Photovoltaics and Energy Security in the Greater Arctic Region

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Executive Summary

The greater Arctic region (>60°N latitude) has been largely overlooked as a promising location for photovoltaic (PV) installations, with lower latitude and warmer regions receiving more attention. While few large PV installations currently exist in the Arctic, a closer examination of the region's geography, climate, PV technology characteristics, and energy needs reveals that PV systems can significantly contribute to energy security in high-latitude areas. This report examines both the opportunities and significant challenges for such a vision.

Unique Environmental Characteristics of the Arctic Region

The Arctic environment presents distinct challenges and opportunities for PV systems due to its unique irradiance, temperature, and snow-related characteristics:

- **Solar Resource**: Solar insolation decreases with latitude above 35°N due to lower solar elevation during winter months and pronounced seasonal variations. Above the Arctic Circle, the sun remains below the horizon during the winter solstice, resulting in dramatic differences in day length, solar elevation, and azimuth ranges. Diffuse fraction increases with latitude, shifting the spectral content of sunlight toward longer wavelengths, which affects PV efficiency and output power.

- **Temperature**: Ambient temperatures decrease with latitude, exhibiting significant seasonal fluctuations compared to lower latitudes. These variations correlate positively with solar irradiance, as colder conditions are often associated with lower irradiance levels.
- **Snow and Albedo**: Snow accumulation can obstruct sunlight and exert mechanical stress on PV components, but it also enhances ground reflectivity through increased albedo. High-latitude regions experience extensive snow cover, often exceeding 200 days annually, with significant snow depth. Permafrost, prevalent above 50°N, pose additional challenges for PV installations.

These environmental factors highlight the need for improved datasets and tailored PV system designs to optimize performance in Arctic and high-latitude locations.

Data Challenges and Modeling for PV Performance

Accurate predictions of PV performance are critical for planning installations and optimizing energy dispatch in high-latitude regions. However, reliable input data—such as solar irradiance, albedo, and meteorological parameters—are often scarce:

- **Data Sources**: Ground-based measurements using research-grade solar radiometers provide the highest quality data but are limited in high-latitude areas due to operational challenges such as snow buildup, calibration drift, and accessibility issues. Alternative sources, including satellite data, reanalysis models, and land surface assimilation models, often suffer from reduced accuracy in high-latitude regions.
- **Site Adaptation Techniques**: These methods can improve the accuracy of satellite or model-derived data by correcting systematic biases using high-quality ground measurements. Despite the challenges, high-quality observations are essential for validating models and improving dataset accuracy.
- **Database Resources**: Public and commercial databases provide solar radiation, albedo, and weather data relevant to high-latitude PV studies, but they vary in spatial and temporal resolution, data sources, and quality control procedures.

The development of rigorous maintenance protocols, specialized quality control measures, and high-quality datasets is essential to support PV deployment in challenging high-latitude environments.

Design and Modeling Adaptations for High-Latitude PV Systems

PV systems deployed in high-latitude regions require specific design adaptations to address unique climatic conditions:

- **System Design**: Fixed-tilt systems are preferred for their simplicity and reliability in freeze-thaw cycles, while tracking systems are less recommended due to operational challenges in cold temperature environments. Ground-mounted fixed-tilt systems often feature larger row spacing to minimize shading losses and higher mounting heights to prevent snow accumulation.
- **Bifacial Technologies**: Bifacial PV systems are particularly advantageous in high-latitude regions, as they leverage increased diffuse light fraction and seasonal snow albedo to enhance energy yield. Vertically oriented bifacial systems, often oriented east-west, reduce snow coverage, align better with daily electricity demand, and improve building integration.
- **Modeling Challenges**: Modeling PV systems in high-latitude regions is essential for financial planning and system design but faces increased uncertainty due to limited data availability, high albedo variability, and challenges in validating models for vertical and façade systems.

Snow loss models, localized sky coefficients, and high-quality ground-station data can improve accuracy and reliability.

- **Economic Modeling**: Economic modeling for PV systems in high-latitude regions is complicated by higher shipping, installation, and maintenance costs in remote northern communities. Despite these challenges, PV modeling remains a critical tool for optimizing system performance.

Performance and Degradation in Extreme Cold Temperatures

PV systems deployed in extreme cold temperatures face unique challenges and opportunities:

- **Temperature Effects**: Solar cell performance improves at lower temperatures due to the widening of the semiconductor bandgap, which increases voltage and overall power output. However, temperature coefficients vary across technologies, necessitating adjustments to PV performance modeling practices.
- **Ground Conditions**: Foundations in cold climates are prone to frost heaving, which can damage PV racking systems. Detailed geotechnical surveys tailored to PV installations are essential to mitigate these risks. In permafrost regions, solar arrays can act as snow fences, leading to snow drifts that insulate the ground and potentially cause permafrost warming and structural instability.
- **Degradation Mechanisms**: Snow load, freeze-thaw cycles, and extreme cold temperatures are primary stressors for PV systems in high-latitude regions. These conditions can lead to cell cracking, moisture ingress, delamination, and material corrosion. However, observed PV systems in colder climates tend to degrade more slowly than those in warmer regions, with a median degradation rate of -0.37% per year for systems above 59°N, compared to -0.75% per year for systems across the continental USA.

Proper design adaptations, such as using durable materials, optimizing racking systems, and integrating snow loss models, are critical for ensuring the long-term viability and efficiency of PV systems in high-latitude environments.

Snow and Ice Management for PV Systems

Snow and ice accumulation significantly impact the design, performance, and reliability of PV systems in cold climates:

- **Snow Behavior**: Snow behavior varies based on temperature, moisture content, and particle size, influencing how it adheres to PV modules and forms cohesive snowpacks or loose drifts. Snow shedding is more effective with higher module tilt angles and sufficient clearance beneath arrays, but snow accumulation beneath modules can obstruct shedding and prolong snow cover. Snow drifting is influenced by the PV array design and then impacts reflected light and also ground temperatures.
- **Energy Losses**: Snow-covered modules experience shading losses that severely limit energy output. Snow loss models simulate the adherence and shedding of snow from the module surface and provide empirical and threshold-based approaches to estimate energy impacts. Site-specific calibration or machine learning techniques can improve accuracy.
- **Mechanical Stress**: Heavy snow loads exert mechanical stress on PV modules, potentially leading to deflection, cracked glass, damaged cells, or frame separation. Standards like IEC 61215-2 and IEC 62938 address uniform and non-uniform snow loads, but real-world conditions amplify risks in Arctic environments.

- **Mitigation Strategies**: Passive solutions include hydrophobic or ice-phobic coatings, steeper tilt angles, and snow fences, while active strategies such as mechanical snow removal, surface heating, and chemical treatments can be costly or environmentally harmful. A combination of tailored design, advanced modeling, and innovative mitigation techniques is necessary to address these challenges.

Integration of PV Systems into Arctic Power Systems

The integration of PV systems into Arctic power systems presents unique challenges and opportunities:

- **Geographic and Political Contexts**: In Nordic countries, national power grids extend into many high-latitude areas, enabling large-scale utility PV installations. In North America, isolated microgrids dominate sparsely populated Arctic regions, requiring tailored approaches to PV integration.
- **Economic Viability**: Utility-scale PV plants are becoming economically viable even in high-latitude locations, but they face challenges such as the "cannibalization effect," where overproduction during peak hours reduces electricity prices and profitability. Land use concerns make dual-use installations, such as agrivoltaics or PV carports, more acceptable to the public.
- **Residential and Rooftop Systems**: These systems offer advantages in self-consumption, avoiding transfer costs and electricity taxes, and reducing grid interaction. Financial incentives and market policies, such as net metering, significantly influence the design and operational strategies of PV systems.
- **Strategies for Integration**: Hybrid PV and wind power plants, energy communities, load shifting, virtual power plants, and energy storage can enhance PV generation and support integration into Arctic power systems. Policies such as investment tax credits, feed-in tariffs, and aggregated net metering incentivize PV adoption, while policies supporting the disposal and recycling of used PV modules encourage sustainable practices.

Integrating PV systems into Arctic power systems requires innovative strategies, supportive policies, and tailored designs to address the unique environmental, economic, and operational conditions of high-latitude regions. Despite the challenges, PV technologies have the potential to play a significant role in the future energy landscape of the Arctic.

Key Takeaways

1. High-latitude solar resource has high seasonality, low sun elevations and a wide range in solar azimuth angles. Fixed arrays experience more time with the sun behind the array than at lower latitudes.
2. Bifacial modules & vertical arrays see significant performance advantages by capturing more light (direct, diffuse, and reflected) and by effectively shedding snow.
3. Lower temperatures lead to higher PV efficiency and likely lower module degradation rates.
4. Foundations must be adapted to ground freezing and frost heaves.
5. Array design should account for snow drifting
6. Many Arctic nations are actively installing PV systems and developing region-specific solutions.