WHITE PAPER

DIFFUSECONTROL

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PVH-RD-OC-WTP-0029-01

PVH

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// Abstract

PVHardware enhanced tracking solution allows even more than increasing Sun power harvest. Through more advanced control algorithms, such as the **Diffuse Control** algorithm, PVH tracking solution **maximizes captured solar energy while minimizing motor consumption**.

A new advanced irradiance model was developed to **optimize the plant tracking setpoint in real-time.** It was tested on DNV software simulation as well as on real setups with precise measurements. This solution, Diffuse Control, enables a low motor-consumption mode while maximizing captured irradiance, obtaining thus **production gains which are ultimately translated in economic gains**.

Thanks to Diffuse Control technology, year production can increase by 1-2 % while motor consumption can decrease by -30 % at the end of the year, depending on the category of the plant. Plants are classified according to a PVH AI algorithm based on the Typical Meteorological Year, which identifies three different plant categories.

The use of more sophisticated models can lead to an extra annual gain of up to 0.3 % in comparison with widely used 0 degrees diffuse setpoint solutions. Gains on production can rise to 20 % on specific days when Diffuse Control is enabled, as against classical sun tracking algorithms, as it was proven with side-to-side real plants, when Diffuse Control algorithm was running in one plant while classical sun tracking was used in another one.

These advanced irradiance models can be configured to be used in plants with or without motor consumption constraints, allowing **easy updates** of the desired optimization configuration whenever it is required.

// Diffuse Control: a strategic boost

Photovoltaic single-axis trackers have typically considered the Sun position as the only target in terms of capturing its energy.

Sun Tracking is based on pure geometry, the sun position is followed by moving the trackers —or plane arrays— as perpendicular to main direction of the Sun rays as possible, independently of real irradiances in the environment of the tracker.

The assumption that the Sun position is the only target to capture the energy can be correct when nothing stands in between the Sun and the photovoltaic modules. However, this simple assumption does not capture as much energy as other more sophisticated models when weather conditions are considered.

Global radiation depends on multiple factors, such as the time of the day, the seasons, the cloudiness, the angle of incidence on the surface, and the reflectance. The power captured by the tracker is intrinsic to the effective irradiances coming directly from the sun and indirectly from environmental reflections from the sky and the ground, along with other trackers. This understanding of the irradiances can be complex and typical approaches consider those irradiances to be geometric.

New models in the understanding of capturing solar energy point to measuring irradiances as the proper way to calculate the optimal panel inclination tilt.

PVH has developed a specific algorithm which allows the solar plants to be more productive when diffuse light predominates. This advanced algorithm **maximizes captured solar energy, alongside with being configurable for minimizing motor consumption at par**.

Diffuse Control algorithm relies on **real-time** weather information captured by the sensors set in the plant. This data is sent to the PVH TBox controller so that the trackers positions are always accurate and can react to weather variations.

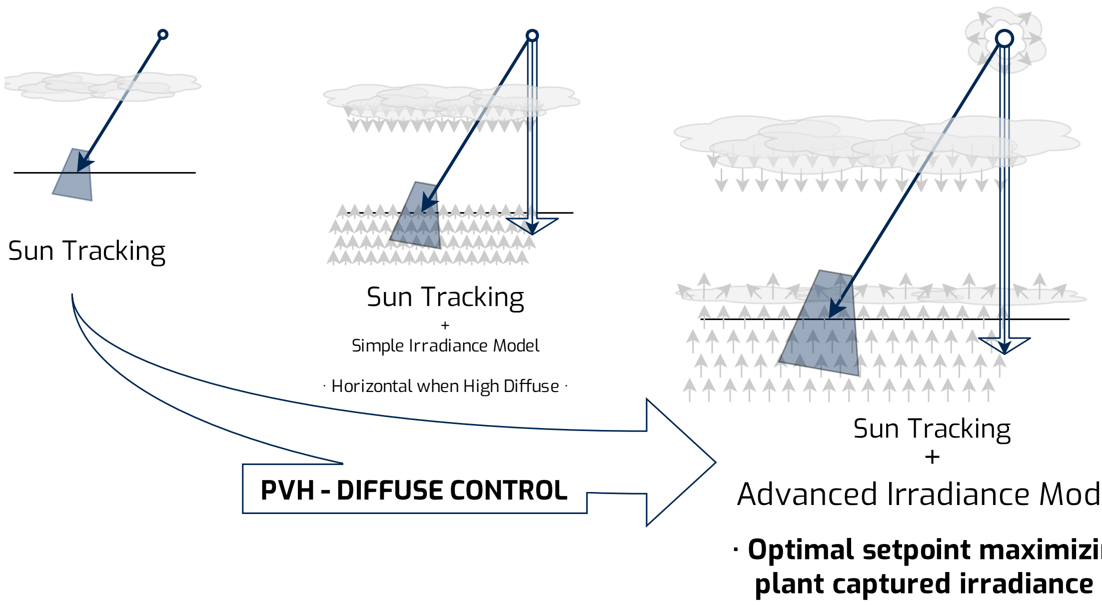

Figure 1. Solar tracking models

// Diffuse Control technology analysis approach

The specific procedures and tools used to conduct the research and analysis discussed in this white paper are described in this section.

PVH Diffuse Control technology uses advanced irradiance models for a deeper understanding of the diffuse irradiance conditions to optimize production. Validation setups were developed for empirical corroboration.

Plant evaluation and classification

PVH developed an AI algorithm based in the Typical Meteorological Year (TMY) to classify the plant according to its diffuse light levels. This algorithm considers a set of calculations from the Global Horizontal Irradiance (GHI) and Direct Horizontal Irradiance (DHI) values and offers an inference which allows to evaluate whether the plant could profit from Diffuse Control technology.

If the plant's diffuse irradiance level is sufficient, the plant's diffuse irradiance level is classified in high, mid and low. Diffuse Control technology is customized according to the plant's features.

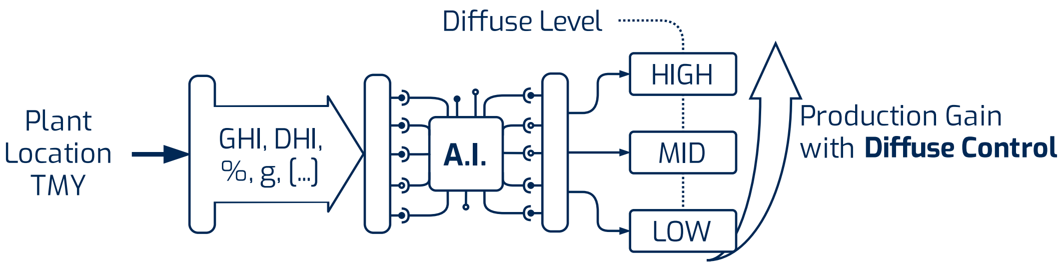

Figure 2. Diffuse level calculation

Diffuse Control technology

The analysis was conducted from both theoretical and practical perspectives.

Regarding the conceptual approach, calculations and simulations were executed to identify the captured irradiance and the production gain.

Furthermore, DNV software tools were utilized to simulate twelve 100-MWp plants, each with different latitudes, tracker configurations, diffuse irradiance levels and terrain types. The simulations examined the impact of Diffuse Control and assessed the suitability of this PVH technology for different locations worldwide and under different levels of diffuse light. DNV tools were used as well for further calculations of average monthly gain (%), annual accumulated gain (kWh/kWp) and the performance ratio average gain (%) for latitudes 57.1, 0 and 37.4, applying Diffuse Control parameters and simple irradiance model parameters.

When considering the latitudes mentioned, the diffuse irradiance level for latitude 57.1 was categorized as high, while the level for latitude 37.4 was deemed medium. The level for latitude 0 was also classified as medium, although, in this latitude, both direct and diffuse irradiance levels exhibit a high level of volatility, which introduces an additional layer of complexity.

The analysis of the different irradiance models was supported by empirical evidence. PVH conducted an outdoors scientific test over several months to determine what model is most effective in enhancing energy production when diffuse light predominates.

The advanced irradiance models, along with the simplified irradiance model and classical sun tracking algorithms, were tested by accurately measuring the irradiance in the tilted plane of three trackers. Row-to-row shadowing while measuring the incident irradiance was avoided in this setup.

The evaluation of Diffuse Control in terms of production was performed using real-world plant installations. Diffuse Control model was implemented in a plant contiguous to another photovoltaic installation where standard solar tracking was applied, as represented in Figure 3. The location of both plants corresponds to a Mid diffuse level in terms of capturable irradiance based on the Typical Meteorological Year (TMY). Their similar location minimizes the differences in cloud effects and irradiance captured by photovoltaic panels. Data spanning an entire year was collected to provide a more accurate comparison and more reliable outcomes.

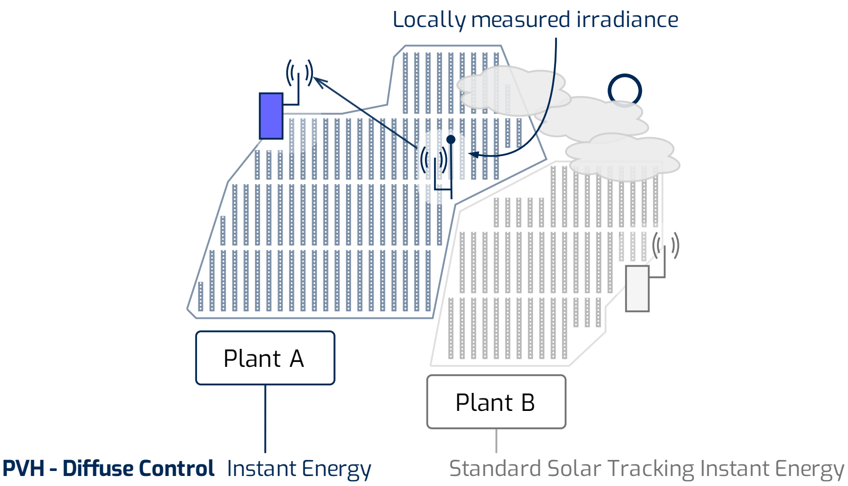

Figure 3. Implementation in real plants

Dynamic Step

With the aim of creating the most efficient technology during diffuse irradiance conditions, PVH developed **Dynamic Step**. This algorithm complements Diffuse Control advanced models.

Fix stepping is the widely extended approach where trackers move a fixed number of times gradually and slightly. However, this approach entails many unnecessary movements during overcast weather conditions. Moreover, it does not adapt to varying irradiance conditions, preventing a more accurate pointing towards the sun beam which would lead to significant energy gains.

Dynamic step applies a strategy based on selective updates. With Dynamic step, the setpoint is only updated when it is profitable in terms of relative energy capture. In other words, Dynamic step reduces the motor movement, and therefore, the motor consumption, by analyzing captured irradiance on-the-go.

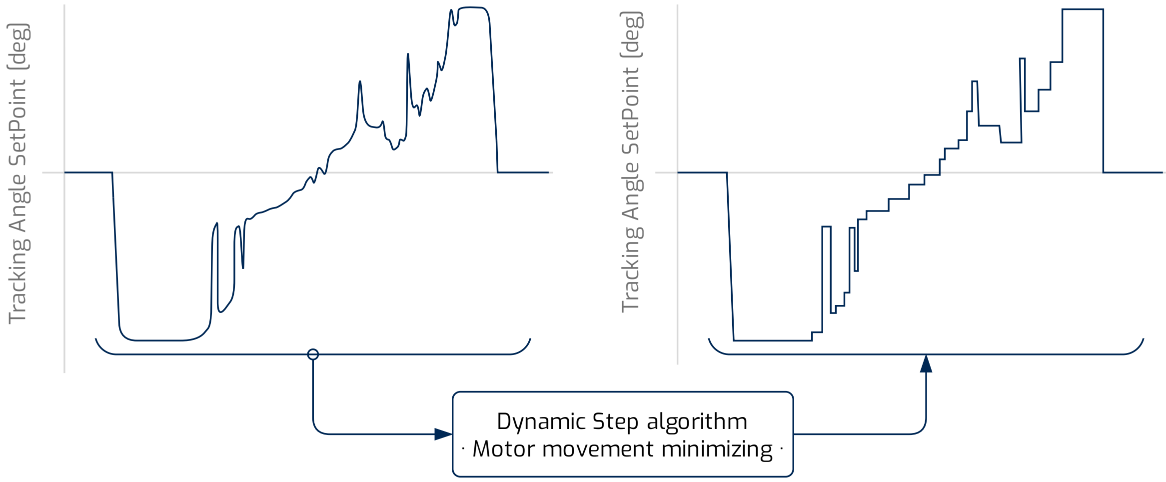

Figure 4. Tracking angle setpoint variations without Dynamic Step (left) and with Dynamic Step (right)

// Diffuse Control implementation results

Analysis was completed from the theoretical point of view as well as from the practical point of view since both analytical and empirical evidence were identified.

From the energy production standpoint, the algorithm that maximizes gains specifically during periods of predominant diffuse irradiance was identified. More advanced irradiance models such as Diffuse Control can capture sun irradiance with a much better performance. More energy is captured throughout the advanced irradiance model than throughout the widely used simplified irradiance model.

The empirical test performed outdoors by PVH over several months compared the irradiance captured by three trackers with different irradiance models. The findings revealed that in diffuse irradiance conditions, the Diffuse Control model captured more irradiance.

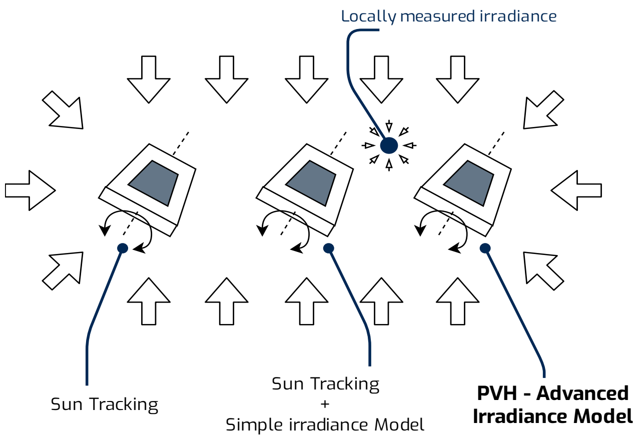

Figure 5. Irradiance capture experiment

Diffuse Control production analysis

Further simulations were conducted through DNV tools to calculate the energy gain in twelve theoretical 100 MWp plants. The plants diffuse level, terrain type and latitude were different to compare the gains.

Latitude (°)	Diffuse level	Terrain type	Gain (%)
57.1	High	Flat	1.088
		Uneven	0.738
51	High	Flat	0.827
		Uneven	0.578
37.72	Mid	Flat	0.260
		Uneven	0.173
0	Mid	Flat	0.181
		Uneven	0.138
37.42	Mid	Flat	0.135
		Uneven	0.105
-23.79	Low	Flat	0.010
		Uneven	0.001

Figure 6. Gain overview

The figures presented below demonstrate that the implementation of Diffuse Control results in higher and more consistent gains in different latitudes.

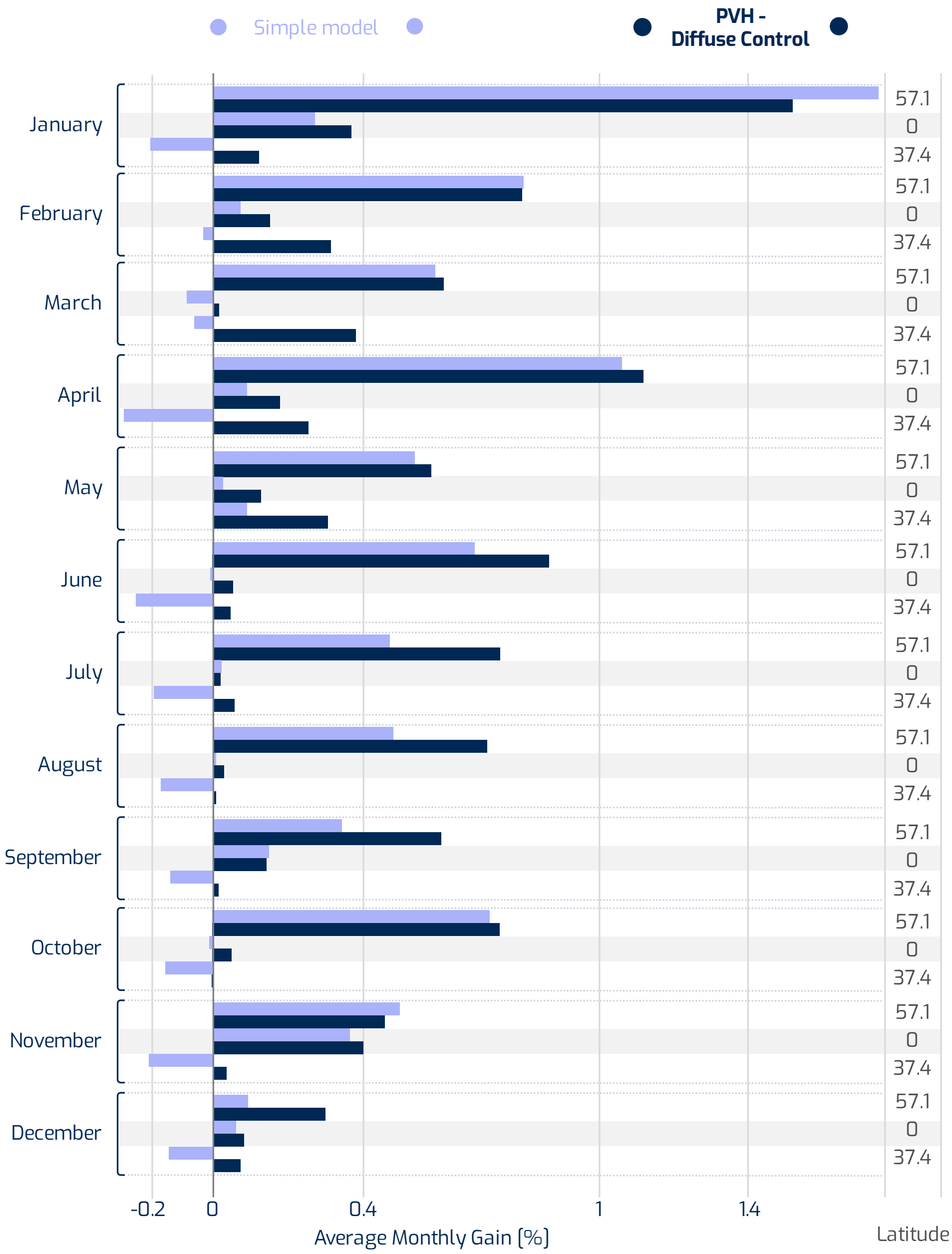

Figure 7. Average gain comparison between Simple irradiance model and Diffuse control model per month

Latitude [°]	Simple model [%]	PVH Diffuse Control [%]
57.1	0.65	0.738
0	-0.122	0.138
37.4	0.081	0.135

Figure 8. Average monthly gain comparison between Simple irradiance model and Diffuse control model

The annual accumulated gain and the performance ratio average gain for latitudes 57.1, 0 and 37.4 when Diffuse Control technology was applied were also calculated. The results per month are shown in the following figure:

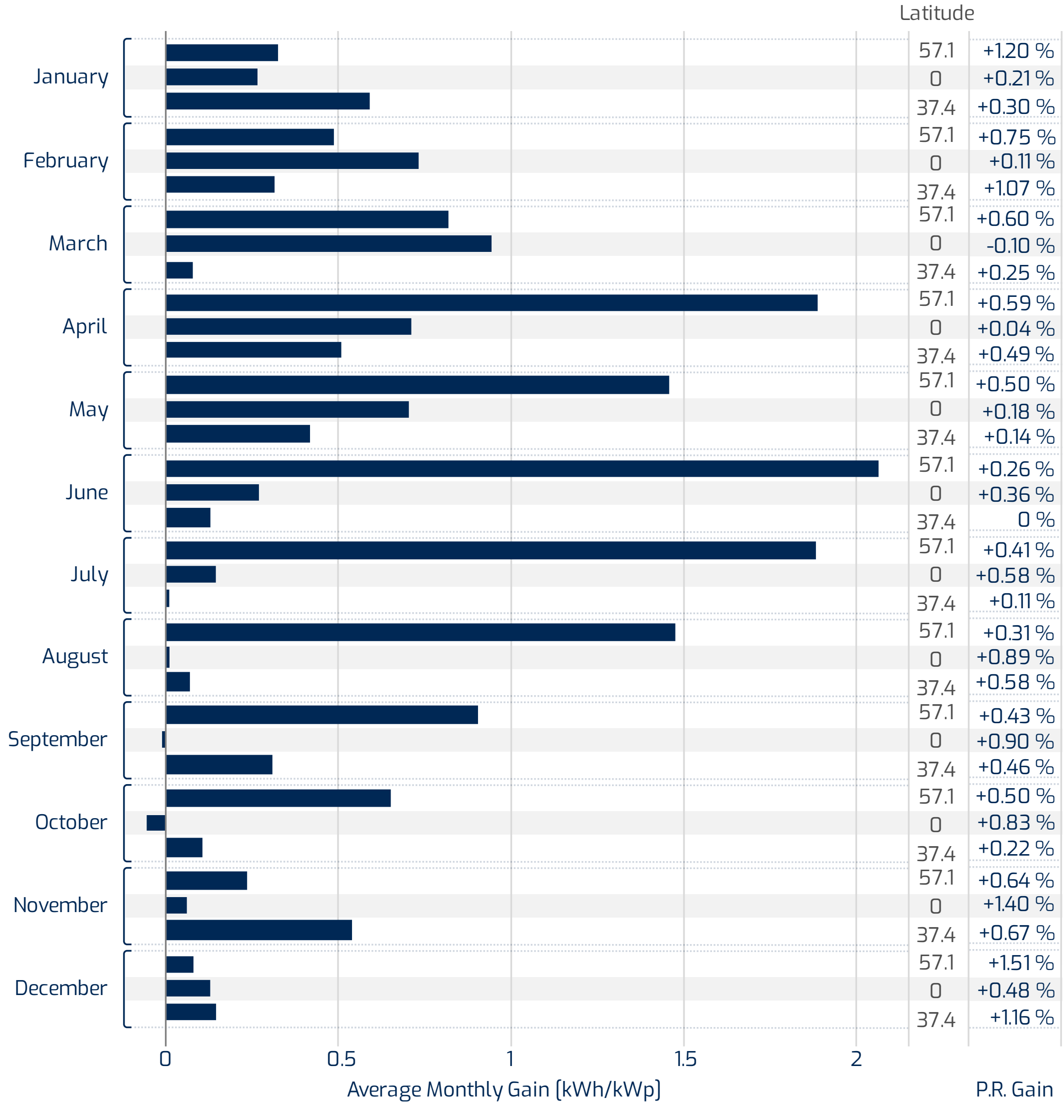

Figure 9. Average gain per month

Latitude (°)	Annual accumulated gain (kWh/kWp)	Performance ratio average gain (%)
57.1	12.24	0.65
0	3.92	0.47
37.4	3.2	0.45

Figure 10. Annual accumulated gain and performance ratio average gain per latitude

Dynamic Step analysis

PVH utilized advanced calculations and simulations to accurately determine the amount of captured irradiance and the subsequent increase in energy production across six hypothetical 100 MWp solar power plants, each situated at distinct latitudes.

		Captured Irradiance Gain (%)		
Latitude (°)	**Diffuse Level**	**Simple model**	**Diffuse Control without Dynamic Step**	**Diffuse Control with Dynamic Step**
57.1	High	0.755	1.045	1.022
51	High	0.455	0.665	0.646
37.72	Mid	0.087	0.193	0.186
0	Mid	0.094	0.345	0.331
-23.8	Low	-0.029	0.017	0.015
37.42	Mid	0.037	0.139	0.132

Figure 11. Captured irradiance

The application of Diffuse Control resulted in an increased capture of irradiance, and the implementation of Dynamic Step further improves the efficiency since it reduces the motor consumption. In terms of motor consumption, the performance of Dynamic Step surpasses that of simple model fix stepping in every simulated analysis, resulting in lower motor consumption.

		Motor Energy Consumption Gain (%)		
Latitude (°)	**Diffuse Level**	**Simple model**	**Diffuse Control without Dynamic Step**	**Diffuse Control with Dynamic Step**
57.1	High	-14.95	-13.89	-31.91
51	High	-4.25	-8.57	-24.43
37.72	Mid	11.33	-3.38	-12.52
0	Mid	3.25	-6.48	-18.52
-23.8	Low	17.35	0.84	-1.45
37.42	Mid	19.09	0.04	-6.26

Figure 12. Motor energy consumption gain

Diffuse Control production analysis in real plants

The results obtained in the two real contiguous plants where standard solar tracking and the Diffuse Control model were implemented showed that the plant where Diffuse Control technology was applied (Plant A) captured more irradiance, resulting in a higher production and energy gain. The plant with simple solar tracking algorithm was considered as reference in terms of production.

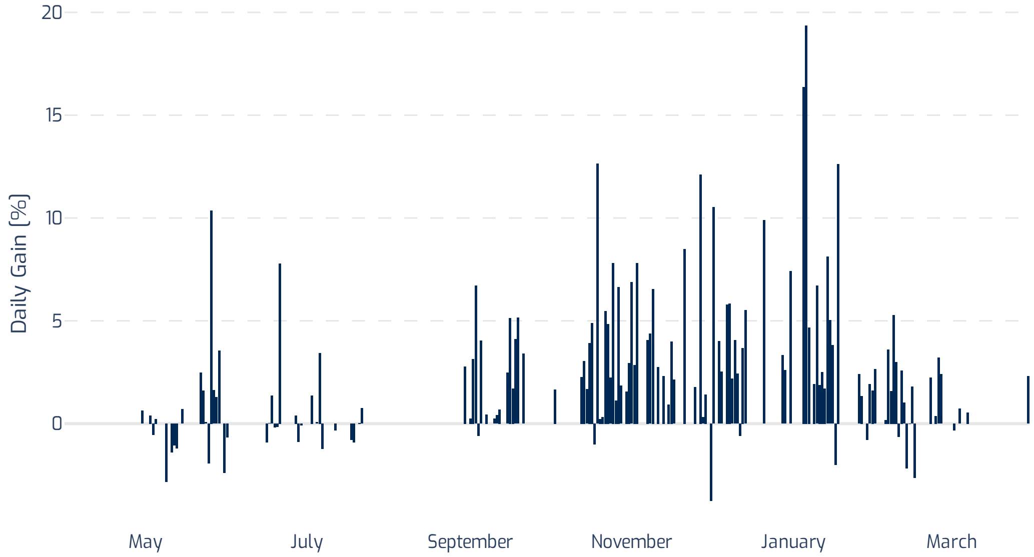

Figure 13. Diffuse Control daily gain comparison between plant A (Diffuse Control) and plant B (Standard solar tracking)

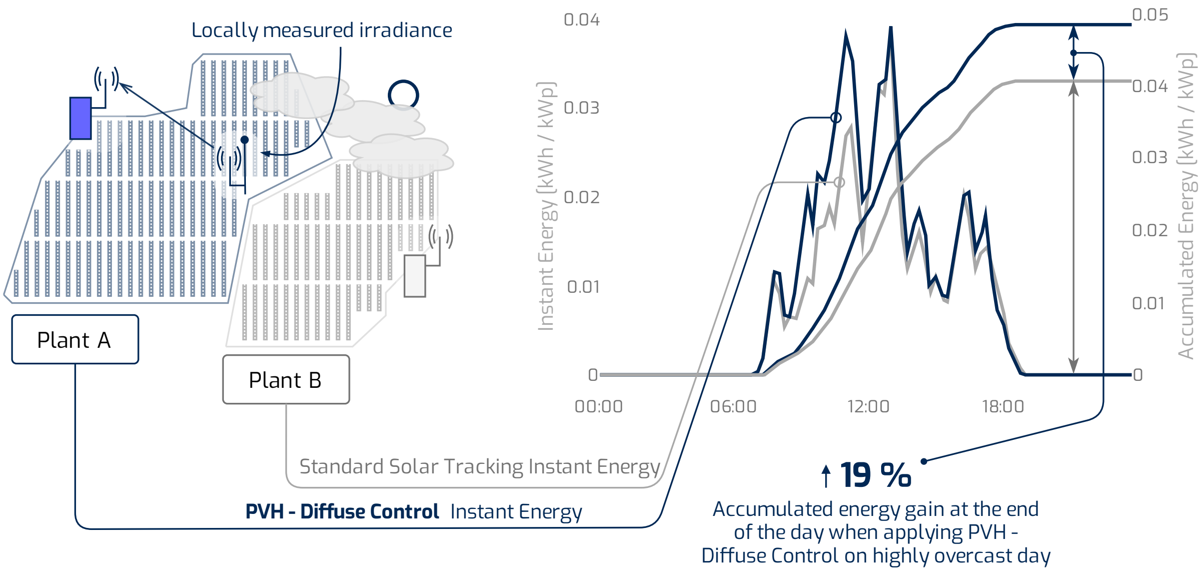

Figure 14. Accumulated energy gain during a highly overcast day

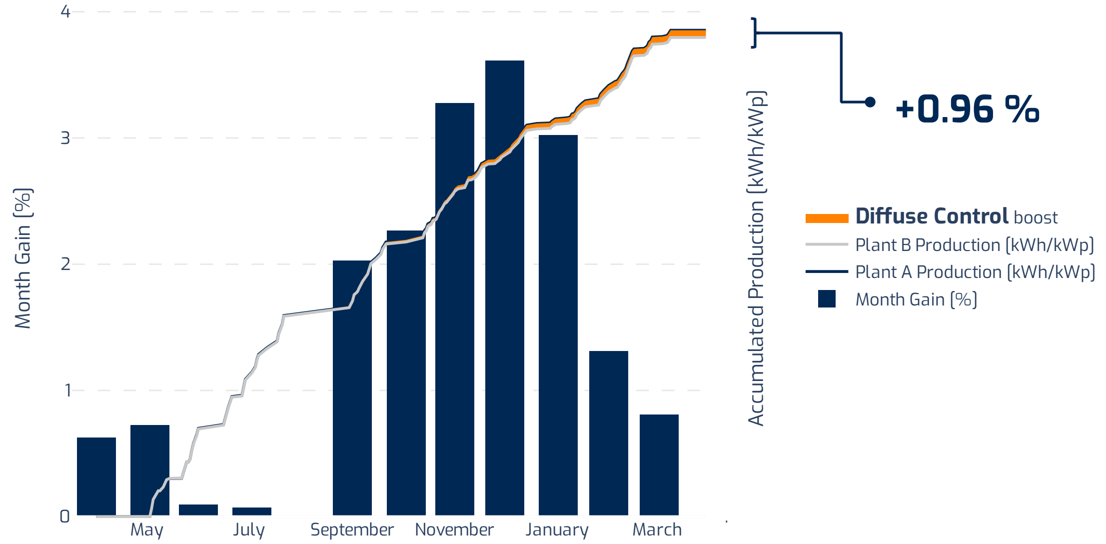

Figure 15. Diffuse Control monthly gain and accumulated production comparison between plant A (Diffuse Control) and plant B (Standard solar tracking)

// Discussion

According to both DNV[1] and PVSyst[2] references, irradiance is compounded by more than isotropic effects within diffuse sky irradiance. Simple models only consider diffuse irradiance to be isotropic. This leads to an unproper maximization of captured irradiance, as it sets the diffuse position to horizontal.

Using DNV software for plants production simulation, the side effects of that misconception of diffuse irradiance can be noticed. Simple irradiance models commonly implemented can even cause negative gains and energy lost at the end of the year.

More advanced irradiance models such as Diffuse Control can capture sun irradiance with a much better performance, as demonstrated through different methods in section **//** Diffuse Control implementation results.

The Diffuse Control is a global plant control mechanism. This means that the optimal tilts calculated by the algorithm will be commanded to every tracker across the entire plant.

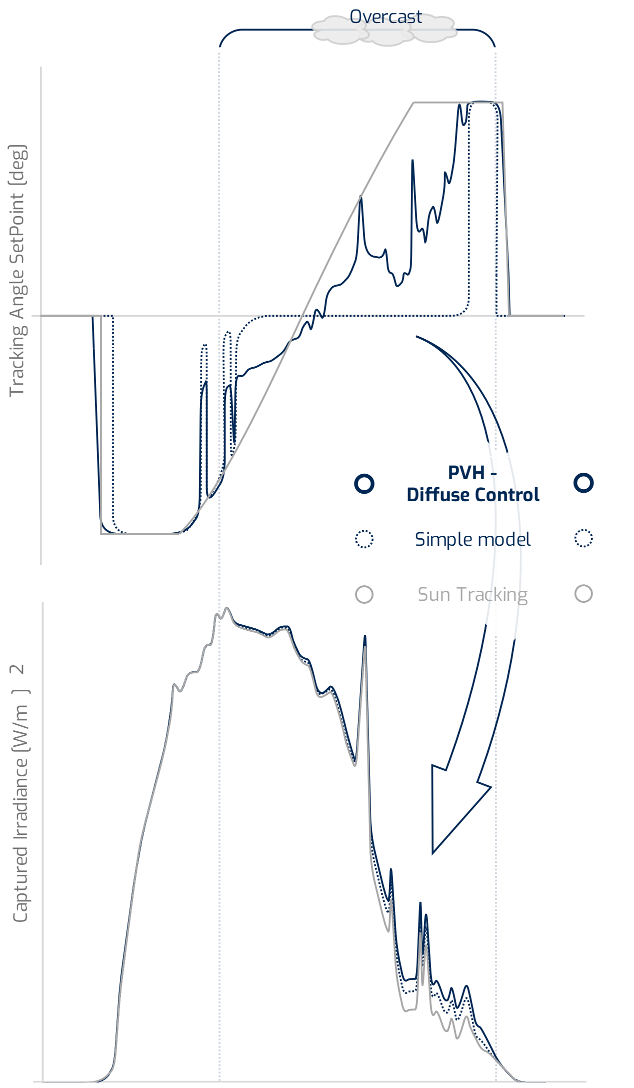

Figure 16. Tracking Angle Setpoint and Captured Irradiance for Sun Tracking, Simple and Diffuse Control models

The first step of the implementation of the Diffuse Control algorithm is to define the category of the plant according to PVH diffuse level categorization system. Secondly, the Diffuse Control kit must be installed on the tower where PVH meteorological monitoring device is and connected to it. The tower must be in a significant location of the plant to improve its outreach. Diffuse Control kit periodically provides information about the composition of the area irradiance. PVH TBox solution must be then configured to receive the information from the Diffuse Control kit (as shown in Figure 17). TBox holds the logic of the Diffuse Control as well as the plant parameters.

Upon receiving irradiance data, Diffuse Control applies the PVH Advanced irradiance model according to the plant's configuration parameters. The configuration process verifies whether Dynamic Step should be considered to prevent excessive motor consumption that may lead to an inadequate interaction

[1] DNV – SolarFarmer. *Calculation Reference*. Retrieved February 16, 2023, from https://myworkspace.dnv.com/download/public/renewables/solarfarmer/manuals/latest/CalcRef/Theory/Transposition.html

[2] PVsyst. *Transposition model*. Retrieved June 28, 2024, from https://www.pvsyst.com/help/models_meteo_transposition.htm

with the in-site batteries' energy. Although this algorithm is more efficient during overcast weather conditions, it works whenever irradiance measurements are available.

The Dynamic Step algorithm not only prevents potential false positives that can occur with forecasting or cloud prediction[3], but it also delivers significant benefits when evaluated alongside the Diffuse Control algorithm. This combined approach has demonstrated remarkable gains in captured irradiance, achieving twice the results compared to simple irradiance models. In terms of motor consumption, Dynamic Step performance is more than twice better than the widely extended simple model fix stepping.

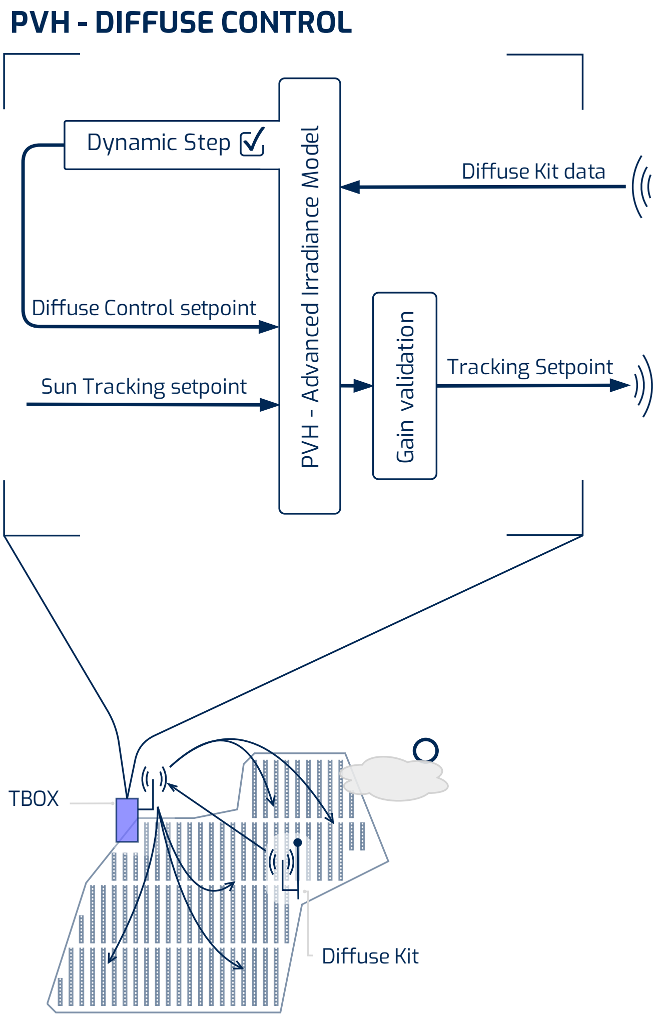

Figure 17. Diffuse Control integrated solution

Subsequently, the optimal setpoint for the measured irradiance data is determined, while the Sun Tracking algorithm independently establishes its own setpoint. Both the Sun Tracking and Diffuse Control setpoints utilize the PVH Advanced irradiance model to calculate the gain in captured irradiance. This step of the sequence, "Gain validation", determines whether the Diffuse Control setpoint is profitable or whether Sun Tracking approach provides the same theoretical gain or more.

The application of the final tracking setpoint is contingent upon the absence of hazardous conditions, such as strong wind or snow, within the plant. When considering wind conditions, it is crucial to avoid the use of a horizontal setpoint approach due to the potential risk of fluttering. Diffuse Control setpoint differs from horizontal, preventing possible fluttering. Notably, wind gusts are more prone to occur during overcast periods, making the Diffuse Control solution a safer alternative to horizontal setpoint approaches.

The research and development of this advanced irradiance model led to increased gains in comparation with simple models which set the tracker setpoint to 0° during overcast conditions. Diffuse Control can improve annual produced energy gains up to 0.3 % compared to horizontal setpoint solutions. Diffuse Control solution can increase plants production by over 1 % at the end of the year, with peaking months of more than 1.5 % increased production, compared to conventional solar tracking.

[3] Antonanzas, F., Antonanzas, J., Martinez-de-Pison, F.J., Urraca, R., (2018) Optimal solar tracking strategy to increase irradiance in the plane of array under cloudy conditions: A study across Europe. *Solar Energy*, *163*, 122-130. https://doi.org/10.1016/j.solener.2018.01.080

During continuous overcast conditions, Diffuse Control can boost gains more than 19 %. This strategy not only increases production gains: **Dynamic Step algorithm combined with Diffuse Control can also provide a 30 % motor consumption reduction compared to conventional sun tracking and, in comparation with horizontal setpoints for overcast days, motor consumption is significantly decreased**. In terms of plant efficiency, Diffuse Control strategy showed improvements in Production Ratio up to 0.65 % compared to conventional solar tracking algorithms.

As shown in the results of the implementation of Diffuse Control technology in a real plant, the period between September and March is marked by adverse climatic events. It is during these events that the Diffuse Control algorithm significantly enhances production. This increase can be observed in Figure 13 and Figure 15.

As seen in Figure 15, the resulting gain at the end of the year, plant A with Diffuse Control algorithm produced **extra 0.96 %** compared to contiguous plant B, without it. Figure 15 shows the evolution of the accumulated normalized production of each plant. At the end of the evaluation period, these accumulated productions clearly show the positive impact of the Diffuse Control solution and how it retrieved positive gains all throughout the year, being most significant during adverse weather periods.

With Diffuse Control, energy production increases, and that directly translates into **economic profit**. Considering the analysis of the obtained results in DNV software, the effect of applying Diffuse Control in a theoretical 100-MWp plant was emulated. The revenue differs depending on the location.

In the table below, the economic analysis of the three previously mentioned, applied locations can be observed to find an estimation of the extra revenue which Diffuse Control could provide:

Latitude (º)	Gain (kWh/kWp)	Extra energy (MWh) for a 100 MWp plant	Revenue (USD) considering the energy price at 60 USD/MWh
57.1	12.24	1224	+73440
0	3.92	392	+23520
37.4	3.2	320	+19200

Figure 18. Economic analysis per latitude

If we estimate, using conservative values according to the International Energy Agency[4], that the solar energy price is 60 USD/MWh, the benefit of installing and enabling PVH Diffuse Control strategy can lead to extra annual gains over 70,000 USD or around 19,000 USD for 100-MWp plants.

[4] SolarPower Europe. *Global Market Outlook For Solar Power 2023 - 2027.* Retrieved July 3, 2024, from https://www.solarpowereurope.org/insights/outlooks/global-market-outlook-for-solar-power-2023-2027/detail

// Conclusion

PVHardware Diffuse Control solution was developed to boost the Sun energy harvest and adapt to weather variations. Thanks to Diffuse Control algorithm, the trackers are always oriented towards the direction from which they get the greatest amount of energy possible when diffuse light predominates.

Through in-site irradiance measurements captured by the Diffuse Control kit, PVH TBox controller optimizes the plant tracking setpoint. Diffuse Control algorithm holds advanced irradiance models and motor movement strategies such as de Dynamic Step solution to maximize captured irradiance while minimizing motor consumptions through the year.

In terms of economic impact, an analysis was carried out. For 100-MWp plants located in regions classified with high diffuse level, the implementation of Diffuse Control can result in generating revenue exceeding 70,000 USD. This estimation is based This estimation is based on the energy prices up until the current date of this document. Throughout an AI developed model with a given location TMY, the plant diffuse level and its revenue range can be determined. In an intermediate diffuse level location, this revenue can vary from 10,000 to 20,000 USD per year.

PVH has selected the best irradiance calculation method, it has been tested in real plants, and the energy gains in absolute terms has been confirmed. Furthermore, PVH can determine whether implementing the algorithm in a specific plant would be beneficial. This profitability can be then identified at an early stage thanks to the diffuse level categorization system. Finally, by implementing very simple requirements, energy production can be enhanced from the first day.

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