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Installing Solar Power Plants in Snowbound Areas: Lessons from Himachal Pradesh, India

THE BOTTOM LINE

Solar power plants can enable a shift away from polluting alternatives such as diesel-based generation, especially in isolated, snowbound areas where the opportunity cost of land is relatively low. Technical solutions to the challenges of difficult terrain and climatic conditions include bifacial modules and so-called passivated emitter and rear cell technology—all with fixed mounting systems. It is important to train staff and to optimize equipment for site-specific risks like heavy snow loads. Both utility-scale projects for export, as well as small setups for supplying local communities, may be explored. This Live Wire recommends practices for setting up solar installations in snowbound terrain, based on the Bank's assessment of technical requirements for setting up a 1 GW solar power project in Spiti Valley, Himachal Pradesh (Evergy Engineering GmbH 2020).

Why should we consider solar photovoltaic (PV) projects in snowbound areas?

Solar PV installations can provide clean and affordable energy in snowbound areas, along with employment for local residents

Transitioning from polluting fossil-fuel generation to solar power is the need of the hour. But where the opportunity cost of land is high, countries must look for solutions that do not occupy valuable land. In India, for example, the government is looking at rough terrain, including snowbound areas, as sites for solar installations. Isolated, snowbound areas may offer good options to harvest solar resources—both at the utility scale for export and at a smaller scale for supply to local communities. Not only do they offer a relatively lower opportunity cost of land; they also often have higher rates of solar irradiation.

The Indian government aims to generate 40 percent of the country's electric power from nonfossil fuels by 2030. To this end, it plans to install 175 gigawatts (GW) of renewable generation by 2022, of which 100 GW will be solar. All states have joined hands to achieve their joint renewable energy purchase obligations, aiming thereby to improve both their energy mix and their energy security. Himachal Pradesh, a hilly state in the north, plans to install about 1 GW in the Spiti Valley in the Lahaul and Spiti district. This area typically sees more than 300 clear and sunny days in a year but is difficult to access and remains snowbound for up to four months of the year.

Tribal farmers in the remote Spiti Valley have come to rely on expensive diesel fuel to supplement an erratic electricity supply (Bisht 2020). The state power distribution company has a distribution feeder network in the valley, but the relative distances, lack of supply (due to the breakdown of a mini hydropower project near Kaza), and the possibility of power shutdowns in winter make it necessary for many commercial establishments to use high-speed diesel generators as their main power source.

Installing solar power plants in snowbound areas offers an important avenue for reducing pollution and mitigating climate change. Moreover, since most solar panels are mounted on barren land or on rooftops, their installation does not involve significant environmental impacts from the breaking of land or slopes (Government of Himachal Pradesh 2016). Investments in such locations bring job opportunities and boost incomes for locals who may otherwise need to seek employment in faraway cities.


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Installing solar power plants in snowbound areas offers an important avenue for reducing pollution and mitigating climate change. Investments in such locations also bring job opportunities and boost incomes for locals who may otherwise need to seek employment in faraway cities.

All in all, the extra costs needed to deal with the challenges of operating in snowbound areas are moderate and will likely be more than offset by the lower cost of land. Also, the additional generation from the solar PV plant can be used to offset any other extra costs incurred during the construction phase and the higher cost of logistics and manpower management in remote, snowbound areas.

What challenges do snowbound solar projects pose—and what solutions are available?

Heavy snowfall and the steep, uneven terrain of remote project sites need to be carefully considered during planning and implementation

Solar PV projects in snowbound areas run the risk of damage from heavy snow loads and even from disasters such as earthquakes and avalanches. While light snowfall can slide off easily without damaging the panels, heavy snowfall can create problems by placing stress on the support structure of the PV system (Gay 2017).

Topography poses another challenge. In mountainous terrain with few flat areas, it can be difficult to find a large enough contiguous land surface suitable for an installation (Government of Himachal Pradesh 2016). While the clear skies and low temperatures in snow-bound, hilly regions may be conducive to solar PV, the remoteness of these locations can pose logistical challenges such as long transport times and a lack of local technical support infrastructure. Proximity to the nearest transmission evacuation facilities also plays an important role in deciding the economics of a proposed project.

However, these challenges can be overcome through a careful planning and design process informed by best-practice experiences. With respect to panels, bifacial modules and passivated emitter and rear cell (PERC) technology provide relatively high energy yields. For mounting, a twin post support system is recommended for areas with heavy snow loads. Technical specifications are discussed below and summarized in table 1.

Solar panels. Crystalline silicon PV modules consist of connected PV cells encapsulated in one of two ways. So-called monofacial modules are held between a transparent front (usually glass) and an opaque substrate; whereas bifacial modules have a transparent front and back. Bifacial modules expose both the front and the back side of solar cells and produce solar power from both sides of the panel. Crystalline silicon technology may be of the monocrystalline

Table 1. Minimum technical specifications for solar projects in snowy areas

Item	Recommendation	Remarks
Solar modules	Bifacial modules and PERC technology preferred.	Maximizes efficiency and long life at lower up-front cost.
Solar inverters	String inverters.	Modular, low-weight, easy to replace, lower lead time.
Mounting structures	Horizontal single axis trackers can be used to maximize generation from the sites. In case fixed-tilt structures are used, additional back rails should be provided to mitigate snow loading.	Incur marginal extra capital expenditure up front, but this is justified by 5–7 percent extra generation.
Structure foundations	Using gravity weights instead of deep drilling.	For fragile snowbound soil strata, soft glacial moraine type soil might be encountered randomly, so a concrete ballast type foundation is preferred.
Transformers	Cast resin dry-type transformers preferred. Heatable transformer banks may be used depending on availability and cost.	Oil-cooled transformers have oil-leakage risk and are extremely hazardous in fragile snowbound areas.
Supervisory control and data acquisition (SCADA)	Site-level SCADA and one central SCADA are preferred.	Very detailed input/output parameters settings and an automated control and operations system is preferred.
Ratio of direct current to alternating current	Less than 1.	Because of the electrical thresholds of inverters and transformers operating in extreme low temperature in winters, a higher margin of safety has been considered.

While the clear skies and low temperatures in snowbound, hilly regions may be conducive to solar PV, the remoteness of these locations can pose logistical challenges such as long transport times and a lack of local technical support infrastructure.

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type, in which wafers are sliced from a large single crystal ingot in a relatively expensive process, or the relatively cheaper but slightly less efficient polycrystalline type, with wafers may be made by a variety of techniques, allowing them to be much larger than the monocrystalline type. Given the logistical constraints, long-term operation and maintenance needs, and the challenges at the installation stage, monocrystalline PV module technology is recommended for snowbound areas.

Different cell architectures, module processing technologies, and product solutions have been introduced in the market in recent years to boost the output of crystalline PV modules and bring down costs. These include PERC technology, half-cut cells, and bifacial modules.

PERC technology improves light capture near the rear surface of a cell and optimizes electron capture. The main advantage of this cell structure is that it enables manufacturers to achieve higher efficiencies than do standard solar cells. While there are more steps in the manufacturing process, the gain in efficiency enables cost reduction at the system level. This cell architecture is the mainstream option for producing high-efficiency solar panels at competitive prices.

Half-cut cells provide several benefits over traditional solar cells, such as improved performance (slightly increased panel efficiencies), and improved physical durability owing to their smaller size and increased resistance to cracking.

The higher average purchase cost of bifacial modules and PERC technology is justified by their higher energy yield. Bifacial technology is particularly well suited to snowbound areas because of the excellent reflectivity provided by snow. Performance analysis conducted for a site in Spiti Valley indicated that bifacial technology would provide the highest energy yield when deployed with horizontal single-axis trackers (HSATs) and would outperform monofacial technologies when deployed with HSATs or with fixed-tilt mounting systems. The risk of component failure in bifacial PV modules is not higher than for any other PV project, since they are manufactured in a manner that is similar to conventional monofacial modules. Bifacial and monofacial PERC technology is widely accepted across markets.

Mounting structures. PV modules are installed on either fixed or "tracking" mounting structures. The structures keep the modules oriented in the right direction with a tilt that is optimized for maximum irradiation and to provide the required structural support. Fixed mounting systems are straightforward to set up: rows of modules are kept at a fixed-tilt angle. By contrast, tracking systems follow the sun's trajectory, resulting in higher irradiation on the collector plane and higher energy production.

Tracking systems generally provide the highest energy yield, followed by manual seasonal tilt systems, fixed-tilt systems facing south, and, finally, fixed-tilt systems in the east-west orientation (which require less space than south-facing systems). Tracking systems and seasonal tilt systems require 1.5–2 times more land to avoid shading as compared with a fixed-tilt system of the same nominal capacity.

For sites in mountainous regions, the installation of trackers is difficult because only limited inclinations are manageable and then only with additional costs (for flexible joints between each table). Trackers can be installed on sites with a maximum north-south slope

Fixed-tilt systems have no moving parts and require no maintenance. The up-front capital cost is lower, and damage to modules caused by the mounting structure can be avoided. The lower energy yield of a fixed-tilt system can be partly balanced out by increasing the installed peak capacity of the modules.

of up to 17°. Additionally, trackers require frequent inspection and maintenance owing to their motorized and moving parts, with electrical components generally needing replacement every five years. Manual seasonal trackers are complex in design and implementation, especially in harsh climatic conditions.

Fixed tilt systems, on the other hand, have no moving parts and require no maintenance. The up-front capital cost is lower, and damage to modules caused by the mounting structure can be avoided. Ground-mounted structures may be supported by a single post (mono-pile) or a twin post (dual-pile) support system. A twin post, although more costly, is recommended for sites subject to strong winds in the north-south direction and high snow loads. Alternatively, custom-designed structures may be used to solve specific engineering challenges or to reduce costs. These also offer a way to use local suppliers or fabricators to fulfill local content obligations. The key is to design a system that is simple and repetitive to install, as labor costs can be a significant element of installation. The lower energy yield of a fixed-tilt system can be partly balanced out by increasing the installed peak capacity of the modules.

Ground-mounted PV systems also require appropriate foundations for the mounting structure (which will affect the choice of support system). The most favorable option needs to be determined specifically for each proposed site, based on a ground survey. Options available for snowbound areas include:

- **Driven piles.** A beam or pile is driven into the ground. This is a low-cost solution that can be quickly implemented. Specialist skills and pile driving machinery are required, and predrilling may be necessary in rocky terrain.
- **Earth screws.** Helical earth screws, typically made of steel, are economical for large-scale installations and are tolerant of uneven or sloping terrain. These require specialist skills and machinery to install. Predrilling may be necessary in rocky ground.
- **Precast concrete ballasts.** This is suitable where the ground is difficult to penetrate due to rocky outcroppings or subsurface obstacles, or in sandy, loose soil unsuitable for piles. This option has little tolerance for uneven or sloping terrain; hence, site preparation is crucial. Consideration must be given to the risk of soil movement or erosion. Once the location of each concrete ballast is prepared, no specialist skills are required for installation.
- **On-site concrete piling.** This option is the most suitable for all systems, as the pilings are customized for a given soil stratum and terrain while having a strong tolerance for uneven and sloping terrain. On-site concrete pilings do not require specialist skills to install.

What sorts of design specifications are called for?

A detailed baseline study will go a long way in ensuring a robust solar project under harsh conditions

Electrical engineering. It is extremely important that the site's average temperature be reflected in the electrical design of the power plant to avoid damaging and overloading the components, as solar cells such as semiconductors are sensitive to temperature. The most affected parameter is the panel's open-circuit voltage. This goes down with an increase in temperature, resulting in reduced power output—and vice versa. Thus, the temperature influences the selected ratio of direct current (DC) to alternating current (AC). For instance, for projects in Spiti Valley, where the average temperature is about –4.4oC, DC/AC ratios between 0.9 and 0.95 are recommended so as not to exceed maximum limit values for electrical thresholds. (The exact ratio depends on the technical specification of the inverter.) This is in line with high-altitude projects all over the world.

To protect against environmental influences such as ultraviolet (UV) light, rain, and snow, the DC and AC cabling should be installed inside the mounting structure and under the PV modules. Cables exposed to sunlight are best protected with additional plastic pipes to mitigate the risk of their outer shield breaking and to avoid isolation problems in the PV power plant. Armored cables are recommended in trenches where no sand is available. (Normally, cables need to be embedded in a layer of sand approximately 20–30 centimeters thick to protect them from damage and to avoid outages due to low isolation resistance.) Where it is difficult to dig deep trenches due to rocks in the substrata, reinforced cable conduits should be used for longevity and electrical safety. Combiner boxes should be installed in protected places (beneath the module rows) to mitigate the risk of damage caused by UV light and/or heavy snow loads. Where this is not possible, additional covers should be installed to protect the

A cell architecture known as passivated emitter and rear cell (PERC) technology is the mainstream option for producing high-efficiency solar panels at competitive prices. Bifacial technology is particularly well suited to snowbound areas because of the excellent reflectivity provided by snow.

combiner boxes from direct sunlight, rain, and snow. Where snowfall is expected to be heavy, the combiner boxes and inverters can be mounted on high frame structures with a tilted roof cover.

Even if oil-cooled transformers have lower losses, dry-type transformers are recommended for Spiti Valley because no environmental problems can be expected in case of damage (oil leakage, etc.). However, if oil transformers are used, they must sit on bowls having a capacity of at least 110 percent of the amount of oil in the transformer in case of leakages. Cast resin transformers have the advantage that mechanical defects can be more easily detected and repaired. In snowbound areas, heatable transformer stations are recommended to protect the transformer and the necessary electrical equipment from the harsh environmental conditions. Outdoor transformers are not recommended. Transformers should be suitable for the altitude and climatic conditions at the site, which may necessitate custom-made solutions. Standard equipment is normally recommended for use only up to an altitude of 1,000 meters and a low temperature of –20°C.

String inverters are recommended for snowbound terrain owing to their overall weight and plug-and-play features, which allow them to be installed easily by trained workers. They also offer a clear logistical advantage: they can be transported easily in a small four-wheel-drive truck or lorry, which increases their availability during an already limited operational season. They can be installed beneath the module rows for protection from the sun, snow, and rain and therefore need no extra building or foundation (which would be required for a central inverter). Inverters should either be sheltered under the module tables or, if this is not possible, installed on high stands/frames (at eye height or more, depending on snowfall) with a covered roof to protect them from direct UV, rain, and snow. In remote sites, fire extinguishers suitable for electrical installations should be provided next to the inverters and/or in the transformer station.

Structural engineering. Structural calculations determine the loads to be transferred through the structure into the ground. Site-specific conditions and wind loads need to be determined. In addition, a soil survey including excavations and sample probes at each site, and at a high resolution, is recommended. Depending on the experience of the surveyor and the complexity of the site, four to five sample probes and one excavation per hectare of land are recommended to determine the necessary embedment depth of the foundation (or its dimensions, in case of a concrete slab foundation). This is also important to determine the right materials and the thickness of the zinc coating. For the rocky terrain of Spiti Valley, concrete slabs are recommended. No special equipment is necessary for putting these in place after adequate land treatment.

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PV modules with frames are recommended for such areas owing to their ease of installation and handling, and because they are more rigid than frameless modules. Glass-glass modules may also be considered to avoid micro or complete cell cracks that could be caused by the sag of glass foil modules due to heavy snow loads. For Spiti Valley, modules certified to withstand pressure (snow) loads with a minimum of 5,400 Pascal have been recommended. In May 2020, the International Electrotechnical Commission published a new standard for determining the mechanical performance of framed PV modules with inclined nonuniform snow loads (IEC 2020).

Additional back rails should be included on the module mounting structure to support the modules and mitigate the risk of bending and breaking under heavy snow loads. An additional back rail placed close to the lower edge of the frame could also mitigate the risk of sliding snow tearing out the frame of the module. While the optimal orientation for one single module row in the Spiti Valley would be a tilt angle of 32° and an azimuth of 180°, depending on the final site layout, a minimum tilt angle (for a fixed-tilt system) of 20° to 25° is

Transformers should be suitable for the altitude and climatic conditions at the site, which may necessitate custom-made solutions. Standard equipment is normally recommended for use only up to an altitude of 1,000 meters and a low temperature of –20°C.

recommended to preserve the installed PV panels' high self-cleaning effect (contaminants cannot stick long to the surface of the PV module because of the ethylene tetrafluoroethylene coating). If seasonal tilt trackers or HSATs are chosen, systems that can change the tilt angle between 10° and 35° (or in case of HSATs, between +/- 55°) are recommended.

What specific measures are needed for solar plants in snowbound environments?

Logistical and climatic constraints must be accounted for in siting, implementation, operations, maintenance, and monitoring

When implementing solar PV projects in remote, snowbound areas, buffer times must be considered owing to logistical and climatic constraints that limit the period available to carry out work. Another factor to be considered is a site's access. For instance, in Spiti Valley, an access road suitable for trucks weighing up to 40 tons is needed. The heaviest parts of a PV power plant include construction equipment like diggers, transformers, module mounting structures, and concrete slabs for the foundations of module mountings.

Major implementation issues are discussed below and summarized in table 2.

In areas with multiple remote project sites, a central logistics area with year-round connectivity can be identified and a logistics study undertaken to review possible access routes from the central logistics area to the project sites. This site should be fenced and equipped with an operations building where the quantity and quality of the goods received can be monitored. It should be big enough to store all the equipment needed at sites that cannot be reached for part of the year. Each site should have an area suitable for preassembly of cables, connectors, and parts of the module mounting structure when work in the field is not possible. For smaller sites where the necessary construction and commissioning works can be finalized in one row, these areas do not necessarily have to be

Table 2. Implementation recommendations

Activity	Guidance and recommendations	Technical comments
Logistics	Centrally located weatherproof yard for major items. Transshipment to sites using smaller all-terrain trucks.	Central yard helps in tracking and transshipment. Also reduces requirements for additional all-weather heavy-duty roads to project locations.
Large civil structures	Prefabricated structures recommended.	Prefabricated structures are modular, faster to install, reduce dependence on local raw materials, and are lightweight but strong.
Plot plan and plant layout	Larger interrow distances and provision for medium-duty roads across solar fields.	Will help in mechanical removal of snow using snow ploughs/dozers. Also reduces chances of shading loss.
Tilt angles and tracking	Fixed tilt: 20–25°. Seasonal mechanical tilt: 30–32°.	High tilt helps capture more solar radiation in winters and also aids in self-cleaning of snow.
Quality, health, safety, and environment management issues	Very strong protocols need to be agreed upon and followed during implementation period.	Considering the distances involved, vagaries of weather, and lack of high-tech medical facilities available at remote locations, extreme care needs to be taken to avoid any industrial accidents like material spillage, physical injuries to staff, and electrical shocks during DC and AC field installation.
Plant security	Entire plant needs to be monitored using closed-circuit television. Perimeter security to be ensured using high-quality unobtrusive chain link fence with patrolling points and solar-powered lighting at adequate intervals.	Ingress of wild animals and even local population needs to be monitored strictly.
Lightning protection	High-capacity plant-level lightning arrestor needs to be implemented.	Sudden storms and heavy snowfall can cause electrical short circuits, so a plant-level lightning arrestor system is extremely necessary.

heated and covered. For larger sites where work is unlikely to finish in one row due to bad weather, partly covered and temperature- and humidity-controlled areas are recommended.

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Small warehouses with adequate spare parts (including substructure and spare modules) and consumables for each site are necessary for safe storage. Containerized solutions are recommended. The amounts should be determined in consultation with suppliers. Having the right spare parts on hand is not only important for ongoing preventive maintenance but also for corrective and even predictive maintenance. The operations building may include a warehouse for spares as well as an on-site monitoring room where the operation and maintenance staff have an overview of all electrical equipment. This can help reduce reaction times and increase availability.

Sufficient clearance (at least 4 meters) should be left between module rows to permit machinery to remove snow, with dedicated areas close to the gates for piling cleared snow.

A dirt road along the fence line is important for security and maintenance reasons.

Exhaustive project documentation is crucial for high-quality and effective operations. The documentation must include the information specified in IEC standard 62446: Photovoltaic (PV) systems: Requirements for testing, documentation, and maintenance.

The provider of operation and maintenance services must have proven ability and experience in large-scale PV projects and in high-altitude locations, and understand the site-specific design, electrical configuration, and technical details. An operations and maintenance checklist appears in box 1.

A unified monitoring system is recommended where multiple project sites are scattered across an area. Integrating these within one supervisory control and data acquisition (SCADA) system streamlines their capacity for comparison and failure detection.

Depending on the site, the following equipment and facilities may be needed:

- At least two cold-resistant pyranometers per 10 megawatts (MW) installed
- A measurement station to track the ambient temperature and input from the module temperature sensors integrated within the SCADA system
- A monitoring system down to the module string level to help detect the exact location of failures and coordinate service activities
- Closed-circuit television cameras covering the entire PV power plant.

Plant-level SCADA or monitoring systems should be made available to allow the plant's visualization and the measurement and monitoring of results down to the level of the combiner box or module. Using such systems, with the help of SCADA, a daily comparison of the performance ratio and inverter output should be carried out to help identify production losses such as those due to snow. Regular reports (in some cases, monthly) should contain information on the amount of energy produced, irradiation, the performance ratio, a logbook of failures and outages, and maintenance activities (current and scheduled).

Installations in snowbound areas require frequent visual inspections and preventive maintenance activities, either whenever the

Box 1. Operations and maintenance checklist

- Provision of a central warehouse and control-center with weatherproof storage facilities for all-season operations and maintenance
- Rigorous preventive maintenance protocols like snow-cleaning after every heavy snow cycle and regular snow removal from solar fields using snow ploughs
- Regular monitoring of all data nodes using SCADA and the preventive checks of all sensors at string monitoring box and inverter levels to minimize risk of unplanned shutdowns
- Five to 7 percent of total modules, and 2.5 percent of string inverters and string monitoring boxes to be stored as operational spares on site at all times to reduce extended shutdowns due to the nonavailability of long-lead items and also considering transportation issues in winter months
- Periodic checking of the entire plant using drone-mounted thermography.

site is accessible or by officials stationed permanently at the site. For project sites in Spiti Valley, quarterly inspections of all the key components of all installed modules are strongly recommended. It is also recommended that the modules be cleaned after each bad weather period using an automated brush system. Inverters with fan cooling should be checked regularly for blockages caused by snow to avoid additional outages. DC and AC combiner boxes should have drying agents to avoid condensation and corrosion. Door sealings and cable entries need to be checked to avoid water ingress and corrosion. In areas with high wind and snow loads, torque checks of at least 25 percent of the total screws of the mounting structure are recommended.

For larger installations (50 MW and above), staff should be deployed on site at all times. It is also advisable to use drone-mounted thermography to periodically check the entire plant for hotspots, major snow accumulation zones, and animal and human intrusion. The first thermographic inspection of each year, using infrared cameras and/or infrared drones, should be scheduled after the snowy period, when the panels are free of snow, since heavy snow loads are a prime cause of damage. Such remote monitoring tools become more important in areas where accessibility and manpower deployment can pose additional constraints. For smaller installations (around 10 MW) this may not be economically viable, so a comprehensive closed-circuit television system should be installed to frequently check for issues such as module soiling or to check the general status of the site after a storm event. This can also be used to plan maintenance activities.

During construction as well as operations, it is recommended that all personnel be trained in applicable health and safety measures. This is of particular importance in high-altitude and alpine regions, where the nearest hospital is far away.

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