



IEA PVPS Task 13
Reliability and Performance of PV Systems



Optimising PV Reliability

Across Climates, Latitudes, and Applications

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1 | Why optimize PV Systems?

New environments, technologies and reliability challenges

2 | Climate-specific optimization

Stressors, failures and design strategies

3 | PV at high latitudes

Arctic conditions, snow and reliability

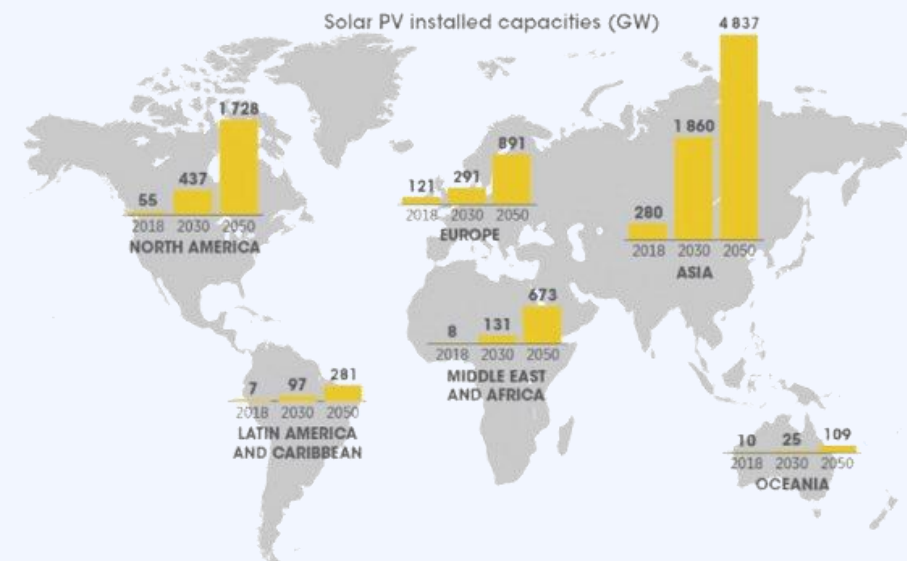
4 | PV systems for integrated applications

BIPV, FPV and agrivoltaics

1. Why optimize PV Systems?



PV in different climates



The world solar PV installed capacity by 2050 (IRENA, 2019).

Key challenges



Climate-specific design

e.g. desert, alpine and high-latitude modules



Tailored testing methods

e.g. for sand, snow, wind, ice



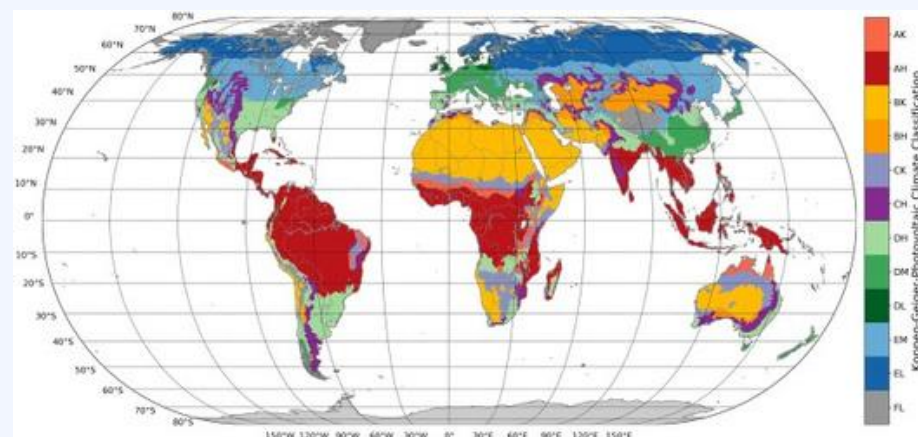
Field data availability

e.g. alpine and Arctic environment, climate-specific degradation rates

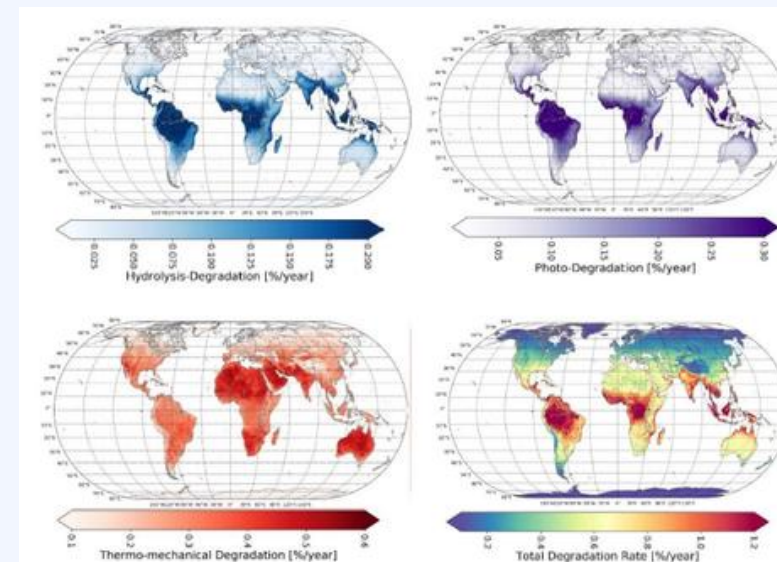


Climate change

increase of catastrophic events



Köppen-Geiger-Photovoltaic climate classification with the 12 most relevant climate zones (Julián Ascencio-Vásquez). <https://doi.org/10.1016/j.solener.2019.08.072>



Global mapping of degradation mechanisms. a) Hydrolysis-degradation, b) photo-degradation, c) thermomechanical degradation, and d) Total degradation rates for a specific monocrystalline silicon PV module using the Kaaya model.

1. Why optimize PV Systems?



PV in different applications



Key challenges



Diversification of products

e.g. coloured, curved, light-weight, semi-transparent,
...



Multifunctionality

e.g. insulating, noise absorption, water tightness



Complexity of system design

e.g. mounting structures, integration, replaceable



Lack of field data

field stressor data, degradation rates

1. Why optimize PV Systems?

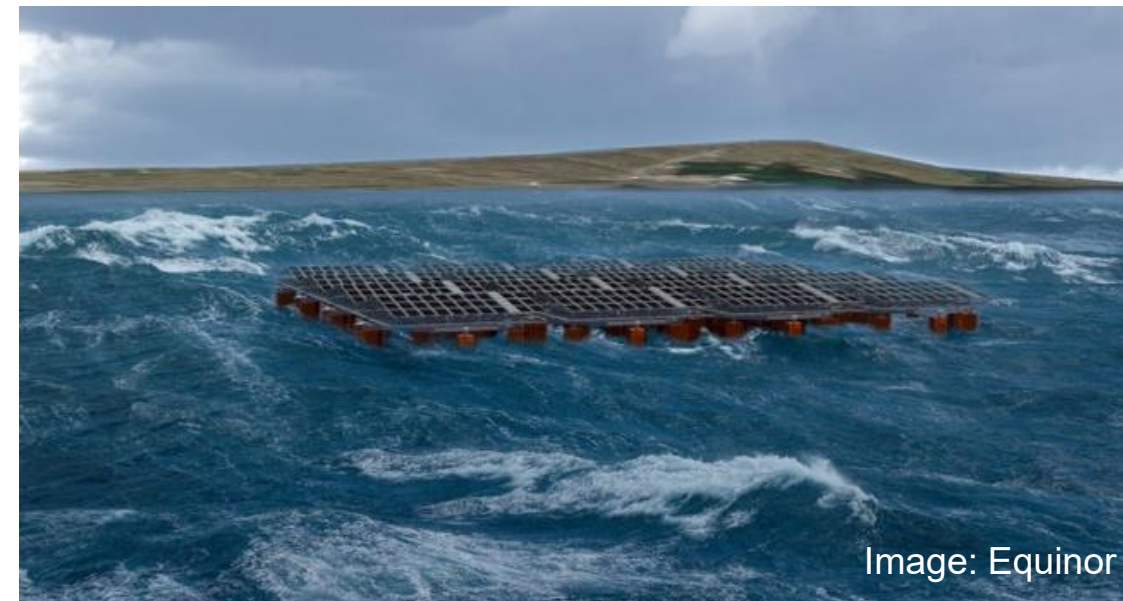


Technology trends towards **higher efficiencies and lower costs** are main drivers for:

- Integration of PV in new environments (from BIPV to IPV, FPV, AV, VIPV,...)
- Numerous innovations in module design (coloured, lightweight, curved,...)

But!

- Module environments are getting more challenging and testing more complex
- Field experience is partially lagging behind, leading to an increased number of failures



2. Climate-specific optimization



Climate-specific stressors: Each climate has its own stressors



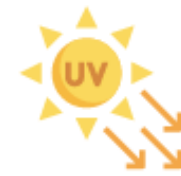
Extreme Temperature
Fluctuations



Low Temperatures



Mechanical Stressors
(Snow, Ice, Wind)



UV Exposure



Humidity



High Temperatures



Soiling



Salt Mist

Design challenges: Tailored, climate-specific system design and mitigation strategies are essential for maximizing PV lifetime and return on investment.

2. Climate-specific optimization



Approach

- 1

Understand the risks

Raising awareness about the risks associated with specific stressors
- 2

Develop climate-specific strategies

Highlighting how developing climate-specific strategies is essential to enhance the reliability and cost-effectiveness of PV systems worldwide
- 3

Adapt PV design

Showing how innovation in module design, adaptation of bill of materials, and system configurations can support the further deployment of PV systems in harsher climates

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 (sand-storms)	-	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 backsheet and encapsulant materials
Moisture Ingress & Humidity	Corrosion (junction box, interconnections), delamination	low-medium (frost)	-	high	Edge sealants, high-barrier backsheet, improved lamination techniques
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	-	High (coastal)	High (coastal)	Anti-corrosion coatings, PID-resistant materials, sealed junction boxes

2. Climate-specific optimization



The study identifies key stressors and provides recommendations to address them.

Hot & Arid Climate

Stressors

- Soiling
- High Temperatures
- Thermal Cycling
- Salty Mist
- **UV Irradiation**
- Strong Winds
- Dust and Sandstorms

Site assessment

- Assess soiling, temperature, wind, and soil properties early.

Optimization of module design and BOM

- Use heat/UV-resistant modules with low temperature coefficients.
- Prefer POE/TPO over EVA to avoid corrosion.
- Test components under desert-specific stress conditions.

System design

- Choose cleaning model (own vs. service) & design layout for easy cleaning.
- Adapt system design to local wind conditions and soil corrosion.

2. Climate-specific optimization



Hot & Arid Climate

Best Practices and Mitigation Strategies

- **Assess soiling rates, dust composition, wind load patterns, and temperature swings** using local climate data to plan cleaning needs and optimize system design and O&M strategies for the site.
- Modules should use **UV- and heat-resistant encapsulants and backsheets, thicker glass for sand protection, and anti-soiling coatings** to minimize cleaning frequency and reduce wear.
- Design for **enhanced ventilation** to lower module temperatures, robust structures for wind and sandstorms, and optimized tilt and spacing to reduce soiling while maximizing energy capture.

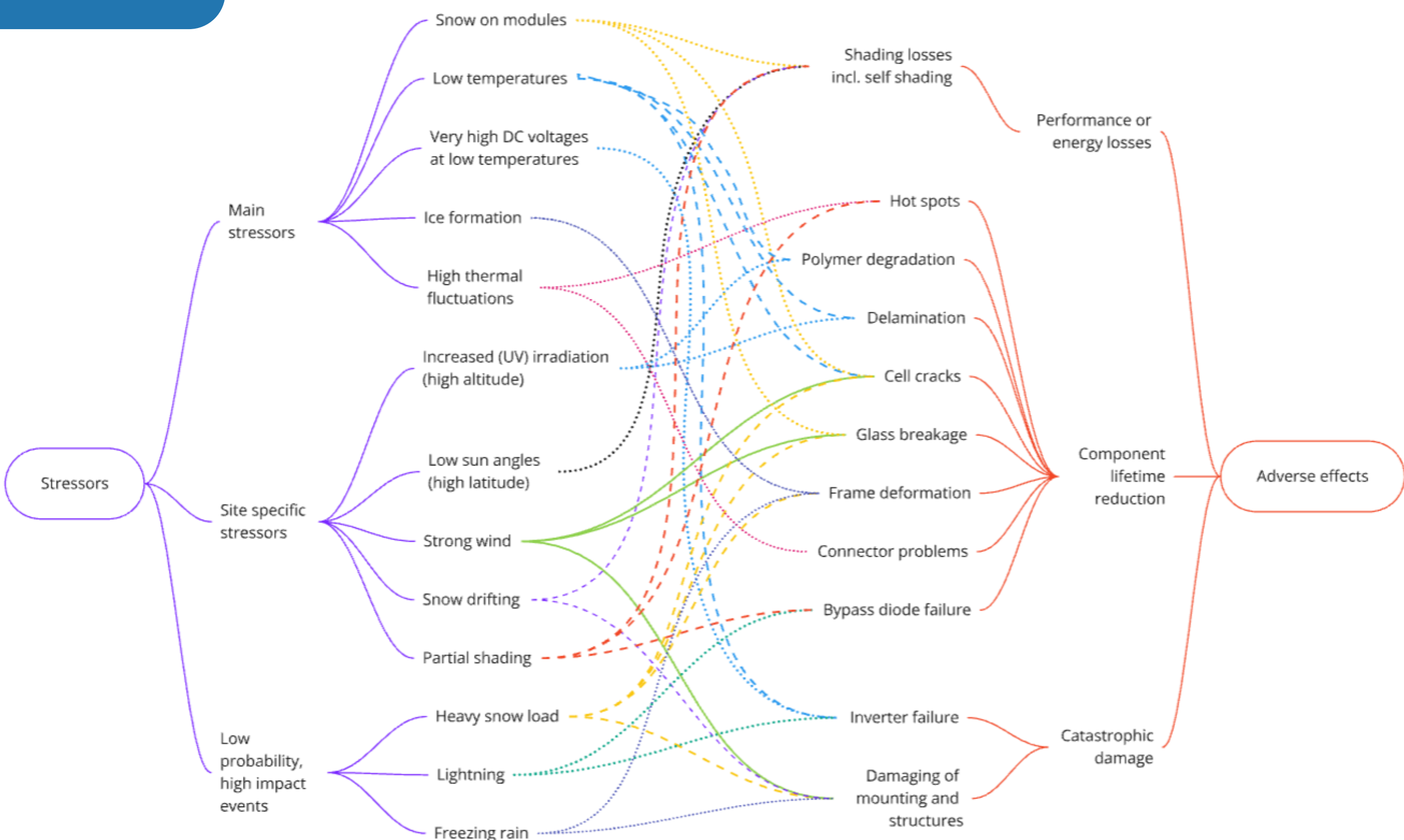


2. Climate-specific optimization



Cold & Snowy Climate

Stressors and their impact on PV power plants



2. Climate-specific optimization



Cold & Snowy Climate



PV system at Wildkogel, Austria
=> Wrong site assessment

Site Assessment

- Assess local snow, wind, UV, fog, and terrain conditions.
- Evaluate risks like avalanches, ice, frost, and site accessibility.

Optimisation of module design and BOM

- Use designs that facilitate snow shedding (e.g., frameless, glass/glass...).
- Consider components & designs less prone to high-UV, snow and/or cold induced stress (e.g., multi wire/busbar modules, thicker joints).

System Design

- Use steep tilt and high clearance for snow shedding
- Choose structures adapted to frost heave; consider snow fences.

2. Climate-specific optimization



Cold & Snowy Climate

Best Practices and Mitigation Strategies

- Perform detailed **snow load analysis**, **wind exposure evaluation**, and **seasonal irradiance studies**. Local weather and historical snow data can be used to anticipate accumulation patterns and drifts.
- Modules should have **reinforced frames**, **thicker glass**, and **flexible encapsulants** to handle snow loads and cold temperatures. **UV-resistant materials** are ideal to withstand high-altitude UV exposure.
- Use **high tilt angles** and **sufficient ground clearance** to reduce snow accumulation, and employ robust racking for snow and wind loads. Shading from snow must be considered when planning cell strings.



Photo credit: HELIOPLANT®



Photo credit: Sedrun Solar

2. Climate-specific optimization



Key takeaways



Standard modules are insufficient

Standard or cost-optimised modules are often deployed despite harsh conditions, increasing the risk of degradation and failure.



Climate-specific materials must be deployed

Reinforced components and advanced encapsulants improve durability, while protective coatings show potential but require further validation.



All solutions require thorough testing and study

Mitigation measures can create trade-offs, making thorough testing and a clear understanding of actual load conditions essential.



Further data gathering will prove essential

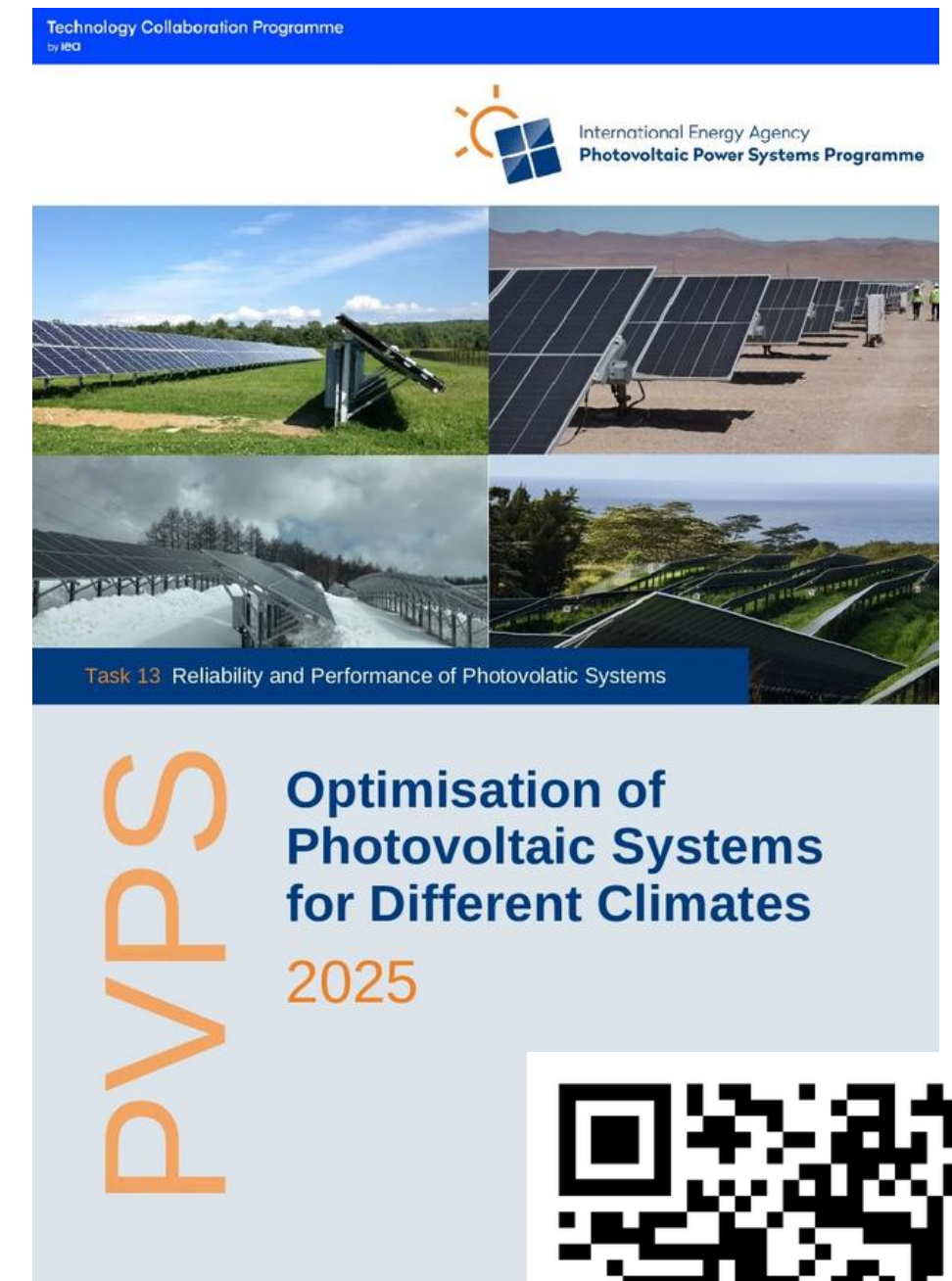
Experience with climate-optimised PV modules is still limited, requiring more field data and lessons learned to be exchanged within the PV community.

2. Climate-specific optimization



Summary

- PV is increasingly deployed across **very different climatic conditions**, from hot deserts and humid tropics to snowy and high-altitude environments.
- **Climate-specific stressors** affect performance and reliability.
- There is **no single optimal PV design** for all climates: module technologies, materials, mounting configurations and system design should be selected according to local conditions.
- This **report provides guidance** for climate-specific PV optimisation, from site assessment to system design and to operation & maintenance.



3. PV at high latitudes



Why PV in the Arctic?



~ **17 million**

people live above 60°N (as of 2026), many rely on imported diesel fuel.



Photo credit: Sunnagroup.com

Challenges:



Dark winters

Months with no/minimal sunlight above Arctic Circle



Extreme weather

Heavy snow loads, high winds, extreme cold affect reliability



Effects on materials

Material property changes at low temperatures (e.g., EVA glass transition at -15°C)



Remote locations

High shipping, installation, and O&M costs



Isolated microgrids

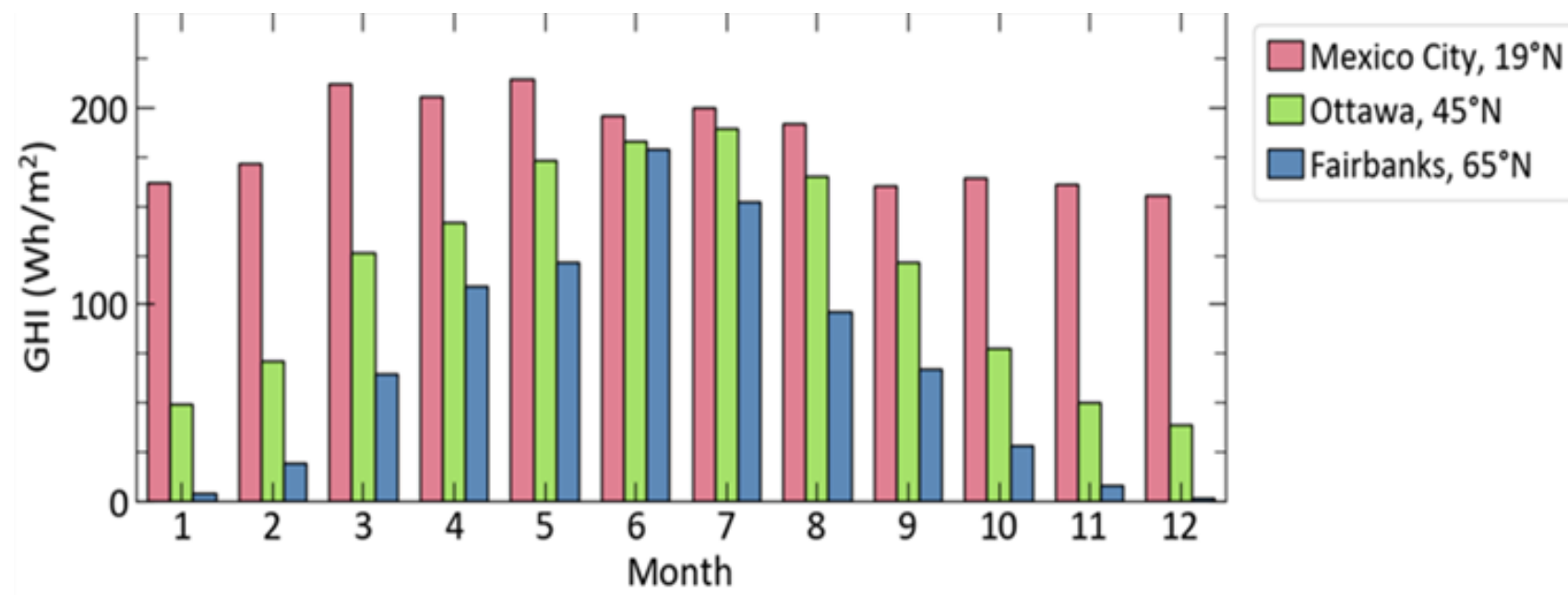
Require significant energy storage

3. PV at high latitudes



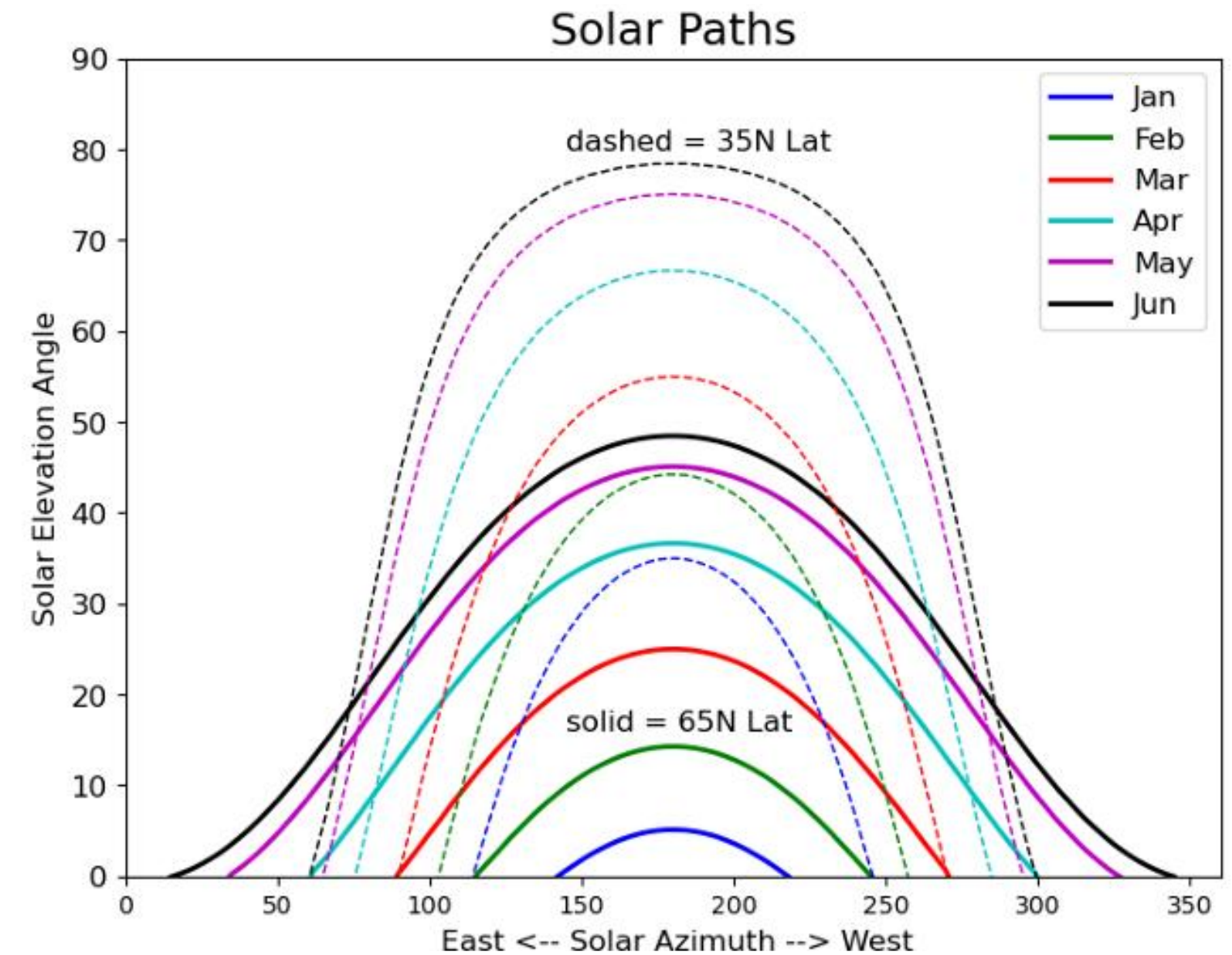
High Seasonality in Solar Resource

- Low solar elevation angles at 65°N
- Very **wide azimuth range** in summer
- GHI, zero in winter for 65°N



Performance Improves in Cold Temperatures

- At -5°C, module power output higher than at 25°C STC
- TOPCon/POLO cells: lower temp coefficients than PERC
- Some HJT cells show nonlinear behavior below -10°C
- **Lower degradation rates:** High temps & UV that drive degradation are suppressed



3. PV at high latitudes



Examples of high-latitude deployments:

South-facing fixed-tilt
Luleå, Sweden



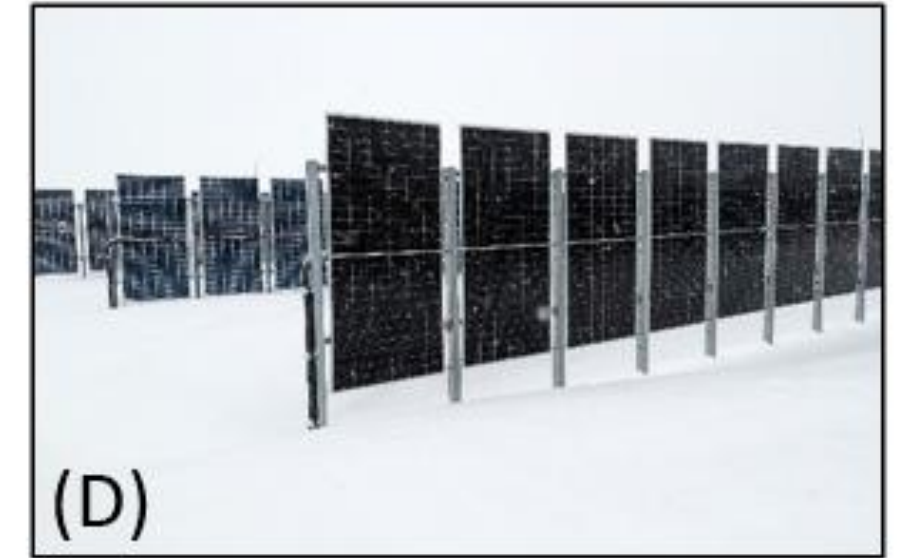
Single-axis tracker
Lillestrøm, Norway



Dual-axis tracker
Fairbanks, USA



E-W vertical
Luleå, Sweden



Rooftop
Fairbanks, USA



Building integrated
Iqaluit, Canada



Artistic
Piteå, Sweden



Fairbanks, USA

3. PV at high latitudes



Vertical bifacial PV for high latitudes

- Capture low-angle sunlight from wide azimuth range
- Better match to daily electricity demand profile
- Improved building integration (façades)
- Substantially reduced snow accumulation losses
- E-W vertical produces more at morning/evening peaks

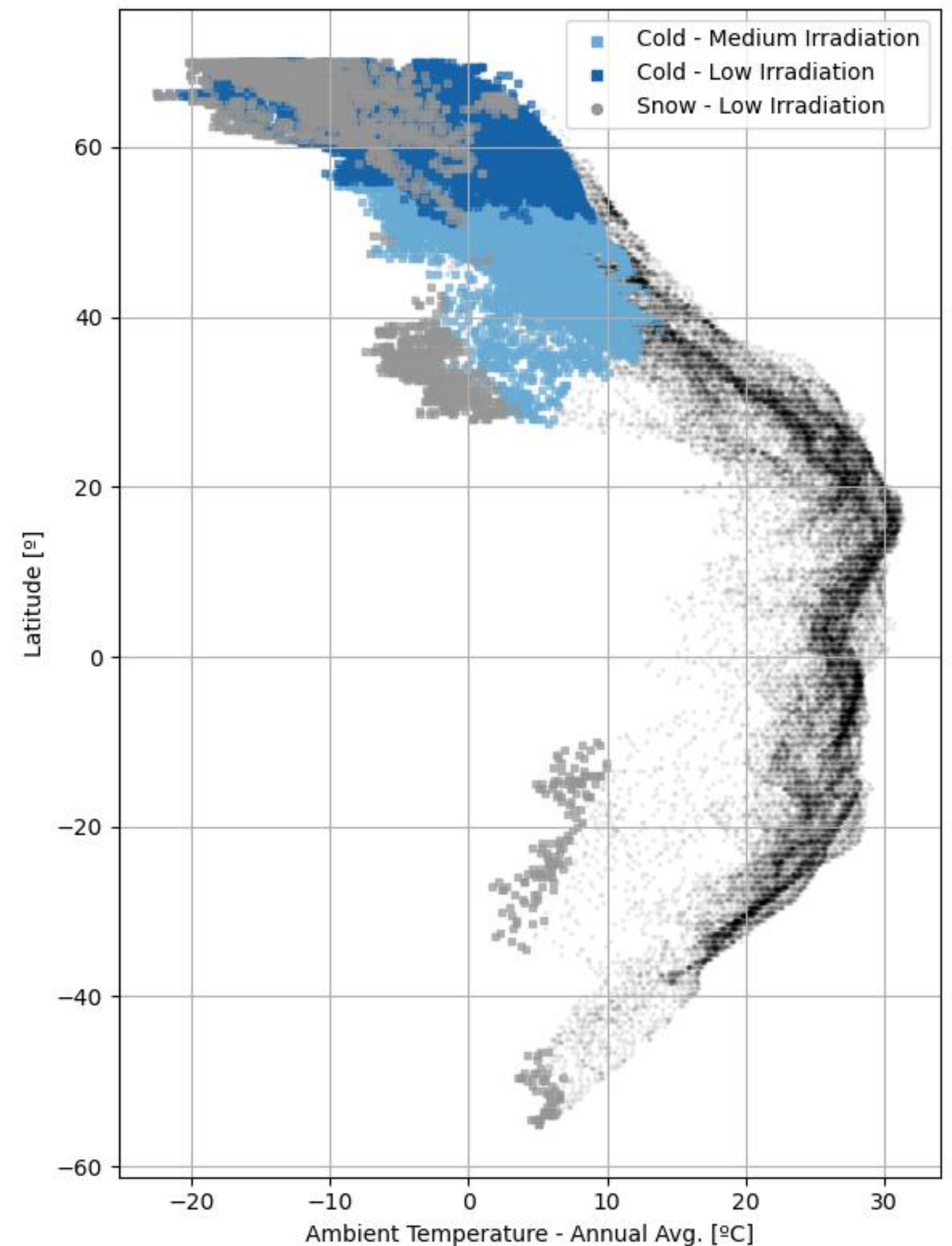


Vertical rooftop arrays in Norway. Photo credit: Over Easy Solar.

3. PV at high latitudes

Annual Ambient Temperatures

- >>>> Correlation of latitude with annual ambient temperature highlighting the cold and snowy/polar Köppen Geiger PV (KGPV) climate zones.
- >>>> Cold temperatures can embrittle encapsulants and solder joints, making modules more prone to cracking.
- >>>> Large temperature swings between day and night lead to thermal cycling, causing microcracks and long-term reliability issues.



3. PV at high latitudes



Design Adaptations for High-Latitude PV

- Fixed-tilt preferred — simpler, more reliable in **freeze-thaw cycles**. Tracking systems face cold-temperature reliability issues
- Foundation design to protect against **permafrost and frost heave**
- Larger **row spacing** needed due to **low solar elevation angles**
- Higher mounting heights** to allow snow shedding
- Snow fences** may be needed around ground-mounted arrays
- Bifacial modules recommended** — leverage albedo & diffuse light
- Vertical E-W bifacial systems**: capture wide azimuth range
- Vertical arrays also shed snow effectively



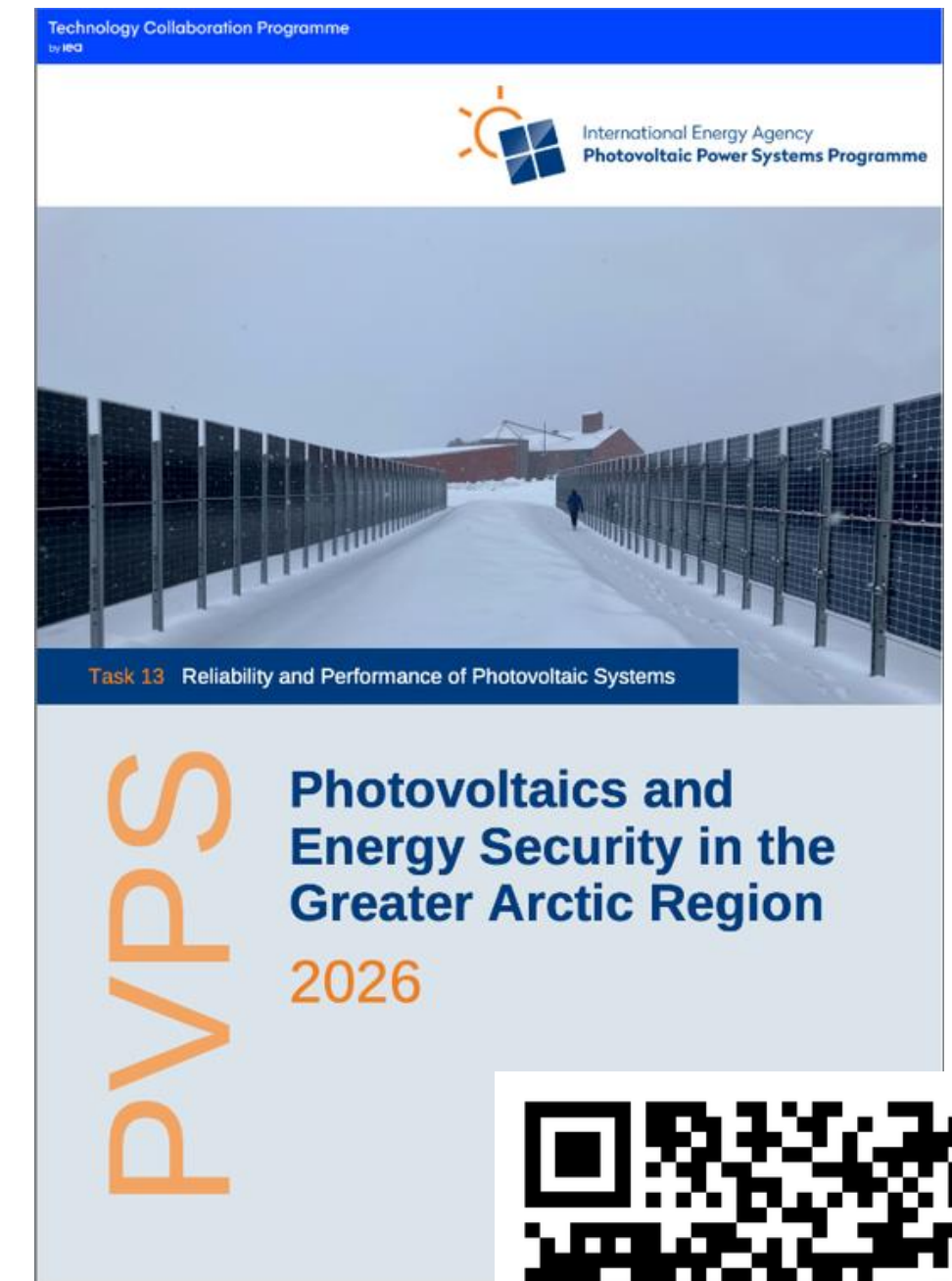
A row of PV modules in Kotzebue, Alaska, with an approximately 3-meter-high snow drift behind the row.

3. PV at high latitudes



Summary

- A recent IEA PVPS Task 13 report shows that **PV can make a meaningful contribution** to Arctic energy systems with climate-specific design.
- It requires **high-quality solar resource and albedo data, improved modelling approaches for snow losses, and careful geotechnical assessments** in permafrost regions.
- Main stressors are **snow load, freeze-thaw, moisture ingress**. Conditions for **bifacial modules** are very good, but frost-resistant foundations, snow-aware design and adapted system engineering are needed to ensure long-term reliability.
- The report explores the unique **opportunities and challenges of deploying PV systems at high latitudes**.



4. PV systems for integrated applications



Integrated PV applications like BIPV, FPV, and AV are driving future PV growth and addressing land-use and sustainability issues.



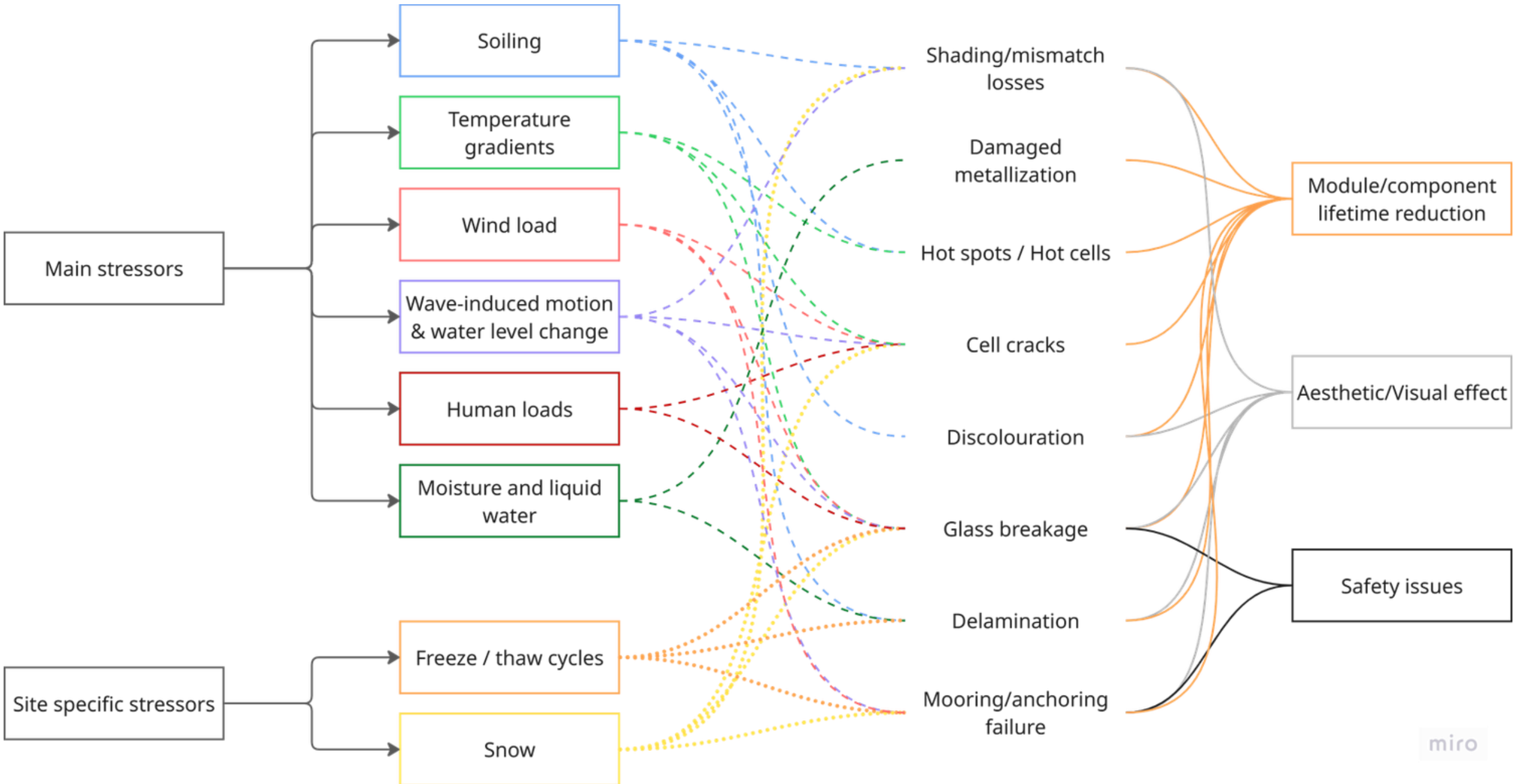
- Optimisation must now consider **reliability, durability, environmental impact, and social acceptance**, not just energy yield and cost.
- New stressors** in integrated PV systems (e.g., shading, humidity, corrosion) mean standard approaches for ground-mounted PV are insufficient.
- Tailored design, materials, standards, and operational strategies** are crucial for long-term performance and reliability of BIPV, FPV, and AV.

4. PV systems for integrated applications



Floating PV

A recent Task 13 report identifies **key stressors** and provides **recommendations** to address them.



**Stress factors,
induced degradation
mechanisms and
failure modes
affecting FPV
systems**

miro

4. PV systems for integrated applications



Application specific PV system optimisation for “Floating PV”

FPV Specific Stressors

- | | |
|--|---|
|  Temperature |  Biofouling & Soiling |
|  Extreme Temperature Fluctuations |  Flora & Fauna |
|  Wave Loads |  Tidal Variations |
|  Wind Loads |  High Voltages |
|  Humidity |  Corrosive Compounds |
|  Shading |  UV Radiation |

Specific requirements/KPIs

- **Safety** (insulation of cables, access to platforms, ...)
- **Operational** (grid connection, maintenance, integration, ...)
- **Environmental** (impact on water quality, water temperature stratification, ...)
- etc.

Case study 1: Installation in cold climates

Problem: water in basin might freeze -> increased pressure from ice on the supporting structure



- Consider additional seasonal load on anchorages from snow and ice
- Installation possible only in warmer seasons

Case study 2: Installation in harsh wind/wave conditions

Problem: high loads -> structural damages, loss of modules

Floating PV system mysteriously washes up on Hong Kong beach

A local environmental organization has published pictures of the stranded array which appeared last week on two beaches. Hong Kong's Agriculture, Fisheries and Conservation Department is currently investigating where the installation came from.

MARCH 29, 2023 EMILIANO BELLINI

HIGHLIGHTS HONGKONG LIFESTYLE SCALE 100 HONGKONG



Image: Facebook 香港海洋委員會 (HKKMA)

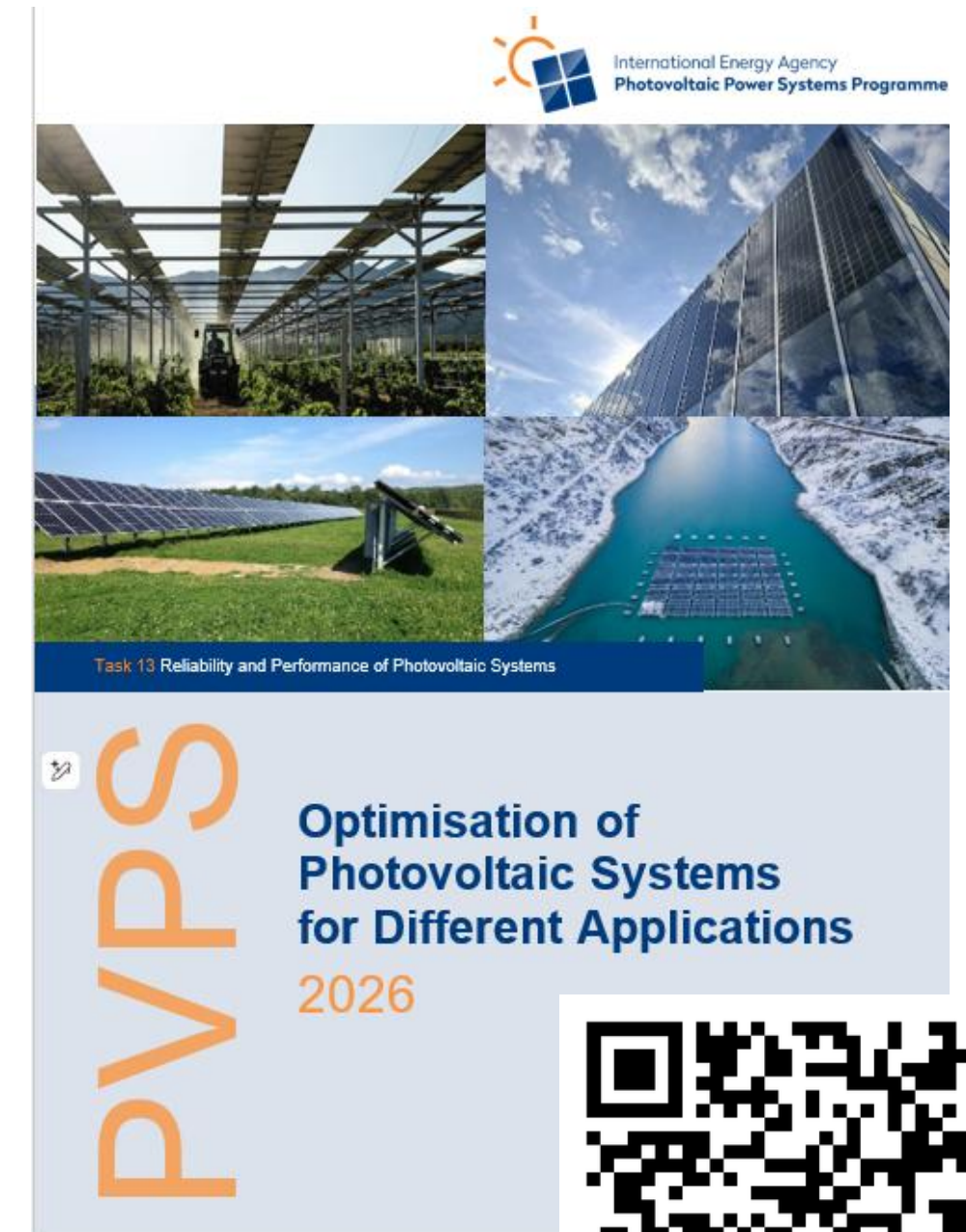
- Appropriate to standard harsher conditions
- Different and specific products for in-land and marine applications
- It should allow easy continuous remote monitoring and periodic in-person visual assessment

4. PV systems for integrated applications



Summary

- PV deployment is diversifying beyond ground-mounted systems towards integrated solutions.
- Diversification introduces application-specific stressors requiring new design criteria.
- Beyond energy yield & cost: focus must extend to reliability, lifetime, environmental compatibility, and social acceptance.
- This report provides structured guidance on optimising PV module/system design across BIPV, FPV, AV.



Thank you for your attention!



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aufgrund eines Beschlusses
des Deutschen Bundestages

