Optimisation of Photovoltaic Systems for Different Climates

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Executive Summary

The impressive worldwide growth in installed photovoltaic (PV) capacity is mainly driven by cost reductions and progress in cell and module technology. This growth is also advanced by increasing global energy demand and the urgent need to combat climate change and reduce dependence on fossil fuels. This has led to PV systems recently being built in harsh climates and becoming economically attractive where they were not previously a viable option. Deserts and tropical zones, as well as cold and snowy regions - once considered either challenging or not affordable for energy production - are today recognised for their significant PV potential. These areas offer high or at least seasonally favourable solar irradiance levels, which can lead to consistent or enhanced energy production.

Large-scale PV deployment in desert climates like the Middle East, North Africa, Northern India, and the Atacama Desert, where high irradiance levels and vast land spaces are available, started already in the early 2000s. In recent years, driven in part by the introduction of bifacial modules, the PV market has also expanded rapidly to latitudes above 40°N, such as the North of America, Europe, and Asia. More recently, PV at high altitudes, such as in the European alpine countries as Switzerland and Austria, where space for ground-based systems is limited and an increase in winter production from renewables is envisaged, has gained interest. The tropical PV market has also grown, driven by rising energy demand and an increasing commitment to renewable energy, combined with consistent daily sunlight near the equator. However, the scarcity of land has favoured the installation of PV on buildings or floating PV over utility-scale ground-mounted systems.

The increasing deployment of PV installations in these very different geographical regions presents numerous challenges in design, commissioning, and operation. Therefore, climate-specific strategies are crucial to address environmental stressors affecting energy yields, module lifetime, and system efficiency. While the design and operation of climate-specific PV systems have progressed, research and innovation must continue to enhance the efficiency, durability, and cost-effectiveness in a wider range of environments. The goal is to ensure that PV can be a reliable energy source regardless of local weather patterns or environmental challenges.

This report specifically explores strategies for enhancing the performance and reliability of PV systems in harsher climates: 'Cold & Snowy', 'Hot & Dry', and 'Hot & Humid'. Guidance is provided to PV system developers on the selection of the most suitable PV module technology by assessing theoretical and real-world energy yield data, performance losses and degradation rates across different climates. The key climate-specific environmental stressors and existing mitigation strategies are reported. Details are given for optimising module and system design for each environment, starting from the site assessment, followed by the component selection, and finally the system design. Case studies showing practical approaches and experience to mitigate risks and optimise performance for each climate are presented. One of the aspects to be considered at the beginning of a PV project design is the selection of the best PV module technology for a specific climate. The implementation of the IEC 61853 PV module energy rating (ER) standard series IEC 61853 provides the end-users with an easy and repeatable method for comparing different products for their energy yield. In addition, it delivers all relevant PV module parameters to increase the accuracy of energy predictions and foster innovation. It can be used by module manufacturers to maximise the energy yield, and not just the efficiency, of the various PV cell and module technologies for different climatic conditions. The increasing number of ER-related publications and the ongoing efforts to introduce a European Energy label for PV modules, described within this report, demonstrates the growing interest and need for standardised and climate-specific energy yield assessment tools.

However, the ER as present today does not give any indication about the long-term reliability of a PV module, which depends on many other aspects such as the bill of material (BOM) and manufacturing process. The degradation rate expressed in percentual power loss per year is needed to determine the payback time and lifetime energy production of a PV project. The inclusion of the degradation rate of PV modules into the ER concept however still represents a bottleneck. In the absence of a standardised approach to assessing the PV module degradation rate, the de-rating information (rate and years) stated in the power warranties are currently used. These are however mainly representative for moderate climates and do not reflect real degradation rates. For example, tropical regions typically show higher degradation rates, whereas colder climates show lower values. How to assess climate-specific degradation rates and include them in the current energy rating approach is still under discussion within the research community.

Understanding PV losses and planning adequate mitigation strategies require a good knowledge of the climate- or site-specific stressors. These start with site assessments, which can be carried out either through specific field campaigns, such as deploying sensors in the field, by collecting data from nearby PV installations, or by analysing satellite/re-analysis data. The early identification of stressors is crucial for all subsequent phases, from the selection of the components through the system design up to the definition of the most cost-efficient O&M strategy. Based on this information, a conscious selection of PV system components and of PV module types is possible.

In cases where knowledge about site-specific requirements and/or the availability of climate-specific PV modules is lacking, standard products are often deployed with a high risk of under-performance or high susceptibility to failures. For instance, the failures occurring in the first desert installations highlighted the need to develop PV encapsulants which can withstand the high irradiation at increased temperatures of that environment. Furthermore, the push for cheaper modules has driven the trend toward larger PV modules with thinner glass, cheaper encapsulants and backsheets, and reduced frame thickness, which are nowadays increasing the degradation and failure rates in harsh environments.

While existing climate specific testing procedures are described and discussed in more detail in a dedicated IEA PVPS TASK 13 Report "Accelerated testing - combined vs. sequential testing and inclusion of specific load situations", this document gives recommendations on the need to select PV modules with known BOM and tested for the specific climate in which they will be installed. Solutions like thicker front glass in glass/glass modules, innovations in module design like new frame geometries, micro-crack-resistant cell interconnection technologies, or encapsulants with lower glass transition temperatures - such as POE or silicone - improve resistance to mechanical stress in harsher environments. Special coatings, such as anti-soiling or heat-dissipating coatings for deserts, snow-repellent coatings for cold climates, or corrosion-resistant coatings for humid environments, are used or under investigation. Although promising, further studies are needed to prove their durability and cost-effectiveness.

Often, mitigation measures aimed at addressing one issue can inadvertently exacerbate another, making it essential to conduct thorough testing or gain a deeper understanding of actual load conditions to identify the most effective solution. For instance, frameless modules are designed to shed snow more efficiently but have a lower mechanical stability and vice versa. The choices in the system design influence the type of modules and components which can be used. Climate-specific system design is often the key to further reducing the risks of underperforming PV systems. The orientation of PV modules and mounting structures play not only a crucial role in performance but can also impact the reliability and lifetime of a system. Mounting structures in cold and snowy regions are typically the most complex and costly, due to high structural demands and the need to manage large snow loads and ice formation. Soiling, although of very different origin for the three climates (e.g. snow, dust, or biological soil), is one of the main factors affecting performance, degradation, and system design. Soiling loss modelling is increasingly employed to predict and mitigate soiling-induced energy losses, though accurately isolating soiling effects remains a challenge. In hot and arid climates, systems must be designed to facilitate cleaning, with requirements varying based on the selected business model. In equatorial locations, soiling losses can be so severe that steeper-than-optimal tilts may be preferable to reduce accumulation, despite the lower irradiation. In cold climates, high tilt angles and sufficient ground clearance help minimise snow accumulation and shading, while snow fences and snow transport simulations further prevent unwanted build-up. The table below provides an overview of stressors, their effects in different climates, and mitigation strategies, described in more detail within the report.

This report aims to raise awareness about the risks associated with specific stressors and highlights how developing climate-specific strategies is essential to enhance the reliability and cost-effectiveness of PV systems worldwide. It shows how innovation in module design, adaptation of bill of materials, and system configurations can support the further deployment of PV systems in harsher climates. Experience with climate-optimised PV modules is still limited, requiring more field data and lessons learned to be exchanged within the PV community.

Table 1: Climate specific stressors, failures and mitigation measures.

Stressors	Failures	Cold & Snow	Hot & Arid	Hot & Humid	Mitigation Measures
Low temperatures	Embrittlement of materials, cracking of encapsulant and solder joints	high	-	-	Use of flexible encapsulants and back sheets
Extreme temperature fluctuations	Thermal cycling cracks (solder joints, inter-connections)	low-medium	low-medium	low-medium	Use thermally stable materials, reinforced interconnections
Mechanical Stress (Snow, Ice, Wind, Sandstorms)	Glass breakage, frame deformation, cell cracks, (severe) power loss	high (snow load)	high (sandstorms)	-	Strengthened module frames, thicker glass, special coatings, smart tracking (for wind or snow)
UV Exposure	Backsheet cracking, encapsulant yellowing, loss of adhesion	low-medium (high altitude)	high	low-medium	UV-resistant cells, backsheet and encapsulant materials
Moisture Ingress & Humidity	Corrosion (junction box, interconnections), delamination	low-medium (frost)	-	high	Edge sealants, high barrier backsheet, improved lamination techniques, moisture resistant cells
High Operating Temperatures	Hot spots, microcracks, encapsulant degradation	-	high	medium	Optimised ventilation, high-temperature-resistant encapsulants
Soiling	Power loss, surface degradation, hot spot	high (snow load)	high (dust, sand)	high (biofilm)	Frameless modules, self-cleaning coatings, scheduled cleaning, tilted installation to minimise accumulation of snow or dust
Salt Mist	Corrosion, electrical insulation failure, PID	-	High (coastal)	High (coastal)	Anti-corrosion coatings, PID-resistant materials, sealed junction boxes

Key Takeaways

1. In cases of limited knowledge about site-specific requirements and/or unavailability of climate-specific PV modules, standard products are often deployed. Furthermore, the push for cheaper modules has driven the trend toward larger PV modules with thinner glass, cheaper encapsulants and backsheets, and reduced frame thickness, which are nowadays increasing the degradation and failure rates in harsh environments.
2. Reinforced front glass, improved frame geometries, micro-crack-resistant interconnections, and advanced encapsulants like POE or silicone enhance durability in harsh conditions. Special coatings for soiling, heat, snow, or corrosion are being explored, but further studies are needed to confirm their longevity and cost-effectiveness.
3. Very often, mitigation measures aimed at addressing one issue can inadvertently exacerbate another, making it essential to conduct thorough testing or gain a deeper understanding of actual load conditions to identify the most effective solution.
4. Experience with climate-optimised PV modules is still limited, requiring more field data and lessons learned to be exchanged within the PV community.

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