



HAL
open science

Analysis and Modeling of CPV Performance Loss Factors in Humid Continental Climate

Mehdi Talebi, Maïté Volatier, Gwenaëlle Hamon, Sylvain Nicolay, Christian
Dubuc, Maxime Darnon

► **To cite this version:**

Mehdi Talebi, Maïté Volatier, Gwenaëlle Hamon, Sylvain Nicolay, Christian Dubuc, et al.. Analysis and Modeling of CPV Performance Loss Factors in Humid Continental Climate. IEEE Journal of Photovoltaics, 2023, pp.1-8. 10.1109/JPHOTOV.2023.3326564 . hal-04284951

HAL Id: hal-04284951

<https://hal.science/hal-04284951>

Submitted on 14 Nov 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Analysis and Modeling of CPV Performance Loss Factors in Humid Continental Climate

M. Talebi^{1,2}, M. Volatier^{1,2}, G. Hamon^{1,2}, S. Nicolay^{1,2}, C. Dubuc³, M. Darnon^{1,2}

Abstract—Local climate and environmental conditions can impact the performance of concentrator photovoltaic (CPV) systems. There is a lack of experimental performance analysis of CPV systems, especially in the region with high snowfall and very low temperature in winters. In this paper, we present first a CPV system performance in humid continental climate and identify snow and frost as sources of losses that are not considered in conventional predictive models. We propose then a method to account for the negative effect of snow and frost on the system, by adding monthly soiling factors in the predictive model. The monthly soiling factors are modeled based on average monthly snow fall and ambient temperature. Applying this method, decrease in Root Mean Square Error (RMSE) between predicted and actual energy production from 24.51 to 5.07 % validates our model in humid continental climate for CPV systems.

Index Terms— Concentrated photovoltaic, humid continental climate, snow and frost losses modeling.

I. INTRODUCTION

Energy supply and global issues caused by greenhouse gases emissions are a concern. Photovoltaic (PV) systems as a renewable energy resource have increased their share of energy production in recent decades [1]. To overcome the rather low efficiency of flat panel PV systems (around 20 % in maximum [2]), concentrator photovoltaic (CPV) has been proposed. Even though the efficiency of such technology has reached over 38% in optimal solar conditions [3], studies are still ongoing to maximize their performance. For instance, shading or soiling which have negative effect on the performance of such technologies, have been considered, mostly in the regions with moderate or hot weather [4-8]. Snow and frost, as two other environmental phenomena in cold regions, can also reduce PV systems energy production [9]. In this regard, it is critical to account for specific climate

This work was supported by the NSERC (RDC-CRD 535854-18) and Prompt (PSO- Projet no. 110) in the framework of the MARS-CPV project. 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). *Corresponding author : Mehdi Talebi*

M. Talebi, M. Volatier, G. Hamon, S. Nicolay, M. Darnon are with Institut Interdisciplinaire d'Innovation Technologique and Laboratoire Nanotechnologies Nanosystèmes, Université de Sherbrooke and CNRS, 3000 Boulevard de l'Université, Sherbrooke, Qc, J1K-0A5, Canada. Their email address are mehdi.talebi@usherbrooke.ca, maitte.volatier@usherbrooke.ca, gwenaelle.hamon@usherbrooke.ca, sylvain.nicolay@usherbrooke.ca and maxime.darnon@usherbrooke.ca, respectively.

C. Dubuc is with STACE Solar Solutions, 75 rue d'Anvers, Saint Augustin, Qc, G3A-1S5, Canada. His email address is christian.dubuc@stacelectric.com

Color versions of one or more of the figures in this article are available online at <http://ieeexplore.ieee.org>

zones, categorized in mild, severe or continental, to correctly quantify electricity generation losses [10]. Output losses by snow and ice coverage have been assessed for flat panel PV systems in annual, monthly, weekly, or daily resolution [9,11-13]. To predict the effect of snow coverage on performance of flat panel PV system, different linear, nonlinear, and time-series models have been introduced [11,14-22]. Direct electricity generation loss and snow cover prediction are the main two categorization used by the models in short-term and long-term resolutions [10]. System properties, weather parameters and properties of snow have also been utilized to further refine the models [10,23,24].

Although, the effect of snow and ice coverage is investigated for flat panel PV systems in previous studies, they have not been yet considered for CPV systems. CPV systems differ significantly from PV systems in the sense that (1) they are necessary mounted on a 2-axis sun trackers which leads to a variable tilt along the day, including high tilt at dawn and dusk, (2) they are sensitive to direct normal irradiance (DNI) only, and do not collect diffuse or reflected light, (3) the front glass (lens parquet) is not in contact with the solar cells and remains therefore at a temperature close to ambient temperature, and (4) the systems are usually placed in horizontal position during the night. Therefore, direct models for snow-induced losses prediction from PV systems cannot be applied to CPV systems.

The objective of this paper is to identify the sources of environmental losses, and more especially snow- and frost-induced losses, in a humid continental-climate, and to propose a method to account for these losses for CPV systems.

Even though such a climate is suboptimal for CPV systems electricity production, the insight provided by this paper can be generalized to other climates and regions, and to other embodiments of CPV technologies.

This paper is divided into five parts. In the first section, we present the CPV plant from Université de Sherbrooke as the case study alongside its geographical and meteorological specificities. Performance analysis of this CPV system in humid continental climate is presented in the second section. Part three proposes a method for accounting for the losses and focuses on two models to estimate monthly snow- and frost-induced losses. Method validation and conclusion are the last two sections, respectively.

II. CPV PLANT OF UNIVERSITÉ DE SHERBROOKE

Sherbrooke city is in a humid continental region. Based on its historical meteorological data, wide range of temperatures (-25°C to +35°C) and significant snowfall in the cold months (around 125 cm annually) [25], make the condition unique for CPV systems. Also, all months except for three summer

months (June, July, and August), have probability of snow fall or below zero temperature [26]. Fig. 1 presents the monthly average temperature measured in the solar park and snow accumulation published by Québec ministry of climate for nearest weather station to the solar park, from February 2021 to January 2022 [25]. For winter months (December to March), the average ambient temperature is below zero and the amount of monthly snow accumulation is larger than 10 cm [25].

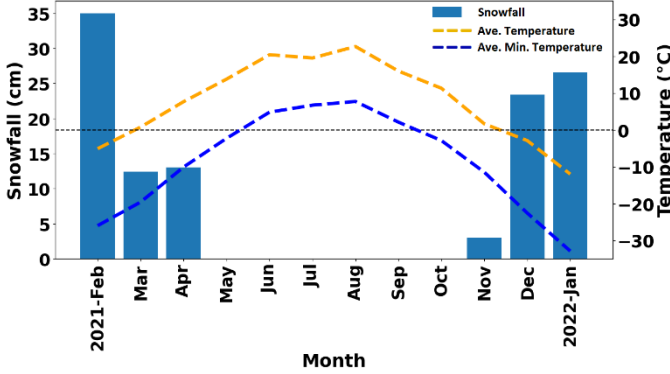


Fig.1. Monthly snowfall, average and minimum temperature in Sherbrooke over a one-year period (Feb 2021 – Jan 2022)

In 2019, the largest Canadian solar park dedicated to industrial collaborations was built at Université de Sherbrooke.

This 1 MWp solar park includes 240 kW CPV plant composed of eight 30 kW trackers from Stace, each having its own inverter. Each CPV system includes 12 CPV modules mounted on a 2-axis tracking system. The direct current (DC) output of each CPV system can be injected to the power network after converting to alternative current (AC) power by their own inverter. Fig. 2 shows five CPV systems in the solar park during a winter day with accumulated snow on the ground.



Fig. 2. Five out of eight CPV systems in Université de Sherbrooke solar park, Quebec

III. CPV SYSTEM PERFORMANCE ANALYSIS IN A HUMID CONTINENTAL CLIMATE

To evaluate the performance of the CPV system, we used the performance ratio (PR) as a metric. It can be calculated as below [27]:

$$PR = \frac{P_{out}(kW)}{\frac{DNI(kWm^{-2})}{P_{rated}(kW)} \cdot 1(kWm^{-2})} (\%) \quad (1)$$

where, P_{out} is AC output power of a CPV system, DNI

represents direct normal irradiance and P_{rated} is the rated AC output power of the CPV system in concentrated standard test condition (CSTC) in which DNI should be $1 kWm^{-2}$.

The PR measured in the solar park for a CPV system is compared to simulated PR obtained from PVsyst. Since PVsyst is designed for flat panel PV systems, the simulation model was built after importing technical information of the CPV system, the solar park meteorological data, and CPV utilization factor (UF) which is a function of DNI , air mass, and ambient temperature. Fig. 3 shows an example of the three elements of UF. In fact, UF describes the deviation of the measured from the simulated short circuit current depending on air mass, DNI and ambient temperature [28].

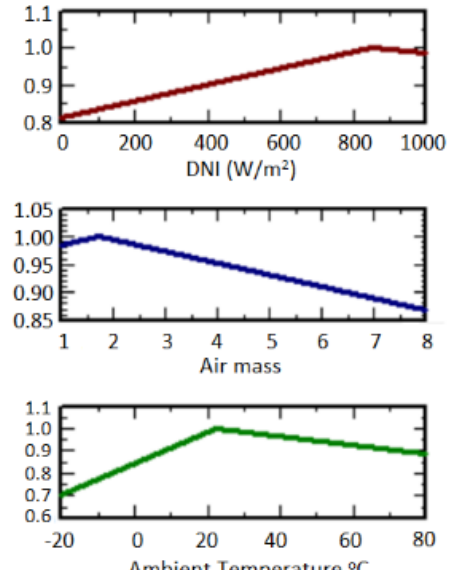


Fig.3. Three elements of CPV utilization factor for importing to PVsyst

The comparison between monthly simulated PR by PVsyst and experimental results from one CPV tracker is shown in Fig.4. Also, the relative loss \widehat{PR} for each month, calculated by (2) is given in Table I.

$$\widehat{PR} = \frac{|PR_S - PR_{Exp}|}{PR_S} (\%) \quad (2)$$

where, PR_S represents simulated PR calculated by PVsyst and PR_{Exp} is experimental PR of the system.

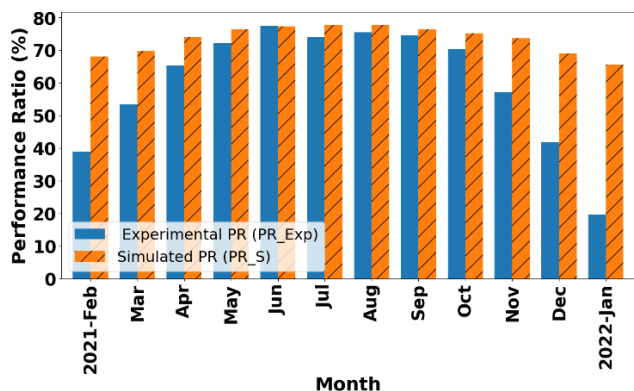


Fig. 4. Comparison between simulated and experimental PR for a CPV system in Université de Sherbrooke solar park

Table I
monthly relative loss

Month	2021 Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	2022 Jan
PR (%)	42.7	23.4	11.6	5.6	0.17	4.8	2.7	23	6.5	22.3	39.2	70

Considering Fig. 4 and Table I, the CPV system performs close to what is predicted by PVsyst from June to September, when there is no probability of snow nor expectation of low temperature. It can be implied that the system presents some constant loss (L_c) below 5%, that may come from different reasons like soiling, spectral variation, tracking errors, and wind effects as well. In opposite, the CPV system PR is below predictions during fall, winter, and spring months, with \widehat{PR} being maximal in January (70%) and above 40% or around 40% in February and December respectively. It is therefore clear that the CPV system performs below expectation outside of summer due to some losses not accounted for in PVsyst model. However, PVsyst models are well validated for CPV systems in warm regions [29]. Therefore, the not-accounted-for losses are attributed to cold-environment-related losses. Two specific characteristics of humid continental regions can affect the CPV system performance and are not taken into consideration in PVsyst. First, considerable snowfall can eventually lead to snow accumulation on the panel. Second, low temperatures can induce frost on the front glass surface. Both effects would lead to losses equivalent to soiling losses and have a negative impact on the output of the CPV system.

To clarify the origin of the losses in the months with probability of snow and frost, we identified three typical days in the winter season: (1) a sunny one with high DNI and without snow and frost on the CPV panels, (2) a day with snow accumulation, and (3) a day with frost coating on the panels.

First, we identified December 12th, 2021, a day without snow and frost with high DNI. As it is shown in Fig. 5 (a), the temperature reached -0.5 C° around 7:30 am but over zero during the night before. That means there was no frost on the panels in the early morning and the rest of the day with temperature higher than 0 C°. Fig. 5 (b) shows that in such a condition performance of the system is proportional to the

DNI so that the average hourly PR is 71.7 % between 9 am and 1 pm which is close to PVsyst prediction with 74.3% for this period. A similar result was confirmed for lower average temperature (-10 C°). Therefore, we can conclude that even in cold situations, the CPV system behaves close to what is predicted by the model when the module front surface is clear from snow or frost.

Second, we identified February 26th, 2022, as a day following snow falls. Fig. 6 shows that in such a day, some snow is accumulated on the panel surface, and is only partially cleared by natural sliding. Even if the tilt angle is steep in the morning (around 85°), eight out of 12 CPV modules of the CPV system are totally covered by snow. Snow starts to melt or slide around noon (Fig.6 (b)), but traces of snow remain on the module during the afternoon (Fig.6 (c)). Fig. 7 shows the effect of the snow coverage on the power output of the system. Except the time between 11 am and 2 pm which was cloudy, DNI was larger than 800 W/m² between 9AM and 4PM. The power output slightly increased in the afternoon, as snow is partly removed. Therefore, in presence of snow, the CPV system performance is strongly degraded by shading so that mean value of the PR for the day during the time with high level of DNI is only 16.6 % which is far from the Calculated PR by PVsyst for the same time (67.5 %). Since PVsyst does not include snow-induced shading, it overestimates the system production, and therefore the PR .

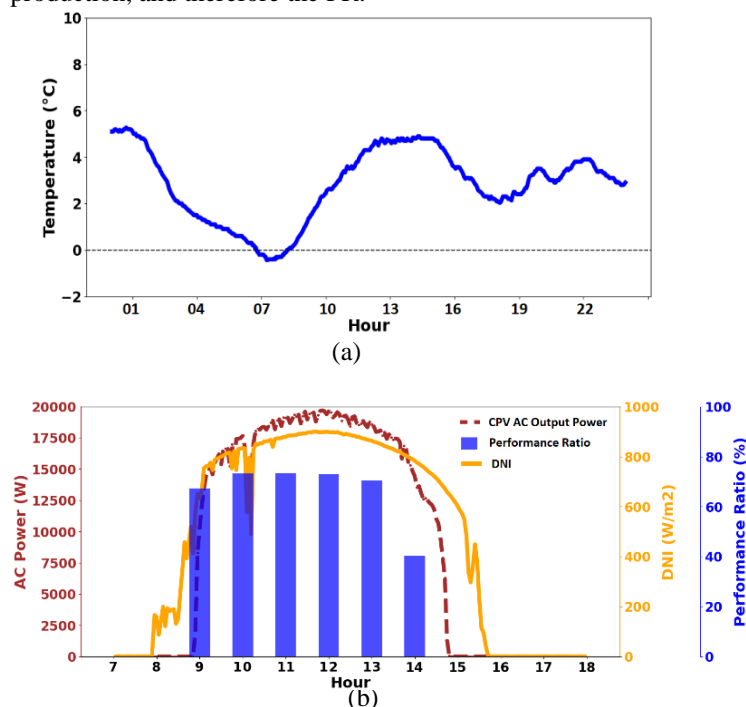


Fig. 5. performance of a CPV system in a typical clear sky in winter, without snow and frost: (a) ambient temperature, and (b) DNI, CPV AC output power, and hourly PR - Université de Sherbrooke solar park -December 12th, 2021

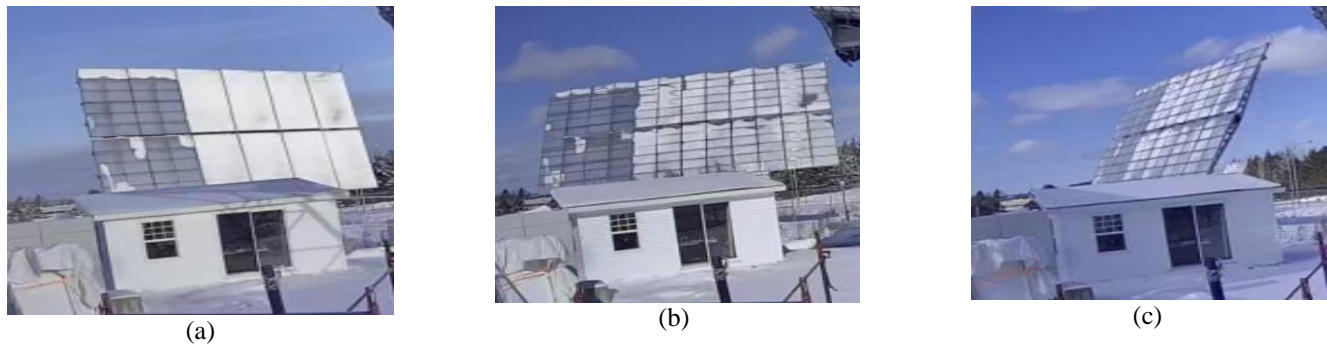


Fig. 6. Front view on a CPV system following the sun and covered partially by snow in a typical winter day in Université de Sherbrooke solar park: (a) early morning; (b) around noon; and (c) afternoon - February 26th, 2022

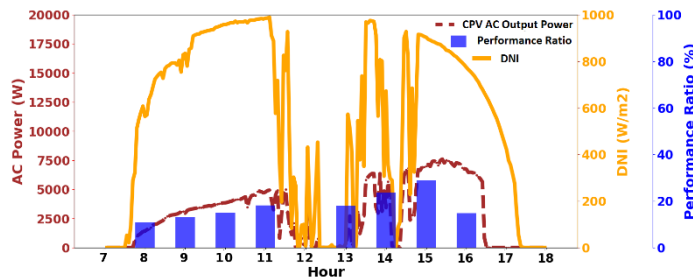


Fig. 7. DNI, AC output power, and hourly PR of the CPV system in case of snow coverage - Université de Sherbrooke solar park – February 26th, 2022

CPV modules is covered by frost at dawn, and that it takes half the day to get rid of it. Simultaneously, a significant reduction of the system performance is observed in Fig. 9 (b). As temperature and sun irradiance rise (Fig 8 (b)) frost gradually melts or is sublimated, and the power output of the system increases from 0 at 8:45AM to 12.4 kW in the early afternoon (Fig. 8 (c)), while the DNI is between 480 and 880W/m² in this period of time, the frost leads to a PR mean value of 24.1%, far below the average PR predicted by the simulator for the same period (73.9%). Like snow, frost has shading effect on the CPV cells that is not accounted for in PVsyst. Therefore, PR overestimation happens in sunny days when we have frost on the panels which happens frequently during the winter.

Third, we identified December 9th, 2022, as a cold winter day with frost accumulation on the panel surface. Fig. 8 shows the CPV system covered by frost on December 9th, 2022, from 9:34 AM to 11:49 AM. We can see that the full surface of the

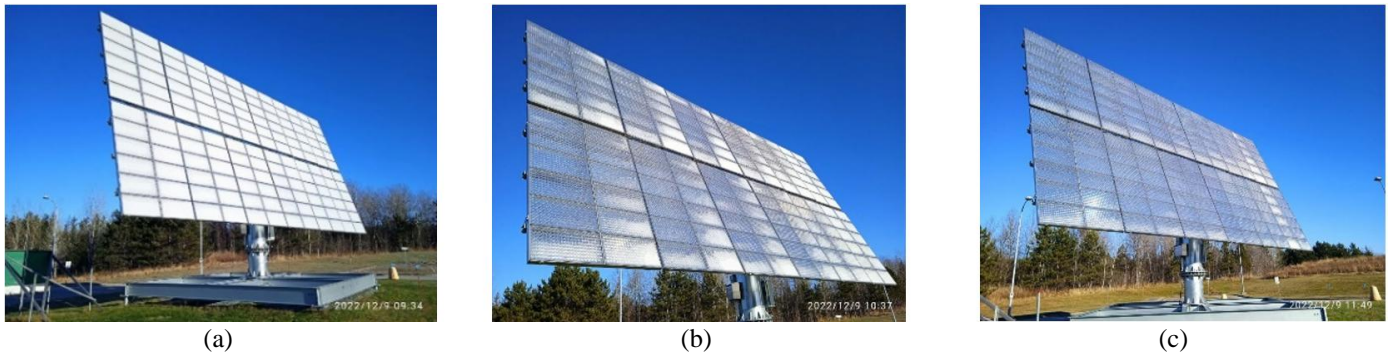


Fig. 8. A CPV system covered by frost at (a) 9:34 am, (b) 10:37 am, and (c) 11:49 am- December 9th, 2022, Université de Sherbrooke solar park

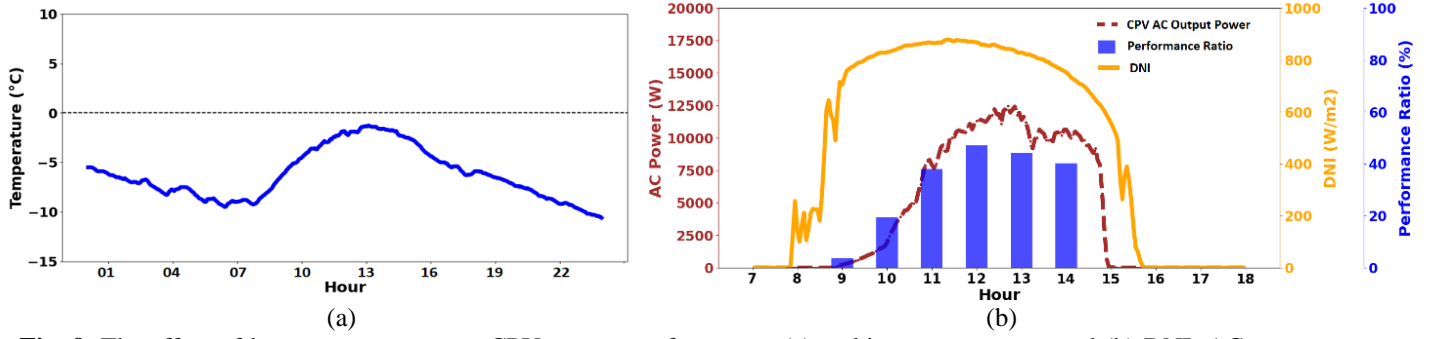


Fig. 9. The effect of low temperature on a CPV system performance: (a) ambient temperature, and (b) DNI, AC output power, and hourly PR- Université de Sherbrooke solar park -December 9th, 2022

Therefore, snow and frost cause losses in cold months that are not accounted for in PVsyst. Since both frost and snow leads to partial covering of the modules, their effect is similar to soiling. In the following, these losses will be considered as soiling losses (P_{sl}).

Considering the three situations described above, we can postulate that the model from PVsyst gives a much better representation of the CPV system performance in absence of snow and frost, and that additional soiling losses should be considered in cold and snowy months to account for the accumulation of frost or snow on the surface of the CPV modules. Therefore:

$$\widehat{PR}(\%) = \begin{cases} P_{sl} + L_c & \text{in the months with snow and frost} \\ L_c & \text{the other months} \end{cases} \quad (3)$$

where, L_c is average losses for the three summer months with no probability of snow and frost which is equal to 2.6 %. In order not to consider the constant losses in the rest of the paper, we define PR_{exp}^* and \widehat{PR}^* as corrected values by:

$$PR_{exp}^*(\%) = PR_{exp} + L_c \quad (4)$$

$$\widehat{PR}^*(\%) = \frac{|PR_S - PR_{exp}^*|}{PR_S} \quad (5)$$

IV: ACCOUNTING FOR LOSSES CAUSED BY SNOW AND FROST.

A) Method description

The method is illustrated in Fig. 10. Since both frost and snow lead to module surface shading similar to soiling, we propose to represent losses due to snow and frost as monthly soiling-losses (P_{sl}). Inputting these monthly soiling losses, the system configuration, and the meteorological data (for instance, the ones of a typical meteorological year) into PVsyst enables to estimate the system performance ratio, considering the losses [30].

The key point is therefore to determine the monthly soiling losses P_{sl} that depend on the extended meteorological conditions (*e.g.*, temperature and snow falls). We propose to quantify P_{sl} using a model that is trained using a one-year dataset of extended meteorological and power production data. The details of the model are explained in the next sections.

To train the model, we first simulate the CPV system in PVsyst using the system configuration, and we simulate the monthly performance ratio PR_S using the one-year meteorological data. The comparison between PR_S and the experimental performance ratio (PR_{exp}) provides the monthly relative losses \widehat{PR}^* . These data are used then to train the model that provides a relationship between extended meteorological data and P_{sl} . Once this training phase is completed, the model can be used to estimate P_{sl} for any year, providing the extended meteorological data are known.

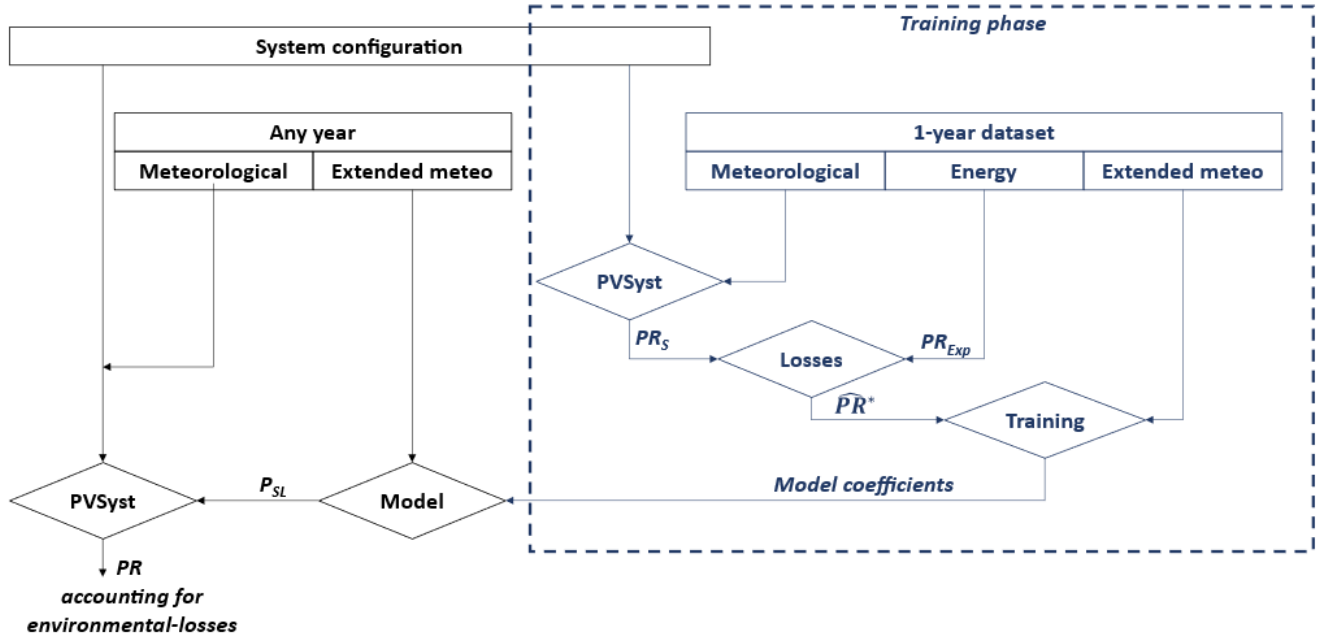


Fig. 10. Flowchart of the methodology for considering environmental-induced losses in PVsystem

B. Monthly soiling losses modeling based on snowfall

As a first approximation, one can consider that losses depend on the amount of snowfall. For a flat panel PV system, losses caused by snow over a one-year period depend on snowfall and the tilt angle of the system [18]. For CPV systems, the modules are installed on a 2-axis tracker, and the tilt angle evolves along the day. Therefore, we propose to model monthly losses with a linear variation as a function of monthly average snowfall only which can therefore be modeled by:

$$P_{SL} = C_s Snow \tag{6}$$

where, C_s is the snow loss coefficient and $Snow$ the monthly snowfalls in cm. Using \widehat{PR}^* , recorded average monthly snow fall for of 2021 (except June, July, and August which have no probability of snow fall), and Linear Regression method shown in Fig. 11, the coefficient C_s is equal to 1.55%/cm. The monthly soiling losses given by the model are presented in Table II.

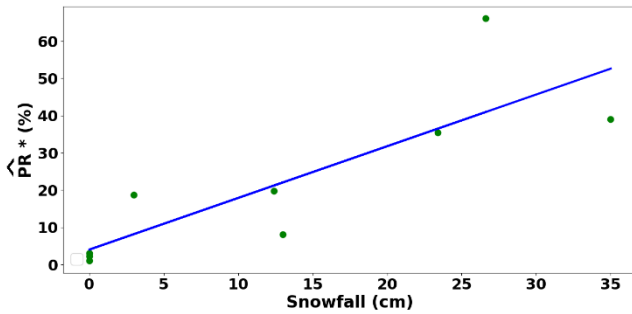


Fig. 11. linear regression between monthly snowfall and \widehat{PR}^*

Table II

Monthly soiling losses, calculated by the model (6), based on snowfall

Month	$P_{SL}(\%)$
Feb-2021	54.2
Mar	19.2
Apr	20.1
May	0
Sep	0
Oct.	0
Nov	4.6
Dec	36.2
Jan-2022	41.2

The percentage of the losses are calculated for the non-summer months using the model and applied as soiling losses in PVsystem. This leads to an improvement in prediction of PR by simulator as shown in Fig. 12. In comparison with the previous results in Fig.4 with root mean square error (RMSE) equal to 22.23%, new results are closer to the measured ones with a RMSE of 7.78%. However, we can see that depending on the months, the losses can be over- (e.g., Feb. 2021) or under- (e.g., Jan 2022) estimated.

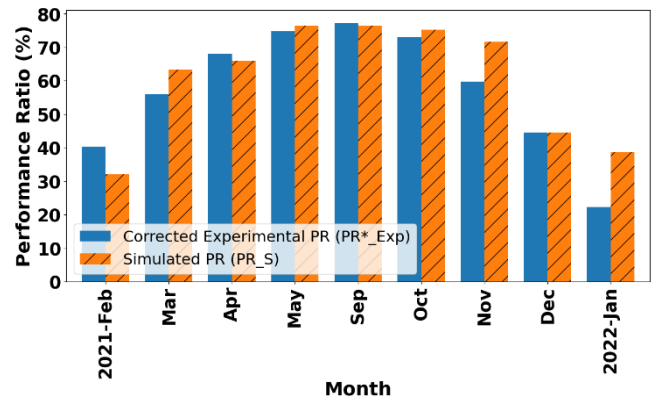


Fig. 12. Experimental and simulated PR by PVsyst considering the effect of snow

C. Monthly soiling losses modeling based on snowfall and frost

The dominant parameter for frost formation is the ambient temperature [9]. We therefore consider ambient temperature as another factor affecting losses in our model:

$$P_{SL} = C_s \text{Snow} + C_t (T_{amb} - T_{frost}) \quad (7)$$

where, C_t is temperature coefficient and T_{frost} is the monthly average frosting temperature. It corresponds to the monthly average temperature below which some frost can be observed during the month.

Using multi regression method based on the nine months of recorded data, the coefficient C_s , C_t , and T_{frost} are equal to 0.101 (%/cm), -2.106 (%/°C), and 13°C, respectively. Importing the soiling loss factors given in Table III to PVsyst which are estimated by the model, brings more proximity between simulated and experimental monthly PR in Fig. 13, so that RMSE decreases down to 2.34%.

Table III
Monthly soiling losses, predicted by the model (7), based on snowfall and frost

Month	$P_{SL}(\%)$
Feb-2021	41.8
Mar	27.1
Apr	12.6
May	1.5
Sep	6.1
Oct.	3.6
Nov	24.3
Dec	36
Jan-2022	55.5

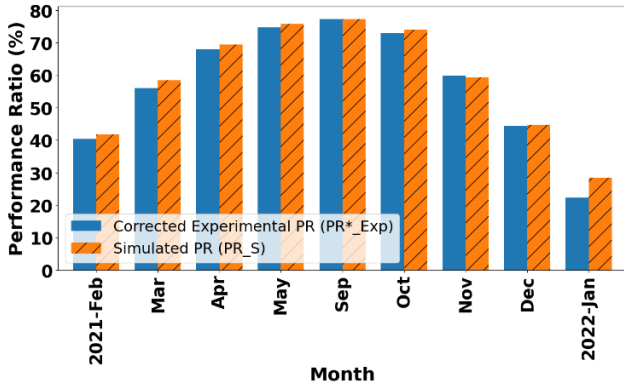


Fig. 13. Experimental and simulated PR considering the effect of snow and frost

Fig.14 shows the relative contribution of snow ($C_s \text{Snow}$) and frost ($C_t(T_{amb} - T_{frost})$) in P_{SL} for each month. It indicates that snow is responsible for less than 11% of the soiling losses and frost causes the majority of these losses in humid continental climate for CPV systems during cold months. In fact, a frosty layer in addition to making shadow, can diffuse the light and prevent its concentration by the lenses on the solar cells. To the best of our knowledge, there

has not been any study to discuss the share of frost in power generation losses in flat panel PV system in regions with high snowfall and very low temperature in winter. Based on our observation, the probability of frost coating on flat panel PV systems is much lower than CPV system. We believe it is due to larger radiative cooling for CPV systems during the night (horizontal position) compared to flat panel PV systems, and to a higher front glass surface temperature for flat panel PV systems compared to CPV systems.

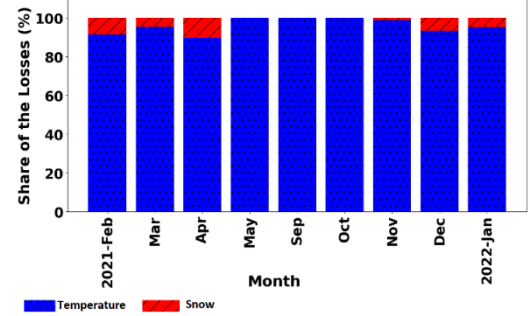


Fig. 14. Monthly share of snow and temperature (frost) in P_{SL} during the cold months

V: VALIDATION

The soiling factors have been calculated based on Feb-2021 to Jan-2022 historical meteorological data and one of the eight CPV systems of our solar park. For validation, the method has been tested on one of the other seven CPV systems during the following winter months of 2022 (February and March). Fig. 15 shows a comparison between PVsyst results and experimental monthly PR after applying the loss factors gained from the model. Without considering snow nor frost, RMSE of the predicted PR is equal to 24.51%. After importing the losses predicted by our model, it decreased down to 5.07%.

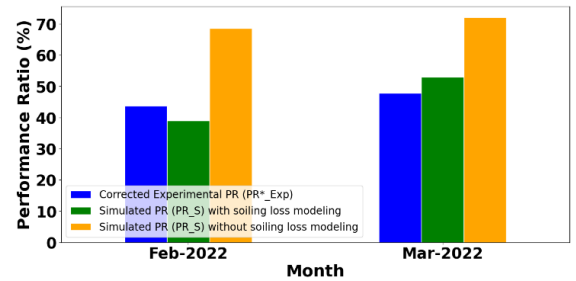


Fig 15. Monthly experimental PR, and PVsyst PR calculation before and after applying snow loss factors gained from the model developed in this study.

VI: CONCLUSION AND DISCUSSION

We investigated the cold-environment-related losses of a CPV system installed in a humid continental region, in Sherbrooke, Quebec, Canada. The first analysis indicated that when the modules are cleared from snow and frost, the system losses are well captured by PVsyst. However, snow and frost lead to additional performance losses in CPV systems that are

not considered in PV_{system}. We proposed a method to account for snow- and frost-induced losses in the regions with high level of snow and cold winters, which uses soiling factors in PV_{system}. A first approach considered a linear relationship between snowfalls and losses and improves the estimation of PR by decreasing RMSE from 22.23 to 7.78%. The better accuracy for the second model that includes frost-induced losses with RMSE equal to 2.34 %, demonstrates that frost-induced losses dominate over snow-induced losses. We demonstrated that snow-induced losses account for less than 11 % of the losses and frost-induced losses plays the main role. We validated the method on another CPV system with two winter months with the corresponding snow and temperature data. The results show an improvement in RMSE by a decrease from 24.51 to 5.07 %. The method can therefore be used to account for snow and frost-induced losses in CPV systems installed in humid continental regions.

To reduce these losses, one must therefore prevent the accumulation of frost on the front surface of CPV systems, which can be done for instance by positioning the modules at steep angles instead of horizontal position during the night (see supplementary data) or by implementing a lens heating system.

The method presented here was applied to assess snow and frost-induced losses in humid continental climate. As a perspective, it could eventually be generalized to other climate conditions and other source of losses such as soiling.

APPENDIX

Based on the results, frost has the main role to reduce the performance of a CPV system in humid continental climate. Therefore, finding a method to reduce frost covering on the panels, can lead to mitigate the negative effect of this phenomena.

Fig. 16 shows two different CPV systems in the solar park (a) totally covered by frost and (b) almost clear, at the same time in the morning of a cold day (9:08 am, December 10th, 2022). Based on the tracking control system, all the CPV systems should be on the safe mode (horizontal position) during the nights but the CPV in (b) had been near to vertical position. According to our observation, the main reason of this difference in frost coverage between the two CPV system is their different tilt angle during the night before. In fact, tilt angle does have a significant effect on the frosting process. It changes both the surface temperature due to radiative cooling [31] and the ability to form, grow and freeze water droplets [32]. Finding optimal position at night to address both safety and minimal frost coverage is therefore a perspective to mitigate frost-induced losses.

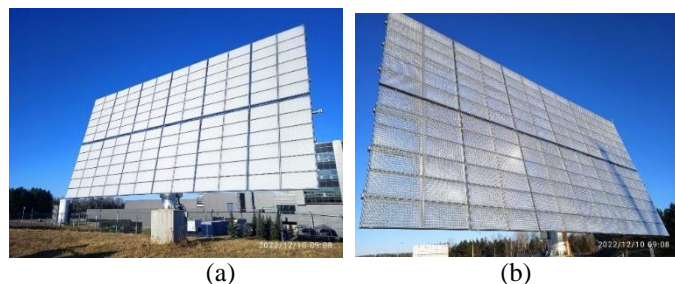


Fig. 16. Two CPV systems in Université de Sherbrooke solar Park at the same time: (a) totally covered by frost; (b) clear of frost coverage

REFERENCES

- [1] E. R. Hossein, R. J. Moraga, "The evaluation of renewable energy predictive modelling in energy dependency reduction: a system dynamics approach," *Int. J. Applied Management Science*, vol. 12, no. 1, 2020.
- [2] [Online]. Available: <https://www.cleanenergyreviews.info/blog/most-efficient-solar-panels>
- [3] A. Ejaz, H. Babar, H. M. Ai, F. Jamil, M. M. Janjua, I.M. R. Fattah, Z. Said and C. Li, "Concentrated photovoltaics as light harvesters: Outlook, recent progress, and challenges," *Sustain. Energy Technol. Assess.*, vol. 46, Aug. 2021, doi: 10.1016/j.seta.2021, doi: 10.1016/j.seta.2021.101199
- [4] M. Vivar and R. Herrero, I. Anton, F. Martinez-Moreno, R. Moreton, G. Sala, A.W. Blakers, J. Smeltink, "Effect of soiling in CPV systems," *Solar Energy*, vol. 84, no. 7, pp 1327–1335, 2010, doi: 10.1016/j.solener.2010.03.031.
- [5] S. Pulipaka and R. Kumar, "Analysis of irradiance losses on a soiled photovoltaic panel using contours," *Energy Conversion and Management*, vol. 115, pp. 327–336, 2016, doi: 10.1016/j.enconman.2016.02.068.
- [6] P. M. Rodrigo, D. L. Talavera, E. F. Fernández, F. M. Almonacid, and P. J. Pérez-Higueras, "Optimum capacity of the inverters in concentrator photovoltaic power plants with emphasis on shading impact," *Energy*, vol. 187, 2019, doi: 10.1016/j.energy.2019.115964.
- [7] L.A.A. Bunthof, F.P.M. Kreuwel, A. Kaldenhoven, S. Kin, W.H.M. Corbeek, G.J. Bauhuis, E. Vlieg and J.J. Schermer, "Impact of shading on a flat CPV system for façade integration," *Solar Energy*, vol. 140, pp. 162–170, 2016, doi: 10.1016/j.solener.2016.11.001.
- [8] P. M. Rodrigo, "Balancing the shading impact in utility-scale dual-axis tracking concentrator photovoltaic power plants," *Energy*, vol. 210, 2020, doi: 10.1016/j.energy.2020.118490.
- [9] E. Andenæs, B. P. Jelle, K. Ramlo, T. Kolås, J. Selj and S. E. Foss, "The influence of snow and ice coverage on the energy generation from photovoltaic solar cells," *Solar Energy*, vol. 159, pp. 318–328, 2018, doi: 10.1016/j.solener.2017.10.078.
- [10] R. E. Pawluk, Y. Chen and Y. She, "Photovoltaic electricity generation loss due to snow – A literature review on influence factors, estimation, and mitigation," *Renewable and Sustainable Energy Reviews*, vol. 107, pp. 171–182, 2019, doi: 10.1016/j.rser.2018.12.031.
- [11] R. W. Andrews and J. M. Pearce, "Prediction of energy effects on photovoltaic systems due to snowfall events," *2012 38th IEEE Photovoltaic Specialists Conference*, Austin, TX, USA, 2012, pp. 003386–003391, doi: 10.1109/PVSC.2012.6318297
- [12] T. Townsend and L. Powers, "Photovoltaics and snow: An update from two winters of measurements in the SIERRA," *2011 37th IEEE Photovoltaic Specialists Conference*, Seattle, WA, USA, 2011, pp. 003231–003236, doi: 10.1109/PVSC.2011.6186627.
- [13] D. S. Ryberg, J. Freeman, "Integration, validation, and application of a PV snow coverage model in SAM," *National Renewable Energy Laboratory*, Technical Report NREL/TP-6A20-68705, Aug. 2017.
- [14] B. Marion, R. Schaefer, H. Caine and G. Sanchez, "Measured and modeled photovoltaic system energy losses from snow for Colorado and Wisconsin locations," *Solar Energy*, vol. 97, pp.112–121, 2013 doi: 10.1016/j.solener.2013.07.029
- [15] B. Hashemi, A. -M. Cretu and S. Taheri, "Snow Loss Prediction for Photovoltaic Farms Using Computational Intelligence Techniques," in *IEEE Journal of Photovoltaics*, vol. 10, no. 4, pp. 1044–1052, July 2020, doi: 10.1109/JPHOTOV.2020.2987158.
- [16] S. Pisklak, "Commercial implementation of a snow impact model for PV performance prediction," *2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC)*, Portland, OR, USA, 2016, pp. 1002–1006, doi: 10.1109/PVSC.2016.7749761.
- [17] M. B. Øgaard, H. N. Riise and J. H. Selj, "Modeling Snow Losses in Photovoltaic Systems," *2021 IEEE 48th Photovoltaic Specialists Conference (PVSC)*, Fort Lauderdale, FL, USA, 2021, pp. 0517–0521, doi: 10.1109/PVSC43889.2021.9518886.
- [18] L. Powers, J. Newmiller and T. Townsend, "Measuring and modeling the effect of snow on photovoltaic system performance," *2010 35th*

- IEEE Photovoltaic Specialists Conference*, Honolulu, HI, USA, 2010, pp. 000973-000978, doi: 10.1109/PVSC.2010.5614572.
- [19] M. B. Øgaard, I. Frimannslund, H. N. Riise and J. Selj, "Snow Loss Modeling for Roof Mounted Photovoltaic Systems: Improving the Marion Snow Loss Model," in *IEEE Journal of Photovoltaics*, vol. 12, no. 4, pp. 1005-1013, July 2022, doi: 10.1109/JPHOTOV.2022.3166909.
- [20] B. Hashemi, S. Taheri and A. -M. Cretu, "Systematic Analysis and Computational Intelligence Based Modeling of Photovoltaic Power Generation in Snow Conditions," in *IEEE Journal of Photovoltaics*, vol. 12, no. 1, pp. 406-420, Jan. 2022, doi: 10.1109/JPHOTOV.2021.3123198.
- [21] C. Baldus-Jeursen *et al.*, "Snow Losses for Photovoltaic Systems: Validating the Marion and Townsend Models," in *IEEE Journal of Photovoltaics*, vol. 13, no. 4, pp. 610-620, July 2023, doi: 10.1109/JPHOTOV.2023.3264644.
- [22] O. W. Westbrook, S. M. MacAlpine and D. A. Bowersox, "Comparison of Measured and Modeled Snow Losses for Photovoltaic Systems in Colorado," *2022 IEEE 49th Photovoltaics Specialists Conference (PVSC)*, Philadelphia, PA, USA, 2022, pp. 0964-0966, doi: 10.1109/PVSC48317.2022.9938919.
- [23] X. Fu, X. Wang, Y. Gong, Y. Wang and Y. Zhang, "Impact of Snow Weather on PV Power Generation and Improvement of Power Forecasting," *2023 International Conference on Power Energy Systems and Applications (ICoPESA)*, Nanjing, China, 2023, pp. 448-453, doi: 10.1109/ICoPESA56898.2023.10140199.
- [24] A. Singh and D. Jones, "Snow Shedding properties of Bifacial PV Panels," *2022 IEEE 49th Photovoltaics Specialists Conference (PVSC)*, Philadelphia, PA, USA, 2022, pp. 0646-0648, doi: 10.1109/PVSC48317.2022.9938947.
- [25] [Online]. Available: <https://weatherspark.com/y/26459/Average-Weather-in-Sherbrooke-Canada-Year-Round>
- [26] [Online]. Available: Climate Atlas of Québec - Daily observations (gouv.qc.ca)
- [27] H. Tawa *et al.*, "Comparison of CPV systems with lattice-matched and mismatched solar cells in long-term outdoor performance," *2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC)*, Waikoloa, HI, USA, 2018, pp. 0961-0964, doi: 10.1109/PVSC.2018.8547428.
- [28] T. Gerstmaier, S. van Riesen, A. Gombert, A. Mermoud, T. Lejeune, and E. Duminil, "Software modeling of FLATCON CPV systems," *AIP Conference Proceedings*, 2010, doi: 10.1063/1.3509185
- [29] M. Benhammane, G. Notton, G. Pichenot, P. Voarino and D. Ouvrard, "Overview of electrical power models for concentrated photovoltaic systems and development of a new operational model with easily accessible inputs," *Renewable and Sustainable Energy Reviews*, vol. 135, 2021, doi: 10.1016/j.rser.2020.110221.
- [30] [Online]. Available: https://www.pvsyst.com/help/soiling_loss.htm
- [31] M. Hu, B. Zhao, S. Jingyu Cao, Q. Wang, S. Riffat, Y. Su, Gang Pei, "Quantitative characterization of the effect of inclination angle on flat-plate radiative cooling performance in buildings," *Journal of Building Engineering*, vol. 59, 2022, 105124, ISSN 2352-7102, doi: 10.1016/j.jobe.2022.105124
- [32] A.Chen, Y. Meng, B. Liu, Y. Li, Z. Miao, "Effects of inclination on the frosting process on cold surface of copper heat exchanger," *Energy and Buildings*, vol. 231, 2021, 110628, ISSN 0378-7788, doi: 10.1016/j.enbuild.2020.110628.