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Yanis Prunier, David Chuet, Sylvain Nicolay, Gwenaëlle Hamon, Maxime Darnon. Optimization of photovoltaic panel tilt angle for short periods of time or multiple reorientations. *Energy Conversion and Management*: X, 2023, 20, pp.100417. 10.1016/j.ecmx.2023.100417 . hal-04166296

HAL Id: hal-04166296

<https://hal.science/hal-04166296>

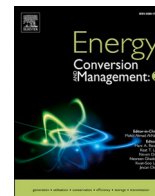
Submitted on 19 Jul 2023

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Optimization of photovoltaic panel tilt angle for short periods of time or multiple reorientations

Yanis Prunier^{a,b}, David Chuet^{a,b}, Sylvain Nicolay^{a,b}, Gwenaëlle Hamon^{a,b},
Maxime Darnon^{a,b,*}

^a Institut Interdisciplinaire d'Innovation Technologique (3IT), Université de Sherbrooke, 3000 Boulevard Université, Sherbrooke J1K 0A5, Québec, Canada

^b Laboratoire Nanotechnologies Nanosystemes (LN2) – CNRS IRL-3463, Institut Interdisciplinaire d'Innovation Technologique (3IT), Université de Sherbrooke, 3000 Boulevard Université, Sherbrooke J1K 0A5, Québec, Canada

ARTICLE INFO

Keywords:

Photovoltaic panels
Optimal orientation
Seasonal tilt
Typical meteorological year
Brute force algorithm

ABSTRACT

Photovoltaic installations typically use fixed-mount photovoltaics (PV) panels with a constant orientation throughout the year. However, this does not maximize the energy output since the irradiance received by the panels depends on the sun position and the weather. This paper presents a novel approach to maximize the energy produced by fixed-mount PV panels for short-term and for permanent PV installations. For permanent installations, we considered a multiple-tilt scenario where the panel orientation is modified throughout the year. We developed a bi-layer algorithm to optimize the angles and timing of adjustments. Our method has been implemented in an open-source software, allowing optimal orientations and dates to be calculated for any installation. The optimal dates and the optimal angles have been successfully calculated for PV panels located at Reykjavik (Iceland), Sherbrooke (Canada), Quito (Ecuador), and Brasília (Brazil). We found that two reorientations per year were the most suitable option for all locations, resulting in a 3 % to 4.8 % gain in annual energy production compared to no reorientation. For short-term installations, using optimal orientation can improve energy production, with for instance 13 % improvement for a monthly installation in Brasilia.

1. Introduction

The orientation of a solar panel directly impacts the output power of a photovoltaic (PV) system. To increase the energy production per unit area, it is crucial to optimize the orientation of the solar array. Ideally, the solar panels are installed on 2-axis or 1-axis motorized trackers. This leads to 40 % and 20 % more energy production than fixed PV systems, respectively [1,2], but induces extra operation and maintenance costs. For fixed PV systems, the optimal orientation is generally obtained by choosing a tilt angle near to the latitude value and an azimuth facing North in the Southern Hemisphere and South in the Northern Hemisphere [3–5].

One trade off to further optimize the orientation of fixed solar panels without the use of motorized tracking systems is to consider reorienting panels regularly throughout the year to maximize energy production as the position of the sun and the weather conditions vary throughout the seasons. In the literature, the scheduled dates of reorientation are arbitrarily defined using the solar seasons. Through the research work of

Soulayman and Hammoud [6], Balouktsis et al. [7] and Despotovic and Nedic [8], a biannual orientation is the most suitable scenario compared to monthly, seasonal or daily adjustments.

However, the choice to use solar seasons is debatable and so the scheduled dates of reorientation could be optimized. The location may also impact the benefit of multiple tilt modification on PV system production.

For shorter-term installations, such as stand-alone PV systems for disaster relief [9,10], it is possible to determine an optimal tilt angle that differs from the angle optimized for annual energy production.

A new method of calculation is presented in this paper to find optimal tilt values and optimal dates of reorientations when considering a multiple tilt scenario.

We describe first the method and its implementation. Then, we use the implemented algorithm to conclude on optimal orientations of PV panels and schedules. This program is made publicly available using a GitLab repository: <https://gitlab.com/3it-cpv-public/panel-orientation>. The program can be used as an effective tool to optimize the orientation

* Corresponding author at: Laboratoire Nanotechnologies Nanosystemes (LN2) – CNRS IRL-3463, Institut Interdisciplinaire d'Innovation Technologique (3IT), Université de Sherbrooke, 3000 Boulevard Université, Sherbrooke J1K 0A5, Québec, Canada.

E-mail address: maxime.darnon@usherbrooke.ca (M. Darnon).

<https://doi.org/10.1016/j.ecmx.2023.100417>

of PV arrays for existing or future photovoltaic plants.

This research work makes a significant contribution to enhancing the efficiency of photovoltaic installations. It presents a robust and flexible methodology for determining the optimal panel orientation that maximizes energy production. Additionally, our study contributes to advancing scientific knowledge by investigating the benefits of biannual orientation and its impact on energy yield.

2. Methodologies

2.1. Optimization method

The optimization method is separated in two layers. The first layer determines the optimal orientation for annual or short-term photovoltaic installations. The second layer optimizes the schedules for a multi-orientation scenario and uses the first layer to find the optimal orientation for each period.

2.1.1. Optimal Orientation

The method to determine the optimal orientation is described Fig. 1. We consider the location defined by its latitude and longitude and the period of use as the two inputs of the first layer. We initially assume that there are no external constraints on choosing the azimuth angle of the panel. In this scenario, the panel should always be facing North when the panel is located in the Southern Hemisphere and facing South in the Northern Hemisphere. Therefore, only the optimal tilt angle θ_{max} must be determined. This hypothesis is valid when the objective is to maximize the energy produced directly at the output of the panels, irrespective of energy demand or tariff variations [11]. In our code, we also allow the user to select a specific value for the azimuth angle of the panel, taking into consideration external constraints such as the orientation of a roof. However, the process for determining the optimal tilt angle remains unchanged.

We calculate a daily energy production library described in the Eq. 1 for a large range of tilt angle $[\theta_i; \theta_h]$ and for each day of the year. The energy produced during the day d at a tilt angle θ is noted $E_{(d,\theta)}$.

$$E_{(d,\theta)} \text{ with } \begin{cases} d \in \llbracket 1; 365 \rrbracket \\ \theta \in \llbracket \theta_i; \theta_h \rrbracket \end{cases} \text{ where } \theta_i \text{ and } \theta_h \text{ represents the tilt range.} \quad (1)$$

The optimal orientation is defined by the tilt angle θ_{max} yielding the maximum energy integrated over the period $[d_i; d_j]$ as described in the Eq. 2. For periods that overlap two years, the period $[d_i; d_j]$ is split in two parts $[d_i; 365]$ and $[1; d_j]$ while imposing the same tilt angle for the two periods. Leap years have been taken into account in the implementation of the code.

$$E_{\theta_{max}} = \max_{\theta \in [\theta_i; \theta_h]} \left[\sum_{d=d_i}^{d_j} E_{(d,\theta)} \right] = \sum_{d=d_i}^{d_j} E_{(d,\theta_{max})} \quad (2)$$

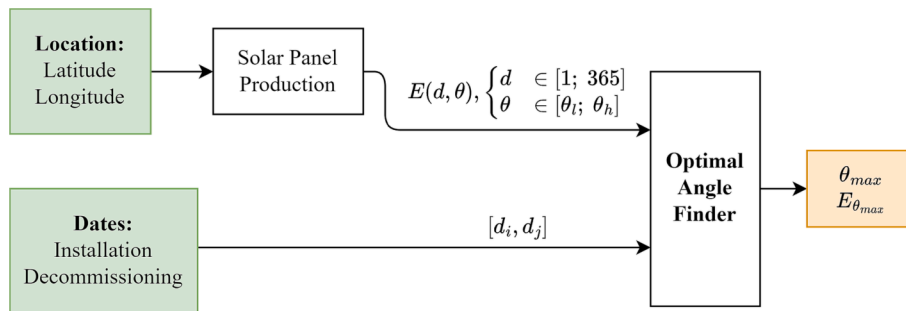


Fig. 1. First Layer schematic.

The optimal tilt angle θ_{max} and the corresponding maximum energy produced $E_{\theta_{max}}$ are the two outputs of this first layer. Therefore, this method allows us to find optimal tilt angles for short term installation, with d_i equals to the installation date and d_j the decommissioning date.

2.2. Reorientations & Scheduling Dates

The second layer of the algorithm is described in the Fig. 2. It determines the optimal scheduling and the corresponding tilt angles to maximize the annual energy produced by reorienting the panel array during the year, the number of reorientation noted N being considered as an input.

To solve this problem, we used the brute force method. It considers all the possibilities and then chooses the one which gives the maximum annual energy produced. In this case, it is therefore necessary to consider all the possible vectors of reorientation dates $\{D_k, k \in M\}$, with M the number of possible partitions of the year.

Using the first layer, the algorithm determines the optimal tilt angle $\theta_{k,j}$ for each period $[d_{k,j}, d_{k,j+1}]$ of the D_k vector and the respective maximal energy produced $E_{k,j}$ for the period. Then it sums the energy values of each period and returns the corresponding total annual energy produced E_k associated with a list Θ_k of the corresponding optimal tilts.

$$\begin{aligned} D_k &= \{d_{k,1}, \dots, d_{k,j}, \dots, d_{k,N}\} \\ \Theta_k &= \{\theta_{k,1}, \dots, \theta_{k,j}, \dots, \theta_{k,N}\} \\ E_k &= \sum_{j=1}^N E_{(k,j)} \end{aligned} \quad (3)$$

After the calculation is completed, the list of all the possible D_k vector noted D , the list of all the E_k energy produced noted E and the list of all the Θ_k vector noted Θ are known (Eq. 4). The notation established is summarized in the Table 1.

$$\begin{aligned} D &= \{D_1, \dots, D_k, \dots, D_M\} \\ E &= \{E_1, \dots, E_k, \dots, E_M\} \\ \Theta &= \{\Theta_1, \dots, \Theta_k, \dots, \Theta_M\} \end{aligned} \quad (4)$$

The last step is to find the maximal annual energy produced, noted $E_{k_{max}}$, by iterating through the vector E . The corresponding vector of dates $D_{k_{max}}$ and vector of tilt angles $\Theta_{k_{max}}$ give the final instructions to the user for a scenario of N reorientations in a year.

2.3. Implementation

The bi-layer algorithm has been implemented in Python and available as an open-source software. A command-line interface has been created and the numerical results presented in this article can be obtained for a new location and for a specific photovoltaic installation following the procedure described in the ReadMe.md file of the GitLab

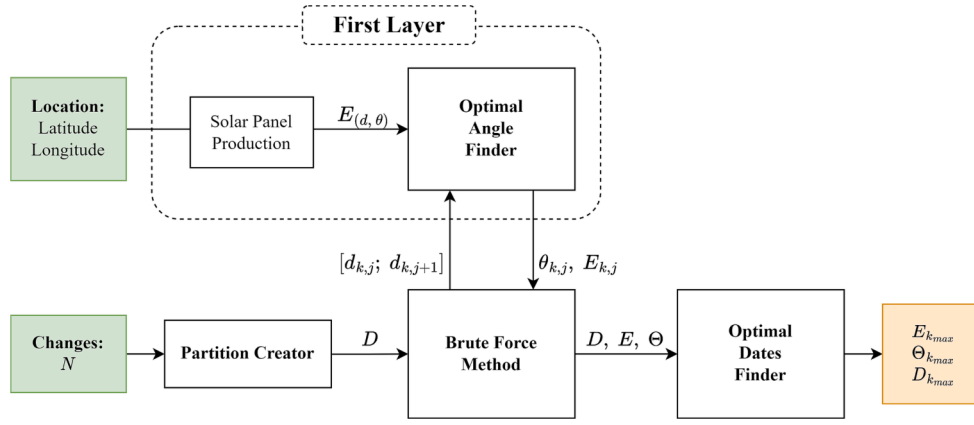


Fig. 2. Second Layer Schematic.

Table 1
Notations for reorientation calculation.

Counters	
N	Number of reorientations
M	Number of possible partitions of the year
Dates	
D	List of all the possible D_k vectors
D_k	Set of reorientation dates for a year
$d_{k,j}$	Reorientation date related to the vector D_k
Energies	
E	List of all the E_k energy produced
E_k	Annual energy produced for the D_k set of dates
$E_{k,j}$	Energy produced between $d_{k,j}$ and $d_{k,j+1}$
Angles	
Θ	List of all the Θ_k angle vectors
Θ_k	List of optimal tilts for the D_k set of dates
$\theta_{k,j}$	Optimal tilt between $d_{k,j}$ and $d_{k,j+1}$

project.

2.3.1. Daily Energy Production

We first used the Python library PVLlib [12,13] and its integrated photovoltaic simulation model to create the daily energy production library. PVLlib uses meteorological samples, the sun position and an electrical model of PV panels to predict the energy production of a photovoltaic array at any location and any days of the year.

For this paper, the objective was to set the PVLlib model in a standard configuration, thus only a minimal set of parameters has been used. $P_{dc0} = 240W$ and $\gamma_{p_{dc}} = -0.0004C^{-1}$ has been set to characterize PV Panel performances. The temperature model has been arbitrarily defined with the open rack glass-glass model provided by Kratochvil et al. [14]. The azimuth angle of the panel is set at South or North depending on the hemisphere. For the meteorological model, an hourly typical meteorological year (TMY) for each location has been used. It is provided by PVGIS [15] which offers TMY on a large scale of locations and which has an API directly integrated in PVLlib. The version 5.2 of PVGIS has been used. These are the necessary and sufficient parameters to define the PVLlib model.

For the chosen location, we calculate the daily energy produced by the PV panel in a tilt range $[\theta_l; \theta_h]$ of plus or minus 45° around the absolute value of the latitude of the panel location, which is known to be close to the optimal annual tilt angle. We verified that calculated optimal tilts never exceed this range. A resolution parameter of 1° has

also been set on the tilt angle to iterate over all the values of the range. Thus, creating the daily energy production library results in the calculation of a maximum of 365×90 energy values.

2.3.2. Brute Force Method

The implementation of the brute force method consists of finding all the possible vectors D_k . The D vector of all the possible D_k set of dates is the size of $M = \binom{365}{N} = \frac{365!}{N!(365-N)!}$. This number M illustrates the limitation of the brute force method as its maximum obtained for $N = 182$ is equal to $M = 3.1 \times 10^{108}$.

To strike a balance between computational burden and capturing key temporal dynamics, a weekly resolution was chosen. By transitioning to a weekly frequency, the size of the list D is reduced to $\binom{52}{N}$, alleviating the computational demand. Utilizing the daily energy production database with this reduced weekly D vector allows us to identify the maximum energy production for each configuration D_k . Consequently, the calculated optimal dates provide accurate results at a weekly resolution.

The vector D is created using the Python libraries *itertools* and *more_itertools* and by considering that the calculation time must not exceed seven days for one reorientation scenario using our laptop (Intel 11th Gen i7-1165G7, 2.8 GHz clock frequency, 16 Go of RAM), it is possible to execute the second layer of the algorithm with N going up to 6. In the future, the code could be optimized using multiprocessing Python feature.

2.3.3. Locations

Four locations presented in the Table 2 have been chosen at various latitudes to visualize the results of the algorithm: Reykjavik (Iceland), Sherbrooke (Canada), Quito (Equador) and Brasília (Brasil).

3. Results

The daily energy produced values for the four locations are represented in a heat map Fig. 3. The X-axis of the Figure represents a whole year, the Y-axis represents the tilt angle and the color illustrates the energy production for each day and each tilt angle. From these heat

Table 2
Locations latitude and longitude considered.

Location	Latitude	Longitude
Reykjavik	64.1113°	-21.7890°
Sherbrooke	45.4048°	-71.8928°
Quito	-0.2200°	-78.5080°
Brasília	-15.7960°	-47.9140°

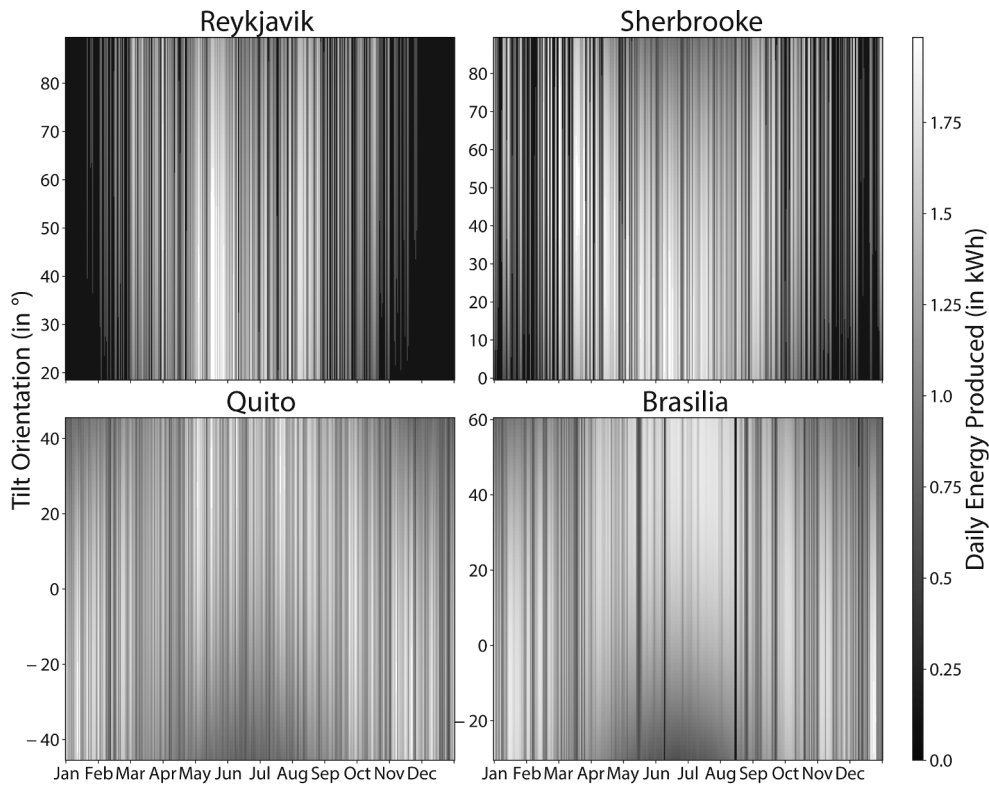


Fig. 3. Daily energy produced for each tilt angle.

maps, we can calculate the annual energy as a function of the tilt angle, as well as the optimal tilt for short term orientation (first layer of the algorithm) and the optimal reorientation dates and tilts (second layer).

3.1. Annual Energy as a Function of the Tilt Angle

The daily energy production library can be used to calculate the annual energy production for each tilt angle and then the first layer finds the optimal tilt θ_{max} . We quantified the sensitivity of the annual energy production to the tilt angle by calculating the range of tilt angles around the optimal tilt value which leads to less than 1 % energy losses compared to the energy obtained with θ_{max} .

The results are presented in the Table 3. We can see that regardless of the location, losses due to suboptimal orientation remain below 1 % as long as the tilt angle is within a range of $\pm 9^\circ$ around the optimal orientation. We also notice that the latitude value is included in this range for all the locations except Reykjavik, where a PV panel set at the latitude value (64°) produces 3 % less energy than at optimal tilt angle.

3.2. Short-Term Installation

The first layer can be used to optimize the tilt angle for a short-term installation. For example, we calculate an optimal tilt angle of 48° for a fixed PV panel installed between the first of June and the first of July in Brasilia. Compared to a panel installed at the optimal annual tilt (22°) and compared to a panel installed following the latitude (16°), 9 % and

13 % more energy can be produced during this period with a panel installed at the calculated angle of 48° , respectively.

The chosen dates highlight the possible benefits of applying this algorithm for short term application. The energy gain depends on the duration and the period of the installation.

3.3. Reorientation & Energy Production Gain

To evaluate the relevance of multiple tilt modification per year, the analysis of all locations with 2 to 4 tilt angle modifications per year has been performed. The maximum energy gain reachable from multiple tilt reorientation over the year is also considered using a fictive scenario with a daily tilt modification (i.e. 365 tilt modifications). In this case, there exists only one D_k vector:

$$D_{daily-tilt} = \{1, 2, 3, \dots, 365\} \quad (5)$$

This scenario is only theoretical since it assumes that the next day's weather is known exactly and therefore the tilt angle is adjusted accordingly. The optimal partitioning D_k and the optimal tilts Θ_{kmax} are calculated for the 2 to 4-orientations and 365-orientation strategies for the four locations.

As an example, the results for the 4-orientation strategy are presented in Fig. 4. In Reykjavik, the tilt angle of the panel has to be set at 56° on March 12th, at 29° on May 7th, at 47° on August 6th and at 73° on September 24th to achieve maximum annual energy production.

We then calculate the gain in terms of energy production, comparing the annual energy produced by those strategies to the energy produced without the reorientation but with an optimal annual tilt determined with the first layer of the algorithm.

The results are shown in the bar chart Fig. 5. The calculated energy gain is location-dependent and the energy production for a biannual reorientation can vary greatly, ranging from a 3.0 % to a 4.8 % gain.

The location where the reorientation scenario leads to the highest energy gain is Brasilia. A biannual orientation could help to increase the

Table 3
Optimal Annual Tilt.

Location	Latitude	Optimal Tilt	Optimal Tilt Range (1 % Losses)
Reykjavik	64.1113°	48°	38° to 57°
Sherbrooke	45.4048°	36°	27° to 45°
Quito	-0.2200°	2°	-8° to 11°
Brasilia	-15.796°	21°	12° to 30°

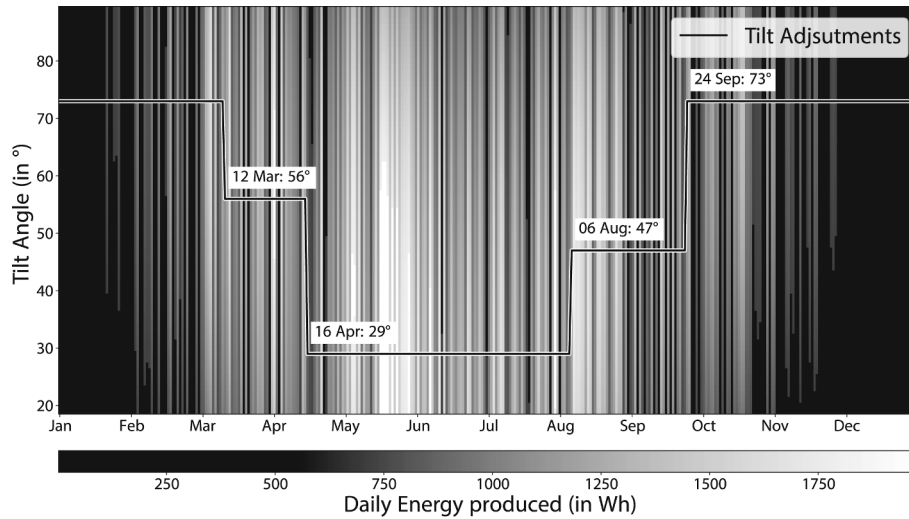


Fig. 4. 4-orientations in Reykjavik.

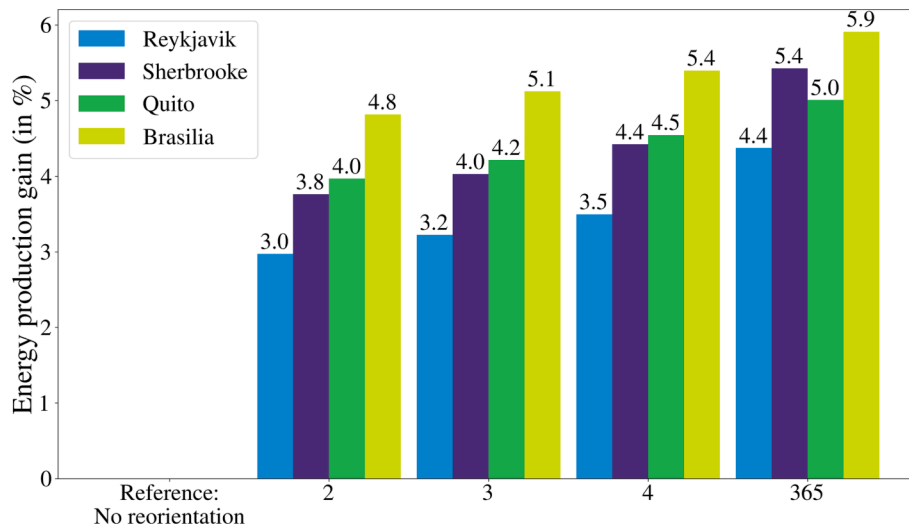


Fig. 5. Energy production gain depending on the location.

energy produced by 4.8 % which is 1.1 % absolute lower than the maximum energy gain of 5.9 % calculated with 365 orientations. With 3 or 4 reorientations, the energy produced is slightly increased to 5.1 % and 5.4 % respectively. The location where the reorientation scenario leads the lowest energy gain is Reykjavik, with 3 %, 3.2 %, 3.5 % and 4.4 % energy gain for 2, 3, 4 and 365 reorientations, respectively.

For all locations, the gain in energy production is not proportional to the number of reorientation and the biannual orientation is already an interesting strategy in terms of energy production.

The algorithm's energy production gain can be more accurately compared to the specific reorientation cost of the PV plant, enabling decision makers and practitioners to assess its feasibility and cost-effectiveness.

3.4. Reorientation & Optimal Scheduling Dates

In the previously presented case of 4-orientations in Reykjavik, we can notice that the duration of each period of the year is not constant. The winter and summer periods have longer duration with 196 and 112 days, respectively, compared to 35 and 49 days in the fall and spring periods, respectively. The tilt angles during the fall and spring periods are set at 56° and 47°, around the central point between the winter (73°)

and summer (29°) optimal tilt and acting as a transition between winter and summer.

The benefit of optimizing the scheduling dates can be assessed by comparing the total energy produced with optimal tilt for a regular reorientation and for an optimized dates vectors. The regular reorientation is defined by a new vector of dates D_{reg} :

$$D_{reg} = \{d_{start}, d_{start} + d_{\delta}, \dots, d_{start} + (N - 1) * d_{\delta}\} \quad (6)$$

$$d_{\delta} = \left\lfloor \frac{365}{N} \right\rfloor$$

This comparison has been made for two and four reorientations. The date of the first reorientation d_{start} has been fixed at the March 22nd according to Soulayman and Hammoud [6] for 2 reorientations using solar seasons. It has been adapted for four reorientation choosing d_{start} for the February 3rd.

The results are given in the Table 4. The interest in optimizing dates seems to be higher with more reorientations because the optimization algorithm locates the date of reorientation during the transition between summer and winter. Finally, we can conclude that for two or four reorientations, wisely choosing the reorientation dates can increase the energy production by up to 0.46 % and 1.26 %, respectively, compared

Table 4
Comparison between regular and optimal dates of reorientation.

Reorientations	Location	Annual energy produced (kWh)		Gain
		Regular dates	Optimal dates	
2	Reykjavik	262.6	263.8	0.46 %
	Sherbrooke	361.5	362.0	0.14 %
	Quito	403.6	403.6	0.00 %
	Brasília	495.3	495.3	0.00 %
4	Reykjavik	263.6	265.3	0.64 %
	Sherbrooke	361.3	365.0	1.02 %
	Quito	402.3	405.2	0.72 %
	Brasília	491.2	497.4	1.26 %

to the regular cut proposed by Soulayman and Hammoud [6].

When considering a complex production model that considers tariff variations and energy demand fluctuations, it is no longer evident that regular dates are the most suitable for changing the orientation. However, our algorithm has the potential to provide the optimal dates in such cases, considering the specific factors of the complex production model and allowing for a more precise optimization of the reorientation schedules to maximize the gain.

4. Conclusion

We developed a new method to optimize the PV panel orientation. It consists of two main layers: the first layer calculates the optimal tilt angle for a chosen period by maximizing the predicted energy production. The second layer calculates optimal tilt and schedules when considering a reorientation scenario. It uses a brute force method and the first layer to maximize the annual energy produced by the PV panel.

The first layer successfully finds the optimal annual tilt angle in the case of a fixed tilt installation. We determined that adjusting the tilt angle of solar panels by a range of approximately $\pm 9^\circ$ would result in a decrease of less than 1 % energy production. For short-term installation, the first layer can also be applied to find specific optimal tilts. That could improve the energy produced by 13 % for a 1-month installation in Brasília.

The second layer optimizes the dates of schedules and finds optimal tilts for each period. By considering 2 to 4 orientations at four different locations, we concluded that 2 orientations improve the energy produced up to 4.8 % in Brasília. Considering more reorientations has a limited energy gain and in the case of a daily orientation scenario, the energy gain is up to 5.9 %.

Using the solar seasons to determine the scheduled dates of reorientation is a fast and simplified method. However, up to 0.14 % and 1.26 % more energy can be produced by optimizing the dates for 2 and 4 orientations, respectively.

We implemented the method in an open-source software. It can be applied for short term installations as well as for permanent installations for any locations. The PV Model can be adapted for a specific study (customized horizon profile, proper PV Panel data sheets, shading on the panels) and thus the accuracy of the algorithm will be improved and the absolute energy production gain obtained with a multi-tilt orientation can be analyzed and compared to the induced costs of this method.

The azimuth angle has been considered fixed to the North/South orientation, but in the future the same method can be applied to optimize the azimuth angle like the tilt angle.

Finally, the maximized quantity can be modified by adjusting the existing library $E_{(d,\theta)}$ using a new output $Q_{(d,\theta)}$, which may include for instance the tariff rates.

CRediT authorship contribution statement

Yanis Prunier: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing - original draft, Visualization. **David Chuet:** Software, Validation, Data curation. **Sylvain Nicolay:** Writing -

review & editing, Supervision. **Gwenaëlle Hamon:** Writing - review & editing, Supervision. **Maxime Darnon:** Conceptualization, Resources, 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.

Data availability

The code related to this article is available in a GitLab repository with the following link: <https://gitlab.com/3it-cpv-public/panel-orientation>.

Acknowledgements

LN2 is a joint International Research Laboratory (IRL 3463) funded and co-operated in Canada by Université de Sherbrooke (UdeS) and in France by CNRS as well as ECL, INSA Lyon, and Université Grenoble Alpes (UGA). It is also supported by the Fonds de Recherche du Québec Nature et Technologie (FRQNT). We also acknowledge Joris Placette for its advice in the building of the calculation method.

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