacts of snow on PV system remain scarce. For instance, the study by Nicolás-Martín

et al. [27] built a model for the global optimal angle calculation based on latitude and irradiation data. Chinchilla et al. [26] created a model based on horizontal irradiation. Barbon et al. [28] tested best installation angle and orientation for both flat and tilted roof. Jacobson et al. [29] presented extensive overviews of annual optimal tilt angle worldwide, offering reference values for each country. Many of these studies either exclude detailed weather data or employ monthly or daily data, potentially failing to capture real-world conditions accurately. Other studies focused on optimal tilt angle measurement based on historical weather data, concentrating on radiation measurement in low or mid latitude area characterized by fewer seasonal variations. These studies predominantly considered the influence of factors such as precipitation and dew point rather than snow conditions. Barbon et al. [28] addressed weather effects, energy losses and shading but did not account for snow effects. Several other studies examined cold regions [17–25]. However, these studies mainly focused on different perspectives like shading or soiling, PV materials or economic aspects. Snow-induced loss might be a small proportion for low/mid latitude. However, for the high-latitude areas where the winter seasons are generally lengthy, the snow effects play an important role so that exclusion of snow effects would significantly influence the reliability of the results.

Some literature links snow effects with PV performance calculation. For example, Rob et al. [30] conducted an in-depth analysis of PV losses during snowfall. Andenæs et al. [31] analyzed and summarized snow loss based on the wavelength. Hadia et al. [18] predicted PV daily power generation in Canada by incorporating fixed snow effect constants, which fail to represent real-world situations. Marion et al. [32] developed model to measure residential PV generation loss due to snowfall with American cases. Another American case study proposed by Heidari et al. [33] evaluated the loss by varying tilt angles in the snow season. Noord et al. [34] calculated the PV loss due to snow similarly with Swedish cases and long-term meteorological data. These studies primarily focused on wintertime and then estimated the mean loss over the year as a percentage factor, which may fail to represent the real PV system performance throughout the whole year. The majority of previous research regarding PV performance or PV tilt angle remains insufficient and unclear on the effects of snow cover which is generally considered as a loss factor rather than an input such as irradiation. On the other hand, there are also many studies specializing on the snow covering and melting process on PV panels. Perovich [35] tested

reflection and transmission of light through spectral observations with various snow depth. Quan et al. [36] studied on the relationship between snow cover depth, PV tilt angle and PV system efficiency. Hosseini et al. [37] modelled variation of power and current with snow cover. Rahmatmand et al. [38] employed an improved numerical approach to predict snow melting on inclined PV panels in Canada, offering insights into snow melting estimation. Huang et al. [39] tested natural melting and sliding on tilted PV and estimated the time and power loss. These studies similarly concentrated solely on one or some specific parameters, such as current or wavelength. Besides, these studies are mainly based on experiments normally arranged in winter, and some of the studies suggested a tilt angle with better performance. However, this may not achieve annual optimal performance since they did not consider the other three seasons. Another issue is that though the accuracy increases, the parameters required for estimation become more. It is necessary to have a more general model with both a satisfactory level of accuracy and compatibility.

In this study, we developed a new optimal PV installation model based on historical weather big data to analyze the impacts of weather

conditions on PV performance in high-latitude cold regions. The snow conditions are included in the new model considering the transmittance change based on snow depth as well as melting rate according to air temperature. In order to show the implementation of the method, we provide an example of urban PV installation in the high latitude city of Hammarby Sjöstad (59.30 N) in Sweden. The study determines the optimal PV tilt angle by using historical meteorological data from the past ten years (2012–2021), including irradiation, air temperature and snow conditions, and compares the results with the commercial angle (the angle commonly chosen by installation companies) and geometry angle. The results show that PV system with the new optimal installation angle can have significantly higher PV power generation than that with traditional PV installation angles. In addition, the new PV installation angle can also successfully reflect the impact of the local weather changes on PV power generation. It can potentially act as a bridge between climate change and future PV power generation.

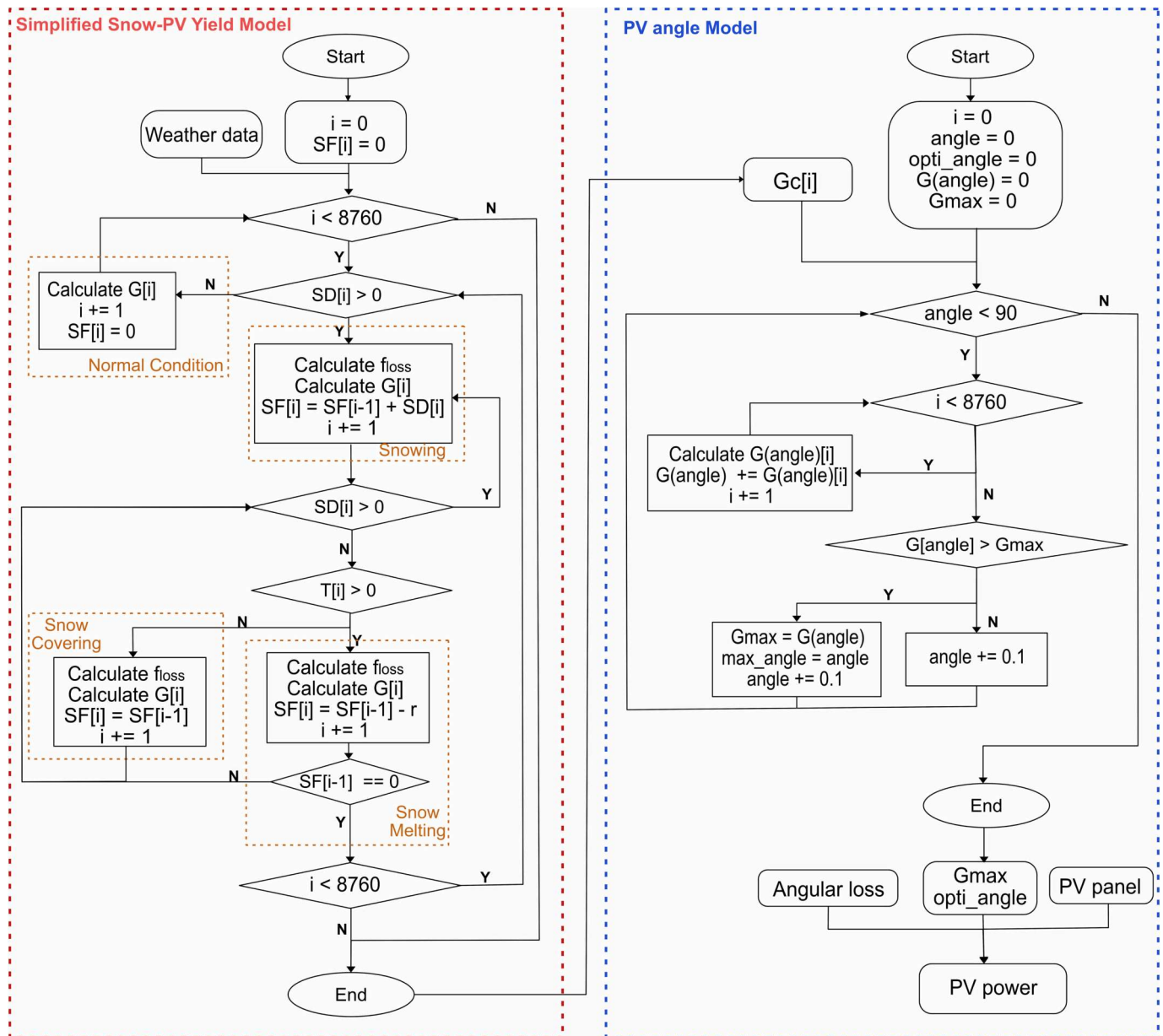


Fig. 1. Flow chart of the optimal PV installation angle model.

2. Methodology

To achieve a more accurate determination of the optimal PV installation angle, a novel model has been developed by coupling an optimal PV installation angle model aimed at maximizing PV power generation with a simplified snow-PV yield model (SPYM). This SPYM model employs historical weather data, including snow condition, as inputs to calculate total available irradiance. The detailed calculation process of this method is illustrated in Fig. 1. The data for this study is collected from relevant databases, namely Solcast and Stockholm City. To ensure precision, hourly weather data is selected. The SPYM model handles various weather conditions, while the optimal PV installation angle model calculates the optimal tilt angle. The total available irradiation for PV (G) is initially calculated and adjusted based on snow conditions (snow depth (SD)), air temperatures (T) and irradiation. SD determines snowy weather and T determines the status after snowfall- melting or covering. A snow factor (SF) is introduced to record the snow accumulation (i.e., snow exists if SF is greater than 0) and r represents the melting rate which is related to air temperature T . Subsequently, using the corrected irradiation data (G_c), the optimal tilt angle (opti_angle) is derived by maximizing total available irradiation (G_{max}) received by the PV panels. The entire model operates at hourly time step. Ultimately, sensitivity studies are conducted on different meteorological years and various operational strategies.

2.1. The simplified snow-PV yield model (SPYM)

Snow conditions are considered in the SPYM model as presented in Fig. 1 (left). The obstruction of solar radiation on the PV cells caused by snow can vary based on the optical properties of snow, which depends on factors such as average grain size, free water content, or the formation of layers within the snowpack [31]. For the sake of simplicity, this study does not account for these factors in the model, and the PV yield is assumed to merely depend on the thickness of snow cover on the PV panels ($SD[i]$). The calculation of this snow loss factor (f_{loss}) refers to the transmittance model from Perovich [35]. The transmittance drops sharply from 1 to 0.1 when snow depth increases from 0 to 2 cm. Then the decrease becomes more smoothly, and the value reaches 0.01 when snow depth increase to 12 cm. When the snow depth is thicker than 12 cm, the value is assumed to be 0. Although this assumption sacrifices some precision, the model requires fewer parameters, which could be easier to obtain and more understandable for those with less specialized knowledge. Thus, The SPYM reads historical weather data as input and runs for 1, 5 or 10 years. The operational diagram in the figure presents a yearly cycle. Depending on the weather conditions, the model is processed differently at each time step i (1-h interval in this study):

- Normal days (without snow):
 - PV operates as usual, and the available total irradiation ($G[i]$) is obtained from the solar radiation data.
 - The snow factor (SF[i]) is set to 0 during this period.
- Snowing:
 - The snow event is considered to have started when the input snow water equivalent is larger than 0,
 - As PV panels are covered by snow, the PV yield decreases with the snow cover becoming thicker. The real available irradiation to the panels is corrected according to the f_{loss} .
 - The snow factor (SF[i]) increases according to $SD[i]$.
- Snow covering:
 - After snowing, the model assumes that the snow remains on panels if the air temperature is below 0.
 - PV panels are kept covered by snow and the yield depends on the thickness of the snow. The real available irradiation to the panels is corrected according to the f_{loss} .
 - Snow factor SF[i] remains the same as the previous value.
- Snow melting:

- After snowing or when panels are covered by snow, the snow is considered to be melting if the air temperature rises above 0 [40].
- The study assumes that the snow would be completely melted after 12 h, but the melting process would be paused if either of these two events is detected: air temperature drops below 0; or snowfall resumes.
- During the melting process, since the snow still covers the panels, the real available irradiation to the panels is corrected according to the f_{loss} .
- The snow factor decreases with a melting rate r during the process. The melting rate r is related to air temperature (Eq. (1)), where C_m is the melting rate factor. According to the literature, the melting rate factor could be 1.5–8 for the urban areas in Sweden [41]. In this study, the average number is chosen and converted to the hourly rate. If the rest amount of snow is smaller than the melting amount ($SF[i] < r$), the snow factor would be set as 0.

$$r = C_m \times T / 24 \quad (1)$$

- Back to normal:
 - After the melting process ($SF[i-1] == 0$) and in the absence of snow, the snow situation is considered concluded.
 - PV modules yield electricity as calculated by $G[i]$ according to radiation data.
 - The snow factor (SF[i]) is set to 0.

The total available horizontal global irradiation for each hour ($G[i]$) is measured and adjusted according to snow conditions. The adjusted available horizontal global irradiation ($G_c[i]$) is then utilized to evaluate the optimal tilt angle in the Swedish context.

2.2. The PV angle model

Due to the cosine effect, the collected solar irradiation depends on the PV tile angle. The outputs from the SPYM are used as input for the PV angle model. The SPYM model outputs mainly the adjusted irradiation data. The PV angle model will be executed with PV tile angles ranging from 0 to 90° with 0.1-degree intervals. The optimal PV tile angle is the one that results in maximum total solar irradiation on the tilt PV panels. The total irradiation on the tilt surface is calculated by Eq. (2). The total global solar irradiation (G) on the PV module at tilt angle β is calculate as the sum of direct (B), diffuse (D) and reflection (R) components (Fig. 2) [42,43]. All panels are assumed to face south (azimuth angle $\alpha = 0$). The angular loss during the PV operation is also estimated in this study. The loss factor of direct, diffuse and reflected radiation is defined as f_b , f_d and f_r , respectively.

$$G(\beta) = (1 - f_b) \times B(\beta) + (1 - f_d) \times D(\beta) + (1 - f_r) \times R(\beta) \quad (2)$$

To be noticed, the direct solar irradiation $B(\beta)$ here differs from solar direct normal irradiance (DNI) since it has considered the cosine effect of the incident angle θ_s (the angle between the solar irradiation and the normal of the PV panel). Since the PV panels used in this study are of the mono-facial type PV modules, they cannot utilize DNI when θ_s is larger than 90°. Although strong solar irradiation still occurs before 6:00 AM and after 18:00 PM solar time during the summer months in Sweden due to its high latitude, the DNI must be set to 0 in the SPYM model, and only diffuse irradiation can be considered for power generation. Consequently, the available direct normal irradiation for the PV panels is adjusted as shown in Eq. (3) within the model.

$$B(\beta) = DNI * \max(0, \cos \theta_s) \quad (3)$$

Considering that the azimuth angle is 0 as the PV panels are oriented towards the south, $\cos \theta_s$ be calculated by Eq. (4) [44].

$$\cos \theta_s = \text{sign}(\phi) * \sin \delta \sin(|\phi| - \beta) + \cos \delta \cos(|\phi| - \beta) \cos \omega \quad (4)$$

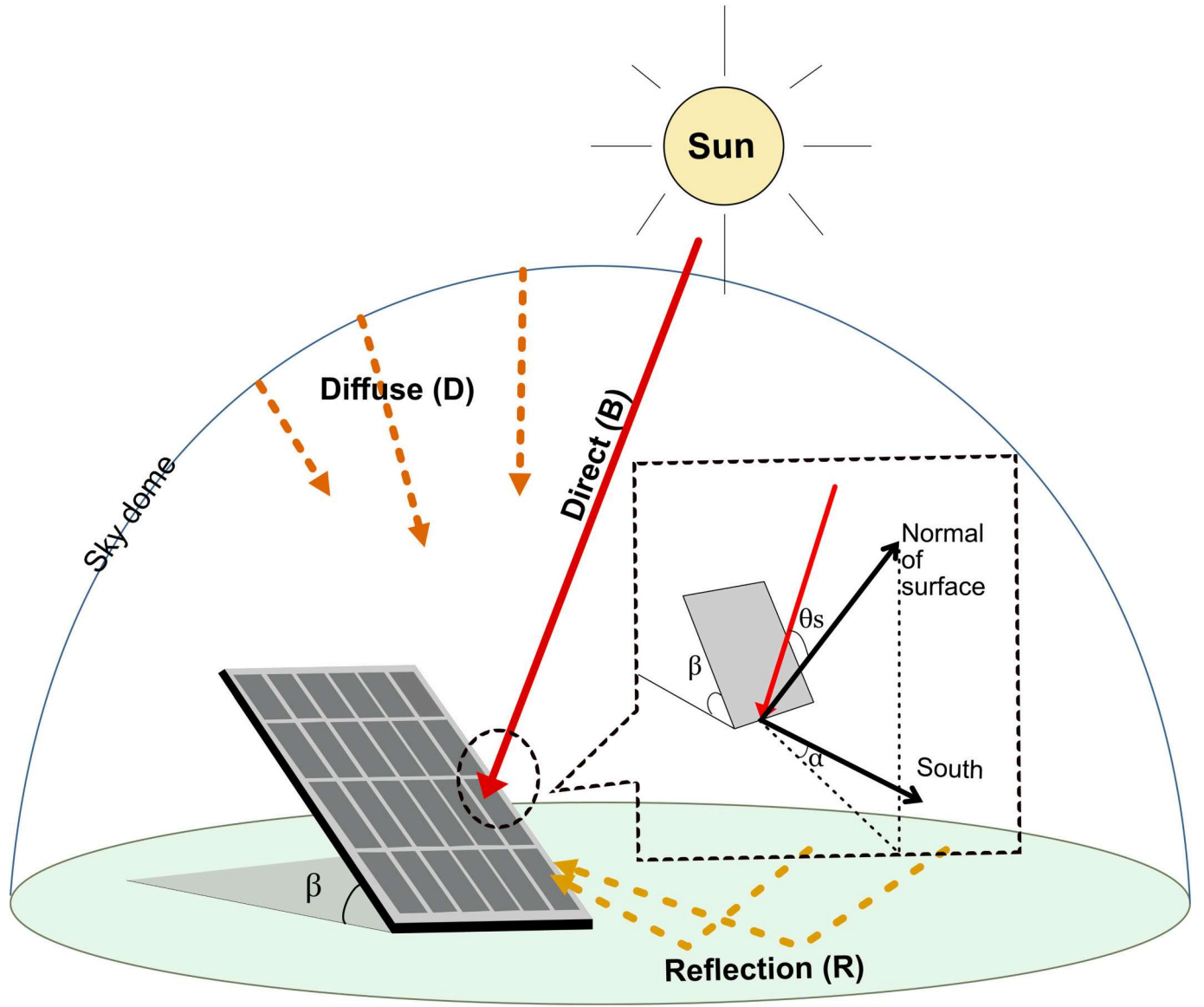


Fig. 2. Different types of irradiations available for PV modules.

where ϕ is the latitude of the location, δ is the declination angle, and ω is the hour angle. As Stockholm (longitude 18.1E and latitude 59.32 N) is in the northern hemisphere, the sign of ϕ is positive. The declination angle δ undergoes continuous change and completes a cycle within a year. However, its variation within a day is relatively small (less than 0.5°). Therefore, it can be treated as approximately constant within a day, and it is commonly determined by Eq. (5).

$$\delta = 23.45^\circ \sin(360^\circ (d_n + 284)/365) \quad (5)$$

where d_n is the day number beginning from January 1st. Notably, both February 28th and 29th share the same day number. Another important parameter is hour angle (ω), which indicates the sun's displacement from its highest position for a given location and day, changing at a rate of 15° per hour. It is negative in the morning and positive in the afternoon. The hour angle at a specific time is calculated using Eq. (6).

$$\omega = 15^\circ (LST - 12) \quad (6)$$

where LST demotes local solar time in hours. In the calculation of various solar angles, solar time is used, which can be converted from local time (LT) through two amendments, as shown in Eq. (7).

$$LST = LT + (E_1 + E_2)/60 \quad (7)$$

The first term (E_1) is due to the difference between the local longitude and the central meridian of the relevant time zone, considering that the sun traverses 1° of longitude in approximately 4 min (Eq. (8)).

$$E_1 = 4(L_c - L_{loc}) \quad (8)$$

The second term (E_2) deals with the impacts of perturbations in the earth's rotation rate. Various correction equations are employed for this purpose, here the equation is cited from [14], as shown in Eq. (9).

$$E_2 = 229.2(0.000075 + 0.001868\cos A - 0.032077\sin A - 0.014615\cos(2A) - 0.04089\sin(2A)) \quad (9)$$

where angle A is calculated by Eq. (10). The units of E_1 and E_2 are both in minutes, and they should be converted to hour, just like LST.

$$A = (d_n - 1) \cdot 360/365 \quad (10)$$

There are mainly two methods to measure diffuse irradiation, depending on whether the radiation is treated as isotropic (D^I) or circumsolar (D^C). Hay and Davies introduced a weighted index to include

both types of diffuse irradiation [9]. It is evident that during sunrise and sunset, the calculation of circumsolar methods could lead to unrealistic results [15]. Thus, to simplify the model as well as to reduce uncertainties, this study regards all diffuse radiation as isotropic, which is used to calculate diffuse radiation absorbed by the PV panels (Eq. (11)). In Eq. (11), DHI means diffuse horizontal irradiation, and it is calculated by Eq. (12) [45], where GHI means global horizontal irradiation, and h represents sun altitude.

$$D(\beta) = D^l(\beta) = DHI^* (1 + \cos\beta) / 2 \quad (11)$$

$$DHI = GHI - DNI^* \sin(h) \quad (12)$$

The study also considers albedo irradiation (R) resulting from reflection off other object surfaces. Due to the complex surrounding conditions in this study area, the ground is assumed to be horizontal and of infinite extent, reflecting solar beam isotropically. Albedo irradiation can be measure through Eq. (13), where ρ demotes the reflectivity of the ground, which is typically set to 0.3 for normal ground conditions [46].

$$R(\beta) = \rho^* GHI^* (1 - \cos\beta) / 2 \quad (13)$$

In this study, the angular loss is also considered. For different types of irradiations, the angular loss is various. The calculation of three angular loss factors is presented as Eqs. (14)–(16) [47].

$$f_b(\beta) = \frac{\exp\left(-\cos\left(\frac{\theta_a}{a_r}\right)\right) - \exp\left(-\frac{1}{a_r}\right)}{1 - \exp\left(-\frac{1}{a_r}\right)} \quad (14)$$

$$f_d(\beta) \cong \exp\left[-\frac{1}{a_r} \left(c_1^* \left(\sin\beta + \frac{\pi - \beta - \sin\beta}{1 + \cos\beta}\right) + c_2^* \left(\sin\beta + \frac{\pi - \beta - \sin\beta}{1 + \cos\beta}\right)^2\right)\right] \quad (15)$$

$$f_r(\beta) \cong \exp\left[-\frac{1}{a_r} \left(c_1^* \left(\sin\beta + \frac{\beta - \sin\beta}{1 - \cos\beta}\right) + c_2^* \left(\sin\beta + \frac{\beta - \sin\beta}{1 - \cos\beta}\right)^2\right)\right] \quad (16)$$

where a_r is the angular loss coefficient, c_1 and c_2 are the fitting parameters. In this study, a_r is set as 0.17, c_1 as $4/(3\pi)$ and c_2 as -0.069 [47].

The optimal PV installation angle and the corresponding total available irradiation are used for calculating PV output power. For a PV panel with a known efficiency under standard test conditions (STC), its power generation in real-world applications mainly depends on the total global irradiation (as calculated in Eq. (1)) and its operating temperature (T), as shown in Eq. (17) [48].

$$P[i] = \frac{P_{STC}^* G(\beta)^*}{G_{STC}} \eta^* [1 + \alpha_T^* (T[i] - T_{STC})] \quad (17)$$

where STC refers to the conditions where irradiance is set at 1000 W/m^2 , and the cell temperature is 25°C , P_{STC} is the maximum power, η is the PV efficiency, α_T is the temperature coefficient, T_{STC} and G_{STC} are temperature and irradiation under standard conditions, respectively.

2.3. Data collection

2.3.1. Case study

This study analyzed the power potential of an urban district, Hammarby, in Stockholm, Sweden. This district actively participates in innovative research and projects through the local citizen-driven initiative known as “ElectricITY” [49]. The area of each rooftop is obtained and adapted from building data, which determines the size of PV system on each rooftop. The PV production potential can be estimated together with the calculated power value.

2.3.2. Weather data

The weather data used for calculating the available irradiation that illuminates the PV panels includes Global Horizontal Irradiance (GHI) (W/m^2), Direct Normal Irradiance (DNI) (W/m^2), Diffuse Horizontal Irradiance (DHI) (W/m^2), Global Tilted Irradiance (GTI) (W/m^2), air temperature ($^\circ\text{C}$) and Snow Depth Water Equivalent (cm). These data were collected from the Solcast dataset [50], which has undergone extensive validation against surface measurements from the Baseline Surface Radiation Network (BSRN) stations located at various global locations and across all climate types, except for polar climates. The dataset covers historical time periods from 2007 to the last 7 days. Ten-year hourly data (from 2012 to 2021) were selected to encompass a range of different weather conditions.

2.3.3. Building data

The building data assists to measure the power generation and provides us with a more intuitive view. The building data for Hammarby Sjöstad (HB) was collected from the data portal of Stockholm City, an open database [51]. Due to the limitation of data, all buildings are assumed to have flat roofs. In total, 277 buildings (statistics from the year 2020) are included in this study.

2.3.4. PV panels

The chosen of PV panel type is based on a commercial PV product from SUMAN® which is available in the Swedish PV market. Some key parameters of the PV panel are listed in Table 1 [52]. These parameters will be used for estimating the PV power potential. All PV panels will be installed on the rooftop of the buildings with the same fixed tilt angle. The distance between each row of the PV arrays is assumed to be 2.4 m [53]. Besides the basic conversion efficiency, the performance of PV panels is also influenced by environmental factors, such as air temperature and dust. Altogether, a total loss of 10% is assumed, including factors like soiling, wiring and availability [29]. Reductions for obstacles and shading effects are 10% and 15% respectively [53]. The expected service life of these PV panels is 20 years.

3. Results and discussion

In this study, three different scenarios are evaluated and compared. The first one is a base case without snow conditions. This scenario refers to common methods for calculating PV tilt angles, considering precipitation and cloud. The second scenario considers snow impacts, including snowfall, cover and melting, which better represents the real weather conditions in cold regions. The third scenario tests the impacts of a snow-dissolved agent if snow melts in one hour of applying the agent. These results are also compared with the commercial angle (15°) and geometric angle (40.7°) for Sweden [29]. The commercial angle is the common choice for PV installation companies, while geometric angle depends solely on the geographic location, regardless of weather conditions.

3.1. Scenario 1 (S1)

In S1, only historical irradiation and temperature data are considered. The optimal angle, as well as the corresponding maximum PV

Table 1
Parameters for solar panels.

Parameters	Value	Unit
Manufacturer	SUMAN	–
Module number	SMF430F-6X24UW	–
PV module type	Monofacial & Monocrystalline	–
Efficiency (η)	19.2	%
Size	2.12×1.046	m^2
Maximum power at STC	430	W
Temperature coefficient (α_T)	-0.0038	$^\circ\text{C}^{-1}$

generation, is analyzed according to 1-year, 5-year and 10-year weather data, as depicted in Fig. 3 (marked in grey, blue, and green colors respectively).

Between 2012 and 2021, the annual optimal angle and irradiation vary with weather conditions. The annual optimal angle fluctuates between 34.0 and 37.7° over the 10 years. The difference between the 5-year and 10-year average angles is within 1° , while the difference can be more than 2° for the annual optimal angles. The PV power generation fluctuates between 46.4 and 52.7 kWh/m^2 . Therefore, even in the same location, the annual PV power generation could vary significantly with weather conditions. The largest difference in the annual optimal angle occurs in the years 2013 and 2020; however, the largest difference of PV generation occurs in the years 2012 and 2018. Therefore, the relationship between the optimal angle and the power generation is not positively correlated. In addition, a similar optimal angle may lead to different maximum power generation under different weather conditions, e.g., in the years 2014 and 2020. Predicting PV production merely based on the tilt angle is difficult. It is a result of multiple factors. Since snow conditions are not included in this case, the main influencing factors are precipitation and clouds. Both factors can affect the PV system during the daytime. Besides, solar irradiation varies significantly in different seasons over high-latitude areas. The same weather event in different seasons would have different effects on PV performance. For example, the years 2013 and 2018 yield similar maximum power generation, but the annual optimal angles for these two years differ by more than 3° . According to the weather statistics from Swedish Meteorological and Hydrological Institute (SMHI), these two years have a similar number of rainy days (144 days for 2013 and 140 for 2018). However, the precipitation patterns differ. In 2018, there was extremely sunny weather during the summer, while in 2013, it was dry in spring and autumn, but rainy and humid in June and August. A sunny summer results in a lower tilt angle.

The annual power generations with 5-year and 10-year average optimal angles are compared to the corresponding values with the annual optimal angle, as shown in Fig. 4. While the PV power generation with multi-year averaged angles is generally smaller than that of the optimal one, the difference is approximately 0.02 kWh/m^2 , representing less than 0.1% of total power generation. In real-world applications, changing the tilt angle annually could lead to increased operational costs. Therefore, utilizing a 5-year or 10-year average optimal angle, could still yield considerable PV power generation with simplifying operations significantly. However, when comparing these two average angles, the 5-year average value (blue bar in Fig. 4) is much lower than the 10-year average value (orange bar) for some years, whereas the blue bar is almost twice as long as the orange one in other years. Thus, it is challenging to determine whether a 5-year or 10-year average angle is

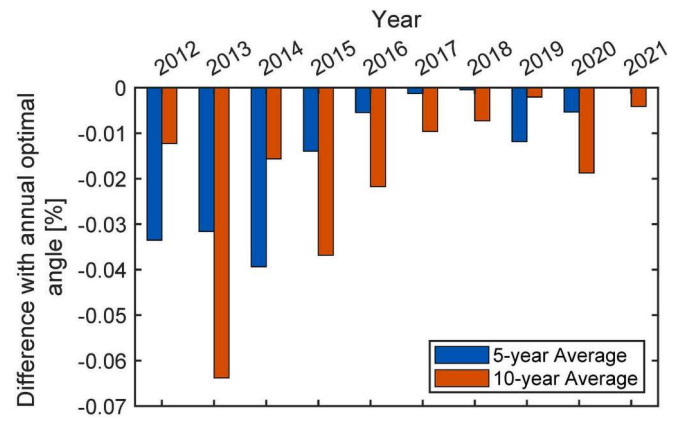


Fig. 4. Comparison of annual PV power generation between the 5-year and 10-year averaged annual optimal angle in scenario 1.

better for a specific year. On average, the deviation with the 5-year average angle is slightly smaller than that with the 10-year average angle (0.014% versus 0.019%).

The year 2013 exhibits a relatively high deviation when the 10-year average angle is applied. In that year, rain was more frequent in summer, while it was quite dry during spring and autumn. These specific weather conditions led to a larger tilt angle than in typical years. As shown in Fig. 3, the annual optimal angle in 2013 also displays the largest deviation from the 10-year average angle. When the tilt angle becomes smaller, the decrease in PV generation during spring and autumn is much more pronounced compared to the increase during summer. Comparing the earlier five years to the latter five years, the deviation from the year 2012 to 2016 is nearly three times that of the years 2017 to 2021. The weather conditions in the former five years varied significantly. In 2012 and 2015, there were prolonged periods of rainy days extending from summer to winter. The year 2013 experienced the most sunshine hours, while 2014 experienced a cloudy and wet summer. On the contrary, from 2017 to 2021, most years were characterized by dry and warm weather. The power generation using the average angles aligns more closely with the values obtained using the annual optimal angles when the weather conditions are similar across the years. However, if extreme weather occurs more frequently, the effectiveness of the average angle in PV power generation diminishes.

3.2. Scenario 2 (S2)

Building upon S1, S2 incorporates snow conditions. Similarly, the optimal angle and the corresponding maximum PV generation are

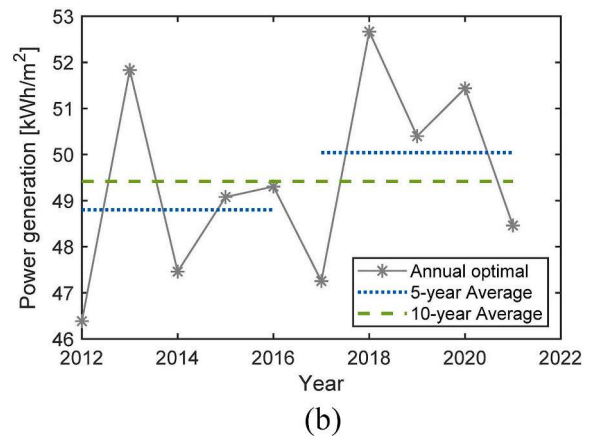
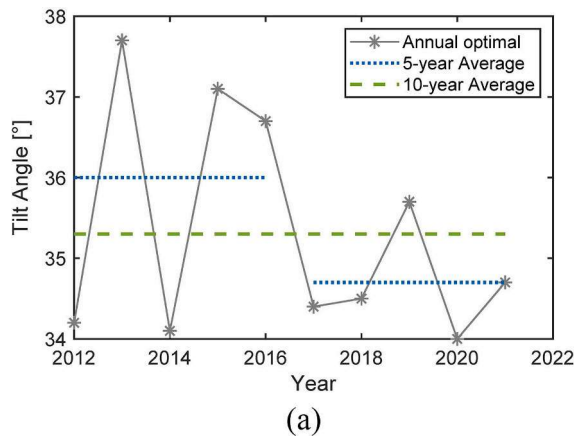


Fig. 3. The annual optimal angle and the annual maximum PV power generation from 2012 to 2021 in scenario 1: (a) Annual optimal angle; (b) Annual maximum PV power generation.

analyzed based on 1-year, 5-year and 10-year weather data. Figs. 5 and 6 present the annual optimal title angle and the corresponding PV power generation for S2. The annual optimal angle varies from 27.6 to 34°, and the PV production fluctuates between 39.4 and 51.0 kWh/m². The 5-year average angle is almost identical to the 10-year average angle, and the difference in annual power generation is within 1 kWh/m². However, when comparing the annual optimal angle with the average angles, although the annual optimal angle for some years closely aligns with the average angle, the difference can be as high as 3.3 degrees (as observed in the year 2017). The variation in annual power generation is approximately 6.8 kWh/m² (notably in the year 2020).

When comparing with S1 (Fig. 3), both the annual optimal angle and the PV power generation decrease in S2. However, the fluctuation becomes more pronounced in S2. Both the range of the annual optimal angle and the PV power generation become wider, spanning from 3.7 to 6.4° and from 6.3 to 11.6 kWh/m², respectively. The largest difference in both the annual optimal angle and maximum PV power generation occur in the years 2017 and 2020 for S2, which contrasts with the case in S1. In S2, the year 2017, instead of 2012, holds the records for the lowest PV power generation, while the year 2020 surpasses 2018 as the peak of PV power generation. Considering the varying snow conditions each year, different degrees of reduction in the annual optimal angle and PV generation are observed due to the inclusion of snow conditions. Therefore, snow conditions could significantly impact the prediction of the PV optimal installation angle, as well as PV performance.

Fig. 6 further illustrates the deviation of the annual optimal angle and the annual PV generation for both S2 and S1 over each year. It is unsurprising that all the values are negative, as snow events hinder sunlight access to PV panels. Generally, a larger angle difference results from relatively heavier snowfall. The year 2020 exhibits the least change in the annual optimal angle and the smallest snow impacts (less than 5%). The main reason for this is that the year 2020 experienced an unusually warm winter, and only a few days had observed snow cover. The years 2013, 2016, 2017 and 2019 stand out as the top four years with the most significant annual power generation reduction during the period from 2012 to 2021. In these years, the annual optimal angles all changed by more than 5.5°, leading to a reduction in annual power generation ranging from 8.1 to 9.7 kWh/m², representing a decrease of over 20%. These years were characterized by similar long and cold winters with substantial snow. In addition to the influence from snowfall, the results are also impacted by the duration of the melting period. Prior to snow melting, PV panels are covered by snow, preventing sunlight from reaching the panels and resulting in minor generation. When the temperatures remain low after snowfall, the snow persists and covers the PV panels for an extended duration. A higher frequency of

melting and covering periods occurring during the daytime leads to a larger decrease in power generation. Hence, even with the same frequency of snowfall, varying PV performance can occur. Notably, the years 2013, 2016, 2017 and 2019 all exhibit significant reductions in the annual optimal angle, as depicted in Fig. 6a, with the largest difference observed in the year 2016. Similarly, these years' experience substantial reductions in annual PV generation, as shown in Fig. 6b, with the maximum reduction occurring in the year 2013 rather than 2016. Thus, with similar snow conditions, temperature and melting time play a crucial role in determining the annual optimal angle and final PV generation.

Fig. 7 provides an overview of the power generation reduction during potential snow months between 2012 and 2021, as well as the total reduction each year. The effects are categorized by different colors: red indicates severe reduction, while green signifies slight decrease. Notably, the snow season in Sweden spans from November to April, encompassing approximately half of the year. It is evident that the year 2020 experienced a relatively short snow season, lasting from December to April, with lower snowfall compared to other years. In contrast, snow events were reported even in May during the years 2014 and 2017. Furthermore, contrary to common perception, the reduction in power generation is more pronounced in March and April than in the typical winter months of December and January. Particularly, severe reduction is predominantly observed in March. This phenomenon is attributed to the longer daylight hours in spring and the potential for greater solar irradiation. When PV panels are covered by snow during daylight hours in the spring, the reduction of power generation is more substantial.

Fig. 8 compares the annual power generation using the 5-year and 10-year average optimal angles with that using the annual optimal angle in S2. The effects of these two angles on power generation are quite similar each year since the values of angles are very close. When compared with S1, as shown in Fig. 4, the difference becomes more significant. The average difference in S2 is more than double, and the maximum difference increases from less than 0.06% to 0.11%. While there is only one case exceeding 0.05% in S1, there are 6 cases in S2. Nevertheless, overall, the effects remain relatively small. In practical applications, the average angle could still be used to simplify operation. Unlike S1, where the year 2013 shows the largest deviation, in S2, the year 2017 ranks as the top year, followed by 2020 and 2016. The top three years are all marked by unusual winters: 2016 and 2017 experienced heavy snow, while 2020 had high temperatures with little snow. Therefore, snow effects play a dominant role, as years with abnormal snow conditions are more likely to exhibit a larger difference.

In summary, during the period of 2012–2021, the annual optimal angle decreases by up to 7.8° during heavy snow events, resulting in an

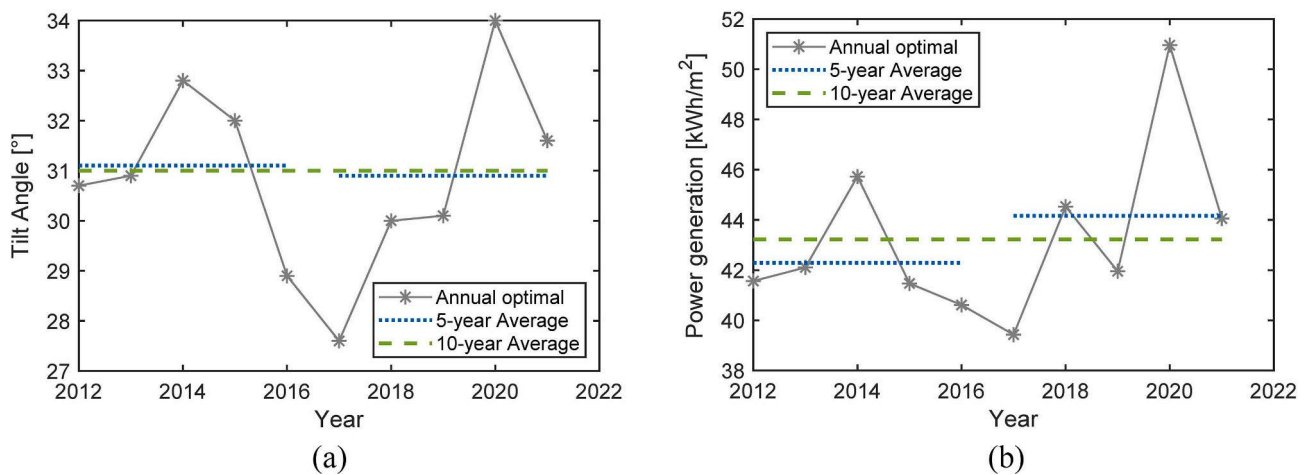


Fig. 5. The annual optimal angle and the annual maximum PV power generation from 2012 to 2021 in scenario 2: (a) Annual optimal angle; (b) Annual maximum PV power generation.

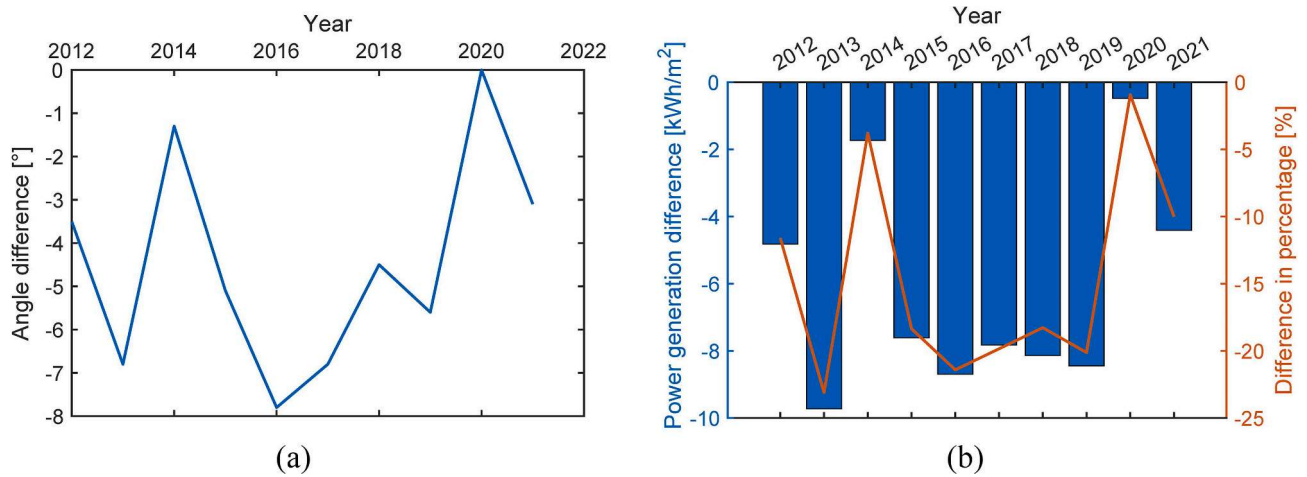


Fig. 6. Comparison of annual optimal angle and annual PV power generation between scenario 2 and scenario 1: (a) Angle difference; (b) PV power generation difference.

Time	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
jan	-0.59	-1.02	-0.33	-0.59	-1.05	-1.00	-0.74	-0.72	-0.01	-0.57
feb	-1.70	-1.34	-0.50	-1.67	-2.26	-1.73	-1.49	-1.85	-0.23	-1.52
mar	-0.17	-5.21	-0.15	-4.04	-3.38	-3.43	-4.24	-3.12	-0.07	-0.87
apr	-2.30	-2.06	0.00	-1.20	-1.16	-1.46	-1.48	-2.49	-0.16	-0.81
may	0.00	0.00	-0.28	0.00	0.00	0.00	-0.02	0.00	0.00	-0.08
oct	0.00	0.00	0.00	0.00	0.00	-0.26	0.00	0.00	0.00	0.00
nov	-0.04	-0.30	-0.04	-0.08	-0.38	0.00	-0.06	-0.15	0.00	-0.12
dec	-0.39	-0.15	-0.46	-0.27	-0.79	-0.24	-0.26	-0.36	-0.01	-0.56
sum	-5.18	-10.09	-1.77	-7.85	-9.02	-8.13	-8.28	-8.70	-0.48	-4.53

Fig. 7. PV generation reduction due to snow effects during snowy months [unit: kWh/m²].

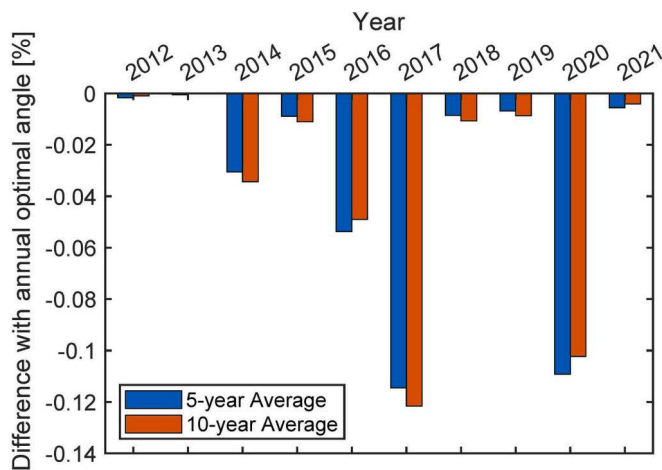


Fig. 8. Comparison of annual PV power generation between the annual optimal angle and 5-year and 10-year average angle in scenario 2.

average annual PV power generation reduction of 14.7%, with a maximum reduction of almost 25%. A significant change in the installation angle would lead to different installation costs, and the reduction in annual PV power generation far exceeds the predicted number in

previous literature (5–10%). Given that extreme weather could occur more frequently due to climate change, the effects of snow on power generation could become even more pronounced in the future. Therefore, the impacts of snow conditions in cold regions should be given more consideration in PV system design.

3.3. Scenario 3 (S3)

In addition to snow conditions, S3 examines the effectiveness of snow removal agents. In this scenario, the snow is assumed to melt within 1 h, instead of 12 h, upon applying the agent. Similar to S1 and S2, the optimal angle and the corresponding maximum PV generation are analyzed based on 1-year, 5-year, and 10-year weather data. Fig. 9 illustrates the annual optimal tilt angle and the corresponding PV power generation in S3. Overall, the annual optimal angle varies from 27.7 to 34.0°, and the annual maximum PV generation fluctuates between 39.6 and 51.1 kWh/m². The 5-year average angle closely aligns with the 10-year average angle, with a difference in annual generation of approximately 0.7 kWh/m². However, when comparing the annual optimal angle with the average angle, the maximum difference is around 3.0 degrees (occurring in the year 2020); and the maximum difference in annual generation is approximately 8.0 kWh/m² (occurring in the year 2020).

Compared with S2, both the annual optimal angle and the annual maximum PV generation increase slightly. The curves in Fig. 9 resemble

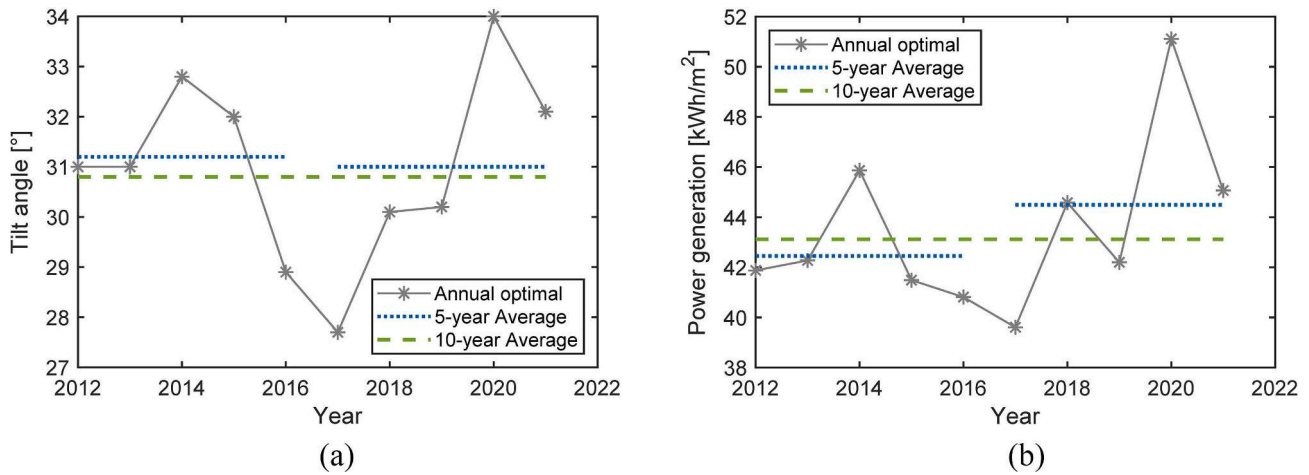


Fig. 9. The annual optimal angle and annual maximum PV power generation from 2012 to 2021 in scenario 3: (a) Annual optimal angle; (b) Annual maximum PV power generation.

those in Figs. 5. Similar to S2, the minimum and maximum values still occur in the years 2017 and 2020, respectively. Although the differences between the 5-year average angle and the 10-year average angle is 0.1 degrees (same as S2), the disparity in annual generation becomes slightly larger. Nevertheless, the distinction between the annual optimal angle and the average angle becomes faintly smaller.

Fig. 10 further illustrates the difference in the annual optimal angle each year and the corresponding maximum PV generation between S3 and S2. Although the annual optimal angle is increasing, the change is relatively small when compared with Fig. 6a, with the difference in each year being less than 1°. Therefore, there is no requirement to alter the tilt angle for the application of the agents. The average improvement in annual PV power generation over the 10-year period is approximately 0.25 kWh/m², representing an increase of 0.6%. This increase is much lower than the average reduction caused by snowy weather. The application of snow removal agent could slightly enhance the PV performance, as PV panels can receive more sunlight after snowfall due to the reduction in melting time. However, compared to the effects of snowfall, the snow impact of melting is minor. On the one hand, the role of snow removal agent is sensitive to weather conditions and varies significantly over the years. According to Fig. 10b, the maximum increase in annual PV generation occurs in the year 2021, with an increase of 1.01 kWh/m², representing a more than 2.3% rise - almost 4 times of the average increase. In 2017, heavy snowfall was accompanied by snow cover due to low temperatures. In contrast, the years 2018 exhibit

similar PV generation reduction in S2, but the increase is only half that of the year 2017. These two years experienced heavy snowfall but were less affected by snow covering. There might be two reasons for the smaller impacts of the melting period. Firstly, the melting processes occur during the night; secondly, the winter temperatures are higher,

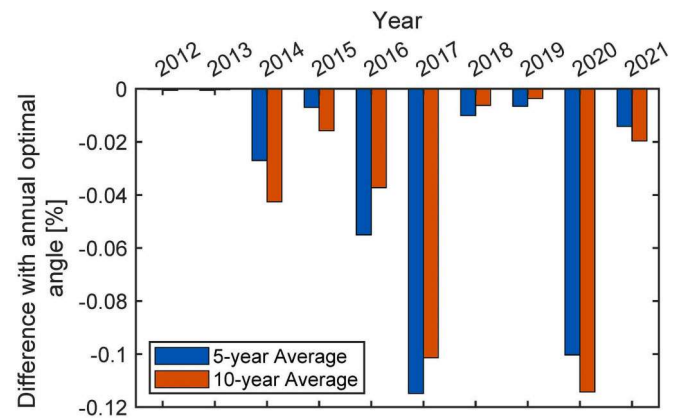


Fig. 11. Comparison of annual PV power generation between the annual optimal angle and 5-year and 10-year average angle in scenario 3.

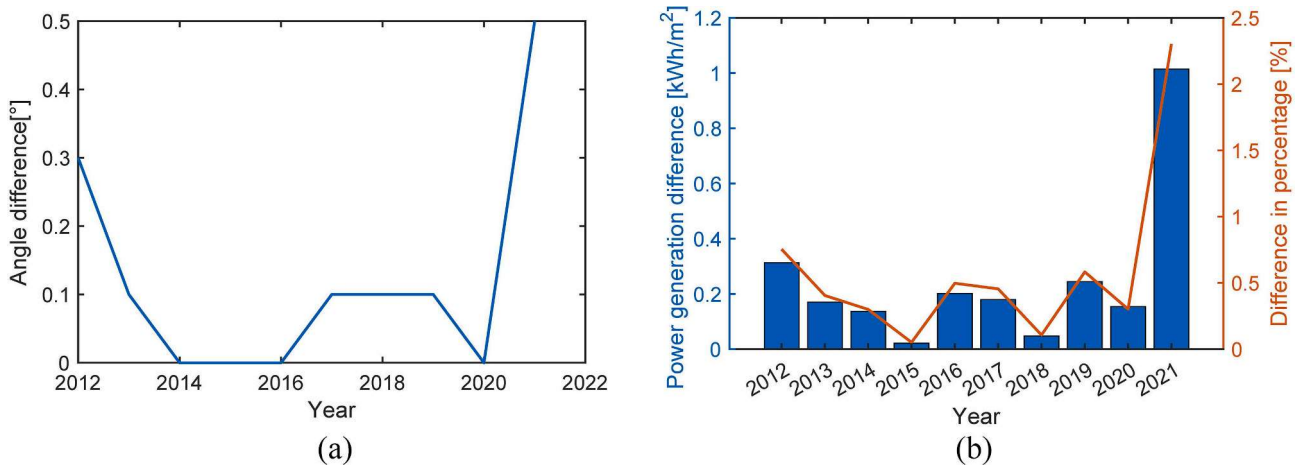


Fig. 10. Comparison of changes in annual optimal angle and annual PV power generation between scenario 3 and scenario 2: (a) Angle difference; (b) PV generation difference.

resulting in shorter snow melting times.

Fig. 11 compares the annual power generation between using the annual optimal angle and using the 5-year and 10-year average optimal angles in S3. The effects of these two angles are quite similar each year, as the angle values of angles are very close. In comparison with S2, the results are similar but show a slight decrease in deviation, changing from 0.18% to 0.11%. Overall, the effects of changing from annual optimal tilt angle to 5- or 10-year average angle on the annual PV generation remain relatively small. In practical applications, the average angle could still be employed to simplify operations. As there is no need to change the tilt angle of the PV panels, the application of snow removal agents could be more flexible. The application of snow removal agents includes manual and automatic approaches. Manual one refers to employing staff to spread the removal agents when snowfall occurs; and automatic one refers to installing heating modules with the panels. The costs for both ways could be considerable. This approach is highly recommended when the melting time is long, such as during a cold winter or when snowfall ends at noon. Otherwise, it might not be beneficial overall since the improvement is relatively small compared to the increased operation costs. There could also be an uncertainty whether the compositions of the manual snow removal agents are environmental-friendly. Even if it is anoxic, it is unsure that the solution of the compounds would corrode the surroundings or not.

3.4. Short summary

Fig. 12 summarizes the variations in the annual optimal angle and annual power generation among the three scenarios during the period from 2012 to 2021. The annual optimal angles for all scenarios fall between the commercial angle and the geometric angle. When comparing S1 with S2 and S3, the inclusion of snow weather results in a smaller annual optimal angle, but the effects can vary significantly, primarily due to different weather conditions in each winter. The reduction in annual PV power generation is substantial with the inclusion of snow. Comparing S2 and S3, the angles are similar, and the discrepancy in annual PV generation is relatively small. This comparison highlights that snow cover significantly and negatively impacts PV production. Although snow removal agents do contribute to performance improvement, their effects are relatively minor compared to this reduction. Considering the negligible difference between the annual optimal angle and the average angle, the angle could be kept consistent in practice to reduce operational costs. Differences in PV tilt angles would lead to varying costs in PV installation. Similar PV performance could be achieved with different tilt angles, allowing for some trade-offs in the decision-making process.

Fig. 13 compares the annual power generation results based on

annual optimal angles with the power generation results of the same PV system using the commercial installation angle and geometrical installation angle. The relative differences in percentage are depicted with curves. The commercial angle refers to the installation angle commonly chosen by PV installers. PV systems in practical application are typically installed at relatively shallow angles (15 to 20°) to reduce installation costs and mitigate shading effects. The geometrical angle is calculated assuming a clear sky. It is based on an ideal weather condition, so the difference becomes relatively small compared with the commercial angle when accounting for the real weather conditions. Compared with the commercial angle, S1 achieves an average improvement of 4.8%, corresponding to an increase of 2.3 kWh/m² in power generation. Similarly, both S2 and S3 show improvements in PV power generation by an average of 2.8%, representing an increment of 1.2 kWh/m². However, with the current installation angle, PV systems are unable to achieve their full potential. Further, the deviations of S2 and S3 are larger than that of S1 when compared to the geometrical angle (averaging 1.07–1.09% versus 0.34%). In cold regions with lengthy snow seasons, additional losses can occur due to the use of common calculation methods.

4. Conclusions

In this study, a novel model for estimating the optimal PV tilt angle is developed, based on historical weather big data that considers snowfall and its melting effects. The annual optimal angle is calculated using historical meteorological data from the years 2012 to 2021, which includes irradiation, air temperature, and snow conditions. The results are compared with both the currently common system using a commercial angle and the system employing common methods with a geometrical angle. The analysis considers multiple dimensions, providing a more comprehensive and realistic evaluation to emphasize the significance of including snow effects in high latitude cold regions. The study validates the substantial impacts of weather on the PV performance and offers a reference case for future PV system design and planning in high-latitude areas. The main conclusions are as follows:

- 1). The PV system with the annual optimal angle outperforms the one with a commercial angle, resulting in an approximate 4.8% increase in power generation. The performance of the 5-year and 10-year average angles is similar, allowing for simpler operation in practice.
- 2). The optimal PV installation angle decreases when considering snow conditions, with the difference dependent on local weather conditions each year, reaching up to 7.8°.

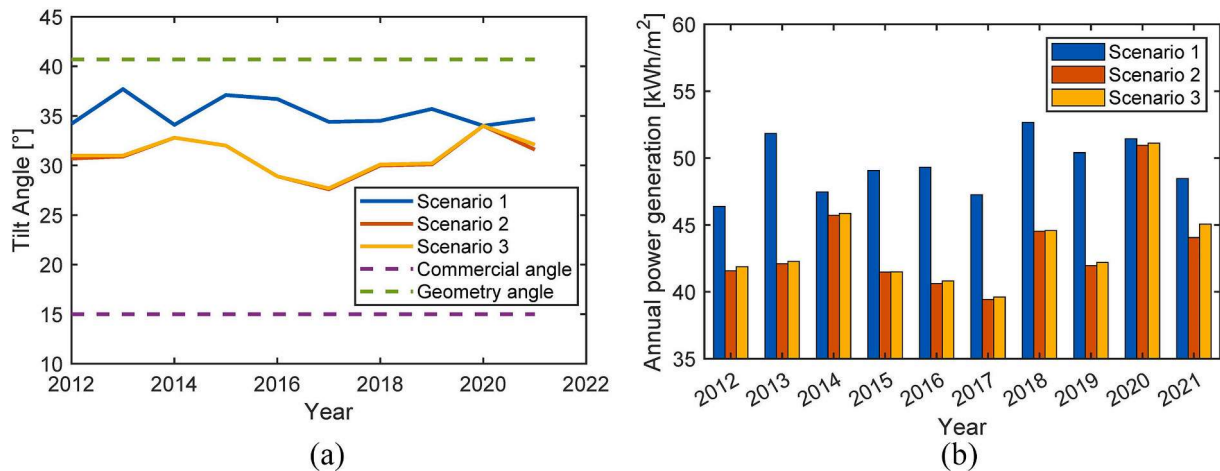


Fig. 12. Comparison of annual optimal angle and annual PV power generation for the three scenarios: (a) Optimal angle; (b) PV power generation.

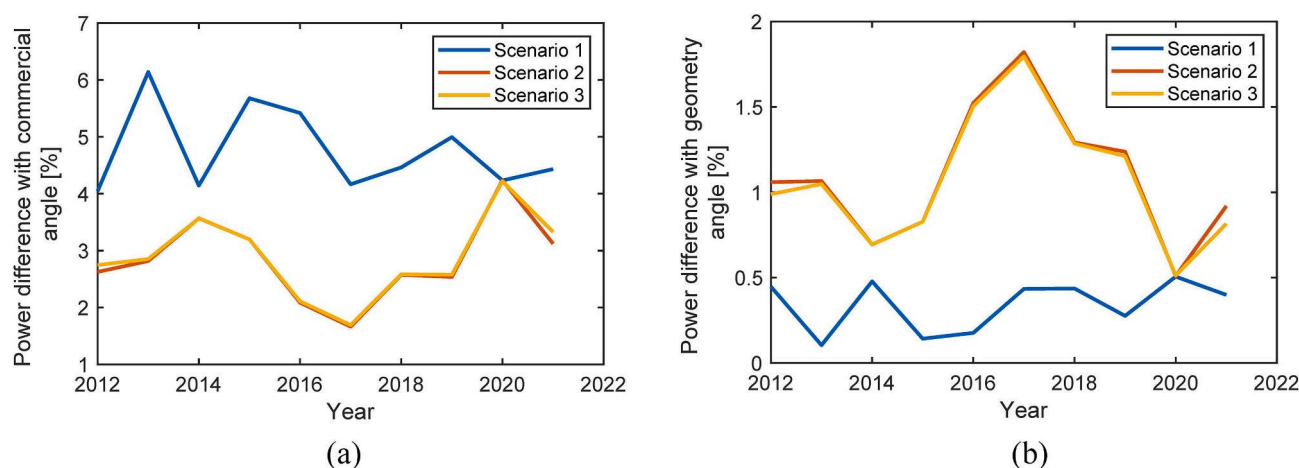


Fig. 13. Comparison of power generation between the three scenarios and commercial/geometry angles: (a) Comparing with commercial angles; (b) Comparing with geometry angles.

- 3). The consideration of snow and melting effects significantly influences the final annual optimal angle and PV power generation, of which 50% occurs in spring. Power generation experiences an average reduction of 14.7% due to snow conditions. The effects of snow in cold regions are much more pronounced than predicted by previous literature (e.g., [18,54]).
- 4). The application of snow removal agents can enhance improve PV performance by 0.1–2.3%, offering flexibility based on specific weather conditions.
- 5). The newly developed optimal PV installation model, based on weather big data, effectively captures the impact of the local weather changes on PV power generation. It could potentially serve as a bridge between climate change and future PV power generation.

The model introduced in this study is more applicable for real PV installation. It could provide an acceptable result without the requirement for complexity of parameters and calculation as well as the restriction on winter seasons. The results from the study can be extended to locations beyond Sweden. The methods are applicable whenever local weather data and PV parameters are available. This method can also be extended using climate simulation data (e.g., EURO-CORDEX: Coordinated Downscaling Experiment - European Domain) to take into account the impacts of climate change. The model is developed using Python and is easily implementable by other users.

In this study, the utilized SPYM model is simplified with certain assumptions. A more accurate melting model could be integrated in future studies, for example, a more accurate melting temperature threshold and snow sliding effects. Additionally, economic feasibility is qualitatively discussed, and it could be explored for example the costs associated with larger angle installation and the use of snow removal agents. The findings reveal that PV system with the new optimal installation angle can achieve significantly higher PV power generation compared to traditional PV installation angles. Furthermore, the new PV installation angle effectively reflects the impact of the local weather changes on PV power generation, potentially serving as a bridge between climate change and future PV power generation.

CRedit authorship contribution statement

Tianqi Ruan: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Fuxing Wang:** Writing – review & editing, Resources, Methodology, Investigation, Formal analysis. **Monika Topel:** Writing – review & editing, Supervision, Resources, Methodology, Investigation.

Björn Laumert: Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition. **Wujun Wang:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

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.

Data availability

Data will be made available on request.

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