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Tuning electricity generation throughout the year with PV module technology

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Abstract

Currently, photovoltaic (PV) installations target a maximization of annual energy yield. In the future however, electricity generation may need to match better with the load profiles in a given environment and climate. In particular this will be a challenge for generation across the seasons, where electrical storage is less suitable, and in the built environment, where wind turbines for generation are much more difficult to integrate.

In this paper we discuss how this challenge may be addressed with climate- and consumption-specific PV module technology. In particular, we demonstrate how the temperature coefficient of a PV system can impact the energy yield throughout the year. After explaining the concept, we apply our electrical-optical-thermal model to do very accurate physics-based bottom-up simulations in different climates. As such, depending on the climate and latitude, a higher temperature coefficient of the PV module may lead to higher energy yields, mostly during the colder season. We also demonstrate that, if higher temperature coefficients are accompanied by improved low-light performance (tunable using the module's series resistance), the seasonal gain can be much higher. We indicate the relevance of our assumptions by basing the module performance in the simulations on (datasheets of) commercial modules.

Keywords

PV module technology, energy yield simulation, temperature coefficient, low-light performance, seasonal balancing by tuning PV generation

1. Background

Currently, the main target in photovoltaic (PV) installations is on getting as much energy as possible out of a module, resulting in a maximization of annual energy yield, namely the energy produced (kWh) per installed nominal power (kWp), in order to achieve the highest possible return on investment. This is a good target in case of:

- Low PV penetration rates such that PV electricity can be easily absorbed by the grid
- A generation profile reasonably aligned to the consumption profile (e.g. cooling needs in hot climates)
- Expensive modules/systems
- A fixed electricity pricing throughout the year

In general, it is a good target if the grid overhead (distribution cost) is limited and the generated energy can be immediately (and locally) consumed, or if storage is readily available (and cheap). However, this is not necessarily the case if the grid overhead dominates over module cost, so in the opposite situation of high PV penetration rate, mismatch between generation and consumption, cheap modules/systems and low or even negative electricity pricing in PV production highs. In such an environment, it may be beneficial to look at better balancing generation and load profiles. This can be done through demand-side-management and integration of storage in the system, but also from the generation side, by tuning the production peaks towards the times of need. It can be relevant on a seasonal level, as well as intraday, and one of the easiest ways of doing this is by optimizing orientation and tilt angles of PV generators, but also the temperature-dependent performance of the used modules can provide a knob for such tuning.

In particular for colder climates, it can be of interest to reduce overall yearly energy yield in favor of a better match in the cold season. Figure 1 conceptually, in an extreme situation, illustrates how a PV system (PV system 2 in Figure 1) may better match the consumption level (in this case fixed throughout the year) than a system maximizing overall yearly energy yield (PV system 1 in Figure 1).

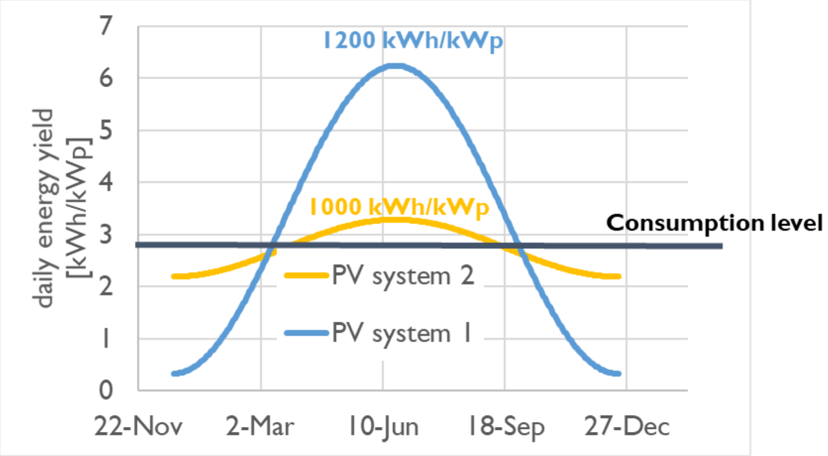


Figure 1: Conceptual illustration indicating how a PV system may sacrifice its overall yearly energy yield for a better match to the seasonal consumption level

While PV systems are typically already matching consumption by default in warmer climates, where production is well aligned with the demand for electrical cooling [1], in colder climates yearly energy yield is sometimes sacrificed for matching daily morning and evening peaks (east-west orientation) or seasonal variations (tilt). Especially the latter one is of interest, since the former one can be solved relatively straightforward through electrical storage, while on a seasonal level this would be much more challenging and costly. Figure 2 illustrates how tilting a South-oriented panel allows to influence its yearly insolation, and therefore energy generation, profile. This simulation illustrates how difficult (or impossible) it is in the Paris climate to optimize for winter production with varying tilt alone, while it is very easy in Kuwait, given the constant amount of sunlight.

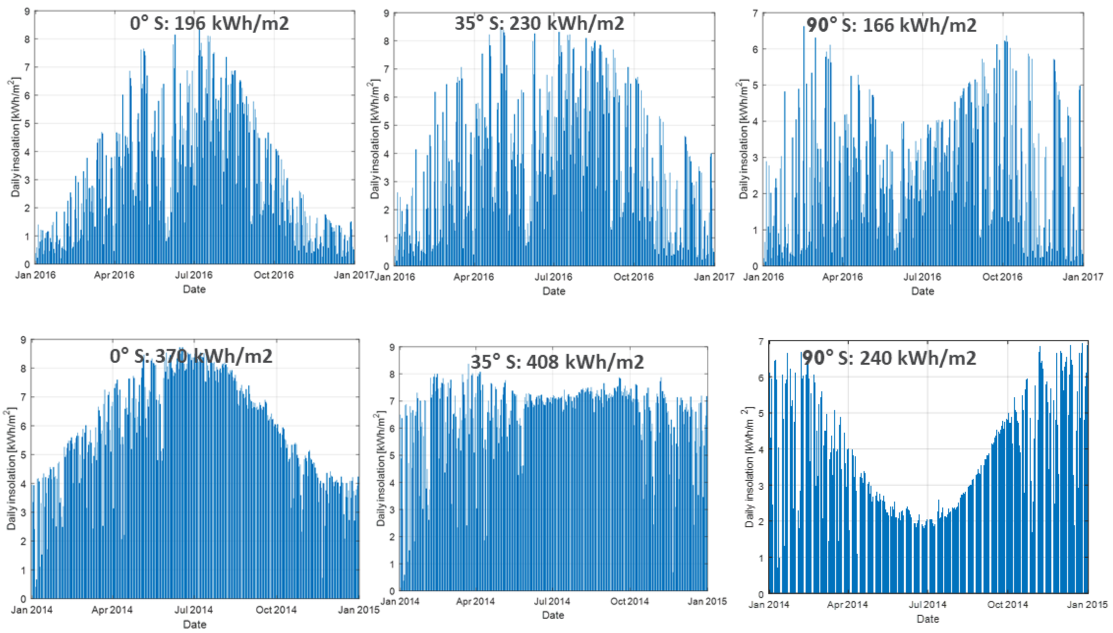


Figure 2: Impact of tilt angle (0°, 35° and 90°) on received daily insolation (across a full year) and overall yearly energy production of a south-oriented panel for Paris (top) and Kuwait (bottom)

On the other hand, the PV module technology itself is sometimes adapted to cope with the installation climate and environment, though implementation is usually focused on limiting degradation (e.g. extra moisture intrusion protection in hot-humid conditions or radiation protection in high UV conditions or space) and overall performance losses (e.g. increased metal cross-sections for cell interconnection for systems with higher peak irradiance of the modules due to climatic conditions or bifaciality).

The above approaches mainly focus on the first-order effects induced by variations in irradiation. In this paper, we want to indicate another possibility to take into account the expected climate and consumption patterns for a system, in particular the second-order effects of temperature on the performance, by tuning the temperature coefficient (TC) for maximum power of the PV module technology to be used. Figure 3 shows conceptually and greatly simplified, how the cell temperature will result in a flattening of the energy yield output over the year, and increasingly so for modules with a higher temperature coefficient. Depending on the exact conditions, the energy yield could even be potentially higher in the cold season for modules with a higher temperature coefficient.

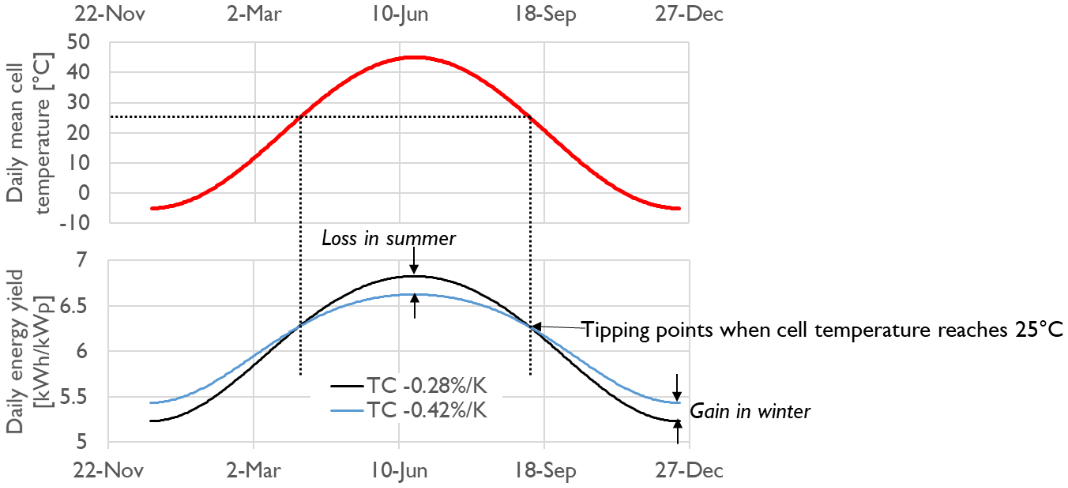


Figure 3: Conceptual indication of the impact of differences in temperature coefficient for maximum power (TC) on seasonal energy yield fluctuations

2. Modeling framework, climate data and module assumptions

To check the real impact of realistic TCs on energy yield in actual conditions throughout the year, we apply our advanced modeling framework [2]-[2] to four hypothetical PV installations at different latitudes experiencing varying climatic conditions and with varying PV module technology. Figure 4 shows the buildup of the used modeling framework. As the framework is only applied here, we refer to [2] and [2] for more information including detailed explanations and validation experiments.

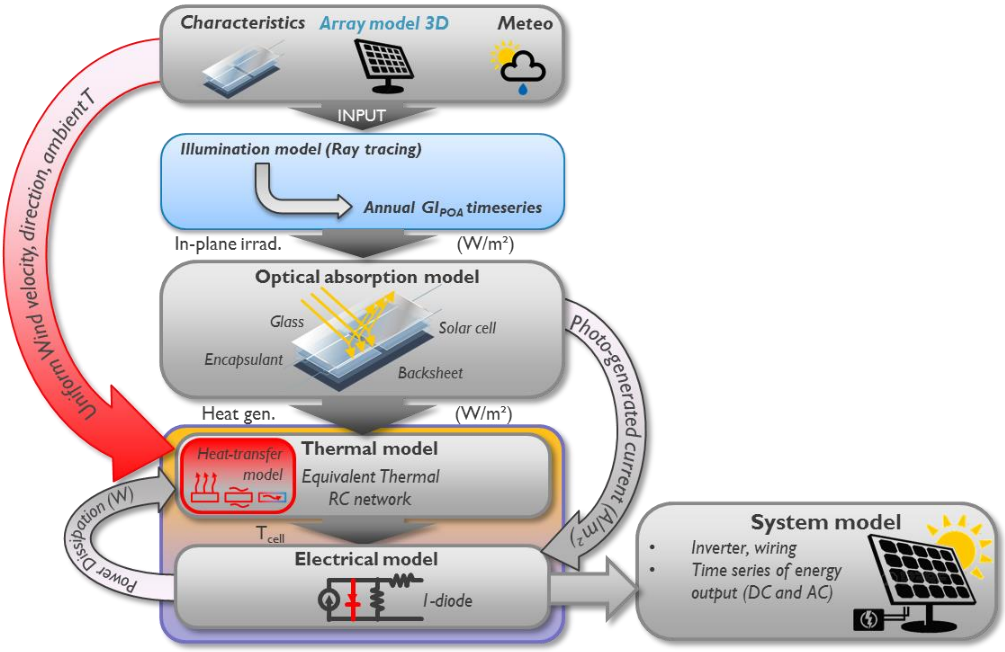


Figure 4: Conceptual representation of the used modeling framework [2], [2]

Climate data have been collected across a full year with a resolution of 1 minute from 4 locations: Kuwait City (Kuwait), Oldenburg (Germany), Ottawa (Canada) and Tampere (Finland). These diverse locations allow to illustrate the impact of the temperature coefficient of the module technology in different climates and latitudes. Measured wind velocity (speed and direction), ambient temperature, Global Horizontal Irradiance (GHI) and Diffuse Horizontal Irradiance (DHI) were available at every location. Using the Perez model [3], [5], Plane-Of-Array (POA) Irradiance is calculated (from the GHI and DHI values) at every location for the full year. We assume the PV panels are South-oriented, with tilt angle at each latitude optimized for annual energy yield [6], as shown in Table 1, where also their respective Köppen-Geiger classification [7] is displayed.

Table 1. Tilt angles [6] and climate classifications [7] for the PV installations simulated in the study

Location	**Tilt angle [°]**	**Köppen-Geiger climate classification**
Kuwait City (Kuwait)	26	BWh
Oldenburg (Germany)	33	Cfb
Ottawa (Canada)	37	Dfb
Tampere (Finland)	40	Dfb

Stand-alone commercially available conventional PV modules made of 60 cells in portrait installation have been considered for the energy yield simulations. Hence, module-level maximum power point tracking (MPPT) has been assumed. For the temperature-dependent PV module behaviour, we always refer to the temperature coefficient for maximum power abbreviated as TC.

3. Energy yield simulations: results and discussion

The simulations have been carried out to determine absolute and relative differences in energy yield between PV module technology that is currently commercially available. As such, the module parameters needed for these simulations, namely photo-generated current, temperature-independent coefficient of diode saturation current, diode ideality factor, and series and shunt resistances, have been calibrated directly from actual module datasheets. Each time, modules with same rated power and area have been selected to ease comparison.

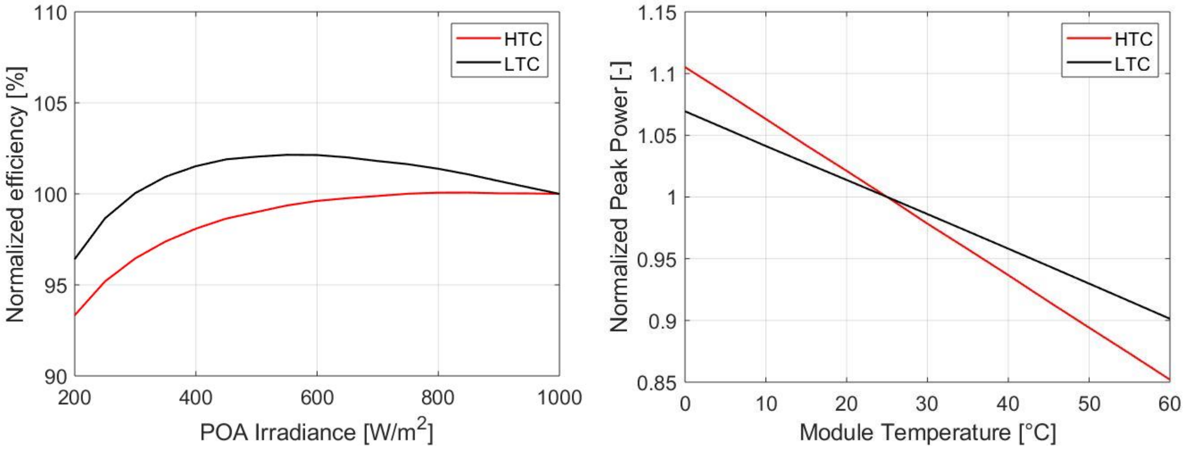
3.1 Impact of temperature coefficient

In this first case, two different types of PV module have been considered, one with a temperature coefficient for maximum power (TC) equal to -0.42 %/ºC [8], the other with a temperature coefficient for maximum power equal to -0.28 %/ºC [9]. In the following, we refer to them as HTC and LTC, respectively. These modules have been chosen as their TC values are representative of the extremes currently available in the high-end market. Based on the datasheet values, summarized in Table 2, the HTC module could be representative for state-of-the-art PERC technology, while the higher Voc for the LTC module indicates a technology with passivated contacts.

Table 2. PV module parameters from datasheets

Parameter	*HTC* [8]	*LTC* [9]
Short-circuit current I_{sc} [A]	9.78	9.38
Open-circuit voltage V_{oc} [V]	40.26	43.89
Maximum power P_{mp} [W]	305	305
Current at maximum power I_{mp} [W]	9.31	8.66
Voltage at maximum power V_{mp} [W]	32.76	35.22
Temperature coefficient of P_{mp} (TC) [%/ºC]	-0.42	-0.28

For detailed (daily) accurate energy yield simulations is important to also assess the low-light performance of both modules as much as possible from the information available in the respective datasheets. In the case of LTC [9], it is claimed that the PV module shows “3.5% relative efficiency reduction at low irradiance (200 W/m^2)”, whereas the datasheet of HTC [8] includes a graphic of normalized peak power as a function of irradiance. This information has been included in the module parameters' fitting procedure, leading to the results shown in Figure 5. From Figure 5(a), it is evident that LTC performs better than HTC at low light. On the other hand, Figure 5(b) shows that LTC performs worse than HTC when the temperature is below 25 °C. Thus, the improved efficiency of HTC due to lower temperature in cold climates is counteracted by a decreased efficiency at low irradiation. In the following subsections, we elaborate and discuss the relative outcome of the simulations with the two PV modules in the cases of the four installation sites using their relevant climatic data.



(a) (b)

Figure 5: Performance of the PV modules under analysis. (a) low-light behavior at a fixed cell temperature of 25 °C and (b) Thermal behavior at a fixed irradiation of 1000 W/m^2.

3.1.1 Kuwait installation

Starting with the hottest climate, at a latitude of 29.4°N, it is immediately clear that here a low temperature coefficient is highly preferable. With an average ambient temperature of 29ºC and high irradiation levels throughout the year, as shown in Figure 6, the cell temperatures are obviously continuously over 25ºC (with an average over operational hours higher than 40ºC).

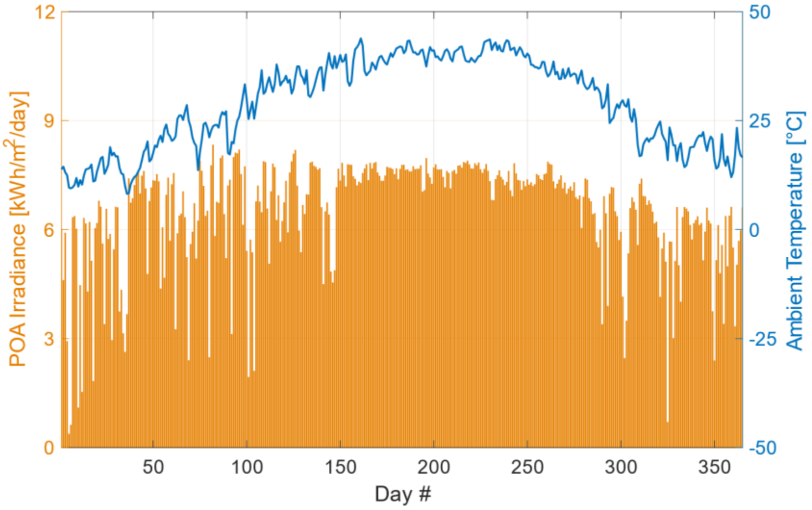


Figure 6: Daily POA irradiance (orange bars) and daily average (over operational hours) ambient temperature (blue curve) values throughout 2014, obtained from the Kuwait data used for the simulations.

Figure 7 shows the simulated daily energy yields as well as the difference between the two PV modules. As the energy yield is referenced to the nominal power (Wp) of the module at 25ºC, the high operational temperature will lead to improved energy yields for PV modules with a lower temperature coefficient. As expected, with the exception of a few days, PV modules with a lower temperature coefficient generate a higher energy yield all over the year in this type of climate.

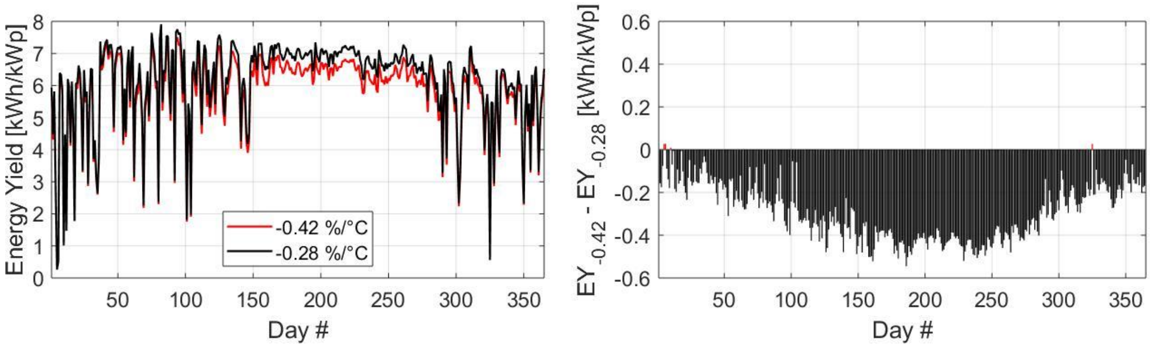


Figure 7: simulated daily energy yield throughout 2014 for the HTC and LTC modules (left), and the resulting difference (right). Red bars in the right plot refer to days where the HTC module leads to a higher energy yield (positive values in the graph, almost none present) than the LTC module. The opposite case is represented by the black negative bars.

While the relative annual energy yield difference amounts to -4.8%, cf. Table 3, the difference peaks to -6.4% in the summer season, as shown further on in Figure 15. Moreover, hot desert climates as in Kuwait require little heating in winter, but all the more cooling in summer. This translates in an increased electricity consumption in summer [1], and so the higher production from the low-temperature-coefficient PV system is even more attractive.

3.1.2 Oldenburg installation

In a more moderate climate in Western Europe, at a latitude of 53.1°N, the results are somewhat similar to the Kuwait ones, but with many additional days of gain due to the use of PV modules with a higher thermal coefficient. With the lower overall temperature and higher fluctuations in irradiance, shown in Figure 8, the differences in daily energy yield between different PV module temperature coefficients for the simulated year are smaller than in Kuwait. As shown in Figure 9, the use of PV modules with a higher thermal coefficient allows for a slightly higher overall energy yield during the first and last months of the year, thus during fall and winter months. However, the losses during spring and summer are much higher, leading at last to a yearly energy loss around 2.4% (Table 3).

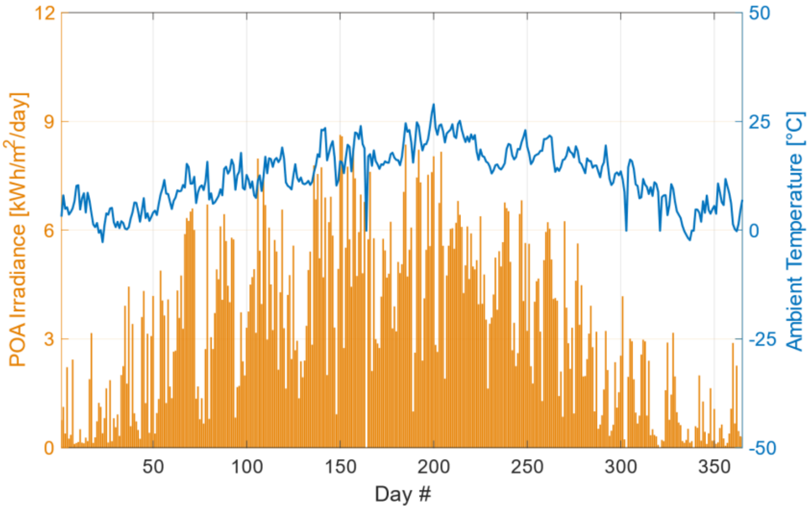


Figure 8: Daily POA irradiance (orange bars) and daily average (over operational hours) ambient temperature (blue curve) values throughout 2014, obtained from the Oldenburg data used for the simulations.

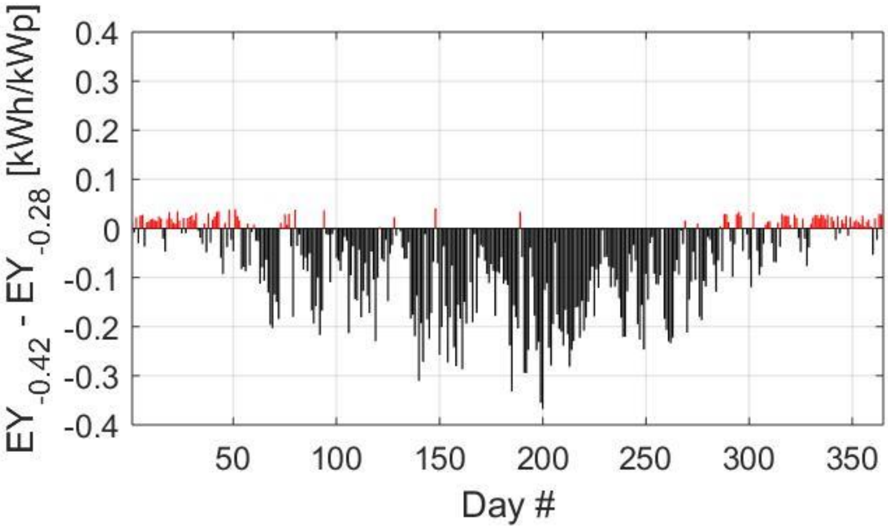


Figure 9: Simulated daily energy yield differences throughout 2014 for Oldenburg. Red bars in the right plot refer to days where the HTC module leads to a higher energy yield (positive values in the graph) than the LTC module. The opposite case is represented by the black negative bars.

3.1.3 Ottawa installation

At a slightly more southern latitude of 45.4°N, Ottawa boasts a higher yearly insolation than Oldenburg, but at the same time experiences more extreme temperature variations typical of an inland climate, and a lower mean ambient temperature of 8.8ºC during operational hours, as is illustrated in Figure 10. This results in a significantly better performance of PV modules with higher thermal coefficients during winter months and comparable performance of HTC and LTC modules during fall months, as shown in Figure 11 and Figure 14.

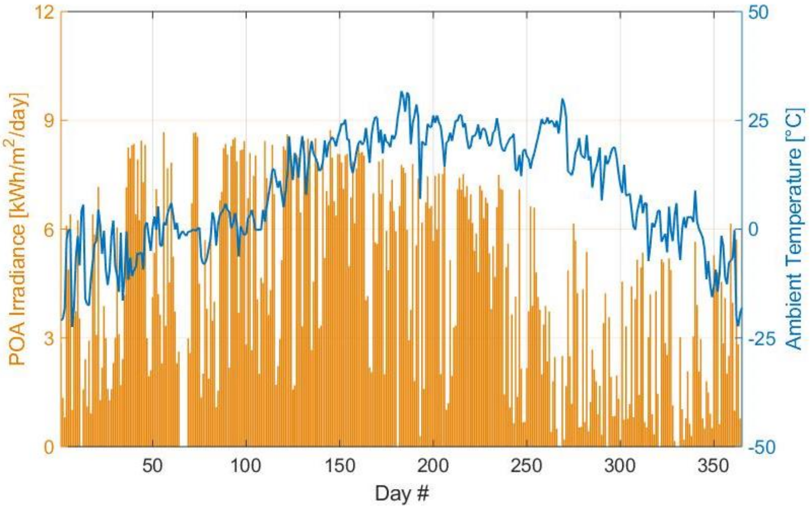


Figure 10: Daily POA insolation (orange bars) and daily average (over operational hours) ambient temperature (blue curve) values throughout 2018, obtained from the Ottawa data used for the simulations.

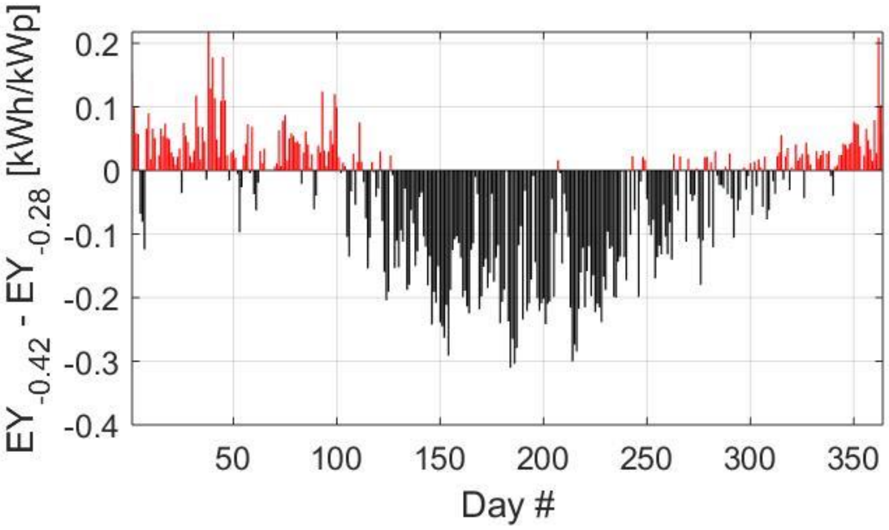


Figure 11: Simulated daily energy yield differences throughout 2018 for Ottawa. Red bars in the right plot refer to days where the HTC module leads to a higher energy yield (positive values in the graph) than the LTC module. The opposite case is represented by the black negative bars.

The use of PV modules with a higher thermal coefficient in this type of climate leads to limited yearly energy yield losses of about 1%. In this location however, heating and electricity consumption are much higher in winter, so the relevance of producing more in winter could favor PV modules with a higher temperature coefficient.

3.1.4 Tampere installation

Much more North, at a latitude of 61.5°N, and as shown in Figure 12, Tampere irradiation is somewhat lower than Oldenburg, especially noticeable in winter. Such low irradiation during winter is partly due to the weather station setup, that is described in detail in [10], where the pyranometer suffers from some shading due to building structures in the morning (all year) and in the evening (in winter), as well as snow/ice coverage in winter.

On the other hand, average ambient temperature over operating hours is deeply below 25ºC, with a yearly average of 6.5ºC. As shown in Figure 13, in this climate the advantages of a higher temperature coefficient are similar to the Ottawa case, though with more limited gain. As shown in Figure 15, slightly better performance of PV modules with higher thermal coefficients are obtained during winter months whereas slightly worse performance occurs during fall months. As for Ottawa, in Tampere heating and electricity consumption are much higher in colder seasons, so the relevance of producing relatively more during winter could favor PV modules with a higher temperature coefficient. The use of PV modules with a higher temperature coefficient in this type of climate leads to yearly energy yield losses slightly above 1%.

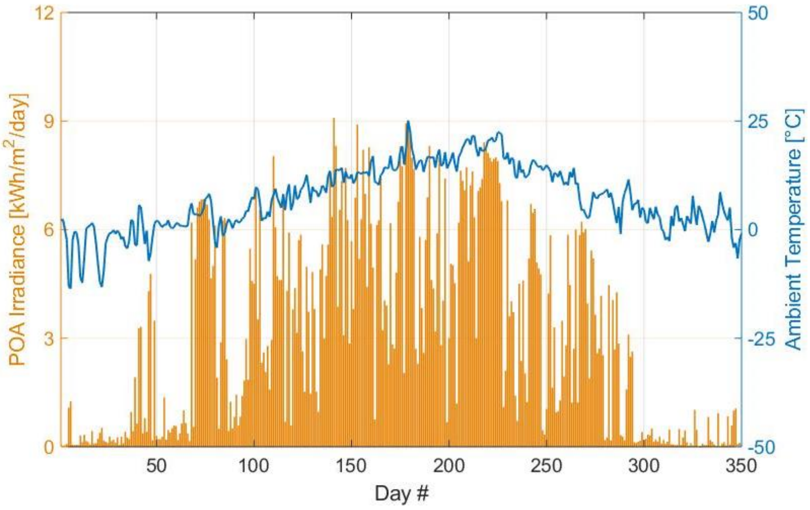


Figure 12: Daily POA insolation (orange bars) and daily average (over operational hours) ambient temperature (blue curve) values throughout 2015, obtained from the Tampere data used for the simulations.

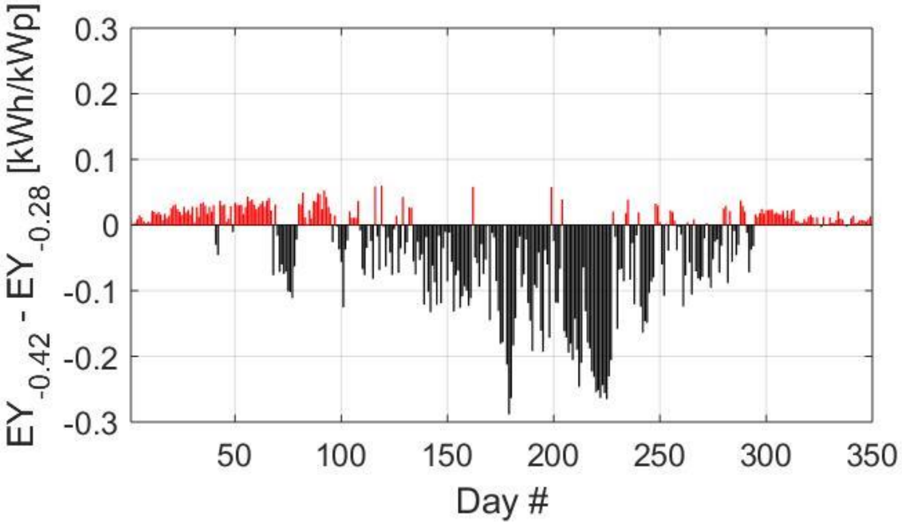


Figure 13: Simulated daily energy yield differences throughout 2015 for Tampere. Red bars in the right plot refer to days where the HTC module leads to a higher energy yield (positive values in the graph) than the LTC module. The opposite case is represented by the black negative bars.

3.1.5 Overview of the simulated installations

Table 3 recapitulates the results, indicating the impact of temperature coefficient of the PV modules on energy yield, depending on the climate, and based on actual weather data. Though these numbers only give the annual differences, the impact can be much higher at particular moments and locations.

Table 3: overview of yearly weather data and simulated energy yields for all locations

		Kuwait	Oldenburg	Ottawa	Tampere
Yearly POA irradiance [kWh/m^2]		2381	1196	1597	1121
Daily variation [kWh/m^2]		1.46	2.32	2.69	2.74
Mean daytime ambient temperature* [^{o}C]		28.9	12.3	8.8	6.5
Annual energy yield [kWh/kWp]	HTC	2130	1126	1560	1025
	LTC	2238	1153	1577	1038
Gain with higher TC [%]	Annual	–4.8	–2.4	–1.1	–1.2

The benefits related to higher thermal coefficients in colder climates are more visible if the energy yield gain is split per season, as in Figure 14. In colder climates as Ottawa and Tampere, energy production during warmer seasons is sacrificed to allow energy yield gain during winter. As a consequence, a better production-demand matching may be obtained. It is worth to note that Tampere's potential is not fully acknowledged due to the used weather data, which was addressed in Subsection 3.1.4.

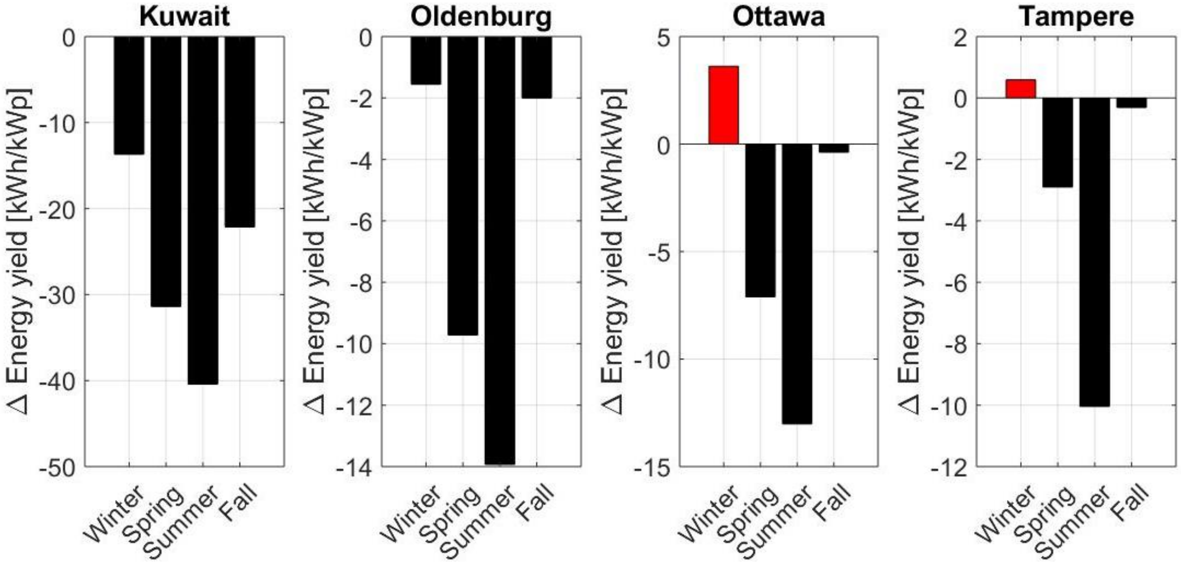


Figure 14: Seasonal absolute gain due to a higher thermal coefficient of the PV module for the different locations. Red bars in the right plot refer to days where the HTC module leads to a higher energy yield (positive values in the graph) than the LTC module. The opposite case is represented by the black negative bars.

Considering also the absolute energy yield values for the seasons, Figure 15 shows the same graph in terms of relative gains. While losses can be very significant for a Kuwait climate, amounting to almost 7%, 1% additional energy during winter may become interesting for colder climates as Ottawa and Tampere. It is important to note though that the effects of snow accumulation on the PV modules was not considered in the simulations.

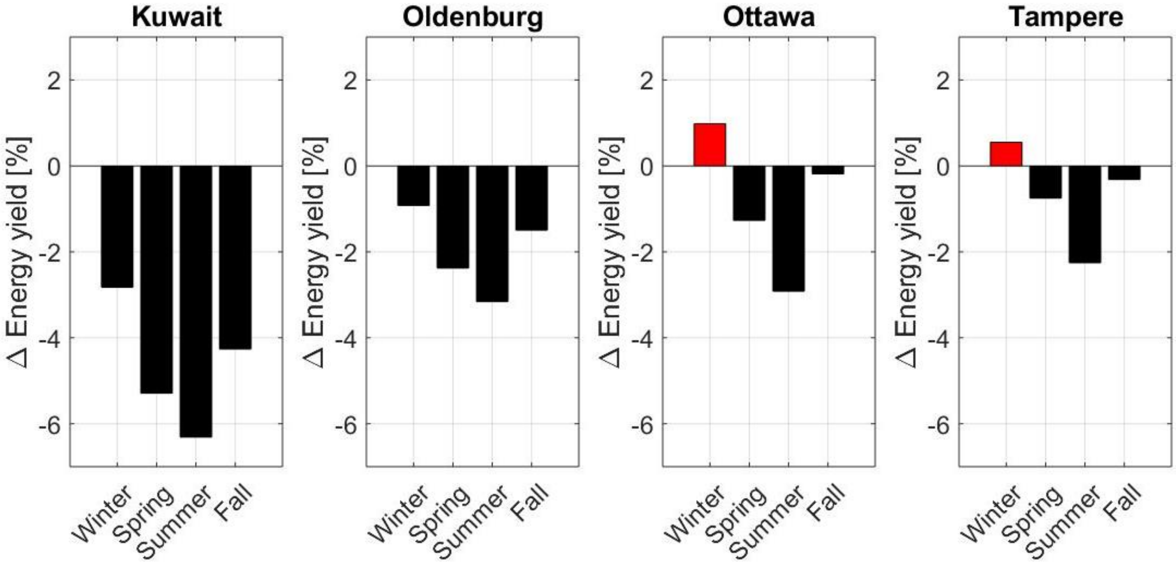


Figure 15: Seasonal relative gain due to higher thermal coefficient for the different locations. Red bars refer to seasons where the HTC module leads to higher energy yield (positive values in the graph) than the LTC module. The opposite case is represented by black negative bars.

3.2 Impact of (improved) low light behaviour

In this Section, we will demonstrate that the energy yield of PV modules with higher thermal coefficients in cold climates can be significantly improved if such a higher thermal coefficient is combined with an improved low light performance. To clarify this point, we will start with the analysis of the typical operating conditions of the HTC module under Kuwait and Ottawa climates in terms of irradiation and PV module temperature, summarized in Figure 16 and Table 4. Specifically, Figure 16 shows the occurrences of a given set of operating conditions. Given the minute resolution of the climate datasets, colors in Figure 16 show for how many minutes the PV module was subjected to a certain irradiance (x-axis) and working at a certain module temperature (y-axis). In Table 4, the same results are summarized for given ranges of PV module temperature and irradiation.

From Figure 16, it is evident that, as expected, production under Kuwait climate occurs most of the time at medium to high module temperatures, and mainly under two different operating conditions: high irradiation around 1000 W/m^2 with high module temperature in the range 50-60 ºC, and low irradiation below 200 W/m^2 with “medium” module temperature in the range 22-32 ºC. On the other hand, Ottawa climate shows clear peaks at low irradiation around 200 W/m^2 and low module temperature in the range 14-24 ºC as well as at 0 ºC. Also, energy production below 25 ºC is dominant in such a climate, as shown in Table 4. Purely looking at temperature coefficients, in a climate like Ottawa much better performance of the HTC module is expected than what is shown in the Section 3.1.3. This expectation is skewed because performance at low temperature often happens in low light conditions, such that improvements due to the higher temperature coefficient are counteracted by lower module efficiency at low-light conditions (cf. Figure 5).

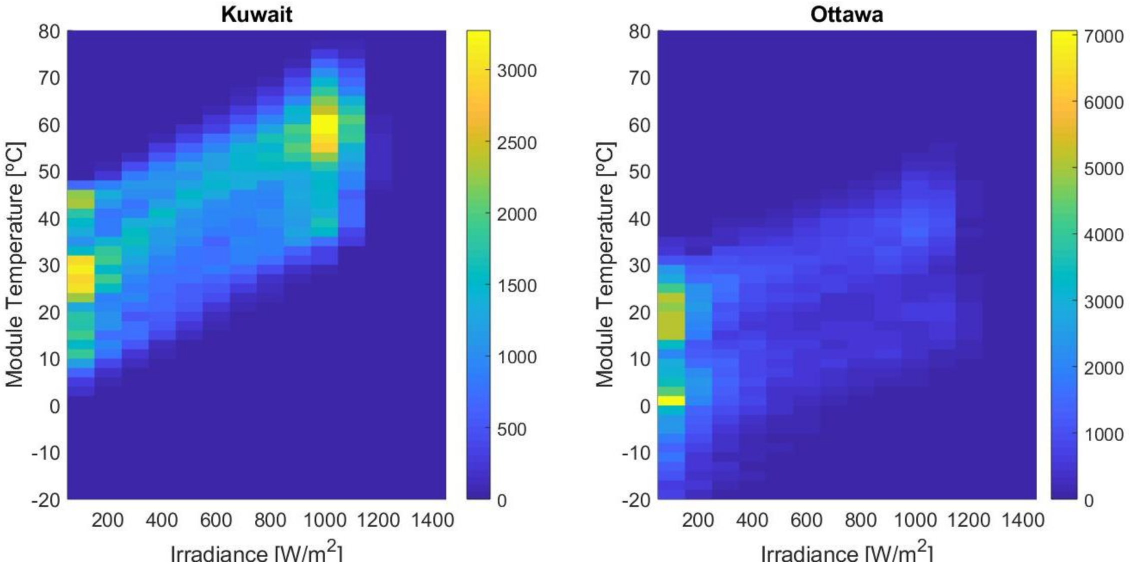


Figure 16: Occurrences (in minutes) of different operating conditions for HTC PV module. Colors show how many minutes the PV module was subjected to a certain irradiance (x-axis) and working at a certain module temperature (y-axis) during one year.

Table 4: Occurrences (in percentages of daytime hours in a full year) of different operating conditions, in terms of irradiance and PV module temperature ranges, for a HTC PV module in the Ottawa climate

Irradiance [W/m^2] Module Temper. [ºC]	0-200	200-800	800-1500	**Total by row**
-45 - +25	41.6	22.7	6.2	70.5
+25 - +85	4.4	13.5	11.7	29.5
Total by column	46.0	36.2	17.8	

However, performance at low irradiation can be engineered by proper cell and module design. As shown in [10], shunt and series resistances strongly affect low light performance of PV modules. Of particular interest is the effect of series resistance for tuning the low light behavior: the higher it is, the better the relative efficiency in the mid-irradiation range. With high series resistance, relative efficiencies higher than 100% can be obtained in the range 300 to 1000 W/m^2. This is the case for the LTC module shown in Figure 5. Therefore, although counter-intuitive, a higher series resistance could be beneficial for modules with higher thermal coefficients in cold climates at high latitude. Again, the starting point has been a real 305 Wp PV module [12] with the same temperature coefficient for maximum power as the HTC module, namely -0.42 %/ºC. Parameter fitting has been performed for such a module as discussed before. Since the datasheet does not provide any usable information about the low light performance, the parameter fitting has been done only considering performance at STC and temperature coefficients. Figure 17 shows the results in terms of low-light performance at 25ºC in comparison with the low temperature coefficient LTC module. It is clear that behavior in low-light is very similar for the two PV modules, although the performance of the LTC module is still better. Compared to Figure 5, low-light performance of this new high temperature coefficient PV module, referred to as HTC+, is much better than the one of HTC. It is worth to note that the fitted series resistance of HTC+ is indeed higher than the fitted series resistance of HTC. This is consistent with the lower Fill Factor, 0.755 and 0.775, respectively, and the lower number of busbars, 3 and 4, respectively, of HTC+ compared to HTC, as from their datasheets.

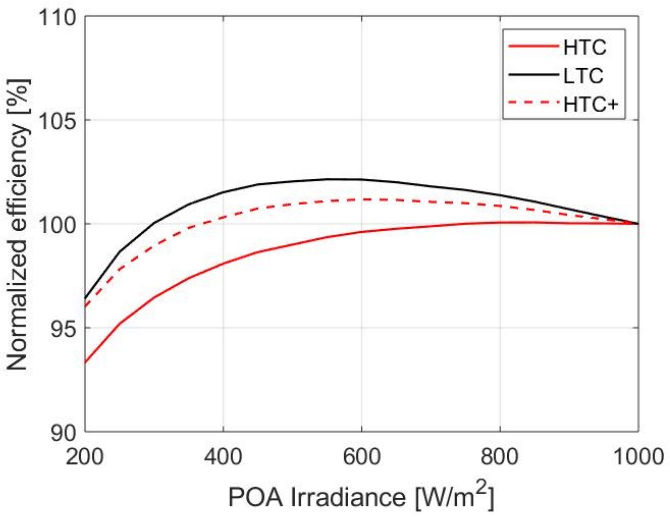


Figure 17: "Relative efficiency of LTC, HTC and HTC+ PV modules as a function of incident irradiance at a fixed cell temperature of 25 °C

The joint effects of higher temperature coefficient and improved low-light performance have been simulated with the new HTC+ PV module model again for the same 4 locations. Results are summarized in Table 5, Figure 18 and Figure 19. Table 5 recapitulates the results, indicating the impact of temperature coefficient of the PV modules on energy yield, depending on the climate, based on actual weather data. As for the results presented in Table 3, these numbers only give the annual differences. However, the impact can be much higher at particular moments and locations. The benefits related to higher thermal coefficients in colder climates are more visible if the energy yield gain is split per season, as in Figure 18 and Figure 19. In colder climates, energy production during summer is sacrificed to allow energy yield gain during colder seasons. As a consequence, a better production-demand matching may be obtained. Particularly interesting are locations such as Ottawa and Tampere where, together with a better spread of production along the whole year, negligible yearlong losses are introduced if PV modules with a lower temperature coefficient are replaced with PV modules with a higher one and a properly engineered low-light behaviour.

Table 5: overview of simulated yearly energy yields of HTC+ and LTC PV modules for all locations

		Kuwait	Oldenburg	Ottawa	Tampere
Annual energy yield [kWh/kWp]	*HTC+*	2153	1142	1578	1038
	LTC	2238	1153	1577	1038
Gain for HTC+ modules [%]	Annual	-3.8	-0.9	-0.1	+0.0

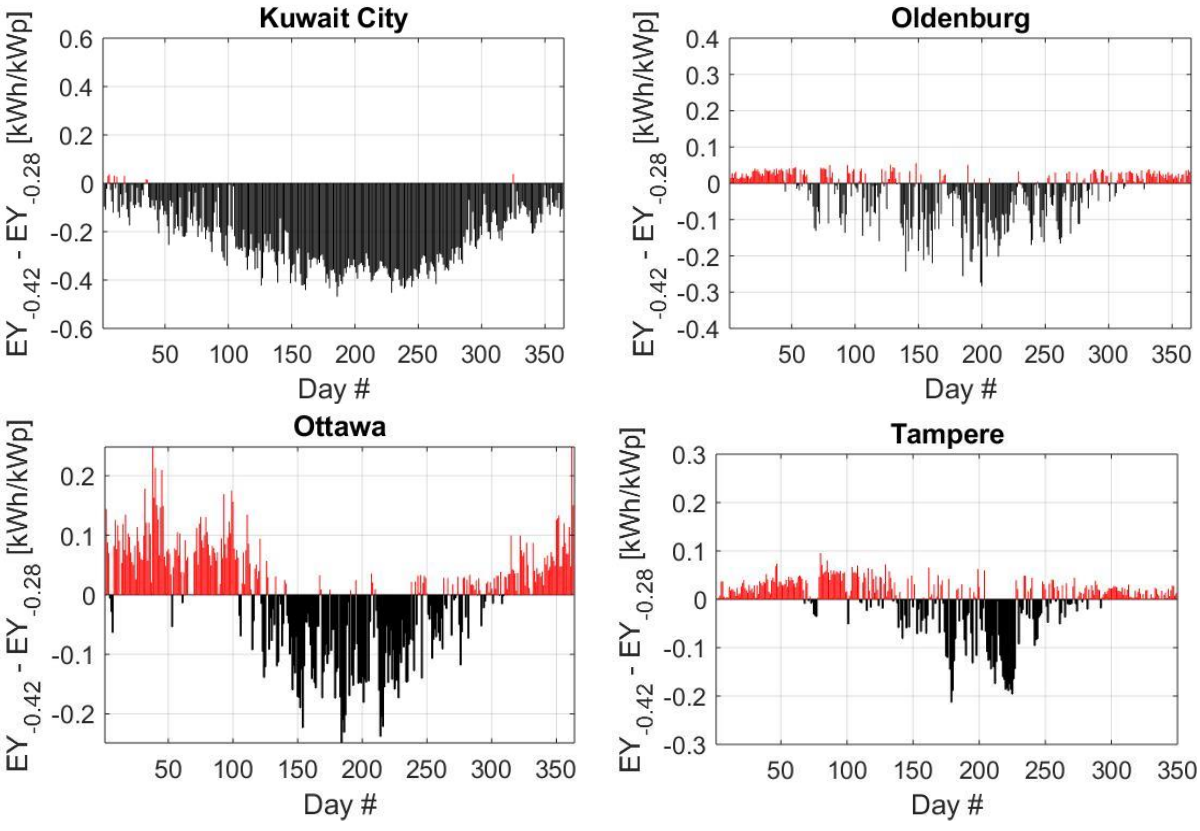


Figure 18: Simulated daily energy yield differences between HTC+ and LTC PV modules for the different climates as in Figures 7, 9, 11 and 13.

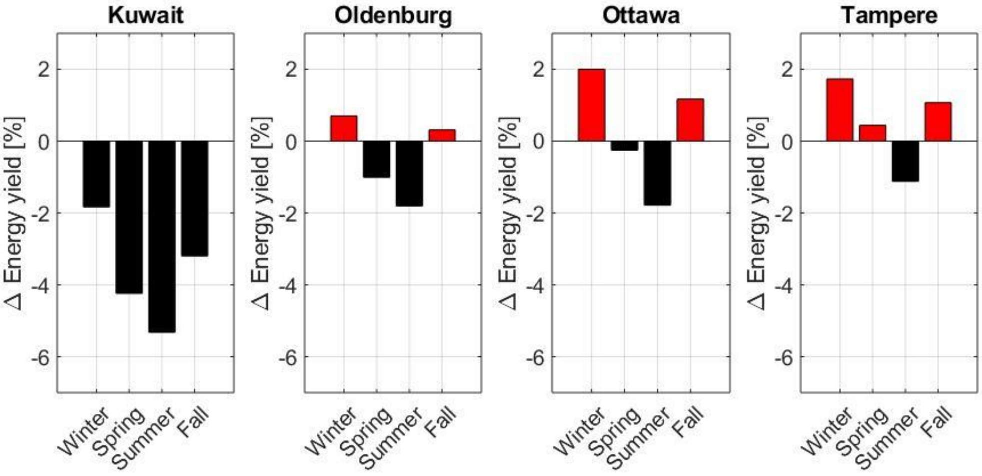


Figure 19: Seasonal relative energy yield gains of HTC+ PV modules with respect to LTC modules for the different locations. Red bars refer to seasons where the HTC+ module leads to a higher energy yield (positive values in the graph) than the LTC module. The opposite case is represented by black negative bars.

Both Oldenburg and Ottawa show energy gains with the HTC+ module during winter and fall. However, in Tampere the advantages of a higher temperature coefficient are visible almost all over the year, with additional energy generated during three seasons out of four. It is only during summer that the PV modules with lower temperature coefficients are performing better, as evident from Figure 18. Additionally, if snow cleaning is duly implemented during winter and shading is avoided, in a climate as Tampere there might even be an overall increase in the yearly energy yield.

4. Conclusion

In this paper, we point out the impact of the temperature coefficient of PV modules on energy yield throughout the year, indicating also the somewhat counterintuitive benefits that a high temperature coefficient may have depending on the climate where it is operational. If low-light behavior is not optimized and only a higher temperature coefficient is considered, some seasonal gain is obtained in 2 out of 4 locations, namely Tampere and Ottawa, whereas in Oldenburg’s and Kuwait’s climate PV modules with a lower temperature coefficient would lead to better performance. However, when a higher temperature coefficient is accompanied by improved low-light performance, the benefits of such PV modules become clear. Except for the Kuwait case, higher production during cold seasons, beneficial for a better production-demand matching, is obtained in all the other cases. For the specific case of Tampere, the use of such PV modules could even lead to an overall increase of the yearly energy yield. Considering little attention is currently paid to times of low PV production, we also point out the potential impact of shading objects or snow cover that may affect results.

Context and outlook

The findings here are meant to fit into a bigger picture in the future where PV production will be optimized to times of electricity scarcity rather than maximizing annual energy yield. Such optimization should then also include “suboptimal” tilt angles combined with the effects reported here. Furthermore, the potential gains and losses here are only expressed as a function of produced electrical energy, as most scientific and technical approach, but market-driven dynamic pricing will further alter the outcome and will obviously need to be assessed in any future practical implementation.

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References

[1] Kuwait Government, Ministry Of Electricity & Water Statistical Year Book 2016 (Electrical Energy).

[2] H. Goverde et al., “Energy Yield Prediction Model for PV Modules Including Spatial and Temporal Effects”, 29th European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC), pp. 3292 – 3296, 2014.

[3] I. T. Horváth, H. Goverde, P. Manganiello, J. Govaerts, L. Tous, B. Aldalali, E. Vörösházi, J. Szlufcik, F. Catthoor, J. Poortmans, Photovoltaic energy yield modelling under desert and moderate climates: What-if exploration of different cell technologies, Solar Energy, Volume 173, 2018, Pages 728-739, ISSN 0038-092X, https://doi.org/10.1016/j.solener.2018.07.079.

[4] R. Perez et al., “Modeling daylight availability and irradiance components from direct and global irradiance”. Solar Energy 44 (5), pp. 271–289, 1990.

[5] R. Perez et al., “The Development and Verification of the Perez Diffuse Radiation Model”. SAND88-7030. 1988.

[6] Jacobson M. Z., Jadhav V., “World estimates of PV optimal tilt angles and ratios of sunlight incident upon tilted and tracked PV panels relative to horizontal panels”, Solar Energy, 169 (2018), 55-66.

[7] Beck, H.E., Zimmermann, N. E., McVicar, T. R., Vergopolan, N., Berg, A., & Wood, E. F. - "Present and future Köppen-Geiger climate classification maps at 1-km resolution". Nature Scientific Data. DOI:10.1038/sdata.2018.214.

[8] ET Solar ET-M660305WW/WB PV module. Datasheet available online (last check November 29th, 2019): https://amazingsolar.com.au/wp-content/uploads/2019/02/ET-Mono-60-cell-290-305W.pdf

[9] NSP D6H_E3A PV module. Datasheet available online (last check November 29th, 2019): https://webbuilder3.asiannet.com/ftp/2257/NSP_1608_Hello325_D6H_E3A_WS_01.pdf

[10] D. Torres Lobera, A. Mäki, J. Huusari, K. Lappalainen, T. Suntio, S. Valkealahti, Operation of TUT solar PV power station research plant under partial shading caused by snow and buildings, International Journal of Photoenergy. 2013 (2013). https://doi.org/10.1155/2013/837310.

[11] Litzenburger, B., et al., “Low Light Performance of Solar Cells and Modules”, 29th European Photovoltaic Solar Energy Conference, Amsterdam, Netherlands, 22nd–26th September 2014.

[12] Up Solar Mono Series 60 cells PV Module. Datasheet available online (last check November 29th, 2019): http://www.eco-distributing.com/assets/images/Upsolar%20mono%20285-305W%20spec%20sheet.pdf