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Hybrid Renewable Energy Systems: Integrating Geothermal, Solar, and Aquifer Thermal Energy Storage

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ABSTRACT

Remote cold-climate communities in Canada continue to rely heavily on diesel-based energy systems, resulting in high energy costs, greenhouse gas emissions, and vulnerability to fuel supply disruptions. To address this context, this study presents a hybrid renewable energy system that integrates geothermal extraction with solar panels and aquifer thermal energy storage (ATES), specifically optimized for Canada's high-latitude climates. Geothermal energy provides continuous baseload heat during long winter nights via engineered wellbore heat exchangers, while abundant summer daylight enables excess solar to be converted into heat and injected into subsurface reservoirs for winter. During winter, the producer of the ATES start working to compliment the power and heat provided by the geothermal system to meet the increasing heating and energy. By leveraging seasonal complementarity and ATES, the proposed system can deliver dispatchable heat and power and advance Canada's decarbonization targets and strengthen energy resilience in remote and indigenous communities. The paper focuses on the overall system architecture, seasonal operating logic, and a preliminary assessment framework that can support future site-specific technical and techno-economic evaluation. Rather than presenting a fully validated simulation or optimization study, this work establishes the system configuration, identifies key design variables, and outlines the main performance indicators required for future modelling and comparative analysis. The proposed geothermal–PV–ATES framework highlights a promising pathway toward more reliable, low-carbon, and resilient community-scale energy systems in northern and remote cold-climate regions.

1 INTRODUCTION

In Canada's northern and remote communities, electricity and heat are still predominantly supplied by diesel generators, resulting in high energy costs, significant greenhouse gas emissions, and vulnerability to fuel supply disruptions (Durand et al., 2025; Arriaga et al., 2013; McFarlan et al., 2018). These challenges are particularly acute in Indigenous and off-grid communities, where the price of delivered diesel can be several times higher than grid electricity and where energy systems are tightly intertwined with questions of self-determination, health, and environmental justice (Mercer et al., 2024; Lim et al., 2024). Recent socio-technical studies emphasize that "diesel exit" strategies must simultaneously address reliability, affordability, and community control rather than focusing solely on least-cost decarbonization pathways (Maynard et al., 2025).

Over the last decade, hybrid renewable energy systems (HRES) and microgrids have been widely proposed as promising pathways to reduce diesel dependence in remote regions. Case studies and reviews show that combinations of solar PV, wind, biomass, batteries and, more recently, hydrogen can substantially reduce fuel consumption and levelized cost of energy when properly sized and operated (López-Castrillón et al., 2021; Zebra et al., 2021). For example, techno-economic assessments in Canadian and international remote communities demonstrate that optimized hybrid microgrids can be cost-competitive with diesel while improving reliability and resilience. Nevertheless, most existing designs are primarily electricity-centric and rely on short- to medium-duration electrical storage (batteries, hydrogen, or flywheels), with limited attention to integrated provision of heat and power under extreme seasonal climates typical of high-latitude regions.

At high latitudes, a strong seasonal mismatch exists between renewable energy supply and heating demand. Solar resources peak in summer, while space-heating loads dominate long, dark winters. This mismatch is particularly pronounced in northern Canada, where heating often constitutes the largest end-use energy demand in buildings. Seasonal thermal energy storage (STES) has been identified as a key enabling technology to bridge this gap by storing surplus thermal energy over months rather than hours or days (Yang et al., 2021). Among STES options, aquifer thermal energy storage (ATES) uses shallow groundwater systems to store heat

and cold between seasons and has achieved large-scale deployment in urban district-energy systems, especially in north-western Europe (Lee et al., 2010; Fleuchaus et al., 2018). Systematic reviews and global surveys highlight the technical maturity and cost-effectiveness of ATES, as well as the importance of hydrogeological conditions, thermal breakthrough and well configuration for system performance (Tas et al., 2025). However, the existing ATES literature largely focuses on temperate, urban or peri-urban contexts, with limited work examining its applicability to remote, high-latitude communities or its integration with other renewable resources such as geothermal energy.

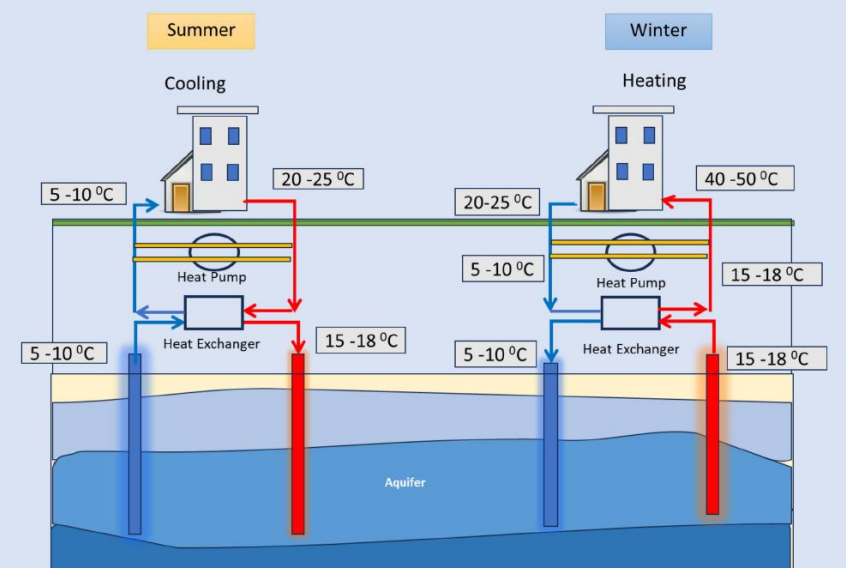


Figure 1. ATES configuration (Shah et al., 2024).

Geothermal energy offers a fundamentally different, complementary role within hybrid systems. Unlike solar and wind, geothermal resources provide continuous, weather-independent heat and, where conditions allow, dispatchable power (Olabi et al., 2020). Comprehensive reviews of geothermal-based hybrids show that combining geothermal with other renewables can enhance capacity factors, reduce curtailment, and provide ancillary services in low-carbon energy systems (Hu et al., 2025). In particular, hybrid solar–geothermal power plants have been investigated for resource-rich regions, demonstrating improved thermodynamic efficiency, higher power output, and reduced geothermal fluid extraction when solar heat is used to supplement geothermal brine (Cardemil et al., 2016). Yet most of these studies focus on grid-connected, utility-scale plants in moderate or arid climates and primarily target electricity generation. They rarely consider multi-vector service provision (heat, power, and cooling), nor do they explore the use of the subsurface not only as a production resource (geothermal wells) but also as a long-duration storage medium (ATES).

Recent work on geothermal resources for remote northern Canadian communities has confirmed that many regions underlain by sedimentary basins or favorable lithologies possess technically exploitable low- to medium-temperature geothermal resources that could support district heating and hybrid systems (Miranda et al., 2022). At the same time, decarbonization assessments for northern Canada stress that no single technology can solve the diesel problem; instead, tailored portfolios of renewables and storage must be co-designed with communities to address local resource, infrastructure and governance constraints. Despite this recognition, there remains a clear gap at the intersection of three strands of research: (i) hybrid renewable microgrids for remote and Indigenous communities; (ii) high-latitude seasonal thermal storage (particularly ATES); and (iii) geothermal-solar hybrid systems. To the best of our knowledge, there has been limited quantitative analysis of how an integrated geothermal–solar–ATES concept could be configured and dispatched to deliver year-round, multi-vector energy services—heat, power and potentially cooling—for high-latitude remote communities.

Accordingly, the objective of this paper is not to present a fully validated simulation or a completed techno-economic optimization study, but rather to introduce a conceptual geothermal–PV–ATES hybrid energy system for remote cold-climate communities and to establish a preliminary framework for its future assessment. The paper focuses on the integration logic of the proposed system, its seasonal operating principles, the key design variables that govern system performance, and the main technical and techno-economic indicators required for subsequent site-specific modelling and evaluation. In doing so, this work aims to provide a structured basis for future research on hybrid renewable energy systems tailored to the distinctive climatic and energy-demand characteristics of northern communities.

2 SYSTEM CONCEPT AND DESIGN

2.1 Overall Architecture of the Geothermal–PV–ATES hybrid System

The proposed hybrid system couples three major subsystems: a geothermal energy subsystem, a solar photovoltaic (PV) subsystem, and an ATES subsystem. Together, these components form a multi-energy concept capable of supplying electricity, space heating, and potentially cooling to remote and Indigenous communities in high-latitude regions of Canada.

Within this concept, the geothermal subsystem is intended to serve as a stable and weather-independent thermal source. Depending on site conditions and system design, geothermal energy may be used directly for district or building heating and, where production temperature is sufficient, may also support a small organic Rankine cycle (ORC) unit for electricity generation. The PV subsystem is designed to provide electricity, with generation varying seasonally and diurnally according to local solar conditions. In summer, when solar availability is highest and heating demand is relatively low, surplus PV electricity can be converted into heat through electric boilers or heat pumps and directed to the ATES subsystem for seasonal storage.

The ATES subsystem is conceived as a pair of warm and cold wells completed in a suitable shallow aquifer. The warm well is intended to store thermal energy for later winter use, while the cold well may support seasonal cooling or act as the return side of the storage cycle. In this way, the subsurface serves not only as a geothermal resource domain but also as a seasonal heat storage medium.

At the system level, the integration logic reflects the energy context of remote northern communities. Geothermal energy is positioned as the thermal backbone of the system, PV provides seasonal electricity and charging potential, and ATES provides the temporal flexibility needed to transfer surplus summer energy into the winter heating season. The overall objective of the architecture is therefore not simply to combine multiple renewable technologies, but to coordinate them in a way that better matches the strong seasonal structure of community-scale energy demand.

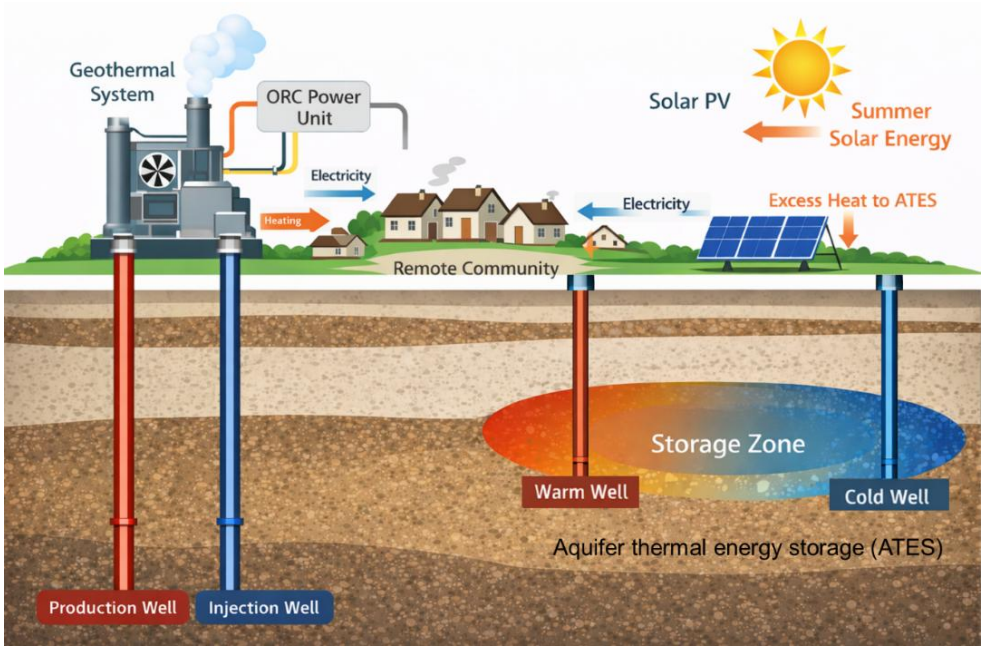


Figure 2. Architecture of the Geothermal–PV–ATES hybrid System.

2.2 Seasonal Operation Mechanism

In summer, the principal operating objective is to capture renewable energy and store surplus heat while continuing to meet local electricity and hot-water demands. During periods of high solar production, PV electricity is first used to serve local electrical loads. When generation exceeds demand, the surplus can be directed to electric boilers or heat pumps for charging the warm ATES well. Under this operating mode, the system uses abundant summer solar resources not only for direct electricity supply but also for seasonal thermal storage.

The geothermal subsystem continues to operate during summer as a stable heat source. Depending on design assumptions and load conditions, geothermal heat may be used directly to serve domestic hot water demand or may also contribute to charging the warm ATES well when immediate heating needs are low. In this conceptual

framework, geothermal energy is therefore treated as a continuous thermal base resource that can support both direct use and seasonal balancing.

The cold ATES well may also play a role during summer where space cooling is relevant. In that case, cool water stored in the aquifer can be used to offset building cooling needs, with thermal rejection managed through the complementary storage cycle. Although cooling demand is generally secondary to heating demand in northern Canadian communities, inclusion of the cold well provides additional flexibility and broadens the potential application of the concept.

In winter, the system shifts into a heat-led operating mode. Geothermal energy provides the main baseload contribution to heating and, where applicable, a stable share of electricity through an ORC unit. Heat stored in the warm ATES well is then recovered to complement geothermal output during periods of higher heating demand. PV continues to contribute electricity during available daylight hours, but its role is comparatively limited because of reduced winter solar availability. Under this conceptual winter strategy, ATES functions as a seasonal buffer that reduces the need for diesel-based peaking or electric resistance heating during the coldest periods.

2.3 Seasonal Balance and Capacity Configuration

In contrast to systems sized primarily against peak electrical demand, the proposed geothermal–PV–ATES concept is guided by a seasonal energy-balancing logic. For heating-dominated remote communities, the first design step is to estimate the portion of annual heat demand that can be reliably supplied by a geothermal baseload over long operating period. Once this baseload contribution has been defined, remaining winter demand can be addressed through seasonal shifting of surplus energy using ATES.

Within this framework, PV capacity is not considered only in terms of instantaneous electricity production, but also in terms of its ability to provide charging energy for seasonal storage. Similarly, ATES capacity is considered not only as a function of storage volume, but also of allowable temperature range, charging and discharging rates, hydrogeological suitability, and long-term thermal balance. The overall sizing problem is therefore inherently multi-criteria, involving trade-offs among renewable fraction, storage utilization, diesel displacement, capital investment, and operational flexibility.

Rather than prescribing a single optimal design, the proposed framework establishes the main design logic and variables that future site-specific analysis should address.

3 MODEL DESCRIPTION

This section outlines the three component models that form the basis of the proposed hybrid photovoltaic–geothermal–aquifer thermal energy storage framework for a representative remote community in northern Canada. The community is assumed to be off-grid or weakly connected, with long cold winters, relatively short but solar-rich summers, and a dominant space-heating demand. The framework consists of three time-synchronized component models: a photovoltaic generation model, a simplified geothermal heat-and-power model, and a lumped ATES model. These models are intended to operate on a common hourly time step and to be driven by consistent meteorological and load inputs, thereby enabling future coupling in a dispatch and comparative evaluation framework.

3.1 Photovoltaic Generation Model

For representative northern Canadian locations, global horizontal irradiance and ambient temperature can be obtained from typical meteorological year data or suitable reanalysis products. In the proposed framework, the PV subsystem is represented by an hourly AC power time series rather than by a detailed electro-thermal module model. This level of representation is consistent with many hybrid renewable system studies, where simplified component models are used to preserve the key dependence on resource availability without introducing unnecessary detail at an early system-design stage.

For each representative site, irradiance and temperature inputs can be converted into hourly PV output using a standard irradiance–power formulation. In general terms, hourly PV power is expressed as a function of plane-of-array irradiance, effective module area, and system efficiency, with optional temperature correction applied to account for module performance variation. In practice, this step may be carried out using PVsyst or an equivalent modelling tool, after which the resulting hourly AC power profile can be imported into the broader system framework. Accordingly, the PV model in the present paper is conceptualized as an exogenous time series P_t^{PV} that captures the dominant seasonal and diurnal variation in solar generation.

3.2 Geothermal Heat and Power Model

The geothermal subsystem is represented at a conceptual level as a stable thermal source associated with a production–injection well pair in a low- to medium-temperature reservoir representative of northern Canadian conditions. The reservoir is idealized as a laterally extensive formation characterized by an effective reservoir temperature T_{res} and thickness H. The purpose of this representation is not to resolve detailed thermo-hydraulic behavior, but to provide a tractable system-level description of geothermal heat supply that can be integrated with PV and ATES in future comparative studies.

Fluid is injected at a controlled mass flow rate m_{geo} and injection temperature T_{inj} , passes through the reservoir, and is produced at temperature $T_{prod,t}$ at the production wellhead. For the present system-level assessment, the production temperature is approximated as a function of reservoir temperature and cumulative extracted energy, with an initial value close to the undisturbed reservoir temperature. The instantaneous useful thermal power delivered at the wellhead is:

$$Q_t^{geo} = m_{geo} c_p (T_{prod,t} - T_{inj})$$

where c_p is the specific heat capacity of the working fluid, approximated here as that of liquid water. Where system design and resource temperature permit, a portion of this thermal power may be converted to electricity through an ORC unit. In simplified form, the corresponding electrical output can be expressed as:

$$P_t^{geo} = \eta_{ORC} Q_t^{geo}$$

where η_{ORC} is an assumed conversion efficiency appropriate to the geothermal production temperature range. The remaining thermal energy, after conversion and internal losses, is treated as useful heat available for district or building-level heating. In future site-specific applications, this simplified representation can be refined through more detailed reservoir and wellbore models, alternative well configurations, and explicit treatment of thermal decline and parasitic loads.

3.3 Aquifer Thermal Energy Storage Model

To exploit the strong seasonality of heating demand and solar availability in northern Canada, the hybrid system incorporates aquifer thermal energy storage as a buffer between summer charging and winter discharging. While the attached literature mainly discusses ground-coupled and hybrid geothermal systems in the context of ground source heat pumps and borehole regeneration, the underlying concept of using the ground as a large-capacity thermal storage medium is directly applicable to aquifer-based storage. In the present work, ATES is represented by a pair of warm and cold wells completed in a shallow confined aquifer with effective pore volume V_{eff} and average temperature $T_{ATES,t}$.

The aquifer is modelled using a lumped energy balance, where the state variable can be taken either as the average aquifer temperature or as the stored thermal energy relative to the undisturbed ground temperature. During summer and shoulder seasons, surplus electricity from PV and the portion of geothermal heat that is not immediately needed for space heating are converted to heat through electric boilers or heat pumps and injected into the warm well. The injected water at temperature $T_{ch,t}$ mixes with aquifer water of temperature $T_{ATES,t}$, gradually increasing the stored energy. In winter, water is pumped from the warm well, delivers heat to the district or building heating system, and returns at lower temperature $T_{ret,t}$, thereby discharging the storage.

At the hourly time scale, the evolution of the ATES state is described by a discretized energy balance analogous to those used for ground regeneration in hybrid geothermal systems. The change in stored energy between time steps t and $t + \Delta t$ is determined by the net heat added through charging, the heat extracted through discharging, and thermal losses to the surrounding formations. The corresponding useful thermal power that ATES can deliver to the community at time t is expressed as

$$Q_t^{ATES} = m_{dis,t} c_p (T_{ATES,t} - T_{ret,t})$$

where $m_{dis,t}$ is the discharging mass flow rate and $T_{ret,t}$ represents the return temperature from the heating network. In practice, this thermal output is constrained by allowable aquifer temperature limits, well hydraulics, pump capacities, groundwater protection requirements, and long-term thermal balance. Although simplified, this representation is sufficient at the present stage to define the role of ATES in seasonal load shifting and to identify the main variables that future site-specific studies should evaluate in greater detail.

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A three-dimensional ATES model was established in COMSOL Multiphysics. The base-case domain is a 500 m × 500 m × 140 m cuboid located at a depth of 500-640 m. The upper and lower 20 m layers represent impermeable confining units, while the middle 100 m layer represents the storage aquifer. Seasonal injection and production were applied in summer and winter, respectively, with intermittent operation during the remaining periods. In the base case, the injection rate was 200 m^3/h, the injection temperatures of the warm and cold wells were 80°C and 5°C, respectively, and the initial aquifer temperature was 30°C. **Figure 3** shows the COMSOL model geometry and mesh.

Figure 4 illustrates the temperature distribution during the first year of ATES operation. Distinct warm and cold thermal plumes develop around the respective wells, and the main heat transport is confined within the aquifer layer. This indicates that the storage process is dominated by seasonal heat injection and extraction within the target formation, while the overlying and underlying confining layers effectively limit vertical thermal dissipation. **Figure 5** presents the temporal variations in warm- and cold-well temperatures. Temperature fluctuations are relatively small during the intermittent periods, indicating limited thermal disturbance when injection and production are suspended. The major well-temperature variations are mainly caused by active injection and production operations. In spring, the warm-well temperature remains higher than the initial aquifer temperature and increases year by year, although the rate of increase gradually decreases. In autumn, the cold-well temperature remains lower than the initial aquifer temperature and decreases progressively, but the rate of decrease also gradually diminishes. After several years of operation, the temperature evolution at both wells becomes nearly repetitive, indicating that the system has approached dynamic thermal equilibrium. At this stage, the influence of residual thermal energy becomes relatively stable, and the thermal interaction between storage cycles tends toward a consistent long-term pattern.

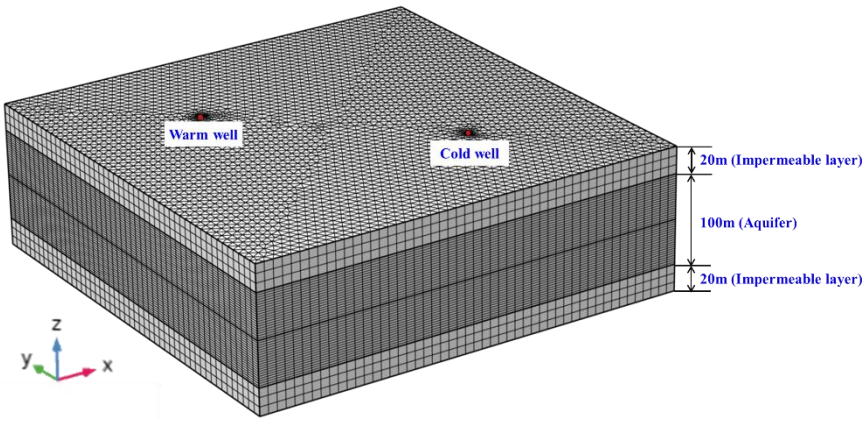


Figure 3. ATES numerical model geometry and mesh.

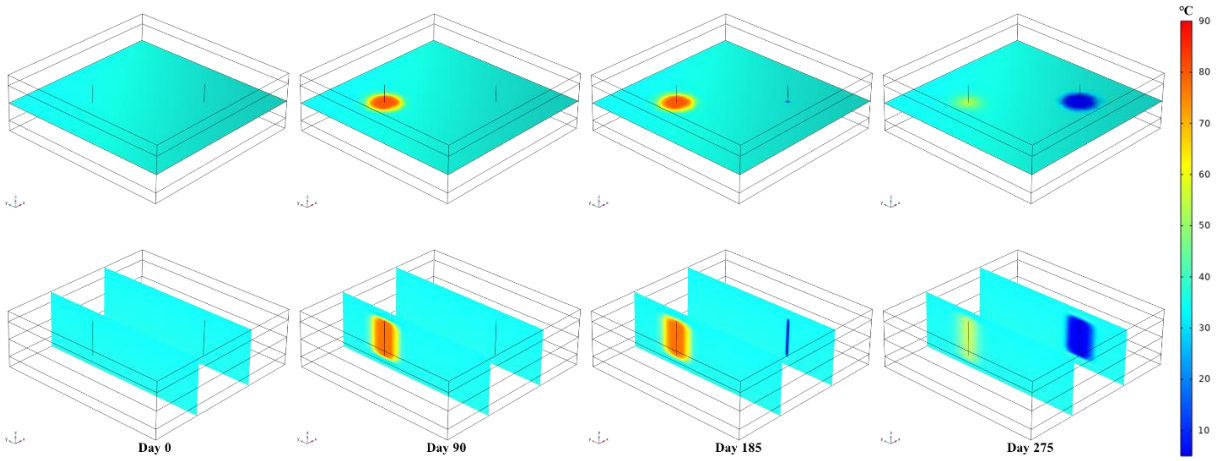


Figure 4. Temperature distribution during the first year of ATES operation.

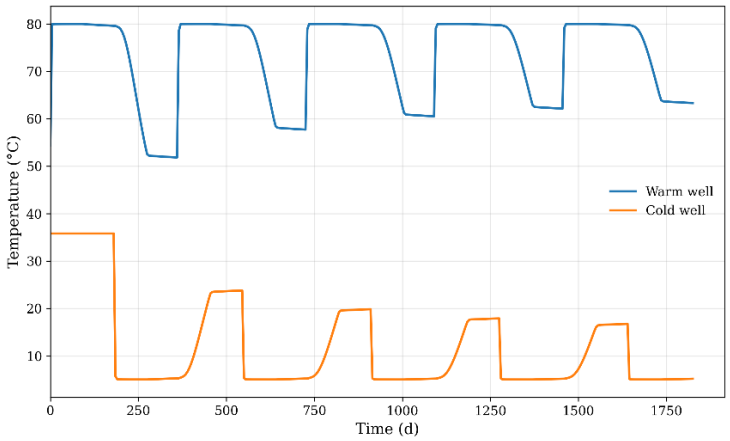


Figure 5. Temperature variation of warm and cold wells with time.

4 SYSTEM OPERATION AND ENERGY DISPATCH STRATEGY

4.1 Annual Operation Framework

The proposed geothermal–PV–ATES system is intended to be evaluated at hourly resolution over a representative meteorological year for a remote northern Canadian community. Within this framework, the PV model provides time-varying electrical generation, the geothermal subsystem provides a relatively stable heat source with optional electricity generation, and the ATES subsystem provides seasonal thermal flexibility. Community demand is represented by hourly time series of electricity, space-heating, and domestic hot-water demand, with winter heating expected to dominate annual energy use.

At each time step, the system logic considers available PV generation, geothermal heat and power potential, the current ATES storage state, and instantaneous community loads. These inputs are then used to formulate a dispatch sequence that allocates energy among direct use, storage charging, storage discharging, and residual backup supply. At the present concept stage, this dispatch strategy is framed as a structured operating logic rather than a completed optimization routine.

4.2 Summer Operation: PV-Led Charging and Geothermal Co-support

In summer, the hybrid system operates in a charging-oriented regime. Hourly PV output is computed from local irradiance and temperature using standard PV performance equations, similar to those employed in hybrid PV–wind–ground source systems for remote buildings. Typical simulations for such systems show that a building-scale PV array can produce on the order of 13 MWh per year, with wind and ground-source subsystems contributing comparable amounts of energy, resulting in renewable fractions around ninety-five percent and LCOE values near 0.12 USD/kWh (Geng et al., 2025). Based on these magnitudes, the community-scale PV plant in the northern Canadian case is sized such that, during clear summer days, PV generation frequently exceeds instantaneous electricity demand.

The dispatch algorithm therefore follows a “PV-first, storage-enabled” logic in summer. At each hour, PV power is first directed to local electrical loads. Once these are satisfied, the residual power is split between ATES charging and optional grid export, if an interconnection exists. Electric boilers or heat pumps convert this surplus electricity into sensible heat, raising the injection temperature into the warm ATES well within hydrogeological limits. At the same time, the geothermal doublet, which operates at nearly constant mass flow to avoid thermal shocks and scaling, supplies baseline heat and some ORC electricity. When space-heating demand is low, part of the geothermal heat is diverted to ATES rather than rejected. This summer operating mode is motivated by the Canadian climate. Studies on urban residential buildings in Fujian show that the timing of solar energy relative to cooling and hot-water loads strongly affects the achievable reduction in operational emissions, especially when electrification is rapid and the share of electricity in direct household emissions increases from around sixty to above eighty percent over a decade (Ke et al., 2024). In the present framework, by systematically using surplus PV to charge ATES when the thermal state of charge is below its seasonal target, summer solar gains are shifted into the winter heating season, thereby amplifying the decarbonization impact of the PV field beyond what would be possible through direct self-consumption alone.

4.3 Winter Operation: Geothermal Baseload and ATES-assisted Heating

In winter, operating priorities shift. Low solar altitude and short daylight reduce PV output significantly, so the geothermal doublet and ATES become the main pillars of heat supply. The geothermal system is scheduled as a

baseload provider: production and reinjection flow rates stay within the operating limits derived from reservoir modeling, and the ORC unit runs close to a stable operating point. Dynamic simulations of hybrid solar–geothermal plants have shown that when geothermal heat is used predominantly for thermal recovery and space heating, overall exergy efficiency lies in the range of roughly forty to fifty percent, whereas cooling-dominated operation yields much lower exergy performance, near twenty percent (Calise et al., 2016). Guided by these findings, the winter control strategy in the northern community keeps the geothermal wells in a heating-oriented mode, with the ORC producing a steady but moderate share of electricity while most of the exergy is extracted as hot water for district or building-level heating networks.

ATES then plays a complementary role. At the start of the heating season, the warm well has accumulated sensible heat from summer charging. As hourly heating demand grows, the controller decides, for each time step, how much of this stored heat to recover. When the ATES thermal state of charge is high and ambient temperatures are extremely low, the system draws more from ATES so that supply temperatures remain within the design band without forcing the geothermal doublet to operate at higher-than-optimal flow rates. Conversely, toward the end of the heating season, when the warm well is partially depleted, the strategy shifts to prioritizing geothermal output, reserving ATES for the most severe cold spells. In the northern Canadian context, geothermal heat acts as the stable supply backbone while ATES provides the seasonal flexibility needed to avoid diesel-based peaking, thereby aligning local operational decisions with longer-term emission reduction trajectories.

4.4 Short-term Dispatch, Storage Use and Optimization Insights

On the hourly time scale, the dispatch logic can be interpreted as a rule-based approximation of a more general optimization problem. The control sequence ranks available resources by their marginal operating cost and emission intensity: PV is always used first when available; geothermal is scheduled next, within its thermal and hydraulic limits; ATES is charged or discharged depending on its state of charge and expected future needs; diesel generation or grid imports are used as a last resort. Hybrid-system reviews highlight that such structured, physically informed rules can come close to the performance of fully optimized controllers, particularly when storage capacities are reasonably sized.

This dispatch framework is directly compatible with more complex multi-energy hub models. For example, in systems where surplus renewable electricity is used to produce hydrogen instead of stored as heat, optimization studies show that designing for a modest annual surplus (on the order of 10-20% above demand) allows meaningful hydrogen production while maintaining high renewable fractions and acceptable LCOE (Bozkurt and Genc., 2024). In the present work, the same principle is applied with ATES as the storage medium: a deliberate summer surplus is created and converted into stored heat, enabling winter peak coverage without over-sizing geothermal or relying heavily on diesel.

Although this paper does not present a completed dispatch optimization study, the proposed framework is fully compatible with more advanced future formulations, including mixed-integer, nonlinear, or multi-objective optimization methods. These future developments could be used to quantify trade-offs among fuel savings, storage utilization, emissions reduction, and capital investment under site-specific constraints.

5 ILLUSTRATIVE CASE CONTEXTS AND ASSESSMENT PATHWAYS

5.1 Alberta Resource-Based Community Context

One relevant application context for the proposed framework is a small Alberta community located within the Western Canada Sedimentary Basin (WCSB), where low- to medium-temperature geothermal resources have been documented. In such a setting, representative climate data, geothermal gradients, and community demand profiles could be used to compare three broad system pathways: a PV–diesel hybrid, a geothermal–diesel hybrid, and the integrated geothermal–PV–ATES concept proposed here.

Within this context, the value of the proposed framework would be to evaluate how geothermal baseload heat, seasonal PV surplus, and ATES flexibility may work together to improve renewable utilization, reduce winter diesel dependence, and support more stable operation of capital-intensive infrastructure. Future site-specific studies in Alberta could use this framework to compare annual renewable fraction, diesel displacement, system reliability, and cost metrics across alternative configurations.

5.2 Remote Indigenous Community Context

A second important application context is a smaller and more isolated Indigenous community farther north, where fuel transportation costs are higher, grid connection is limited or absent, and heating demand is strongly

seasonal. In these settings, the hybrid concept may be particularly relevant because the combination of local geothermal potential, summer solar availability, and seasonal heat storage could reduce long-term exposure to diesel price volatility and fuel supply risk.

At the same time, such applications also require greater caution because of logistical constraints, higher uncertainty in local resource characterization, and the need to align technical design with community priorities and governance realities. In this context, the framework proposed in this paper is intended to support future site-specific assessment rather than to prescribe a universal solution. A meaningful evaluation would need to consider not only technical feasibility and cost, but also local ownership, operational capacity, and broader energy sovereignty objectives.

5.3 Future Comparative Evaluation

For both application contexts, future studies based on the proposed framework should compare the geothermal–PV–ATES concept against simpler baseline systems lacking either geothermal supply or seasonal storage. The purpose of such comparison would be to identify the specific conditions under which ATES meaningfully improves system performance, the degree to which geothermal energy can reduce winter heat deficits, and how PV sizing interacts with seasonal storage requirements. In this way, the proposed framework serves as a structured basis for future quantitative work rather than as a substitute for it.

5.4 Key Design Considerations and Future Assessment Needs

Several design variables are expected to strongly influence the future performance of geothermal–PV–ATES systems in remote cold-climate communities.

- Geothermal resource quality is likely to be a primary determinant of system feasibility. Reservoir temperature, well depth, flow rate, and the temperature delivered to the surface will affect both useful heat production and the possible role of ORC-based electricity generation. Where geothermal temperatures are modest, the system may function primarily as a heat-led concept rather than as a substantial power-generation system.
- ATES performance will depend on effective storage volume, allowable operating temperature range, thermal losses, aquifer hydraulics, and groundwater protection requirements. The long-term success of seasonal storage depends not only on nominal storage capacity, but also on whether charging and discharging can be maintained within hydrogeological and operational constraints.
- PV sizing must be considered in relation to both local electricity demand and the charging requirements of ATES. A PV system that is too small may provide insufficient summer surplus for meaningful seasonal storage, whereas excessive PV capacity could result in avoidable curtailment if thermal storage capacity is limited.
- Dispatch strategy and control philosophy are expected to influence both system efficiency and diesel displacement. Key future questions include when geothermal energy should be prioritized relative to stored heat, how aggressively seasonal charging should be pursued, and what level of backup supply remains necessary under different climate and load conditions.

These considerations highlight that the value of the proposed hybrid concept is not determined by any single subsystem in isolation, but by the coordinated interaction among geothermal supply, seasonal storage, PV generation, and community demand.

6 CONCLUSIONS

This paper presents a preliminary pathway toward an integrated geothermal–PV–ATES hybrid energy system for heating-dominated remote communities in northern cold-climate regions. The proposed concept is motivated by the strong seasonal mismatch between solar availability and winter heating demand, together with the need to reduce long-term dependence on diesel-based energy supply.

Within this framework, geothermal energy is envisioned as a stable thermal backbone, PV as a source of seasonally variable electricity generation, and ATES as a seasonal buffer capable of shifting surplus summer energy into the winter heating season. The main contribution of this study is not a fully coupled system-level simulation, but the establishment of a subsystem-level physical basis for future hybrid-system integration.

The ATES numerical results indicate that, under the base-case operating conditions, the storage aquifer can sustain stable multi-year seasonal thermal cycling and gradually approach dynamic thermal equilibrium. The simulated temperature evolution of the warm and cold wells suggests that residual thermal effects become progressively stabilized after several years of operation, supporting the feasibility of ATES as a repeatable

seasonal storage component. Together with the geothermal subsystem modelling, these results provide important insight into the thermal supply and storage behavior relevant to future geothermal–PV–ATES coupling.

Future work should focus on detailed hourly coupling of PV generation, geothermal production, and ATES operation, as well as hydrogeological constraints, geothermal resource characterization, and comparative assessment against diesel-based or non-storage baseline systems. Overall, the proposed geothermal–PV–ATES concept, supported by the present subsystem-level modelling results, provides a promising pathway for future investigation of low-carbon, reliable, and resilient energy systems in remote cold-climate regions.

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