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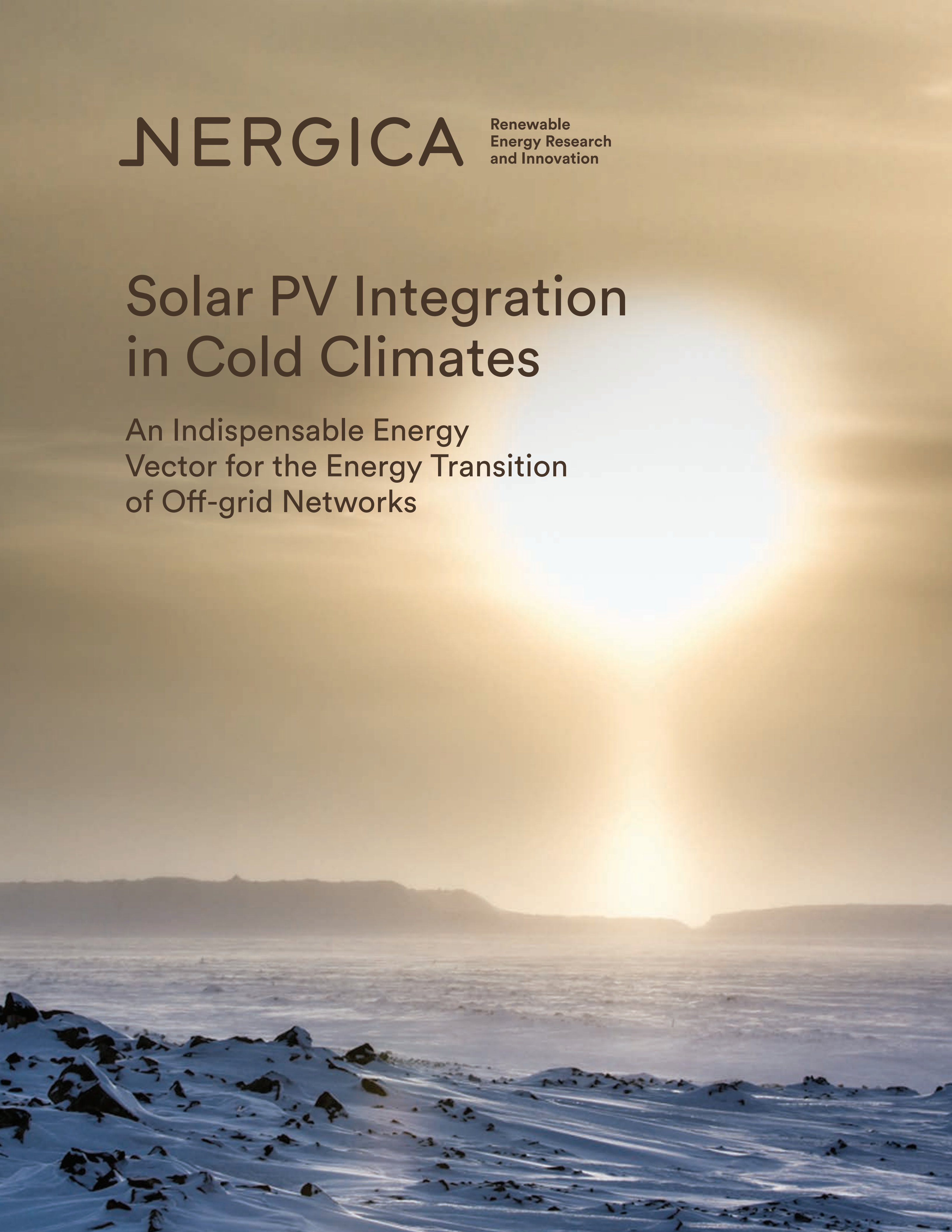
Solar PV Integration in Cold Climates

An Indispensable Energy Vector for the Energy Transition of Off-grid Networks



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Authors
Sergio Gualteros, MScA, Eng.
Marc Provost, M.Eng. Jr., CanmetENERGY
Lucie Fauteux, Editor

Technical review
Karim Belmokhtar, PhD, Jr. Eng.
Yves Poissant, PhD, CanmetENERGY

Language review
Louise Boulet, Editor
Caroline Farley

Photos
Justin Bulota
Jacques Gratton
Nergica

Layout
Ghislaine Roy

English translation
David Soares, DÉSS

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List of Abbreviations and Acronyms

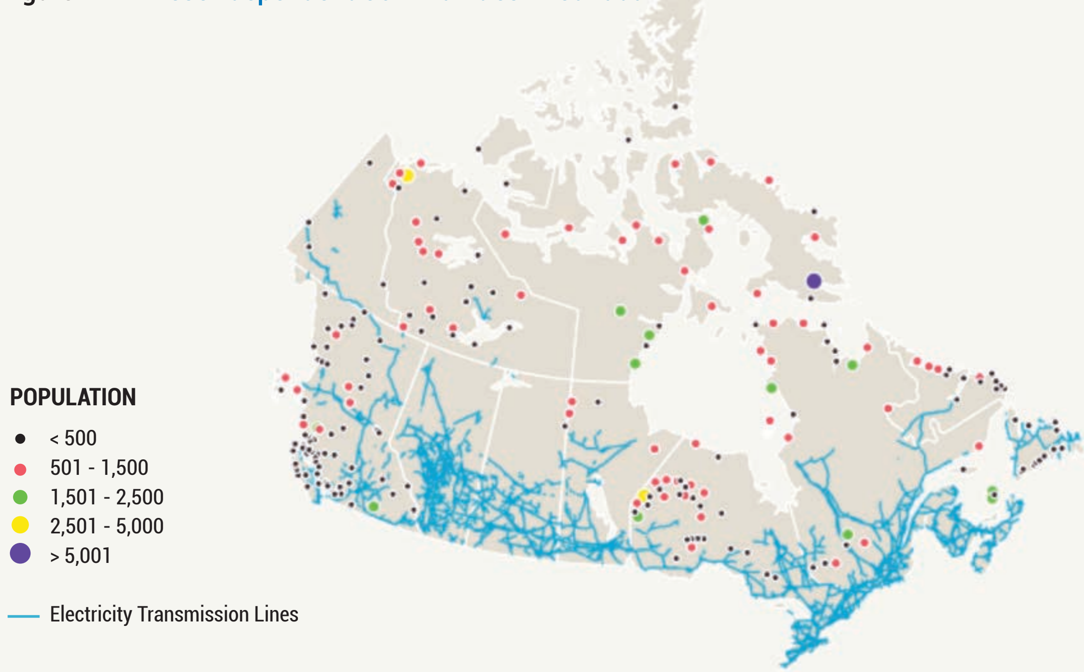
BOS	Balance of System
GHG	Greenhouse Gas
HQD	Hydro-Québec Distribution
IEA	International Energy Agency
LED	Light-Emitting Diode
NPV	Net Present Value
NRCan	Natural Resources Canada
POA	Plane of Array
PV	Photovoltaic

Northern Canada and Northern Quebec: a Unique Energy Context

Canada comprises over 270 remote communities with a combined population of approximately 190,000 inhabitants. These communities, most of which are found in the northern parts of the country, are essentially powered by off-grid systems, 75% of which use fossil fuels (Figure 1) [1]. In the current environmental, political and energy contexts, communities relying on fossil fuels, concerned by the impact of their consumption on the environment and public health, not to mention the prohibitive cost of such energy, are increasingly looking to renewables for their electricity production [2]–[5].

Recent technological developments in the field of renewables have lowered the costs associated with deploying this type of energy and made it more accessible. This is why communities, governments, utilities, universities and research centres are showing a strong interest in integrating renewables into existing off-grid networks [6]–[8].

Figure 1 Diesel-dependent Communities in Canada



References: [1], [9]

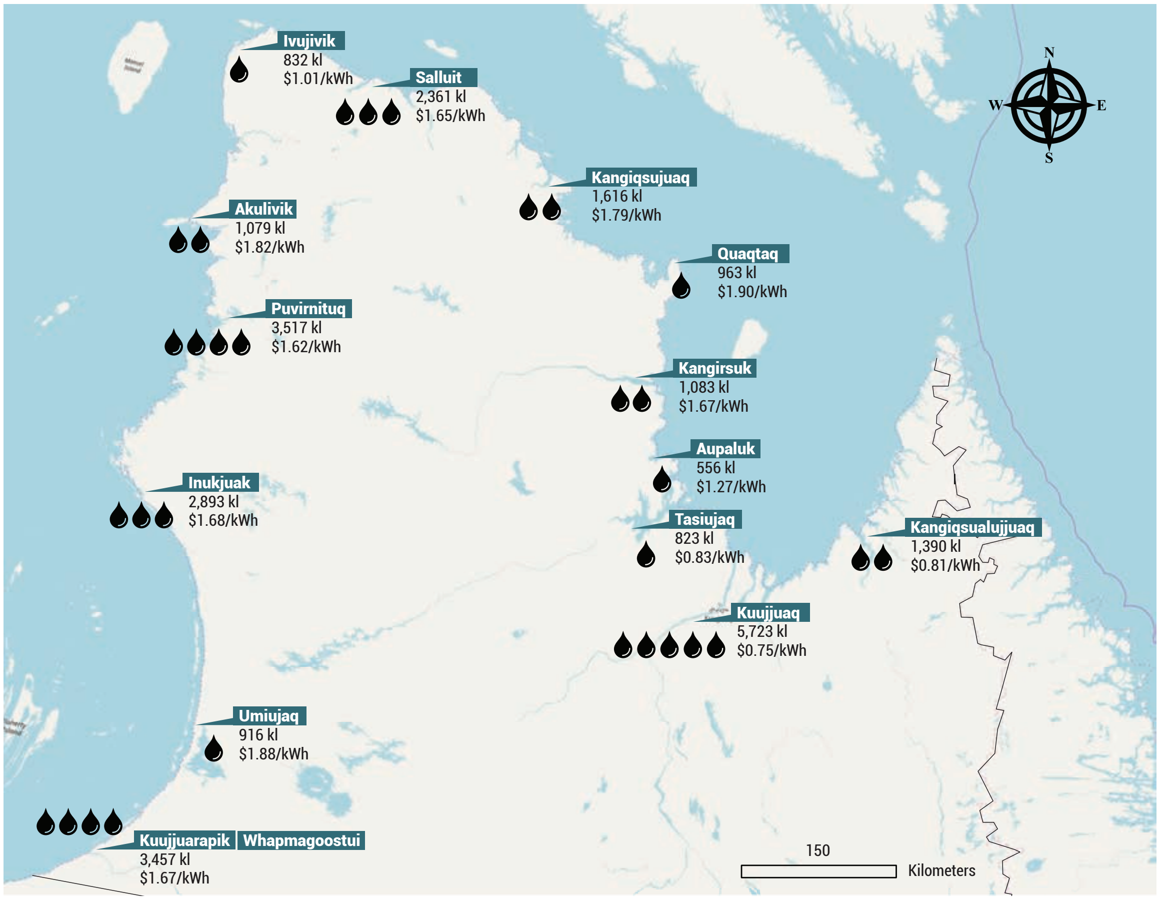
Photo: Justin Bulota

Quebec

Quebec is no exception. Despite the launch of a handful of renewable integration projects, energy supply in the vast majority of Quebec's remote communities remains essentially provided by diesel generators, which, in any given year, consume substantial quantities of fossil fuels (Figure 2).

Indeed, electricity production in Hydro-Québec's off-grid networks produces over 223,000 tonnes of greenhouse gases (GHG) per year, of which approximately 70,000 are attributable to Nunavik and the Cree village of Whapmagoostui [10].

Figure 2 Cost of Electricity Production and Associated Diesel Consumption in Nunavik and Whapmagoostui [1]



References : [1], [6], [10], [11]

1 The electricity production costs indicated on the map date back to 2010. The most recent information released by Hydro-Québec indicates that the average cost of electricity production in its off-grid networks is $0.588/kWh [10].

To date, few renewable energy sources have been integrated into the off-grid networks presented in Figure 2. However, projects on PV development potential in Quebec's Far North are currently being carried out, notably by Nergica and the CanmetENERGY-Varennes research centre [5], [12], [13].

Solar PV integration in off-grid networks of northern Quebec is currently the focus of two pilot projects being carried out in Quaqtaq and Kuujjuaq.

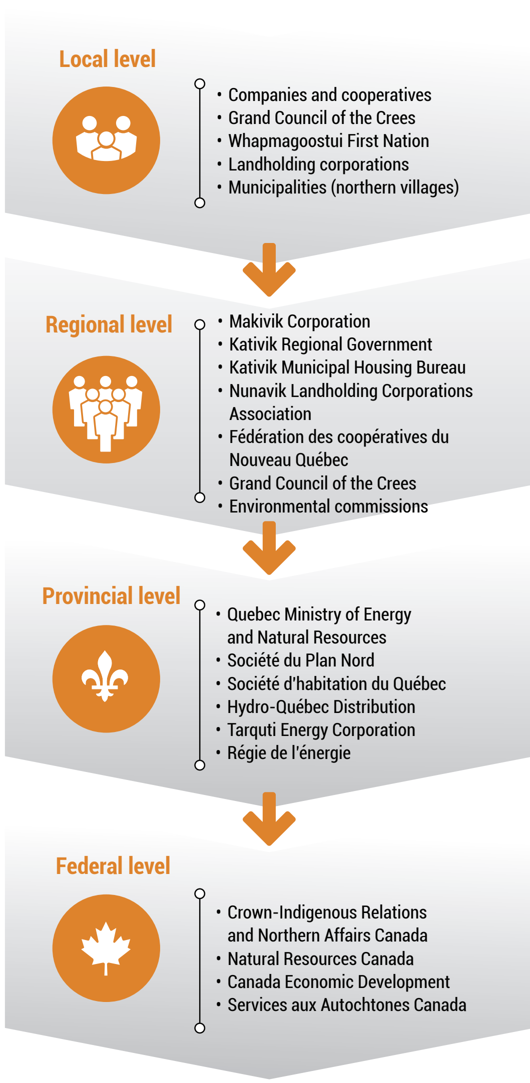
Quaqtaq: In 2018, Hydro-Québec installed a 21 kW PV system [14]. Intended to support the development of PV integration expertise in northern communities, this system resulted in savings of 6,000 litres of diesel in its first year of operation [15]. Additionally, 24 kW of solar panels were installed on the roofs of four residences in September 2019 [16].

Kuujjuaq: The Makivik Corporation installed a 70 kW array on its main office and on the Nunavik Research Centre. These installations would notably be used to study the effects of snow and ice on PV modules and on electricity production [17].

Photo: Justin Bulota

The success and long-term viability of renewable energy projects in northern Quebec's off-grid networks is contingent on an in-depth understanding by any stakeholders who might have a direct or indirect role to play in the business environment. Recent work carried out by CanmetENERGY helped to clearly identify these stakeholders at the local, regional and provincial levels.

Figure 3 Business Environment for Renewable Energy Projects in Northern Quebec



Moreover, CanmetENERGY recently conducted a study in which it calculated PV production potential by establishing the maximum system size that could be installed in Whapmagoostui and the off-grid communities of Nunavik if all rooftop space on which it was technically possible to install such systems were to be employed [12]. In addition to estimating the resulting energy yield, this study also calculated how much diesel fuel could be offset with such installations.

The results of this study show that, notwithstanding any limitations that an off-grid network operator might impose on solar PV integration, the resulting energy production could cover up to 50% of electricity needs in some of these communities. Annual diesel consumption for all communities combined could be slashed by 11.6 million litres.

Solar PV could represent an answer, or at least part of the answer, to the issue of reducing diesel reliance in the remote communities of Canada's northern regions. However, a number of questions remain with regard to the performance of PV systems deployed in cold climates and the challenges of integrating them in terms of grid stability and reliability.

A joint collaboration of Nergica and CanmetENERGY, the PV solar optimization and integration in cold climates project helped identify the main factors affecting PV system performance, determine the barriers that hamper their deployment in off-grid networks in northern Quebec, and present the performances of such a system operating in real-world cold climate conditions.

Harvesting the Sun in Cold Climates: A Surprising Paradox

Produced from light emitted by the sun, solar PV currently enjoys higher growth rates globally than any other renewable energy source [18]. Increasingly advanced technologies are helping to improve the efficiency of PV systems and drive costs significantly downward. According to a study published by the International Energy Agency (IEA), the cost of commercial PV projects in Canada plummeted by approximately 80% between 2007 and 2017 [19].

Likewise, solar PV is now a clean and financially competitive energy source that offers considerable advantages for northern Quebec and northern Canada, where most electricity is generated using fossil fuels. In this context, this energy source would help communities curb their reliance on fossil fuels, in addition to helping achieve the GHG emission reduction targets endorsed by Canada [20] and Quebec [7].

The solar potential of Canada's arctic regions is promising. For example, the solar potential in Kuujjuaq (1,033 kWh/kW), Iqaluit (1,059 kWh/kW) and a number of other communities in the Far North is greater than that of Tokyo (885 kWh/kW) and Berlin (848 kWh/kW). These capitals represent countries that were respectively ranked 3rd and 4th globally in 2017 in terms of installed PV capacity.

In this context, the integration of solar PV in cold climate regions represents a promising option. Besides its affordable cost, solar PV is easily customizable and scalable, system maintenance is simple and inexpensive, and the service life of modules can reach or exceed 25 years in most cases. However, as interesting an option as it is, it still presents significant technical challenges. The extreme climate conditions and the variable production of PV systems must be taken into account in order to ensure the success of their integration and optimize their yield.

In this context, Nergica and CanmetENERGY have teamed up to overcome these challenges and propose potential solutions.

Maximizing Penetration Levels While Safeguarding the Grid

Photo: Justin Bulota

Impact on Grid and Gensets

Numerous studies and analyses demonstrate that the maximum penetration rate of PV on a given grid is directly dependent on the adverse impacts that are likely to arise [22]–[29]. Indeed, integrating small and medium-sized PV systems[2] in an off-grid network can have an impact on the latter's reliability and stability (Table I).

In the context of off-grid networks, a number of operating conditions must be observed for gensets in order to preserve equipment integrity, reduce the frequency of maintenance work and extend the useful life of the generator(s). As a general rule, primary and auxiliary gensets are designed to operate at 50-85% of their rated capacity, while gensets programmed to run at a constant power setting can operate at 70-100% of their rated capacity. Furthermore, the use of gensets at loads of less than 30% for extended periods is not recommended [33].

Improper operation will lead to damaged components, a reduced life cycle, increased fuel consumption and unplanned stoppages [33].

Table I **Effects of Integrating PV Systems into Off-grid Networks**

Phenomenon	Repercussions on grid
Voltage fluctuations on the grid	May cause PV systems to trip offline and, consequently, cascade effects.
Phase imbalance	Mainly caused by single-phase inverters connected to a three-phase grid. Minor impact on the grid.
Increased total harmonic distortion in current	Can occur at low levels of sunlight. Impact directly dependent on grid penetration rate.
Flicker	Caused by very short-term variation in the resource. Minor impact on the grid.
Reduced grid inertia	Whenever the energy production of the PV system trends upward, the load handled by the gensets will correspondingly decrease. The magnitude of the impact is directly dependent on the penetration rate on the grid.

References: [23], [30]–[32]

2 This study is limited to systems with an installed capacity of less than 500 kW, as per the definition of system size proposed by the IEEE standard 929-2000 [1].

Restrictions Imposed by Canadian Off-grid Network Operators

The main measure used to mitigate the effects of integrating variable energy sources, notably PV, in off-grid networks remains capping their penetration levels. Indeed, operators impose limits in order to comply with operational constraints and to ensure a reliable power supply [6].

Northwest Territories Power Corporation (NTPC)

In its GHG and fossil fuel reliance reduction plan 2012-2017, the Government of the Northwest Territories determined the proportion of generator-produced electricity that could be replaced by PV systems.

Using PV systems for electricity production could help meet up to 20% of the average load normally provided by gensets [34].

Qulliq Energy Corporation (QEC)

The Qulliq Energy Corporation, which oversees the management and operation of Nunavut's electrical grid, has implemented a net metering program. This program allows clients to produce their own electricity from renewable energy sources while remaining connected to the utility's grid.

The maximum power that can be fed into the distribution network at any given time is 10 kW [35], [36]. The maximum installable power is limited to 7% of the annual average maximum load of the section of distribution grid where the system will be deployed [37].

ATCO Electric (Yukon)

Most of Yukon's communities are powered by hydroelectricity. However, thermal stations power the majority of the territory's off-grid networks.

Projects operated by independent power producers are limited to 20% of the total combined production of all off-grid networks [39].

Hydro One (Ontario)

Hydro One has created a net metering program for any client that generates electricity from renewable sources (wind, hydro, solar or biomass).

Hydro One regulations for microgeneration connections (up to 10 kW) to its distribution network establishes a threshold corresponding to 7% of the maximum annual load of the grid section [38].

Hydro-Québec Distribution

Residential and commercial clients in off-grid networks can take advantage of Hydro-Québec Distribution's (HQD) self-generation program, which contains certain requirements. Additionally, the particular context of off-grid networks that rely on thermal stations means that other conditions must also be taken into account [40].

- **Minimum operating level of gensets**

  Operating gensets on a low power setting can cause a number of problems ranging from higher fuel consumption to premature wear.

  Most genset manufacturers recommend that their equipment not be operated at more than 30% of their rated capacity.

- **Stability**

  Stability refers to the spinning reserve, i.e. the unused capacity of a genset, which is used to absorb abrupt fluctuations in the electric load and to avoid going offline.

  HQD's stability criterion indicates that gensets must operate at less than 90% of their rated capacity [16].

- **Maximum installable capacity for renewables**

  The self-generation program caps the installed capacity of renewable energy systems to 50 kW [41]. In addition to complying with applicable conditions and regulations, **large-scale projects that plan to exceed this limit could be required to conduct additional studies in order to assess their impact on grid stability and reliability.**

Despite significant effort and political will, the integration of solar PV in Quebec's Far North is hampered by the grid's capacity to absorb this energy while continuing to meet stability and safety criteria.

Table II presents data from CanmetENERGY's recent study, which calculates PV production potential in the off-grid communities of Nunavik and in Whapmagoostui (see Page 2) [12]. This table presents the maximum PV capacities that can be installed while complying with the restrictions imposed on the eleven off-grid networks for which electricity consumption data are available.

Criteria taken into account are the following:

1. Minimum operating level;
2. Stability, as defined by Hydro-Québec Distribution (see p. 9); and
3. The installed capacity of new systems, which is limited to 5% of the rated capacity of the smallest generator or the combination of generators needed to meet the minimum load of the off-grid network.

In most cases, the upper limit of 5% for installable renewable capacity constrains the integration of solar PV in the province's off-grid networks. In terms of production, the solar power generated could cover an average of 0.5% of the communities' annual needs [5].

Table II **Integratable PV Power in Off-grid Networks of Northern Quebec**

Community	Maximum PV power [kW] (Criteria 1 and 2)	Maximum PV power [kW] (Criteria 1, 2 and 3)
Aupaluk	42	11
Inukjuak	291	73
Ivujivik	50	12
Kangiqsualujjuaq	23	23
Kangirsuk	90	23
Kuujjuaq	481	120
Kuujjuarapik*	112	57
Puvirnituq	347	87
Quaqtaq	64	16
Salluit	171	43
Umiujaq	103	33

Reference: [5]

* The Kuujjuarapik station also powers the community of Whapmagoostui.

Operating in Cold Climates: Tapping a Remarkable Potential

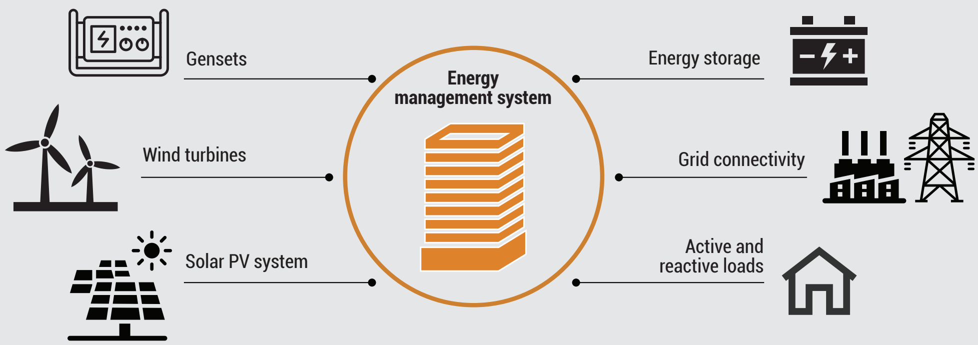
Solar PV production in cold climates is contingent on a number of factors including the available solar resource, the selected technology, wind chill effects, snow cover and, evidently, the installation layout and characteristics of the system.

Photo: Justin Bulota

Infrastructures Going Solar, Too

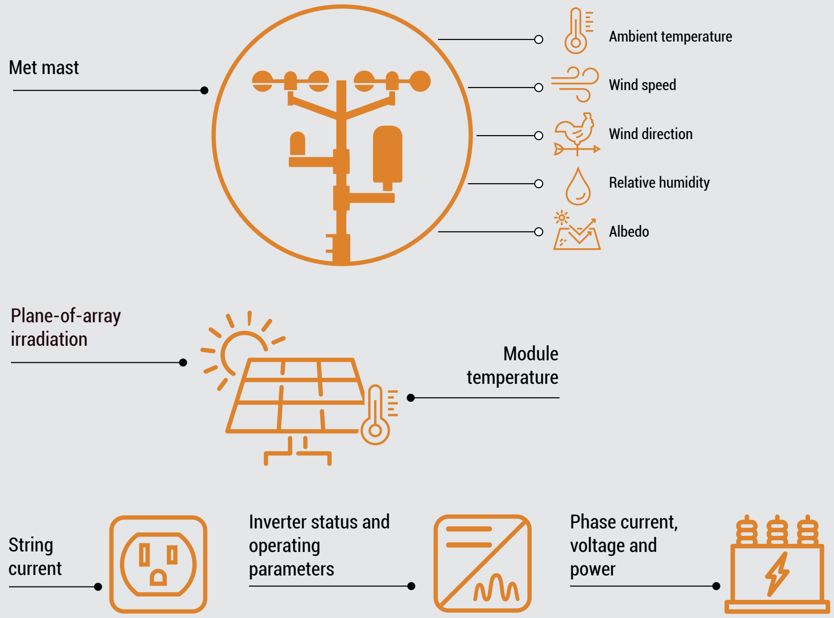
Located in Rivière-au-Renard, Quebec, Nergica's full-scale outdoor research site (Figure 4w) comprises wind turbines, a PV system and a microgrid. The latter is used to conduct a range of analyses in the field of renewable energy integration, both for off-grid systems and for systems connected to Hydro-Québec's distribution grid.

Figure 4 Nergica's Microgrid



Designed for research purposes, Nergica's PV system features instrumentation that exceeds existing performance monitoring standards [42]. Besides the sensors installed on the PV structure itself, more advanced instrumentation was installed on a nearby met mast.

Figure 5 Instrumentation of Nergica's PV System



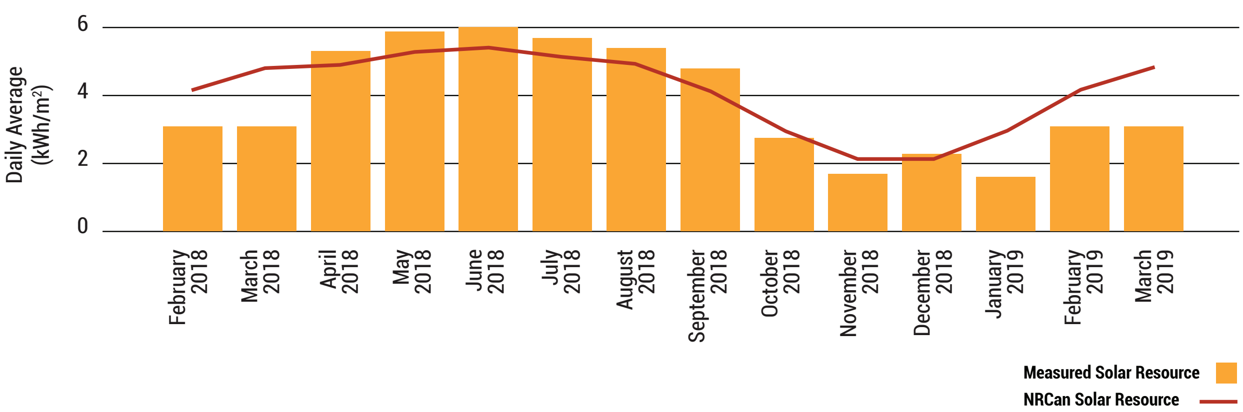
Operational data collected from Nergica's PV system in the context of the PV solar optimization and integration in cold climates project [13] carried out from November 2016 to April 2019 were used to conduct a number of analyses that served as a basis to determine system performance or to quantify the effect of different climatic variables (solar irradiation, ambient temperature, wind speed) on such performance.

Solar Resource

The results obtained under the project showed that the solar resource, which can be interpreted as the number of hours of maximum sunshine at 1,000 W/m^2 per day and which is expressed in kWh/m^2, was 3.96% higher in 2018 than the average proposed by Natural Resources Canada (NRCan) in its solar resource and PV maps of Canada. These maps present estimates of how much electricity can be produced by PV systems (in kWh/kW) and the average daily solar irradiance (in kWh/m^2) for over 3,500 municipalities in Canada [43] (Figure 6). The figures proposed by NRCan are interannual averages calculated using historic data; differences of 4-8% can appear from one year to another.

In summer, the irradiance measured in situ exceeds the proposed figures. The winter solar resource is less than NRCan's figure, but the higher potential between April and September mitigates the impact of this divergence.

Figure 6 Solar Resource at Nergica's Research Site

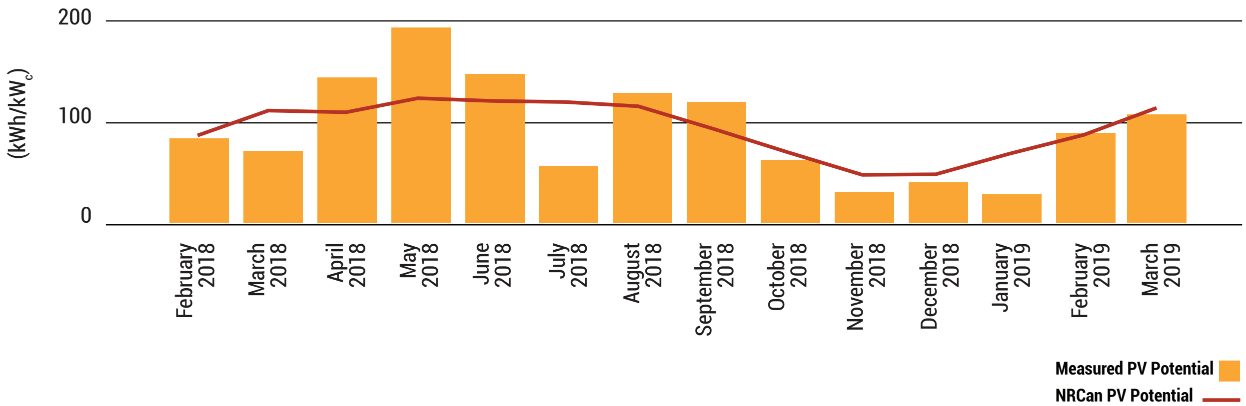


Annual Productivity

The PV potential of Nergica's research site in 2018 was 0.97% higher than the average proposed by NRCan (Figure 7). The annual trend is very similar to that of the solar resource, except for the month of July, when maintenance work performed on Nergica's infrastructures affected the technical availability of the equipment. This situation explains the difference between the profile for PV potential and the one for the solar resource presented in the following figure.

Normalized PV potential (in kWh/kW$_p$) is a parameter that indicates the expected production of a PV system over a given period (typically one year). Its value varies as a function of the solar irradiation available at the site where the system is installed and the position of the panel (tilt and orientation).

Figure 7 PV Potential at Nergica's Research Site



PV potential and solar resource data from Nergica's research site are used to develop an initial annual production profile (Table III). Although the differences between NRCan averages and the results of the Year 1 energy yield study are minimal, and even if the study was carried out over just one year, certain monthly disparities are worth pointing out. For example, the energy production of the first two months of the year is less than the information provided by NRCan, whereas the trend is reversed in summer, when energy production exceeds NRCan's estimate.

Lastly, the particularly high production in April and May is mainly attributable to low temperatures and considerably less snowfall with respect to the preceding months.

Table III **Annual Comparison of Solar Resource and PV Potential**

Annual comparison

Parameter	Unit	NRCan	Measured	Percentage
Solar resource	kWh/m^2 Daily average	3.92	4.08	103,96%
PV potential	kWh/kW_p	1,122.00	1,132.91	100,97%

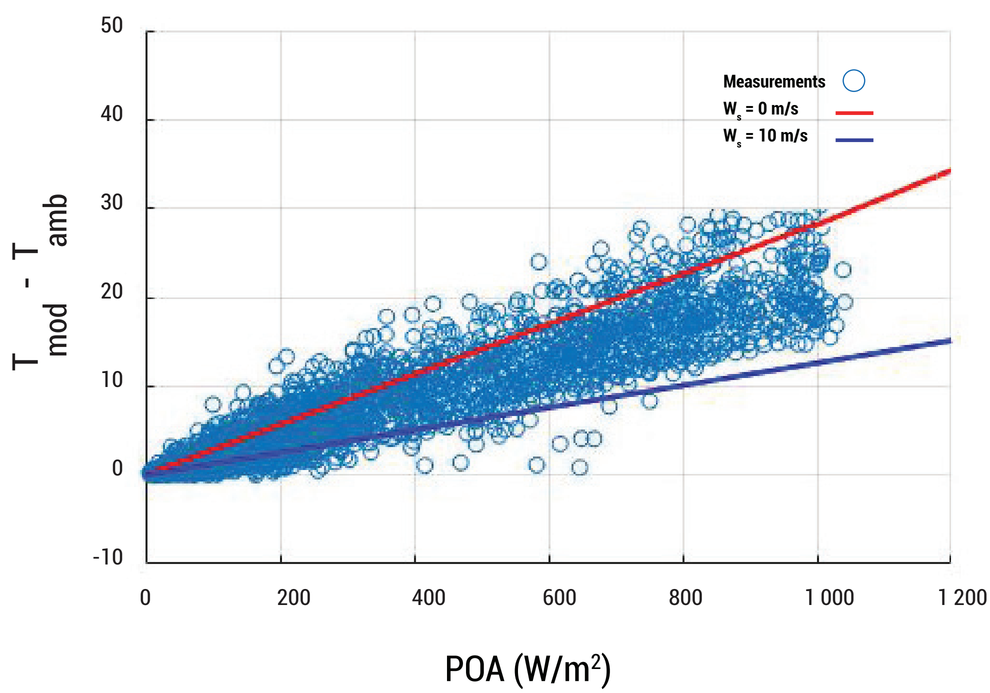
Wind Chill

In addition to depending on the solar resource, the yield of silicon PV modules is partially contingent on their temperature which, when lower, results in higher efficiency.

Wind therefore has a considerable effect on yield, as it can lead to cooling via natural convection. Analyses conducted by Nergica on its PV system notably quantified how much the modules are cooled as a function of wind speed (Figure 8) and demonstrated their higher production, essentially during the winter months.

For example, assuming an incident sunlight on the module surface of 1,000 W/m², a wind speed (W_s) of 10 m/s can lead to a temperature reduction of the modules of approximately 16°C, which translates into a power output increase in the order of 8.2%.

Figure 8 Effect of Wind Speed on Module Temperature



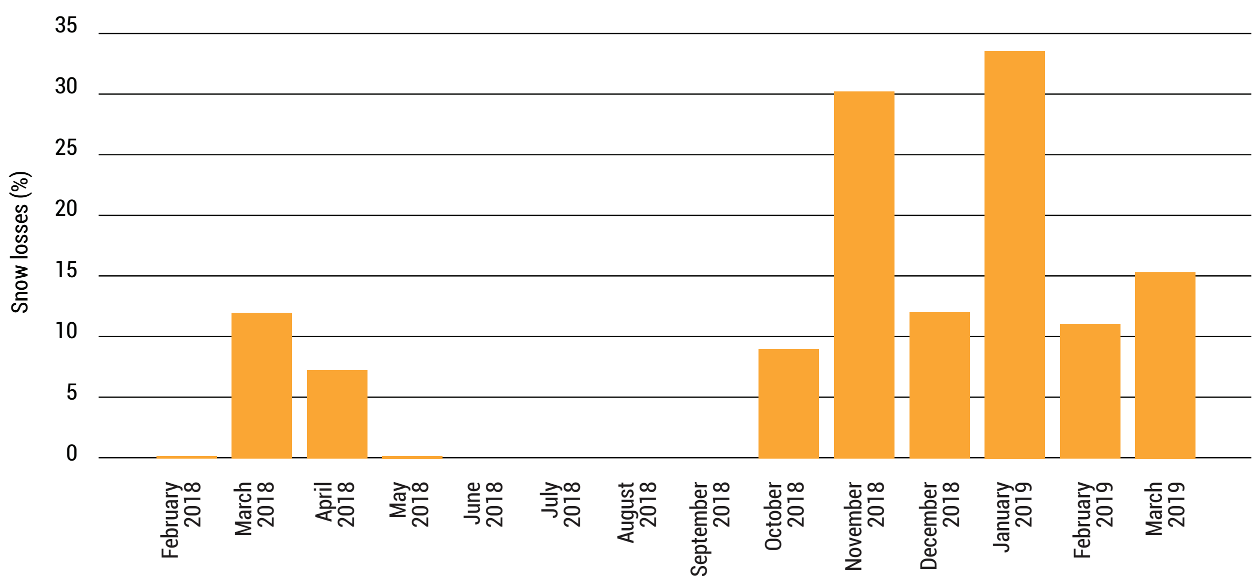
Snow Cover

Undoubtedly, one of the main factors contributing to PV production losses in winter is the effect of snow cover on the modules, which prevents sunlight from reaching their surface.

Based on analyses performed by Nergica using numerical methods for comparing production as well as image analysis, annual losses attributable to snow accumulation on the modules were estimated to be in the order of 6%. Based on these analyses, it can also be affirmed that conventional methods, which are based on how much snow is on the ground [44], generally under estimate losses. Figure 9 presents the percentage of monthly losses caused by snow accumulations on the modules.

Over the course of the year, i.e. April 2018 to March 2019, snow-related losses are 5.93%. The most significant losses (-33.52%) were recorded in January 2019 and the lowest figures (-7.31%) in April 2018.

Figure 9 Losses Caused by Snow Accumulation on PV Modules



System Layout

In cold climates, snow and ice can accumulate on PV modules, thereby blocking the sunlight, reducing power production and, in rare cases, damaging the modules. Mountainous areas exposed to atmospheric icing are particularly problematic in this regard [45], [46].

The likelihood of snow accumulation on the modules can be reduced, however.

- Using higher tilt angles, which increase the likelihood that the force of gravity will cause the snow to slide off. A lower tilt angle (< 30°) will prevent the modules from shedding snow, which leads to lower energy production in winter months.
- By taking into account the module layout, i.e. installing modules such that the shorter side is parallel to the ground [45] (Figure 10).

Figure 10 PV Module Layout

- By choosing modules with a larger surface area, since small modules have a tendency to retain snow longer than large ones [45]. Indeed, the longer the panel, the more snow will tend to slide off under the force of gravity.
- By choosing frameless modules, as frames can prevent snow from shedding [47].
- By striving to install modules on south-facing façades, which allows for higher energy production in winter, when the sun is lower in the sky, and considerably reduces the risk of snow accumulation. Other advantages of this type of installation include reduced structural failures caused by high winds and less material required for installation, which translates into lower initial investment costs.
- By taking into account maximum historic snow accumulations in order to ensure that the structures are raised off the ground accordingly [48].
- Lastly, by considering the characteristics of the electrical load over the course of the year when choosing the position of the modules. Evidently, orientations and tilt angles can be selected with a view to optimizing the balance between load and power production. For example, an east-west orientation can be used to obtain a flat production profile, meaning the peak production around noon is lower [49], [50].

Photo: Justin Bulota

Taking Advantage of Constantly Evolving Technologies

There are numerous types of PV solar modules, which can be categorized as a function of their technology readiness level. Some make use of proven technologies, while others rely on emerging technologies or those still under development.

Table IV presents a comparative analysis of the different types of modules currently available. This analysis takes into account their yield as well as the advantages and disadvantages of using each in cold climate conditions.

Table IV **Comparison of Different Types of PV Modules Available on Market**

Proven technologies			
Type of solar module	**Yield**	**Advantages**	**Disadvantages**
Monocrystalline silicon (mono-Si)	~ 20 - 26%	- High yield and long service life	- Relatively high cost - Fragile - Low yield at high temperatures and low light conditions
Polycrystalline silicon (poly-Si)	~ 15 - 22%	- Low cost - Good price-performance ratio	- Slightly lower efficiency than that of monocrystalline silicon - Fragile - Low yield at high temperatures and low light conditions
Thin film: amorphous silicon (a-Si)	~ 7 - 14%	- Relatively low cost - Easy to manufacture, flexible - Lower sensitivity to temperature effects - Good yield in low light conditions	- Shorter service life - Low yield
Bifacial modules	~ 20%	- Lower installation and BOS costs - Less surface required for modules - Higher production in winter due to reflective properties of snow	- High cost - Installation standards to be met to avoid shading on both sides of modules - Few systems installed in cold climates or in off-grid networks

Technologies under development

Type of solar module	Yield	Advantages	Disadvantages
Heterojunction silicon	~ 26%	- Combination of advantages of monocrystalline silicon, polycrystalline silicon and amorphous silicon - Simple design - Fewer steps in manufacturing process - Lower sensitivity to temperature effects	- Low technology readiness level
Cadmium telluride (CdTe)	~ 16 - 22%	- High yield - Lower sensitivity to temperature effects	- High cost - Toxicity (if not recycled)
Copper indium gallium selenide (GICS)	~ 20 - 23%	- High yield - Flexible, cell thickness - Low temperature coefficient - Efficiency less affected at higher temperatures	- Low technology readiness level - Complex production process using rare elements - High cost

Emerging technologies

Type of solar module	Yield	Advantages	Disadvantages
Perovskite PV cell	~ 24%	- Very high yield - Lightweight - Flexible - Variable transparency and tint - Favourable cost	- Technology still under development - Reliability issues - Structural stability: low resistance to humidity, pressure, high temperatures and UV rays - Lead used in manufacturing process
Perovskite-silicon tandem	~ 28%	- Very high yield - Lightweight - Semi-transparent - Favourable cost	- Technology still under development - Reliability issues - Structural stability: low resistance to humidity, pressure, high temperatures and UV rays - Low long-term operational stability - Toxic components (liquid electrolyte) - Particularly difficult manufacturing process in terms of depositing perovskite layer onto silicon
Dye-sensitized Solar Celll (DSSC)	~ 12%	- Robust, lightweight - Promising substitute for existing low-density technologies - Good yield in low light conditions - Higher yield at high temperatures - Low toxicity - Moderate flexibility	- Technology still under development - Low yield and low intrinsic stability - Short service life - Reproducibility (mass production) - Airtight liquid electrolyte: toxic vapour hazard - Low flexibility when electrolyte is solid - High cost
Quantum Dot Solar Cell (QDSC)	~ 17%	- High yield - Low cost - Good price-performance ratio - Lightweight, flexible - Easy to manufacture	- Technology still under development - Toxic semi-conductor material used to manufacture heavy metal QDSCs
Organic solar cells	~ 16%	- High yield - Lightweight and flexible structure - Semi-transparent - Low cost - Good price-performance ratio - Easy to manufacture - Environmentally-friendly material	- Technology still under development - Reduced operational lifetime - Stability issues - Low resistance - Significant photochemical degradation

References: [51]-[63]

Emerging Technologies and Penetration Levels: Turning to Innovative Solutions

Although the constraints associated with integrating solar PV represent a barrier to the optimal deployment of this energy source in northern climates, demand-side management and certain emerging technologies could help boost penetration rates while at the same time ensuring grid stability. In this context, such an approach to management and these technologies represent an attractive option for both communities and governments aiming to provide a clean, sustainable and low-carbon power supply at the lowest cost.

Photo: Justin Bulota

Demand-side Management

The aim of demand-side management is to modify demand rather than concentrating efforts solely on production, through a combination of incentives, disincentives and the deployment of new technologies. For example, an incentive could entail offering rebates for the purchase of LED light bulbs, which consume considerably less energy than their incandescent counterparts. Conversely, a disincentive could consist of variable electricity rates as a function of the hour of the day. Such a measure would therefore encourage certain users to shift their consumption to times of the day when demand is lower. Lastly, it is possible to promote the implementation of new technologies, e.g. smart thermostats that can adjust energy consumption as a function of several factors, notably the availability of the solar resource.

A number of measures in this regard are already in place in Quebec's off-grid networks [8].

1. **Energy efficiency programs** offered by Hydro Québec Distribution (HQD) that include: 1) a "dissuasive" rate to discourage electric space heating and 2) a program that aims to promote the use of propane or fuel oil for space heating (HQD pays 90% of maintenance fees and guarantees a fixed price for propane, regardless of the current price).

2. **Energy-saving interventions** offer clients in off-grid networks ways to lower their electricity consumption. HQD has changed out public lighting in favour of LED light bulbs and is encouraging residential clients to do the same. The Crown corporation is also offering support for the insulation of buildings and roof spaces, consumption analysis, acquisition of a three-element water heater, etc.

3. **Awareness campaigns** to reduce the peak power loads in winter.

Energy Storage

Using energy storage can improve the integration of solar PV. Indeed, storage systems (e.g. batteries) enable the power output of solar PV systems to be stocked and made available for subsequent use when the solar resource is no longer sufficient. Otherwise, electric thermal storage systems are sometimes used to store excess energy in a different and easily usable form.

Storage systems can be employed to considerably mitigate the constraints imposed on renewable energies in off-grid networks, as the gensets can run at an acceptable power setting at all times, and since surplus energy produced during the day can be used at a later time as needed. Adding storage systems also entails other advantages, mainly improved stability and a better balance between load and energy production. Challenges — mostly cost-related — remain for the integration of storage sources.

Variable-speed Gensets

Variable-speed gensets are a promising option to reduce fuel consumption and increase the amount of renewable energy that the grid can absorb. This technology aims to decouple the genset's rotational speed and the grid frequency through the use of power electronic interfaces.

In another approach, the use of variable transmission systems would allow the rotational speed of the diesel engine to be decoupled from that of the electric generator. In this type of genset, the diesel engine can function in optimal conditions for each attributed load value, which leads to a higher efficiency and a better performance at low settings (typically, less than 30% of the nominal capacity of the diesel engine).

Although this technology has received relatively little attention, it can have a significant impact on the transformation of off-grid networks that rely mainly on thermal power plants for their electricity production.

PV System With Advanced Inverters

One option for communities aiming to achieve higher PV penetration is the use of advanced inverters. Such inverters allow for real-time reductions in the system's power output. It then becomes possible to consistently comply with the limits imposed to maintain the balance between production and demand.

Energy production will always increase with the connection of additional PV modules, but the useful contribution of each new module decreases, as the greater the capacity installed, the more time over the course of the year output will exceed demand: such output must therefore be curtailed to maintain the production-demand balance.

This way, the annual energy yield per kilowatt of installed capacity decreases with the size of the system. Consequently, the cost associated with installing the PV system should remain favourable with respect to the use of thermal stations to produce a given unit of energy. The upper capacity limit for this type of installation is therefore a function of the project's Net Present Value (NPV).

It should also be noted that advanced inverters can provide other services to the distribution grid, notably auxiliary services such as reactive power compensation, voltage regulation, gradual increase of power output and the possibility to avoid grid disconnections during frequency or voltage disturbances. Decentralized auxiliary management services for the distribution grid can be considered a new added value for solar power.

This latter topic will be the focus of continued collaboration between Nergica and CanmetENERGY. This research initiative aims to determine the relevance of deploying advanced inverters in off-grid networks in Quebec and throughout Canada in the context of distributed production.

By using new technologies, industry players can push the boundaries of solar PV integration in off-grid networks and enhance the value proposition of this energy source thanks to the decentralization of auxiliary grid management services.

The complementary infrastructures and technical expertise that Nergica's team has developed unquestionably represent an important asset for the integration of solar PV in cold climates and in off-grid networks in Canada.

A Powerful Real-time Simulation System

Through the Cégep de la Gaspésie et des Îles, Nergica has acquired a simulation platform from OPAL-RT. This cutting-edge equipment is helping to provide the data and information needed to simulate solar PV systems and other renewable energy systems. This platform allows physical modules to be added to numerical simulations. The results produced by these simulations faithfully reproduce the behaviour of the infrastructures that make up Nergica's microgrid.

One of the main advantages of this platform is the possibility to develop and validate cutting-edge solutions with high accuracy before they are deployed in the field. This notably helps cut costs and reduce risks during the design and validation phases of renewable energy systems. Amongst other things, Nergica can test the impact of renewable energy sources (solar PV, wind, hydrokinetic, etc.) on microgrid reliability and resilience and implement algorithms to mitigate these effects.

The challenges associated with integrating solar PV into off-grid networks are related to transients, which can create disturbances and generate risks for grid stability and reliability. Additionally, the integration of variable energy sources can considerably affect energy quality.

On the other hand, advanced inverters can mitigate these risks as well as improve energy quality by providing auxiliary services. Simulation systems that integrate hardware in the loop can be used to study disturbances and assess the advantages that using advanced inverters can offer in the context of off-grid networks.

Conclusion

The culmination of a collaborative research effort between Nergica and CanmetENERGY, this white paper presents the primary factors affecting PV system performance, barriers hampering their deployment in off-grid networks in northern Quebec and northern Canada as well as the performance of these PV systems operated in real-world cold climate conditions.

Recent technological advances confer solar PV an enviable position in the ongoing energy transition of remote communities. Undeniable advantages include costs of deployment, well known logistical requirements and scalability that can meet the needs of communities.

Applied research efforts must be undertaken in order to overcome the challenges that hinder solar PV integration and prevent it from achieving higher penetration levels in off-grid networks. The avenues of action identified in this document are evidence of the remarkable potential of this energy source which, together with other technologies, innovative energy-saving measures or changes in consumer habits, can help accelerate the energy transition and reduce the over-reliance of off-grid communities on diesel fuel.

Photo: Jacques Gratton

Who are we?

Nergica is a centre of applied research that stimulates innovation in the renewable energy industry through research, technical assistance, technology transfer and technical support for businesses and communities. Its mission: to create new opportunities for renewable energy.

More precisely, Nergica specializes in developing solutions for renewable energy integration, optimizing wind farm and solar array performance and supporting growing SMEs. The organization carries out its activities by drawing from a multidisciplinary team of experts, research infrastructures in a natural setting that are unavailable elsewhere in Canada, and custom services that support innovation.

Initially recognized for its expertise in cold climates and O&M, Nergica also offers advanced services for the development and assessment of new technologies, commercialization of innovations, adapted meteorology, microgrids, energy storage and grid management. Initially known as the TechnoCentre éolien when it was founded in 2000, Nergica is an official college centre for technology transfer (CCTT) and is affiliated with the Cégep de la Gaspésie et des Îles (CGÎ).

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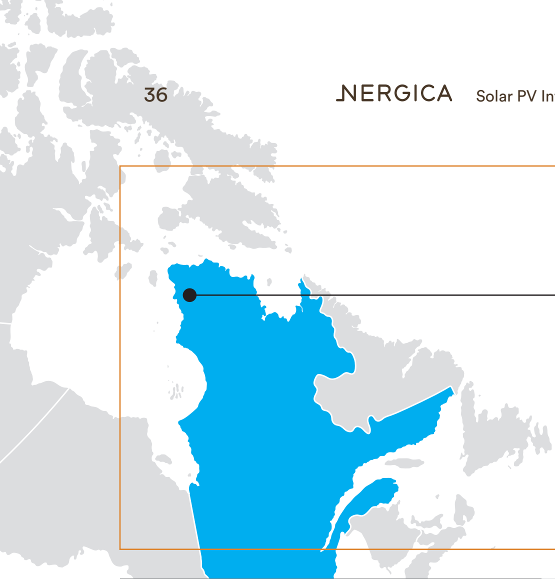
Appendix

Energy Profiles of Northern Quebec Communities *

* Reference: [12]

Photo: Justin Bulota



Akulivik

633 inhabitants

60.81° N, 78.19° W

Generation Infrastructure

Number of generators	3
Capacities	565/727/727 kW
Installation year	2015
Average energy efficiency	3.59 kWh/l
Annual consumption	919 kl
Annual CO_2 emissions	2,445 t

Penetration Limits

	2015	2025
Maximum PV respecting all criteria	*	*
Spinning reserve (20%)	*	*
Minimum genset load (30%)	*	*
Penetration ration (power)	*	*
Penetration ration (energy)	*	*

Distribution Infrastructure

Feeder voltage	4.16 kV
Number of phases	3
Longest feeder	2,800 m (estimated)

Potential diesel savings and CO_2 reductions

	Diesel	CO_2
Penetration limits 2015 (0 kW)	*	*
Penetration limits 2025 (0 kW)	*	*
Maximum rooftop PV (2 MW)	496 kl	1,319 t

Electric Load

2016 data

Annual energy use	3.66 GWh
Peak load	742 kW
Daily average load	*

2026 Forecast

Annual energy use	4.72 GWh
Load growth	2.6% per year (compared to 2016)

DAILY AVERAGE LOAD BY MONTH

Load data unavailable for this community.

Solar Resource and PV Potential

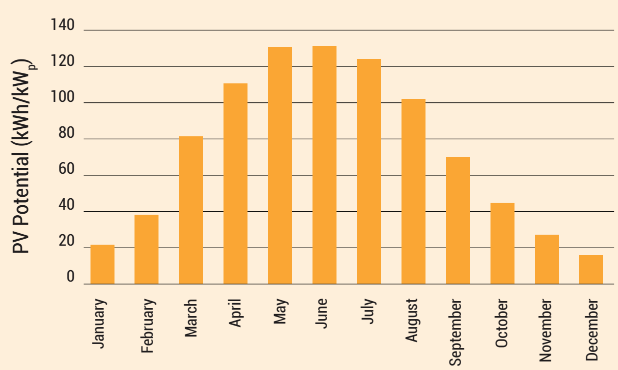
Tilted surfaces (tilt angle = latitude)

Average irradiation	3,25 kWh/m²
Annual PV potential	890 kWh/kW
Monthly PV potential	See chart

Rooftop PV potential

Estimated rooftop surface area	15 x 10³ m² Max.
Rooftop PV	2 MW
Estimated annual production	1,923 MWh

MONTHLY PV POTENTIAL PER kW_p **



* Data not available ** Kilowatt-peak

Aupaluk

209 inhabitants

59.3° N, 69.6° O

Generation Infrastructure

Number of generators	3
Capacities	210/250/320 kW
Installation year	Before 1981
Average energy efficiency	3.75 kWh/l
Annual consumption	427 kl
Annual CO_2 emissions	1,135 t

Penetration Limits

	2015	2025
Maximum PV respecting all criteria	42 kW	42 kW
Spinning reserve (20%)	42 kW	42 kW
Minimum genset load (30%)	59 kW	116 kW
Penetration ration (power)	0.11%	0.08%
Penetration ration (energy)	1.9%	1.4%

Distribution Infrastructure

Feeder voltage	4.16 kV
Number of phases	3
Longest feeder	1,000 m (estimated)

Potential diesel savings and CO_2 reductions

	Diesel	CO_2
Penetration limits 2015 (0 kW)	9.6 kl	26 t
Penetration limits 2025 (0 kW)	9.6 kl	26 t
Maximum rooftop PV (2 MW)	206 kl	548 t

Electric Load

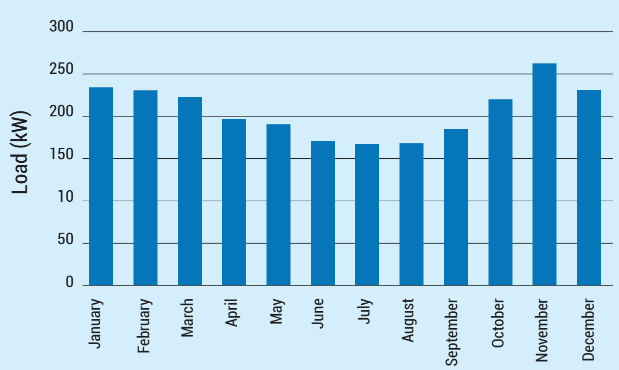
2016 data

Annual energy use	1.89 GWh
Peak load	375 kW
Daily average load	206 kW
Monthly average load	See chart

2026 Forecast

Annual energy use	2.5 GWh
Load growth	2.8% per year (compared to 2016)

DAILY AVERAGE LOAD BY MONTH



Solar Resource and PV Potential

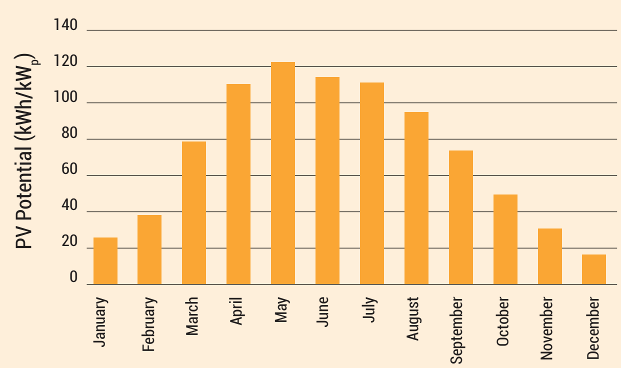
Tilted surfaces (tilt angle = latitude)

Average irradiation	3.13 kWh/m^2
Annual PV potential	857 kWh/kW
Monthly PV potential	See chart

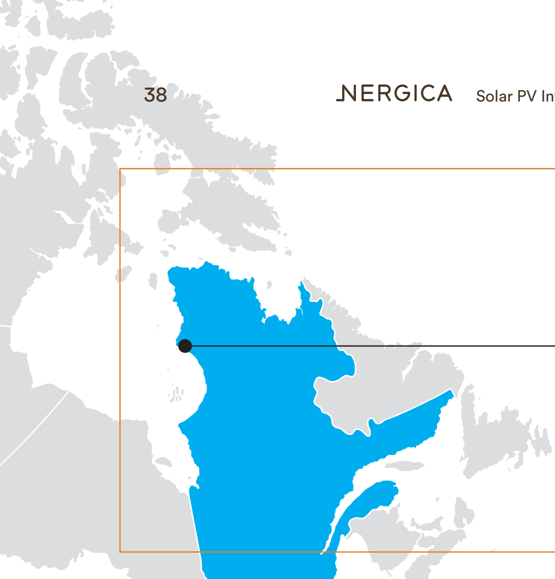
Potentiel PV sur les toits

Estimated rooftop surface area	7 x 10^3 m^2 Max.
Rooftop PV	0.9 MW
Estimated annual production	853 MWh

MONTHLY PV POTENTIAL PER kW$_p$ *



* Kilowatt-peak



Inukjuak

1,757 inhabitants

58.45° N, 78.1 W

Generation Infrastructure

Number of generators	4
Capacities	855/600/1,168/1,135 kW
Installation year	Before 1981
Average energy efficiency	3.84 kWh/l
Annual consumption	2,395 kl
Annual CO_2 emissions	6,371 t

Penetration Limits

	2015	2025
Maximum PV respecting all criteria	244 kW	291 kW
Spinning reserve (20%)	291 kW	291 kW
Minimum genset load (30%)	244 kW	463 kW
Penetration ration (power)	13%	13%
Penetration ration (energy)	2.1%	2.1%

Distribution Infrastructure

Feeder voltage	4.16 kV
Number of phases	3
Longest feeder	2,800 m (estimated)

Potential diesel savings and CO_2 reductions

	Diesel	CO_2
Penetration limits 2015 (0 kW)	58.8 kl	156 t
Penetration limits 2025 (0 kW)	70.1 kl	186 t
Maximum rooftop PV (2 MW)	1,180 kl	3,139 t

Electric Load

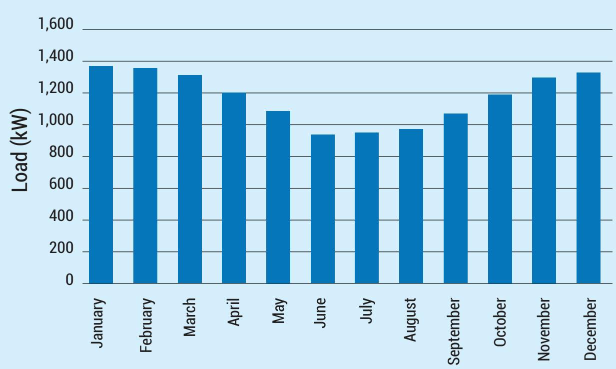
2016 data

Annual energy use	10.52 GWh
Peak load	1,823 kW
Daily average load	1,174 kW
Monthly average load	See chart

2026 Forecast

Annual energy use	12.94 GWh
Load growth	2.1% per year (compared to 2016)

DAILY AVERAGE LOAD BY MONTH



Solar Resource and PV Potential

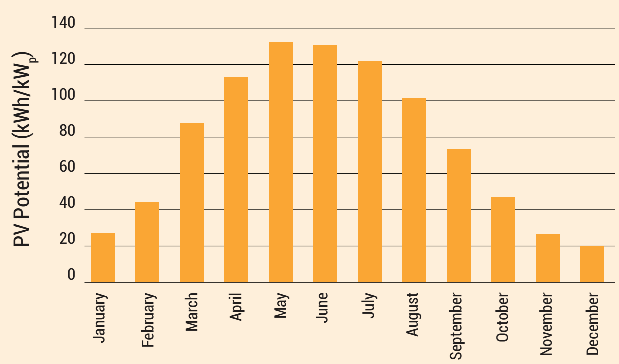
Tilted surfaces (tilt angle = latitude)

Average irradiation	3.38 kWh/m^2
Annual PV potential	925 kWh/kW
Monthly PV potential	See chart

Rooftop PV potential

Estimated rooftop surface area	37×10^3 m^2 Max.
Rooftop PV	4.9 MW
Estimated annual production	4,874 MWh

MONTHLY PV POTENTIAL PER kW_p *



* Kilowatt-peak

Ivujivik

414 inhabitants

62.42° N, 77.91 W

Generation Infrastructure

Number of generators	3
Capacities	250/365/365 kW
Installation year	Before 1987
Average energy efficiency	3.35 kWh/l
Annual consumption	627 kl
Annual CO_2 emissions	1,667 t

Penetration Limits

	2015	2025
Maximum PV respecting all criteria	50 kW	50 kW
Spinning reserve (20%)	28 kW	69 kW
Minimum genset load (30%)	244 kW	463 kW
Penetration ration (power)	6%	8%
Penetration ration (energy)	0.8 %	1.2 %

Distribution Infrastructure

Feeder voltage	4.16 kV
Number of phases	3
Longest feeder	1,100 m (estimated)

Potential diesel savings and CO_2 reductions

	Diesel	CO_2
Penetration limits 2015 (0 kW)	6.5 kl	17 t
Penetration limits 2025 (0 kW)	11.6 kl	31 t
Maximum rooftop PV (2 MW)	302 kl	803 t

Electric Load

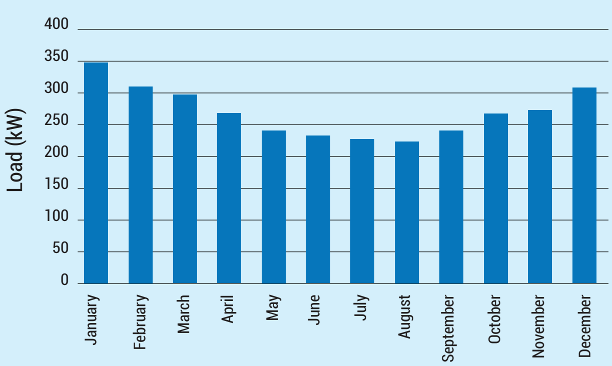
2016 data

Annual energy use	2.56 GWh
Peak load	460 kW
Daily average load	270 kW
Monthly average load	See chart

2026 Forecast

Annual energy use	3.28 GWh
Load growth	2.5% per year (compared to 2016)

DAILY AVERAGE LOAD BY MONTH



Solar Resource and PV Potential

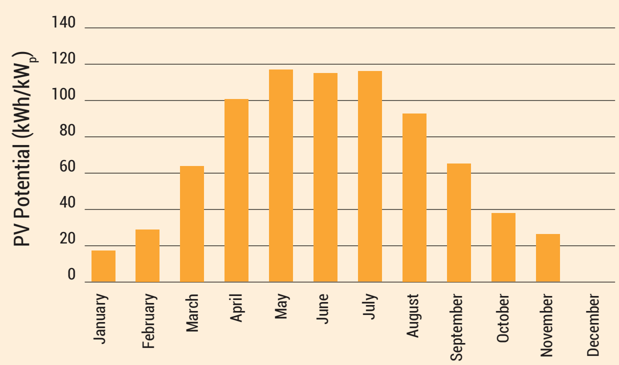
Tilted surfaces (tilt angle = latitude)

Average irradiation	2.84 kWh/m^2
Annual PV potential	777 kWh/kW
Monthly PV potential	See chart

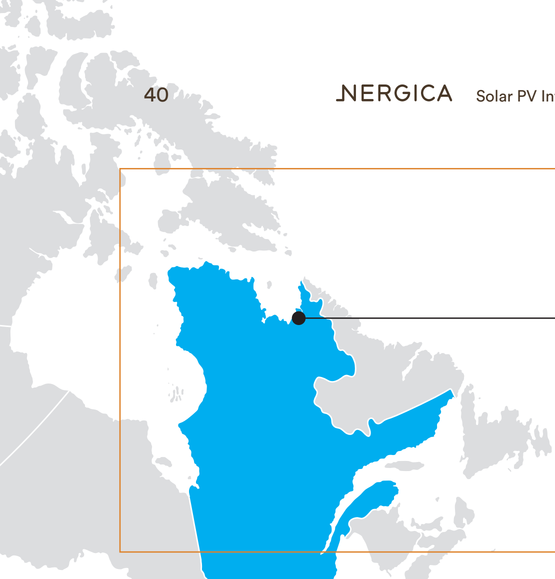
Rooftop PV potential

Estimated rooftop surface area	10×10^3 m^2 Max.
Rooftop PV	1.3 MW
Estimated annual production	1,175 MWh

MONTHLY PV POTENTIAL PER kW_p *



* Kilowatt-peak



Kangiqsualujjuaq

942 inhabitants

58.69° N, 65.95 W

Generation Infrastructure

Number of generators	3
Capacities	560/560/855 kW
Installation year	Before 1986
Average energy efficiency	3.47 kWh/l
Annual consumption	1,268 kl
Annual CO_2 emissions	3,373 t

Penetration Limits

	2015	2025
Maximum PV respecting all criteria	0 kW	23 kW
Spinning reserve (20%)	112 kW	112 kW
Minimum genset load (30%)	0 kW	23 kW
Penetration ration (power)	*	2%
Penetration ration (energy)	*	0.3%

Distribution Infrastructure

Feeder voltage	4.16 kV
Number of phases	3
Longest feeder	3,500 m (estimated)

Potential diesel savings and CO_2 reductions

	Diesel	CO_2
Penetration limits 2015 (0 kW)	*	*
Penetration limits 2025 (0 kW)	5.4 kl	14 t
Maximum rooftop PV (2 MW)	536 kl	1,426 t

Electric Load

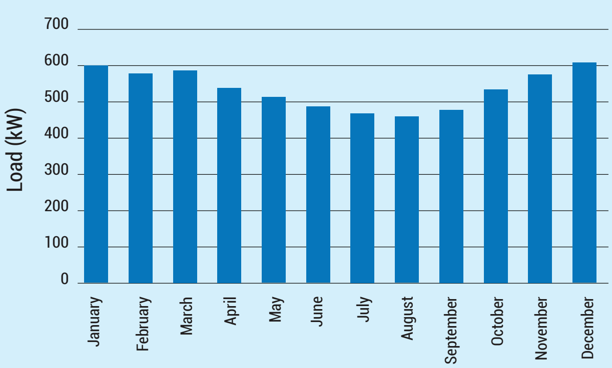
2016 data

Annual energy use	1.89 GWh
Peak load	375 kW
Daily average load	206 kW
Monthly average load	See chart

2026 Forecast

Annual energy use	2.5 GWh
Load growth	2.2% per year (compared to 2016)

DAILY AVERAGE LOAD BY MONTH



Solar Resource and PV Potential

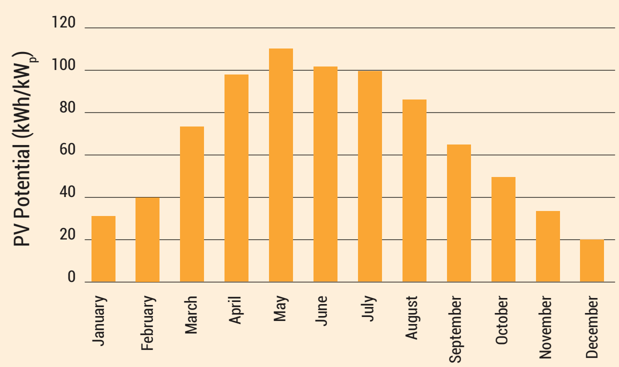
Tilted surfaces (tilt angle = latitude)

Average irradiation	2.95 kWh/m²
Annual PV potential	808 kWh/kW
Monthly PV potential	See chart

Rooftop PV potential

Estimated rooftop surface area	17 x 10³ m² Max.
Rooftop PV	2.3 MW
Estimated annual production	1,978 MWh

MONTHLY PV POTENTIAL PER kW_p **



* Data not available ** Kilowatt-peak

Kangiqsujuaq

750 inhabitants

61.6° N, 71.96 W

Generation Infrastructure

Number of generators	3
Capacities	409/560/560 kW
Installation year	Before 1981
Average energy efficiency	3.34 kWh/l
Annual consumption	1,198 kl
Annual CO_2 emissions	3,186 t

Penetration Limits

	2015	2025
Maximum PV respecting all criteria	*	*
Spinning reserve (20%)	*	*
Minimum genset load (30%)	*	*
Penetration ration (power)	*	*
Penetration ration (energy)	*	*

Distribution Infrastructure

Feeder voltage	4.16 kV
Number of phases	3
Longest feeder	2,700 m (estimated)

Potential diesel savings and CO_2 reductions

	Diesel	CO_2
Penetration limits 2015 (0 kW)	*	*
Penetration limits 2025 (0 kW)	*	*
Maximum rooftop PV (2 MW)	627 kl	1,668 t

Electric Load

2016 data

Annual energy use	5.18 GWh
Peak load	959 kW
Daily average load	*

2026 Forecast

Annual energy use	6.25 GWh
Load growth	1.9% per year (compared to 2016)

DAILY AVERAGE LOAD BY MONTH

Load data unavailable for this community.

Solar Resource and PV Potential

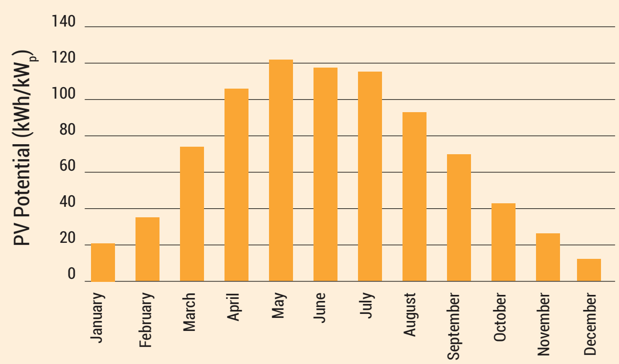
Tilted surfaces (tilt angle = latitude)

Average irradiation	3.06 kWh/m^2
Annual PV potential	838 kWh/kW
Monthly PV potential	See chart

Rooftop PV potential

Estimated rooftop surface area	19×10^3 m^2 Max.
Rooftop PV	2.5 MW
Estimated annual production	2,222 MWh

MONTHLY PV POTENTIAL PER kW_p **



* Data not available ** Kilowatt-peak

Kangirsuk

567 inhabitants
60.02° N, 70.01 W

Generation Infrastructure

Number of generators	3
Capacities	450/450/560 kW
Installation year	Before 1988
Average energy efficiency	3.48 kWh/l
Annual consumption	977 kl
Annual CO_2 emissions	2,599 t

Penetration Limits

	2015	2025
Maximum PV respecting all criteria	90 kW	90 kW
Spinning reserve (20%)	90 kW	90 kW
Minimum genset load (30%)	99 kW	150 kW
Penetration ration (power)	13%	11%
Penetration ration (energy)	2.1%	1.8%

Distribution Infrastructure

Feeder voltage	4.16 kV
Number of phases	3
Longest feeder	1,500 m (estimated)

Potential diesel savings and CO_2 reductions

	Diesel	CO_2
Penetration limits 2015 (0 kW)	21.8 kl	58 t
Penetration limits 2025 (0 kW)	21.8 kl	58 t
Maximum rooftop PV (2 MW)	484 kl	1 287 t

Electric Load

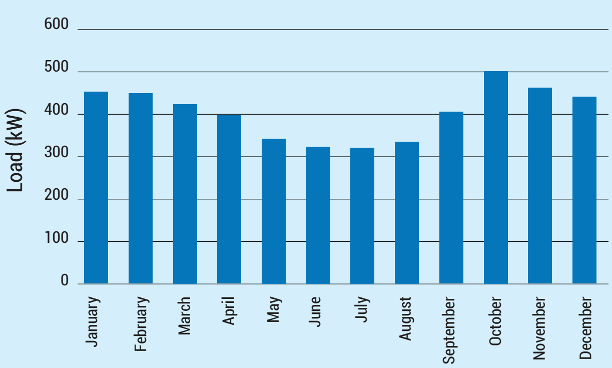
2016 data

Annual energy use	3.58 GWh
Peak load	681 kW
Daily average load	405 kW
Monthly average load	See chart

2026 Forecast

Annual energy use	4.17 GWh
Load growth	1.5% per year (compared to 2016)

DAILY AVERAGE LOAD BY MONTH



Solar Resource and PV Potential

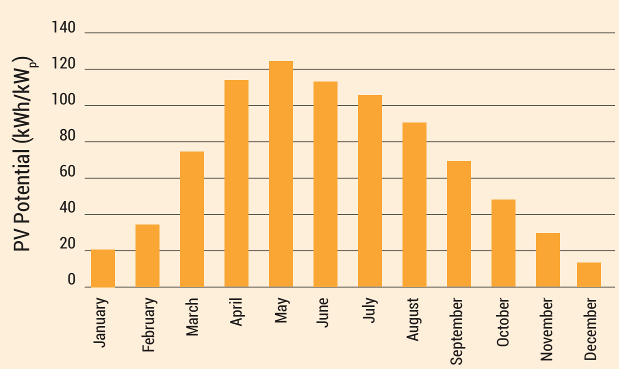
Tilted surfaces (tilt angle = latitude)

Average irradiation	3,08 kWh/m²
Annual PV potential	843 kWh/kW
Monthly PV potential	See chart

Rooftop PV potential

Estimated rooftop surface area	15 x 10³ m² Max.
Rooftop PV	2 MW
Estimated annual production	1 753 MWh

MONTHLY PV POTENTIAL PER kW_p *



* Kilowatt-peak

Kuujjuaq

2,754 inhabitants

58.11° N, 68.39 W

Generation Infrastructure

Number of generators	5
Capacities	1,202/1,202/1,202/1,202/1,202 kW
Installation year	2011
Average energy efficiency	3.86 kWh/l
Annual consumption	4,767 kl
Annual CO_2 emissions	12,680 t

Penetration Limits

	2015	2025
Maximum PV respecting all criteria	481 kW	481 kW
Spinning reserve (20%)	481 kW	481 kW
Minimum genset load (30%)	785 kW	1 247 kW
Penetration ration (power)	13%	11%
Penetration ration (energy)	2%	1,6%

Distribution Infrastructure

Feeder voltage	25 kV
Number of phases	3
Longest feeder	3 900 m (estimated)

Potential diesel savings and CO_2 reductions

	Diesel	CO_2
Penetration limits 2015 (0 kW)	106 kl	282 t
Penetration limits 2025 (0 kW)	106 kl	282 t
Maximum rooftop PV (2 MW)	2,249 kl	5,982 t

Electric Load

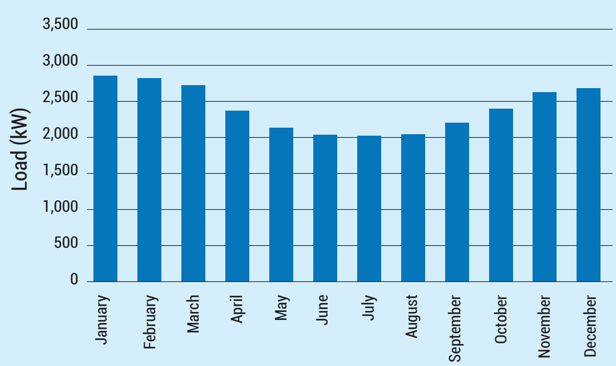
2016 data

Annual energy use	20.73 GWh
Peak load	3,576 kW
Daily average load	2,408 kW
Monthly average load	See chart

2026 Forecast

Annual energy use	26.08 GWh
Load growth	2.3% per year (compared to 2016)

DAILY AVERAGE LOAD BY MONTH



Solar Resource and PV Potential

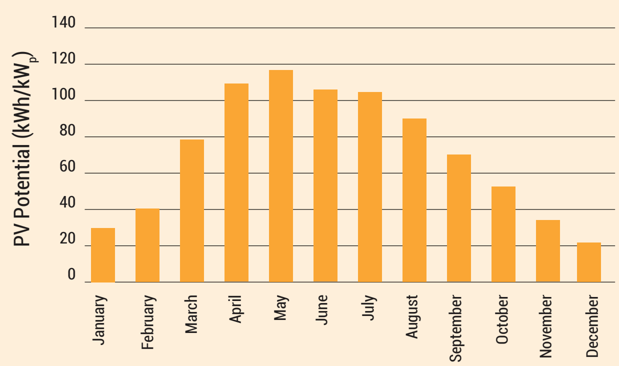
Tilted surfaces (tilt angle = latitude)

Average irradiation	3.11 kWh/m²
Annual PV potential	851 kWh/kW
Monthly PV potential	See chart

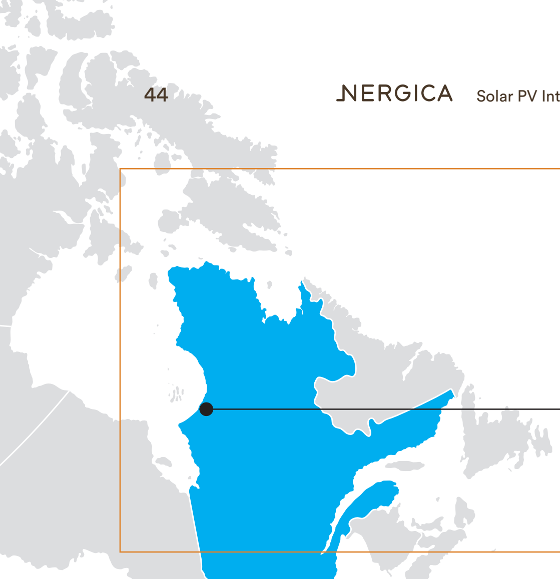
Rooftop PV potential

Estimated rooftop surface area	77 x 10³ m² Max.
Rooftop PV	10.2 MW
Estimated annual production	9,314 MWh

MONTHLY PV POTENTIAL PER kW_p *



* Kilowatt-peak



Kuujjuarapik

686 inhabitants

55.27° N, 77.76 W

Generation Infrastructure

Number of generators	3
Capacities	1,135/1,135/1,135 kW
Installation year	Before 1981
Average energy efficiency	3.63 kWh/l
Annual consumption	2,400 kl
Annual CO_2 emissions	6,384 t

Penetration Limits

	2015	2025
Maximum PV respecting all criteria	29 kW	112 kW
Spinning reserve (20%)	227 kW	227 kW
Minimum genset load (30%)	29 kW	112 kW
Penetration ration (power)	1%	5%
Penetration ration (energy)	0.2 %	0.7 %

Distribution Infrastructure

Feeder voltage	4.16 kV
Number of phases	3
Longest feeder	2,200 m (estimated)

Potential diesel savings and CO_2 reductions

	Diesel	CO_2
Penetration limits 2015 (0 kW)	7.2 kl	19 t
Penetration limits 2025 (0 kW)	28 kl	74 t
Maximum rooftop PV (2 MW)	749 kl	1,992 t

Electric Load

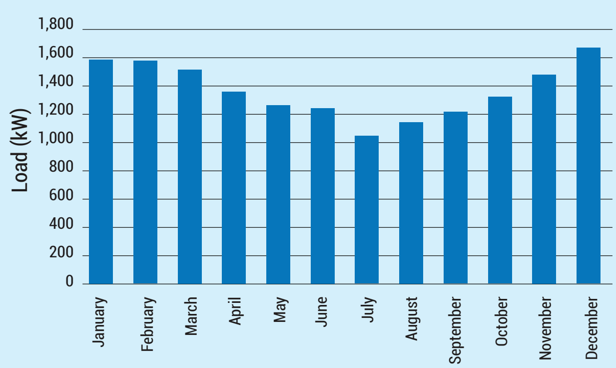
2016 data

Annual energy use	12.26 GWh
Peak load	2,030 kW
Daily average load	1,372 kW
Monthly average load	See chart

2026 Forecast

Annual energy use	14.39 GWh
Load growth	1.6% per year (compared to 2016)

DAILY AVERAGE LOAD BY MONTH



Solar Resource and PV Potential

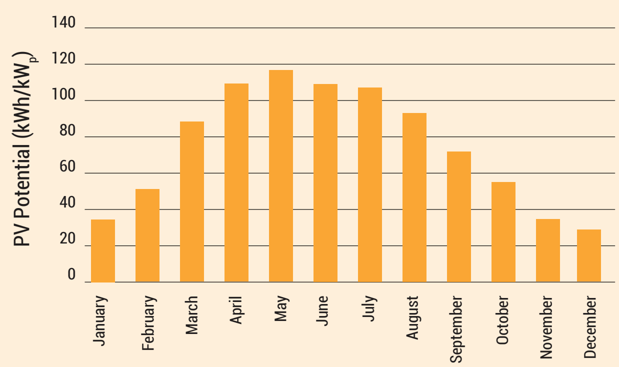
Tilted surfaces (tilt angle = latitude)

Average irradiation	3.31 kWh/m²
Annual PV potential	906 kWh/kW
Monthly PV potential	See chart

Rooftop PV potential

Estimated rooftop surface area	23 x 10³ m² Max.
Rooftop PV	3 MW
Estimated annual production	2,887 MWh

MONTHLY PV POTENTIAL PER kW_p *



* Kilowatt-peak

Puvirnituq

1,779 inhabitants

60.04° N, 77.27 W

Generation Infrastructure

Number of generators	3
Capacities	600/1,135/1,135 kW
Installation year	Before 1981
Average energy efficiency	3.76 kWh/l
Annual consumption	2,713 kl
Annual CO_2 emissions	7,216 t

Penetration Limits

	2015	2025
Maximum PV respecting all criteria	315 kW	347 kW
Spinning reserve (20%)	347 kW	347 kW
Minimum genset load 30%)	315 kW	699 kW
Penetration ration (power)	16%	13%
Penetration ration (energy)	2.2 %	1.8%

Distribution Infrastructure

Feeder voltage	4.16 kV
Number of phases	3
Longest feeder	2,200 m (estimated)

Potential diesel savings and CO_2 reductions

	Diesel	CO_2
Penetration limits 2015 (0 kW)	70.6 kl	188 t
Penetration limits 2025 (0 kW)	77.8 kl	207 t
Maximum rooftop PV (2 MW)	1,300 kl	3,458 t

Electric Load

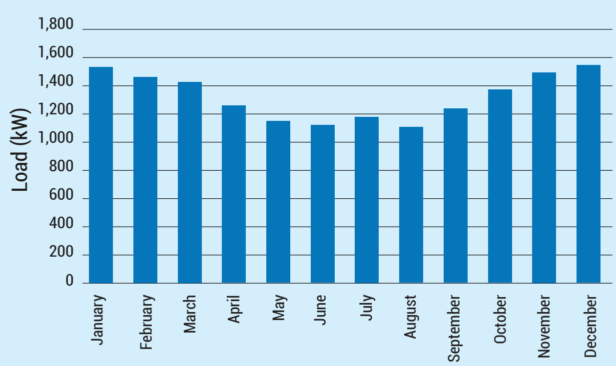
2016 data

Annual energy use	11.97 GWh
Peak load	2,020 kW
Daily average load	1,323 kW
Monthly average load	See chart

2026 Forecast

Annual energy use	14.39 GWh
Load growth	1.6% per year (compared to 2016)

DAILY AVERAGE LOAD BY MONTH



Solar Resource and PV Potential

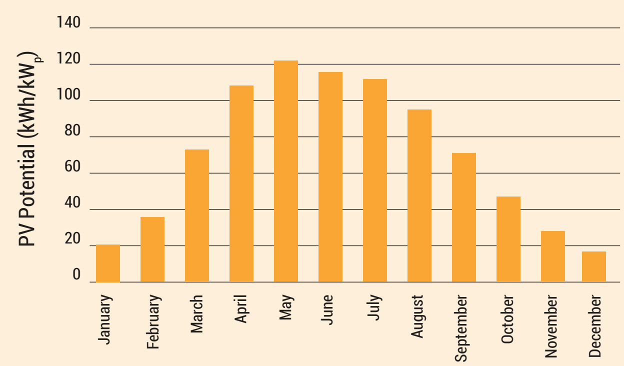
Tilted surfaces (tilt angle = latitude)

Average irradiation	3.08 kWh/m²
Annual PV potential	843 kWh/kW
Monthly PV potential	Voir graphique

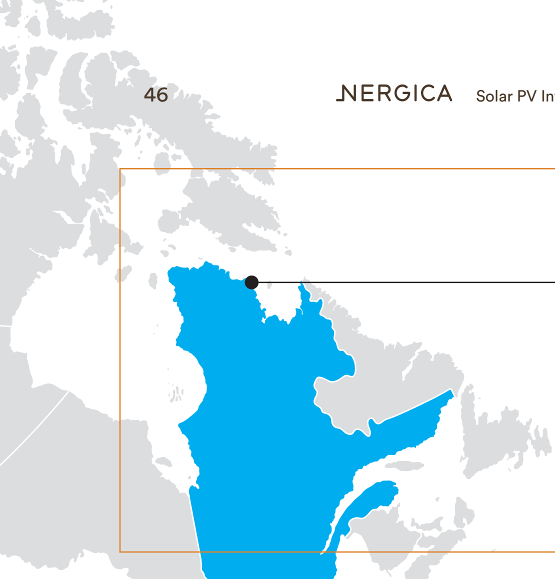
Rooftop PV potential

Estimated rooftop surface area	44 x 10³ m² Max.
Rooftop PV	5.8 MW
Estimated annual production	5,211 MWh

MONTHLY PV POTENTIAL PER kW_p *



* Kilowatt-peak



Quaqtaq

403 inhabitants

61.05° N, 69.63 W

Generation Infrastructure

Number of generators	3
Capacities	320/365/400 kW
Installation year	1988
Average energy efficiency	3.52 kWh/l
Annual consumption	682 kl
Annual CO_2 emissions	1,814 t

Penetration Limits

	2015	2025
Maximum PV respecting all criteria	64 kW	64 kW
Spinning reserve (20%)	64 kW	64 kW
Minimum genset load (30%)	108 kW	189 kW
Penetration ration (power)	11%	8%
Penetration ration (energy)	1.8%	1.4%

Distribution Infrastructure

Feeder voltage	4.16 kV
Number of phases	3
Longest feeder	1,100 m (estimated)

Potential diesel savings and CO_2 reductions

	Diesel	CO_2
Penetration limits 2015 (0 kW)	15.9 kl	42 t
Penetration limits 2025 (0 kW)	15.9 kl	42 t t
Maximum rooftop PV (2 MW))	397 kl	1,056 t

Electric Load

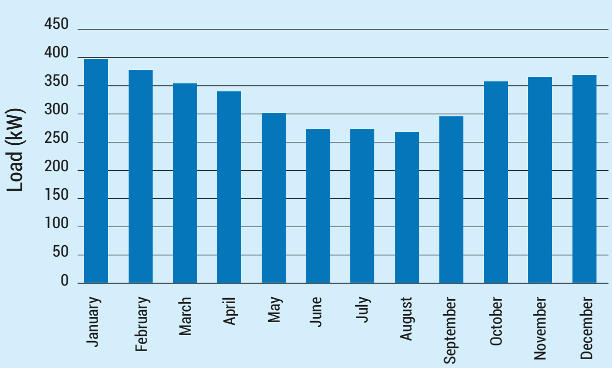
2016 data

Annual energy use	3.03 GWh
Peak load	575 kW
Daily average load	331 kW
Monthly average load	See chart

2026 Forecast

Annual energy use	4.04 GWh
Load growth	2.9% per year (compared to 2016)

DAILY AVERAGE LOAD BY MONTH



Solar Resource and PV Potential

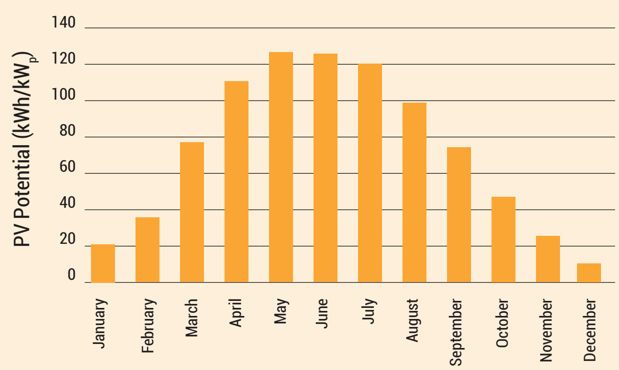
Tilted surfaces (tilt angle = latitude)

Average irradiation	3.19 kWh/m²
Annual PV potential	873 kWh/kW
Monthly PV potential	See chart

Rooftop PV potential

Estimated rooftop surface area	12 x 10³ m² Max.
Rooftop PV	1.6 MW
Estimated annual production	1,522 MWh

MONTHLY PV POTENTIAL PER kW_p *



* Kilowatt-peak

Salluit

1,483 inhabitants

62.2° N, 75.64 W

Generation Infrastructure

Number of generators	3
Capacities	855/855/1,168 kW
Installation year	1990
Average energy efficiencye	3.75 kWh/l
Annual consumption	1,947 kl
Annual CO_2 emissions	5,178 t

Penetration Limits

	2015	2025
Maximum PV respecting all criteria	171 kW	171 kW
Spinning reserve (20%)	171 kW	171 kW
Minimum genset load (30%)	266 kW	416 kW
Penetration ration (power)	12%	10%
Penetration ration (energy)	1.6%	1.4%

Distribution Infrastructure

Feeder voltage	4.16 kV
Number of phases	3
Longest feeder	2,900 m (estimated)

Potential diesel savings and CO_2 reductions

	Diesel	CO_2
Penetration limits 2015 (0 kW)	36.4 kl	97 t
Penetration limits 2025 (0 kW))	36.4 kl	97 t
Maximum rooftop PV (2 MW)	852 kl	2,266 t

Electric Load

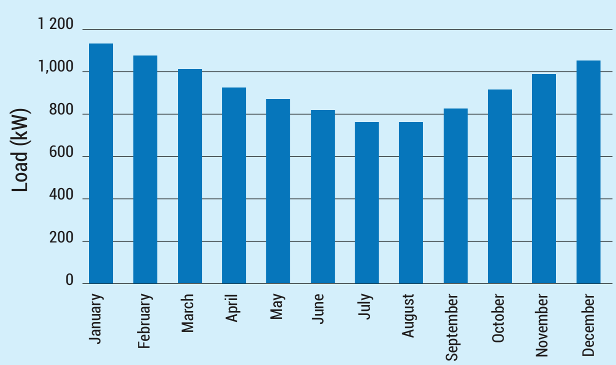
2016 data

Annual energy use	8.3 GWh
Peak load	1,428 kW
Daily average load	930 kW
Monthly average load	Voir graphique

2026 Forecast

Annual energy use	10.08 GWh
Load growth	2% per year (compared to 2016)

DAILY AVERAGE LOAD BY MONTH



Solar Resource and PV Potential

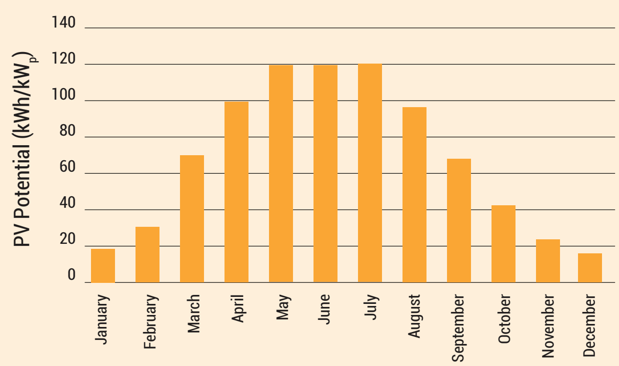
Tilted surfaces (tilt angle = latitude)

Average irradiation	2.92 kWh/m²
Annual PV potential	799 kWh/kW
Monthly PV potential	See chart

Rooftop PV potential

Estimated rooftop surface area	30 x 10³ m² Max.
Rooftop PV	4 MW
Estimated annual production	3,749 MWh

MONTHLY PV POTENTIAL PER kW_p *



* Kilowatt-peak

Tasiujaq

369 inhabitants

58.7° N, 69.93 W

Generation Infrastructure

Number of generators	3
Capacities	210/320/320 kW
Installation year	1981
Average energy efficiency	3.24 kWh/l
Annual consumption	*
Annual CO_2 emissions	*

Penetration Limits

	2015	2025
Maximum PV respecting all criteria	*	*
Spinning reserve (20%)	*	*
Minimum genset load (30%)	*	*
Penetration ration (power)	*	*
Penetration ration (energy)	*	*

Distribution Infrastructure

Feeder voltage	4.16 kV
Number of phases	3
Longest feeder	3,800 m (estimated)

Potential diesel savings and CO_2 reductions

	Diesel	CO_2
Penetration limits 2015 (0 kW)	*	*
Penetration limits 2025 (0 kW)	*	*
Maximum rooftop PV (2 MW)	293 kl	779 t

Electric Load

2016 data

Annual energy use	2.58 GWh
Peak load	452 kW
Daily average load	*

2026 Forecast

Annual energy use	3 GWh
Load growth	1.5% per year (compared to 2016)

DAILY AVERAGE LOAD BY MONTH

Load data unavailable for this community.

Solar Resource and PV Potential

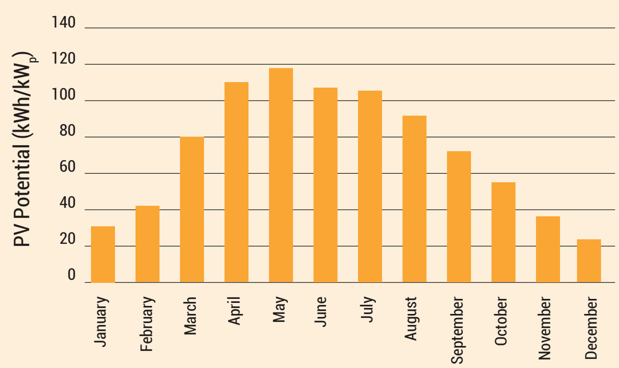
Tilted surfaces (tilt angle = latitude)

Average irradiation	3.15 kWh/m²
Annual PV potential	862 kWh/kW
Monthly PV potential	See chart

Rooftop PV potential

Estimated rooftop surface area	8 x 10³ m² Max.
Rooftop PV	1.1 MW
Estimated annual production	998 MWh

MONTHLY PV POTENTIAL PER kW_p **



* Data not available ** Kilowatt-peak

Umiujaq

442 inhabitants

56.55° N, 76.55 W

Generation Infrastructure

Number of generators	3
Capacities	250/400/400 kW
Installation year	1987
Average energy efficiency	3.51 kWh/l
Annual consumption	769 kl
Annual CO_2 emissions	2,046 t

Penetration Limits

	2015	2025
Maximum PV respecting all criteria	103 kW	103 kW
Spinning reserve (20%)	103 kW	103 kW
Minimum genset load (30%)	103 kW	103 kW
Penetration ration (power)	18%	14%
Penetration ration (energy)	3%	2.3%

Distribution Infrastructure

Feeder voltage	4.16 kV
Number of phases	3
Longest feeder	2,200 m (estimated)

Potential diesel savings and CO_2 reductions

	Diesel	CO_2
Penetration limits 2015 (0 kW)	25.1 kl	67 t
Penetration limits 2025 (0 kW)	25.1 kl	67 t
Maximum rooftop PV (2 MW)	316 kl	841 t

Electric Load

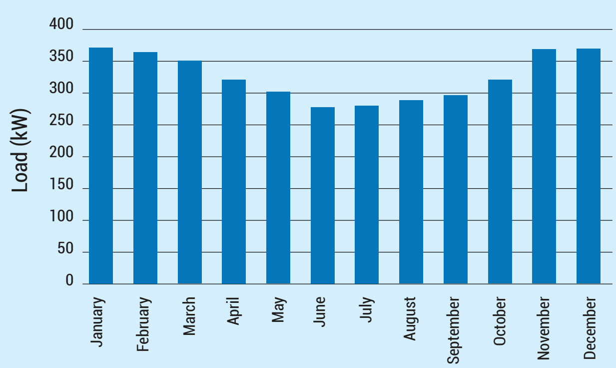
2016 data

Annual energy use	2.97 GWh
Peak load	558 kW
Daily average load	327 kW
Monthly average load	See chart

2026 Forecast

Annual energy use	3.79 GWh
Load growth	2.5% per year (compared to 2016)

DAILY AVERAGE LOAD BY MONTH



Solar Resource and PV Potential

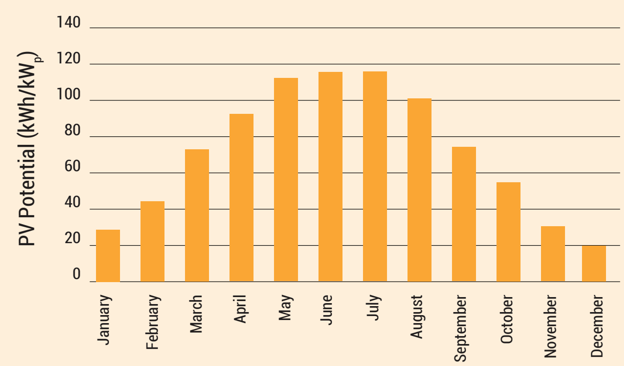
Tilted surfaces (tilt angle = latitude)

Average irradiation	3.12 kWh/m²
Annual PV potential	854 kWh/kW
Monthly PV potential	See chart

Rooftop PV potential

Estimated rooftop surface area	10 x 10³ m² Max.
Rooftop PV	1.3 MW
Estimated annual production	1,230 MWh

MONTHLY PV POTENTIAL PER kW_p *



* Kilowatt-peak

Whapmagoostui

984 inhabitants

55.28° N, 77.75 W

Generation Infrastructure

Number of generators	3
Capacities	1,135/1,135/1,135 kW
Installation year	Before 1981
Average energy efficiency	3.63 kWh/l
Annual consumption	2,400 kl
Annual CO_2 emissions	6,384 t

Penetration Limits

	2015	2025
Maximum PV respecting all criteria	29 kW	112 kW
Spinning reserve (20%)	227 kW	227 kW
Minimum genset load (30%)	29 kW	112 kW
Penetration ration (power)	1%	5%
Penetration ration (energy)	0.2%	0.7%

Distribution Infrastructure

Feeder voltage	4.16 kV
Number of phases	3
Longest feeder	2,200 m (estimated)

Potential diesel savings and CO_2 reductions

	Diesel	CO_2
Penetration limits 2015 (0 kW)	7.2 kl	19 t
Penetration limits 2025 (0 kW)	28 kl	74 t
Maximum rooftop PV (2 MW)	699 kl	1,859 t

Electric Load

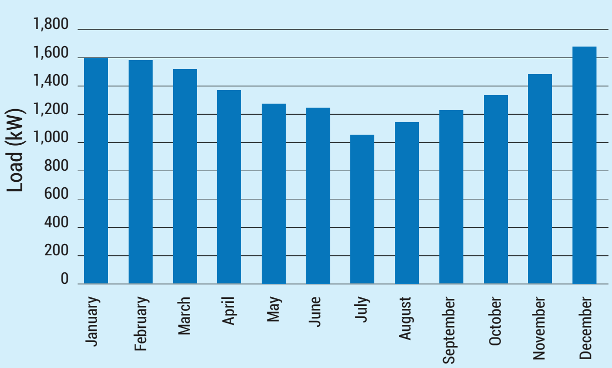
2016 data

Annual energy use	12.26 GWh
Peak load	2,030 kW
Daily average load	1,372 kW
Monthly average load	See chart

2026 Forecast

Annual energy use	14.39 GWh
Load growth	1.6% per year (compared to 2016)

DAILY AVERAGE LOAD BY MONTH



Solar Resource and PV Potential

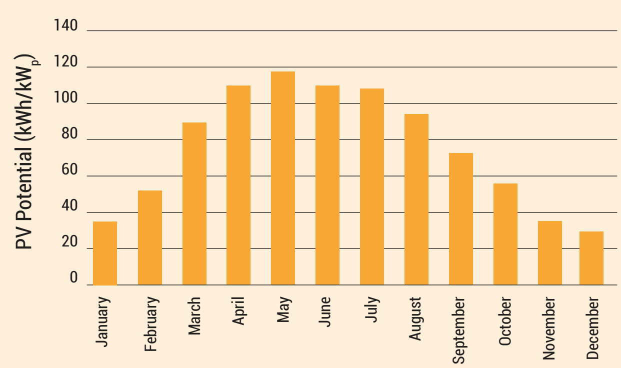
Tilted surfaces (tilt angle = latitude)

Average irradiation	3.31 kWh/m²
Annual PV potential	906 kWh/kW
Monthly PV potential	See chart

Rooftop PV potential

Estimated rooftop surface area	21 x 10³ m² Max.
Rooftop PV	2.8 MW
Estimated annual production	2,706 MWh

MONTHLY PV POTENTIAL PER kW_p *



* Kilowatt-peak

NERGICA

70 Rue Bolduc, Gaspé, QC G4X 1G2
nergica.com

T +1 418 368-6162 | info@nergica.com

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