

Thermally Managed Battery Storage in Integrated Renewable Energy Systems for Remote Communities: A Combined Techno-Economic and Phase-Change-Material Perspective

Ms. Shraddha. A. Salve¹, Ms. Gayatri. C. Bharmal², Ms. Harshali. D. Patthe³, Ms. Rutika More⁴, Mr. Bhimrao Dabhade⁵, Ms. Jaya Wagh⁶

¹²³⁴⁵⁶Department of (Electrical Engineering), Guru Gobind Singh College Of Engineering And Research Center, Nashik.

ABSTRACT - Electrifying remote, off-grid communities with integrated renewable energy systems (IRES) is a practical route to displacing diesel generation. A recent techno-economic study of a community in Canada's Inuvik region showed that a solar PV, wind, biomass-gasifier and lithium-ion battery system can meet a 238.7 kW peak load at a net present cost (NPC) of \$3.61 M and a levelized cost of electricity (LCOE) of \$0.255/kWh. That design, however, treats the battery as a fixed-cost, fixed-life component (550 \$/kWh, 10-year life) and does not model its thermal environment. In parallel, the electric-vehicle literature reports that phase change material (PCM) battery thermal management systems (BTMS) can reduce maximum cell temperature by about 22–40%, improve temperature uniformity by 2–5 °C and extend cycle life. This article combines the two bodies of work. It (i) summarizes the system model, optimization method and results of the remote-community IRES, (ii) summarizes Li-ion thermal behaviour and PCM-based thermal management, and (iii) develops an integrated screening analysis linking thermal management to IRES lifetime cost. Using the published cost data and discount parameters, avoiding one battery replacement is worth about \$286,000 in present value (roughly 7.9% of the reported NPC), which bounds what a thermal-management upgrade can justify. The published C-rate and climate conditions further indicate that, for a low-C-rate, cold-climate microgrid, insulation, preconditioning and a passive PCM buffer are preferable to aggressive active cooling. A design checklist and research directions are provided.

Keywords: Integrated renewable energy systems Remote communities HOMER Net present cost Levelized cost of electricity Lithium-ion battery Battery thermal management Phase change material.

Article type: Synthesis / review with integrated analysis.

1. INTRODUCTION

More than 300 communities in Canada, many of them Indigenous, live off-grid, and extending the grid to every corner of a country of roughly ten million square kilometres is not financially feasible [1]. Most rely on diesel generators, which are carbon-intensive and costly to fuel

and maintain. Studies of Arctic and sub-Arctic microgrids consistently find that hybrids of renewables and storage are the economically preferred path away from diesel [3]–[6], and Canada has committed to clean electricity in more than 200 remote communities that still depend on diesel by 2035 [1].

Single renewable sources are intermittent. Combining solar, wind and biomass lets the strengths of one source offset the weaknesses of another, and a battery stores surplus energy for shortfalls [1]. The battery is therefore pivotal: it is among the more expensive components, must be replaced within the project lifetime, and behaves strongly as a function of temperature.

The two bodies of work combined here come from different communities. The first is a design-and-optimization study of an IRES for a remote northwestern Canadian community performed with HOMER [1]. The second is a comprehensive review of PCM-based thermal management of Li-ion batteries in electric vehicles (EVs) [2]. They rarely meet: the IRES study treats the battery as an economic block with nominal efficiency and lifetime, while the BTMS review addresses thermal physics and packaging for vehicles. Physically, however, a cell in a microgrid enclosure faces the same temperature windows, ageing mechanisms and safety concerns as a cell in a vehicle.

The objectives are to (1) summarize the IRES model, case study and sensitivity results of [1]; (2) summarize battery thermal behaviour and PCM-based BTMS performance from [2]; (3) build an integrated analysis connecting thermal management to IRES lifetime cost; and (4) derive design guidance and open research questions. The integrated analysis in Section 6 is an illustrative synthesis of published numbers; no new simulations or experiments are reported.

1.1. Approach of this synthesis

The two source studies were read for quantities that can be linked: the battery capacity, cost, life and operating range in the IRES [1]; and the temperature windows, ageing behaviour, thermal-management performance and

practical constraints in the BTMS review [2]. The link is made through the economic indicators of [1] (NPC, LCOE, discount and inflation rates) so that the thermal benefits reported in [2] can be expressed in the same units as the IRES design. Where the sources do not provide a number, for instance the installed cost of a stationary PCM package, this is stated rather than assumed.

2. BACKGROUND AND RELATED WORK

2.1. Integrated renewable systems for remote communities

A large literature applies HOMER and metaheuristic optimizers to hybrid system sizing. Examples include a solar-wind-diesel-battery system in Malaysia whose NPC was 29.7% below that of a conventional plant, and the observation that adding batteries improved stand-alone system efficiency [1]. For Canada, Das and Cañizares found diesel-renewable hybrids optimal in Arctic microgrids [3]. Sambor et al. optimized a 25 kW PV, battery and diesel microgrid in Yukon, where solar with batteries could meet 96% of load in June but only 3% in December and 67% year-round [4]. Stringer and Joanis found that decarbonizing Canada's remote microgrids is not prohibitively costly, with wind cheapest for many communities in 2020 and solar PV expected to become cheapest in future [5]. Alaskan experience identifies management of distributed resources and resilient design as principal technical hurdles [6], and a life-cycle comparison shows that leaving diesel can cut carbon intensity from 1345.46 to 175.56 kg CO₂/MWh [7]. A gap noted in [1] is that some battery-equipped studies did not disclose battery cost; none tied battery life to its operating thermal environment.

2.2. Thermal management of lithium-ion batteries

Li-ion cells operate best at roughly 15–35 °C [2], [8]. Above about 35–40 °C, side reactions, breakdown of the solid electrolyte interphase and electrolyte decomposition accelerate fade and, in extremes, thermal runaway. Below about 15 °C, ionic conductivity falls and resistance rises; at sub-zero temperatures lithium plating during charging reduces capacity and creates dendrite-related safety risks [2]. Temperature non-uniformity across a pack accelerates cell-to-cell imbalance.

BTMS designs are active (air, liquid, immersion, refrigerant), passive (PCM, heat pipes, insulation, spreaders) or hybrid. PCMs absorb heat as latent heat during melting, need no pumps or fans and add no parasitic load; their weakness is low thermal conductivity (about 0.2–0.3 W/m·K for paraffin), which motivates additives such as expanded graphite, carbon nanotubes (CNT), graphene and metal foams [2].

2.3. Economic indicators and optimization

LCOE and NPC are the most relevant economic indicators for such systems, and the achievement of their minimum values defines the optimal configuration [1]. NPC is the present value of all system costs over the project lifetime minus the present value of revenues; LCOE is the annualized total cost divided by the electrical load served. HOMER takes the load profile, resource data, component specifications, constraints and emission data as inputs, simulates the hourly power balance of each feasible configuration, discards infeasible ones, and reports NPC, LCOE, resource contributions, renewable fraction and emissions together with a sensitivity analysis [1], [14]. This workflow is the framework into which battery thermal behaviour would have to be inserted.

3. INTEGRATED RENEWABLE ENERGY SYSTEM MODEL

3.1. System description

The system comprises solar PV, 10 kW wind turbines, a biomass gasifier with internal combustion engine (ICE) generator, a lithium-ion battery and a converter (Fig. 1). Solar and wind are prioritized over biomass, which supplies power on demand when they cannot meet the load [1]. HOMER performs an hourly power balance for predefined scenarios under multiple constraints and ranks feasible configurations by NPC and LCOE.

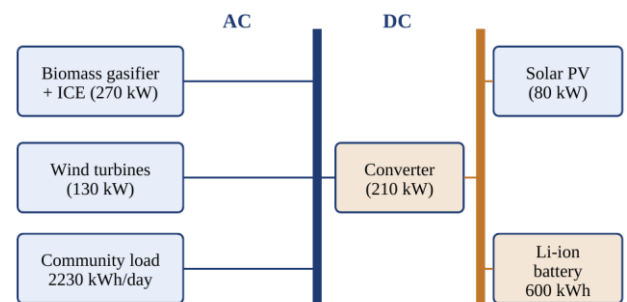


Fig. 1. Architecture of the integrated renewable energy system, with Scenario 1 capacities (adapted from [1]).

3.2. Component and economic models

PV output is modelled as

$$P_{PV} = P_0 f_{PV} (I_T/I_s) [1 + \alpha(T_c - T_s)], \quad (1)$$

where P_0 is nominal power, f_{PV} a derating factor, I_T and I_s the incident and standard-condition radiation, α the temperature coefficient, and T_c , T_s the operating and standard-test cell temperatures. Wind turbine power follows $P = 8\rho v A C_{wp}/27$, with hub-height speed $v = v_{ref}(H/H_{ref})^\gamma$ and $\gamma = 0.15$. Biogas generator net output is

$P_{bioel} = P_{bio,tot} - P_{aux} = \eta_{bioel} G_{LHV} V_{bio}$, with a biogas lower heating value of about 5.5 MJ/kg. Table 1 lists the cost and technical data.

Table 1. Economic and technical characteristics of system components [1].

Item	Biomass	PV	Wind	Conv.	Battery
Capital	4500 \$/kW	1000 \$/kW	20,000 \$/10 kW	150 \$/kW	550 \$/kWh
Replace	3500 \$/kW	1000 \$/kW	16,000 \$/10 kW	150 \$/kW	550 \$/kWh
O&M	525 \$/kW/yr	20 \$/kW/yr	500 \$/unit/yr	20 \$/kW/yr	10 \$/kW/yr
Efficiency	35%	17%	40%	90%	90%
Lifetime	20 yr	20 yr	20 yr	20 yr	10 yr

The real interest rate is $i = (i' - f)/(1 + f)$, with nominal discount rate $i' = 6.5\%$ and inflation $f = 5\%$, giving $i \approx 1.43\%$. (The source prints the denominator as $i' + f$, which appears to be a typographical slip.) The capital recovery factor is

$$CRF(i,N) = i(1+i)^N / [(1+i)^N - 1] \quad (2)$$

with $NPC = C_{atot}/CRF(i,N)$ and $LCOE = C_{atot}/E_{load}$ [9]. Constraints are 0% annual capacity shortage, a 10% operating reserve, a 100% renewable fraction and a 20-year project life [1].

4. Case-study results

4.1. Resource, load and optimal configurations

The site is in the Inuvik region, with annual mean wind speed 5.3 m/s at 10 m and strongly seasonal solar radiation. The community averages 2230 kWh/day (813,950 kWh/yr) with a 238.7 kW peak between 5 and 8 p.m. [1]. Table 2 gives the two lowest-cost designs; both use a 270 kW biomass generator at 45 \$/dry ton.

Table 2. Optimized systems for the sample community [1].

Parameter	Scenario 1	Scenario 2
Solar PV (kW)	80	50
Wind (kW)	130	110
Converter (kW)	210	160
Battery (kWh)	600	500
Capital cost (M\$)	1.89	1.78
O&M (\$/yr)	101,288	106,986

Parameter	Scenario 1	Scenario 2
NPC (M\$)	3.61	3.66
LCOE (\$/kWh)	0.255	0.262
Biomass / wind / PV share	61.2 / 30.7 / 8.08%	68.3 / 26.5 / 5.15%

Annual production is 883,090 kWh in Scenario 1 (Fig. 2). Component LCOE is about \$0.301/kWh for biomass, \$0.087/kWh for solar and \$0.079/kWh for wind. The wind turbines reach a 23.6% capacity factor over 7189 operating hours; the PV array operates 3615 hours per year and produces almost nothing in winter [1].

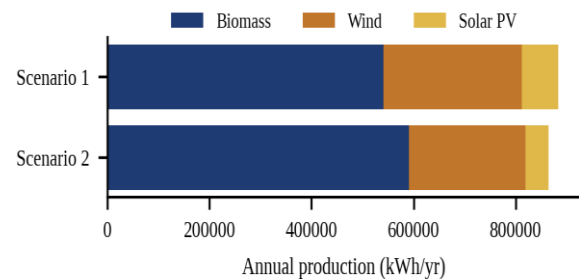


Fig. 2. Annual electricity production by source for the two optimized scenarios (data from [1]).

4.2. Sensitivity

NPC is most sensitive to biomass generator cost, discount rate and inflation (Fig. 3). A 20% battery capital cost rise adds only about 2.3–2.5% to NPC, making the battery a second-tier driver. The study does not vary battery lifetime, the quantity thermal management acts on.

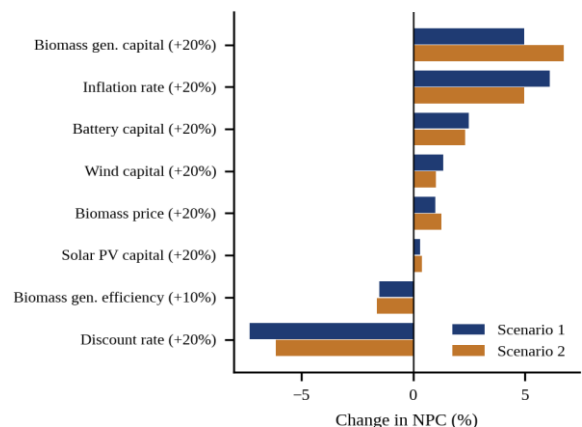


Fig. 3. Selected NPC sensitivities (data from [1]; plotted by the present author).

5. BATTERY THERMAL MANAGEMENT WITH PCMS

5.1. Thermal regimes

Heat in a Li-ion cell arises from ohmic heating, reversible entropic heat and irreversible heat from side reactions; it rises with C-rate, state of charge and ambient conditions and accumulates in dense modules [2]. Fig. 4 summarizes the operating regimes.

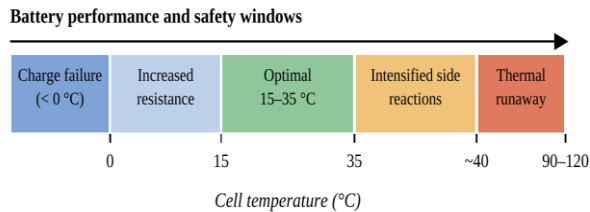


Fig. 4. Thermal operating regimes of Li-ion cells (summarized from [2], [8]).

High temperatures accelerate electrode degradation and electrolyte decomposition and can start thermal runaway, which propagates between cells; low temperatures reduce ionic conductivity, capacity and power and promote lithium plating [2]. Temperature gradients across a pack add cell-to-cell imbalance and shorten system life. BTMS options differ in how well they address these effects; Table 3 condenses the comparison given in [2].

Table 3. Comparison of cooling approaches (condensed from [2]).

Metho d	Unifor mity	Energy use	Comple xity	Fast charge	Upkee p
Air cooling	Poor; hot spots	Very low at low load	Easy	Not suitable	Minim al
Liquid cooling	Moderat e to good	Pumps and control s	Routing, leak risk	Suitable with good design	Period ic; corrosi on
Passive PCM	Moderat e	Very low, silent	PCM contain ers	Limited without fillers	Virtual ly none
Hybrid PCM + active	Excellen t	Low to modera te	Several subsystem s	Fully compati ble	Active part

5.2. PCM-based and hybrid systems

A PCM melts at a designated temperature, typically 30–50 °C for Li-ion applications, absorbing heat and delaying temperature rise, then re-solidifies when the load falls [2].

Pure paraffin is cheap, stable and high in latent heat but conducts poorly. Composites with expanded graphite, CNT, graphene or metal foam raise conductivity, while micro- and macro-encapsulation and shape stabilization address leakage. No enhancement is universally best: expanded-graphite paraffin offers the best balance of conductivity, cost and manufacturability, whereas CNT, graphene and metal-foam variants carry cost, dispersion and weight penalties [2]. Hybrid designs add air, liquid, heat-pipe, fin or thermoelectric elements (Table 4).

Table 4. Representative hybrid PCM-BTMS results compiled in [2].

Study	Configuration	Reported outcome
Ammar et al. 2025	Graphite-paraffin PCM + liquid	Hybrid $T_{\max}$ 36.7 °C, ΔT 1.0 °C vs PCM-only 42 °C
Zhou et al. 2025	PCM in honeycomb cold plates	$T_{\max}$ 29.6 °C, ΔT 2.0 °C; volume –49%
Saxena et al. 2025	Cold plates + PCM, intermittent flow	Pumping power –83.9%
Chen et al. 2025	Wave plate + tubular composite PCM	$T_{\max}$ –22.2%; ΔT –16.8%
Sun et al. 2025	Topology-optimized plate + PCM	$T_{\max}$ < 319 K at 5C; power –44.8%
Xie et al. 2023	PCM + micro heat pipes + liquid	ΔT 6.9→3.9 °C; $T_{\max}$ –13.78%
Saeedipour et al. 2025	Liquid + U-heat pipes + PCM	Peak –9.32 K; ΔT < 5 K; pumping –53%

5.3. Durability, safety and limits

In a PCM-cooled module cycled 200 times, maximum temperature at the 200th cycle fell from 51.7 to 47.5 °C relative to the non-PCM case and cycle life was extended by 65.3% [2], [10]. A composite PCM with expanded graphite and a silica flame retardant extended thermal-runaway delay from 21 s to 396 s [2], [11]. Against this, [2] stresses that hybridization is most effective under high C-rate, fast-charge or high-ambient conditions and gives diminishing returns beyond a certain active-cooling power; at moderate C-rates optimized passive or low-power hybrid systems often perform comparably with less energy and weight. Most PCM work targets heat removal, so cold operation needs combination with heating elements or thermal buffers [2].

5.4. Heating for low temperatures

At low ambient temperatures resistance and ion-mobility penalties reduce charge/discharge efficiency and available energy, so heating is used to keep the battery above about 0 °C. Internal methods include self-heating by pulsed current and embedded metal foils or films; external methods include positive-temperature-coefficient heaters, warm-coolant loops and heated air [2]. Resistive heating is simple and cost-effective, while heat pumps and inductive heating offer higher efficiency and integration potential. Thermal insulation helps keep the battery stable during storage or low demand but does not extract heat, so it is unsuitable alone for high-load or high-temperature cases [2]. These findings matter for a sub-Arctic microgrid, where PCM would be one element of a combined insulation, heating and buffering strategy.

5.5. Evaluation metrics

A PCM-based BTMS is assessed on heat absorption capacity and rate, peak temperature, spatial uniformity, life-cycle stability and safety [2]. Capacity alone is insufficient: a material with high latent heat but slow response may not prevent rapid spikes, and parametric analysis in [2] indicates that raising latent heat from 160 to 200 kJ/kg yields minimal improvement, whereas raising conductivity or optimizing liquid-flow direction lowers peak temperature substantially. PCM-liquid hybrids become less effective during high-C-rate charging unless PCM conductivity exceeds about 1 W/m·K, and temperatures stay below 40 °C at coolant flow above 2 L/min in the cited analysis. A PCM must also keep consistent phase-change behaviour with minimal supercooling and segregation over hundreds or thousands of cycles. Vibration effects reported in [2] are specific to vehicles and are largely absent from a stationary installation, which is one reason EV results cannot be transferred unchanged.

5.6. Practical integration considerations

The review identifies five practical constraints [2]. (i) Packaging: bulk PCM adds volume and weight and lowers pack-level energy density; porous foam layers infused with PCM between cells are one compact solution. (ii) Electrical and chemical compatibility: PCM around active cells must be electrically insulating and chemically compatible with housings and electrodes. (iii) Control: PCM buffers heat and delays response, so BTMS algorithms and sensor placement may need recalibration. (iv) Scalability and cost: nanomaterials, composite synthesis and encapsulation raise production cost, and large-scale manufacturing of high-performance formulations remains cost-prohibitive. (v) Standards: compliance with testing and safety requirements is needed before commercial use. For a stationary microgrid battery, constraint (i) is relaxed

because weight and volume are less critical than in a vehicle, whereas (ii)–(v) remain.

6. INTEGRATED ANALYSIS: THERMAL MANAGEMENT AND IRES ECONOMICS

All inputs are published values; the calculations are screening estimates.

6.1. Operating regime of the microgrid battery

In Scenario 1 a 600 kWh battery is paired with a 210 kW converter. If the converter limits battery power, the maximum rate is about $210/600 = 0.35C$. This is our inference, not a result of [1], and actual dispatch may be lower. It nonetheless places the battery in a low-to-moderate C-rate regime, far from the 3–5C cases in which hybrid PCM systems show their largest gains. Heat generation is modest relative to an EV pack, and a thermal buffer is mainly useful for summer ambient peaks or poorly ventilated enclosures.

The Inuvik location points the other way. With minimal winter solar output the system relies on wind and biomass, and the battery faces low temperatures unless housed in a heated enclosure. Below about 15 °C resistance rises and capacity falls, and sub-zero charging risks lithium plating [2]. The energy required to keep the battery in its window is not represented in the HOMER model of [1].

6.2. Value of extending battery life

The battery has a 10-year life in a 20-year project, implying one replacement at year 10 costing $550 \text{ \$/kWh} \times 600 \text{ kWh} = \$330,000$. With $i \approx 1.43\%$ its present value is

$$PV = 330,000 / (1.0143)^{10} \approx \$286,000. \quad (3)$$

If thermal management allowed a full 20-year life, this replacement would be avoided: an upper-bound saving of about \$286,000, or 7.9% of the \$3.61 M NPC, more than three times the NPC effect of a 20% battery capital cost rise (2.49%). A partial extension, such as the 65.3% cycle-life gain reported for a laboratory module [10], would not by itself remove the replacement within 20 years, so realistic savings are smaller and depend on salvage-value treatment; moreover, [10] reflects a specific cell and protocol that may not transfer to a stationary battery.

Because the real rate is low, deferring the replacement is worth little; only avoiding it matters. Table 5 gives the present value of the replacement for alternative timings, ignoring salvage value.

Table 5. Present value of the battery replacement for different timings ($i = 1.43\%$, NPC = \$3.61 M; salvage ignored).

Replacement at	PV of \$330,000	Saving vs. year 10	% of NPC
Year 10 (base case)	\$286,400	–	–
Year 13	\$274,400	\$11,900	0.33%
Year 16	\$263,000	\$23,400	0.65%
Avoided (20-yr life)	\$0	\$286,400	7.9%

The value of avoidance also depends on the financial parameters. Table 6 recomputes the present value of the year-10 replacement when the discount rate or inflation rate is raised by 20% (the variations used in [1]); NPC itself also changes in those cases, so only dollar values are shown.

Table 6. Sensitivity of the present value of the year-10 battery replacement (\$330,000) to financial parameters.

Case	Nominal rate / inflation	Real rate i	PV of replacement
Base	6.5% / 5%	1.43%	\$286,400
Discount rate +20%	7.8% / 5%	2.67%	\$253,600
Inflation +20%	6.5% / 6%	0.47%	\$314,800
Discount rate –20%	5.2% / 5%	0.19%	\$323,800

Higher discount rates shrink the value of avoided future spending, while higher inflation raises it, so the economic case for thermal management is weakest where capital is most expensive. This mirrors the finding of [1] that the discount rate is among the most influential variables for NPC.

The same figure sets an allowance: a PCM thermal package, with integration and maintenance, would have to cost below about \$286,000 in present value (roughly \$477/kWh of installed capacity) to pay back in the best case. The sources give no installed PCM-BTMS costs for stationary systems, and [2] notes that large-scale manufacturing of high-performance PCMs remains cost-prohibitive; this is a data gap, not a conclusion.

6.3. Mapping strategies to the microgrid

Table 7. Thermal management strategies mapped to remote-community IRES conditions.

Condition	Risk	Suggested strategy (consistent with [2])
Long cold winters, low solar	Lower capacity; plating risk on charge	Insulated, heated enclosure; preconditioning before charge; PCM/thermal buffer to smooth swings
Summer enclosure heat; evening peak	Elevated cell temperature, faster ageing	Passive composite PCM (e.g., expanded-graphite paraffin) as buffer
Low-to-moderate C-rate	Modest heat generation	Passive or low-power hybrid; avoid heavy active cooling
Remote site, limited maintenance	Pump/fan failure, leakage	Prefer passive, maintenance-free elements; avoid complex liquid loops
Safety in community facility	Thermal-runaway propagation	Flame-retardant composite PCM, spacing, monitoring

This follows the conclusion of [2] that optimal BTMS design is condition-dependent. For a remote microgrid, low parasitic load and low maintenance matter as much as peak thermal performance, and a silent, maintenance-free passive PCM buffer suits both. Active heating still adds value in winter, but its energy should be counted at the system's marginal cost, which in [1] is the biomass-dominated LCOE of about \$0.30/kWh.

6.4. Implications for optimization

HOMER-type optimization could be made more realistic in two ways: by making battery lifetime a function of temperature or throughput rather than a fixed 10 years, so the optimizer can value thermal management; and by adding an auxiliary enclosure heating and cooling load to the electrical demand. Since the battery sits close behind the dominant NPC drivers, replacement timing can shift NPC by several percent.

7. DESIGN GUIDELINES

Combining the findings of [1] and [2] gives the following checklist for a remote-community microgrid with lithium-ion storage.

- **Define the battery duty first.** Estimate the maximum C-rate from the converter and battery sizes (about 0.35C in Scenario 1) before selecting a thermal strategy; at low C-rates, heat generation is modest.
- **Treat cold and heat separately.** Winter conditioning (insulation, heating, preconditioning before charge) and summer heat control (passive buffering, ventilation) have different solutions [2].
- **Prefer passive, maintenance-free elements** where access is limited: composite PCM, insulation and heat spreaders carry no pumps or fans that can fail.
- **Choose moderate-conductivity composites** such as expanded-graphite paraffin unless a higher-performance material is justified by cost and manufacturability [2].
- **Count the parasitic energy.** Heating and cooling loads should be added to the electrical load in the optimization, valued at the marginal cost of generation.
- **Value life, not only capacity.** Represent battery life as a function of temperature or throughput, and compare thermal-package cost with the present value of avoided replacement (Table 5).
- **Design for safety.** Use flame-retardant composites, cell spacing and temperature monitoring to limit propagation of a thermal-runaway event [2].

8. DISCUSSION

What the combined view adds. The IRES study shows that a mix of biomass (61–68% of energy), wind and a small solar share can supply a remote community at \$0.255–0.262/kWh with a 100% renewable fraction. The BTMS review shows that the battery inside it has a narrow thermal window whose value is measured in cycle life and safety. Together they turn the battery from a cost line into a design variable.

Caveats.

- Different applications. The BTMS review concerns EV packs with high power density, vibration and mass limits; stationary microgrid batteries run at lower C-rates and are not weight-limited. Many PCM gains come from simulations at 3–5C and may not transfer.
- Cold-climate gap. PCM work focuses on heat removal; for Inuvik, winter conditioning is likely the dominant need [2].
- Economic gap. The upper bound in Section 6.2 assumes complete avoidance of replacement, ignores salvage value and uses no installed PCM cost.

- Source consistency. The case-study text gives 44,782 kWh/yr for Scenario 2 PV while the table gives 44,580; the table value agrees with the stated total of 864,193 kWh/yr and is used here [1].
- Scope. No new simulation is presented; results should be validated with HOMER runs using a degradation-aware battery model and measured enclosure temperatures.

9. FUTURE WORK

- Implement a temperature-dependent ageing model in the microgrid optimization and re-run the Inuvik case with and without thermal management.
- Quantify enclosure heating and cooling loads from local meteorological data and include them in the load profile.
- Obtain installed-cost and durability data for passive composite PCM modules at stationary scale and compare with the \$286,000 allowance.
- Evaluate hybrid PCM with heating elements for sub-zero conditions [2].
- Explore data-driven control co-optimizing dispatch and thermal state, as machine-learning methods are emerging for thermal-runaway prediction [2].
- Assess sustainability, including bio-based, recyclable PCMs and life-cycle emissions of the thermal package against the diesel emissions avoided [7].

10. CONCLUSION

The IRES of [1] shows that a solar–wind–biomass–battery microgrid can supply a remote Canadian community with a 100% renewable fraction at an NPC of \$3.61 M and LCOE of \$0.255/kWh. The review of [2] shows that passive and hybrid PCM systems can lower peak cell temperature, improve uniformity and extend cycle life, with benefit depending strongly on C-rate, climate and system-level penalties. Combined, they show that battery thermal management is an economically relevant but so far unmodelled part of remote-community microgrid design: avoiding one battery replacement is worth up to about \$286,000 (7.9% of NPC) in the case study, and the low C-rate and cold, remote setting favour insulated, preconditioned and largely passive thermal solutions. Validation with degradation-aware simulation and real cost data is the next step.

ABBREVIATIONS

BTMS, battery thermal management system; CNT, carbon nanotube; CRF, capital recovery factor; EV, electric vehicle; ICE, internal combustion engine; IRES, integrated renewable energy system; LCOE, levelized cost of electricity; LIB, lithium-ion battery; NPC, net present cost;

O&M, operation and maintenance; PCM, phase change material; PV, photovoltaic; SEI, solid electrolyte interphase.

DECLARATION OF COMPETING INTEREST

The author declares no known competing financial interests or personal relationships that could have influenced this work.

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This article synthesizes two published open-access works [1], [2]; all primary data and conclusions attributed to them belong to their original authors.

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