Feasibility of Phase-Change Energy Harvesting in Cold Climates via Ice-Driven Latent Heat Recovery

Yuan Li (iD)*

X-Here Trek Laboratory for Future Ice-Based Hydrogen Energy & Resilient Environments, Howard Beach, NY, USA

ARTICLE INFO

ABSTRACT

This study investigates the feasibility of generating renewable energy by harnessing the latent heat released during the cyclical freezing of water. We propose a novel system wherein solar thermal energy is used to melt ice, and the resultant water is refrozen by exposure to the surrounding environment, acting as an environmental cold sink. The key innovation involves capturing the considerable latent heat released during the freezing phase via a working fluid and converting it into mechanical work using a low-temperature differential heat engine. Our thermodynamic modeling demonstrates that net energy production is theoretically achievable, contingent upon specific conditions of solar irradiance, ambient temperature, and heat engine efficiency. This work proposes a new pathway for energy generation in cold climates, potentially utilizing the extensive natural reservoirs of ice present in polar and alpine regions.

*Corresponding Author
Email: liyuan0614@163.com
Tel: +(01) 917-863-9163

1. Introduction

The global transition to sustainable energy has spurred the search for innovative renewable resources [1]. While solar and wind power dominate, their effectiveness plummets in polar, alpine, and extreme winter climates due to prolonged darkness, low solar irradiance, and harsh conditions [2-5]. This limitation creates a pressing need for niche energy-harvesting technologies that leverage the abundant resources of cold environments. One such vast and virtually untapped resource is the latent heat of fusion stored in water ice. The phase change from water to ice releases a significant amount of energy, with a latent heat of fusion (L_f) of 334 kJ/kg [6]. This represents a remarkably high energy density (Table **1**); the latent heat released by freezing one cubic meter of water is approximately equivalent to the energy required to lift ~340 m^3 of water over 100 meters. This energy reservoir exists on a massive scale in expansive sea ice, perennial lake ice, and seasonal ice formations across the Earth's colder latitudes [7]. Yet, this immense potential remains passive, slowly dissipating into the environment during ordinary freezing cycles without being harnessed. Currently, the release of latent heat is a slow and undirected ambient process, where thermal energy from freezing water bodies is simply transferred to the colder atmosphere [8]. We propose a paradigm shift: by creating a controlled, cyclical process of melting and freezing, this ubiquitous energy flow can be transformed into a continuous and reliable power source. Although the principles of latent heat are well-understood and commonly used for thermal energy storage [9], actively extracting this energy from a perpetual, natural cycle for mechanical or electrical work remains a largely unexplored frontier. Previous research has focused on phase-change materials for inert buffering, not active energy generation [10]. This report addresses this gap by introducing and analyzing the thermodynamic feasibility of the Cryo-Thermal Cycle. This novel concept is designed to produce renewable energy by systematically utilizing the latent heat released during the engineered freezing of water, establishing a theoretical foundation for leveraging cold climates as a key component of a sustainable energy system.

Table 1:   Energy density comparison.

Energy Source	Energy Density (Approx.)	Notes
Latent Heat of Fusion (Water)	~334 kJ/kg	Core focus of this study
Lithium-ion Battery	~700-1,000 kJ/kg	For electricity storage [11]
Gasoline	~46,000 kJ/kg	Chemical energy for combustion [12]
Pumped Hydro (100 m head)	~1 kJ/kg	Gravitational potential energy [13]

2. The Cryo-Thermal Cycle: Principles, Physics, and Implementation Pathways

## 2.1. Core Concept and Operational Principle

The Cryo-Thermal Cycle is an innovative thermodynamic process designed to convert environmental thermal energy into usable work by systematically managing the phase transitions of water (Fig. **1**). This engineered cycle transforms diffuse thermal gradients into mechanical or electrical energy through a four-stage process that actively incorporates natural cold sinks as integral system components. The cycle's operation is defined by four sequential stages:

Stage 1: Melting (Controlled Energy Input). The cycle initiates with the application of thermal energy to melt a mass m of ice. Solar thermal energy, collected via systems optimized for cold, low-irradiance conditions (e.g., Evacuated Tube Collectors (ETCs)), is the most viable sustainable source for this stage [14]. The theoretical energy requirement is given by $Q_{melt} = mL_f$. Accounting for system inefficiencies, the actual solar input required is $E_{in} = Q_{melt}/\eta_{solar}$, where η_{solar} is the composite efficiency of the solar collection and thermal transfer system.

Stage 2: Freezing (Controlled Energy Release). The resulting meltwater is transferred to a specialized freezing chamber, or crystallizer, which acts as a high-efficiency heat exchanger. Upon exposure to a natural cold sink (e.g., sub-freezing ambient air), the water refreezes, releasing its latent heat: $Q_{freeze} = mL_f$ [15], making thermal energy available for capture through controlled crystallization.

Stage 3: Heat Harvesting (Energy Transfer). The latent heat released during freezing is transferred through the walls of the crystallizer to a closed-loop circuit containing a low-freezing-point (significantly below 0°C) working fluid (e.g., a glycol solution). The efficiency of this heat exchange process is characterized by the parameter η_{heat_xfer} [16].

Stage 4: Power Generation (Energy Conversion). The heated working fluid drives a low-temperature differential heat engine, such as an Organic Rankine Cycle (ORC) system [17] or a Stirling engine [18], configured for small temperature gradients. The electrical energy output is thus: $E_{out} = \eta_{engine}\eta_{heat\_xfer}Q_{freeze}$, where η_{engine} is the conversion efficiency of the heat engine.
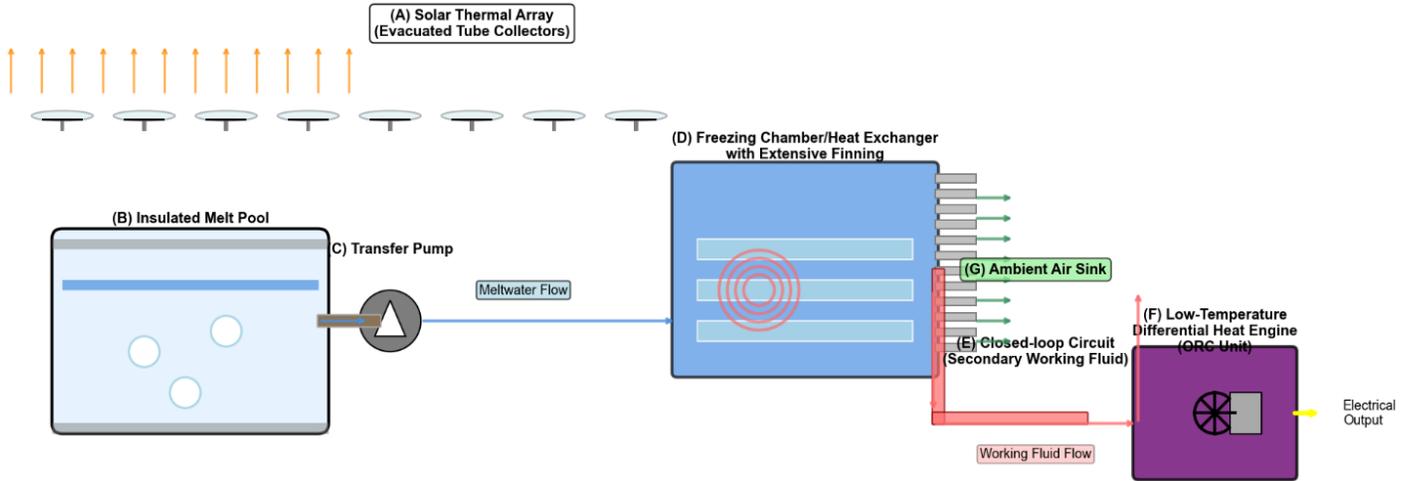
Figure 1: Conceptual system design of a single cryo-thermal unit. Schematic diagram illustrating the core components and operational workflow of the proposed cryo-thermal energy harvesting system. The cycle begins with (**A**) Solar Thermal Array (Evacuated Tube Collectors), which provides the primary energy input. This energy is used to melt ice in the (**B**) Insulated Melt Pool. The resulting meltwater is then pumped by (**C**) Transfer Pump to the (**D**) Freezing Chamber/Heat Exchanger, a key component designed with extensive finning for rapid heat rejection. Within this chamber, the water refreezes, releasing its latent heat of fusion. This heat is absorbed by a secondary, closed-loop circuit (**E**), which transfers it to the (**F**) Low-Temperature Differential Heat Engine (e.g., an Organic Rankine Cycle unit) to generate electricity. The (**G**) Ambient Air Sink serves as the ultimate heat rejection pathway. Solid blue arrows trace the meltwater flow, while red arrows indicate the path of the secondary working fluid. This integrated design aims to continuously convert the latent heat from cyclical ice formation into usable electrical power.

2.2. Thermodynamic Analysis and the Fundamental Challenge

The net energy output of a direct-conversion Cryo-Thermal Cycle is governed by the First Law of Thermodynamics [6]: $E_{net} = E_{out} - E_{in} = \eta_{engine}\eta_{heat\_xfer}Q_{freeze} - Q_{melt}/\eta_{solar}$. For a viable system with $E_{net} > 0$, this simplifies to the condition: $\eta_{engine}\eta_{heat\_xfer}\eta_{solar} > 1$. This inequality presents a fundamental thermodynamic challenge: the product of three sub-unity efficiencies must exceed unity, which is impossible for a direct-conversion system. This conclusion is reinforced by the Second Law. Considering a heat engine operating between freezing water at $T_{hot} = 273$ K and an ambient cold sink at $T_{cold} = 253$ K, the maximum theoretical Carnot efficiency is: $\eta_{Carnot} = 1 - (T_{cold}/T_{hot}) = 1 - (253 / 273) \approx 7.3\%$. Practical low-temperature engines typically achieve only 30-50% of this Carnot limit, resulting in a realistic η_{engine} of just 2–4% [17]. This definitively confirms the impossibility of a positive net energy balance for the simple, basic cycle (Table **2**).

2.3. Reconciling the Paradox: From Direct Cycle to Enhanced System Architectures

The apparent paradox is resolved by re-evaluating the system boundaries and energy accounting. If solar input is considered an abundant, *free* resource from an energy (not economic) perspective, the balance shifts: $E_{net} \approx E_{out} > 0$. This reframing reveals the cycle's true value not as a standalone energy generator, but as a solar energy amplification and storage mechanism. The cycle effectively converts diffuse, intermittent solar thermal energy into

concentrated, dispatchable power through phase-change mediation. To this end, this insight leads to three enhanced architectural pathways that achieve feasibility by bypassing the limitations of the direct cycle:

1) **Solar-Driven Heat Pump Integration.** By using a fraction of the generated electricity or a separate solar PV system to power a heat pump, the energy input for melting is effectively amplified. A heat pump with a Coefficient of Performance (COP) of 3–4 can move multiple units of heat per unit of electrical energy consumed. This creates an effective solar efficiency: $\eta_{solar\_effective} = \eta_{solar\_collector} \times COP_{heat\_pump}$. For example, with $\eta_{solar\_collector}$ = 0.6 and COP = 3.5, $\eta_{solar\_effective}$ becomes 2.1, thereby satisfying the condition for a positive net energy balance (Table **2**).

2) **Temperature Cascade Systems.** This architecture decouples the heat engine from the 0°C limitation. The latent heat from freezing water is transferred not immediately to the power cycle, but to a secondary phase-change material (PCM) with a higher melting point (e.g., a salt hydrate at 40–60°C; [19]. This secondary cycle then drives the ORC or Stirling engine. The Carnot efficiency is dramatically increased; for T_{hot} = 333 K and T_{cold} = 253 K, η_{Carnot} rises to ~25%, making efficient power generation feasible.

3) **Hybrid Seasonal Energy Storage Application.** The most straightforward practical implementation re-conceptualizes the system as ultra-long-duration thermal storage. Excess solar thermal energy collected in summer is used to melt ice, storing the energy for months. During winter, the natural freezing process provides a reliable source of low-grade heat for building heating or base-load power generation. This leverages the cycle's inherent advantage-minimal thermal losses in cold climates-to address a key limitation of electrochemical batteries.

Table 2: Parametric analysis for direct-cycle feasibility (η_{heat_xfer} = 0.85).

| η_{solar}	Required η_{engine}	Practical η_{engine}	Feasibility
0.6	>1.96	~0.03	Not Feasible
0.5	>2.36	~0.03	Not Feasible
0.4	>2.94	~0.03	Not Feasible
0.3	>3.92	~0.03	Not Feasible

2.4. Conclusion and Path Forward

While a direct-conversion Cryo-Thermal Cycle is thermodynamically impossible, this analysis demonstrates that sophisticated system designs can yield practical and feasible implementations. The cycle's core innovation lies in transforming its perceived limitation—the reliance on external cold sinks—into its primary advantage (Fig. **2**). That is, the Cryo-Thermal Cycle represents a novel energy vector that: Amplifies Intermittent Solar Energy through phase-change mediation; Enables Seasonal Energy Storage with unprecedented duration and minimal losses; and Provides Dispatchable Power by leveraging natural environmental cycles. Future research should therefore focus not on the infeasible simple cycle, but on the development of integrated systems utilizing heat pumps, cascaded PCMs, and seasonal storage strategies. This establishes the Cryo-Thermal Cycle as a scientifically robust, complementary technology to conventional renewables, particularly in cold-climate regions.

3. System Architecture, Scalability, and Deployment Models

The translation of the Cryo-Thermal Cycle from principle to practice demands a system architecture that is robust, efficient, and inherently scalable (Fig. **3**). Its potential utility is predicated on deployment across large zones, leveraging vast natural ice reservoirs to overcome its underlying low energy density (Table **1**).

3.1. Critical Component Analysis

The system's viability is contingent upon the performance and integration of three core technological subsystems:
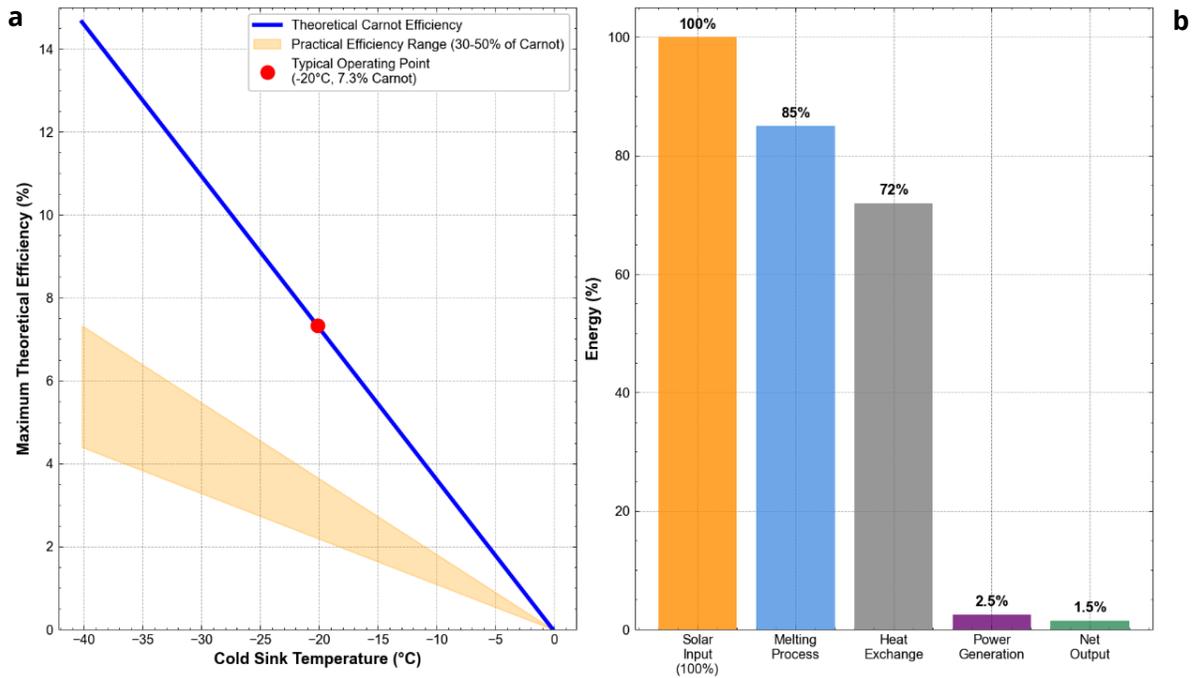
Figure 2: Thermodynamic analysis of the cryo-thermal cycle. Thermodynamic evaluation of the proposed energy cycle. (**a**) Carnot Efficiency vs. Cold Sink Temperature: Plots the maximum theoretical (Carnot) efficiency for a heat engine operating between a hot source at 0°C and a variable cold sink. The shaded region represents a realistic, practical efficiency range (30-50% of Carnot), with a typical operating point highlighted at -20°C. (**b**) System Energy Flow Analysis: A representative Sankey-style bar chart showing the estimated energy losses at each stage of the system, from the initial solar input to the final net electrical output, underscoring the system's overall energy conversion efficiency.
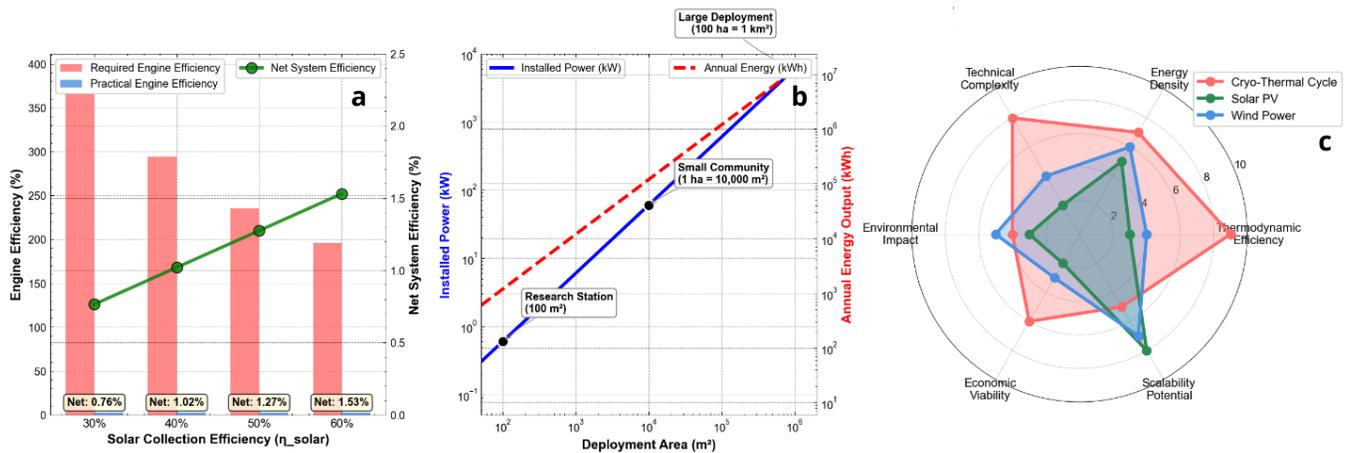
Figure 3: System performance and feasibility analysis. Comprehensive evaluation of the cryo-thermal cycle under varying environmental and design conditions. (**a**) Direct Cycle Feasibility Analysis (η_{heat_xfer} = 0.85): Examines the critical relationship between solar collection efficiency and heat engine performance requirements. The analysis contrasts theoretical efficiency demands against practical, achievable engine efficiencies, with net system output shown on the secondary axis. This comparison reveals the fundamental technological challenge: even with high solar collection efficiency, the system requires engine performance beyond current practical limits to achieve viable net output. (**b**) Power Output vs. Deployment Scale: Log-log projection of installed electrical capacity and annual energy generation as functions of deployment area. The scaling analysis demonstrates the technology's potential trajectory from pilot-scale research stations (100 m²) to utility-scale implementations (100 hectares), highlighting the substantial area requirements for meaningful power generation. (**c**) Technology Challenge Assessment: Radar chart comparing key development challenges across energy technologies, where higher scores indicate greater obstacles. The cryo-thermal cycle shows pronounced challenges in thermodynamic efficiency and technical complexity, while maintaining relative advantages in environmental compatibility. This comparative framework identifies key development priorities relative to established renewable technologies like solar PV and wind power.

1) **Solar Thermal Collection.** In the cold, low-irradiance target environments, the choice of solar collector is crucial. ETCs are the superior candidate, as their vacuum insulation minimizes convective heat loss, enabling efficient operation even in sub-zero ambient temperatures and under diffuse light [14]. This high performance is essential for maximizing the solar energy input term (E_{in}) in the system's energy balance. Arrays would be angled to optimize capture of the low-angle winter sun.

2) **The Freezing Heat Exchanger (Crystallizer).** This subsystem represents one of the most significant engineering challenges. It must simultaneously facilitate rapid, complete freezing of water and efficiently transfer the released latent heat to the secondary working fluid. An optimal design requires an extremely high surface-area-to-volume ratio, likely achieved through extensive external finning or an internal matrix of micro-channels [16]. The construction material must exhibit high thermal conductivity (e.g., aluminum alloy) and exceptional resistance to corrosion and thermal fatigue induced by repeated freeze-thaw cycles [20]. The efficiency of this component, η_{heat_xfer}, is a direct multiplier of the system's energy output.

3) **Low-Temperature Differential Heat Engine.** The modest temperature gradient (typically 5-15°C) between the warmed working fluid and the ambient sink necessitates specialized conversion technology. ORC engines, which utilize a low-boiling-point organic fluid, are the most viable option, allowing it to vaporize and drive a turbine with the low-grade heat available [17]. Stirling engines, known for high theoretical efficiency at small ΔT, present an alternative [18]. The central limitation is the fundamental thermodynamic ceiling; practical efficiencies (η_{engine}) for these devices operating under such conditions are a mere 2–5% of the heat input [21].
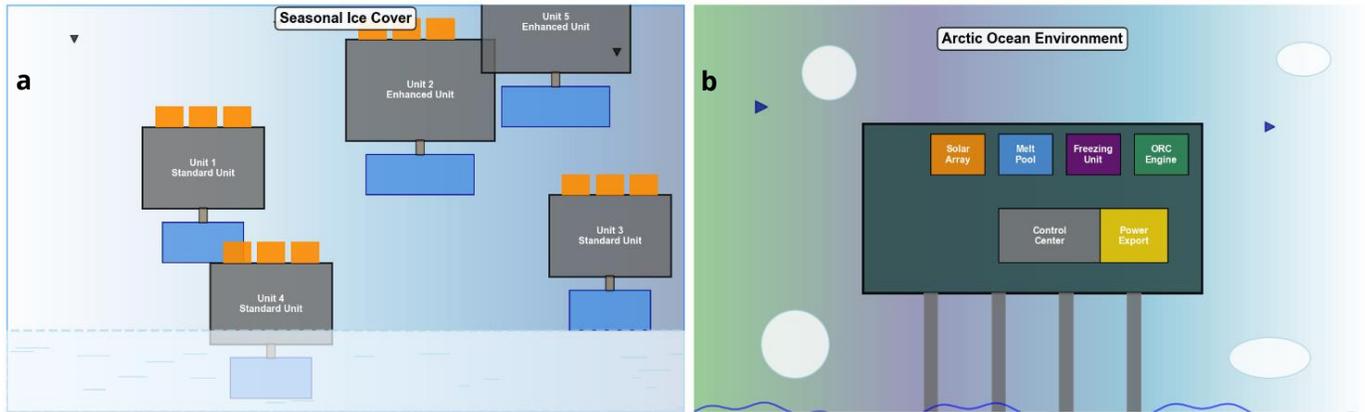
3.2. Scalability and Deployment Models

To generate meaningful power, the system must be deployed at scale. Two primary models are conceptualized (Table **3**):

1) **Lacustrine (Lake-based) Arrays.** This model offers the most tractable near-term application. Modular, floating units could be deployed on seasonal ice-covered lakes, forming distributed *cryo-farms* (Fig. **4a**). This approach leverages abundant freshwater ice, avoiding the complexities of salinity, and is naturally synchronized with seasonal freezing cycles.

2) **Maritime (Ocean-based) Systems.** While offering a vastly larger resource base, maritime deployment introduces immense engineering complexity (Fig**. 4b**). The primary obstacle is brine rejection during seawater freezing, which creates concentrated channels that lower the local freezing point, impede heat transfer and complicate the phase-change process [22]. A feasible marine system would likely require a closed-loop freshwater cycle, using collected precipitation (snow melt) or an integrated, system-powered desalination unit to supply the pure water working mass [23]. Platforms would need rigorous engineering to withstand polar sea states and ice dynamics [24].

In conclusion, while the system's core constituent elements are based on existing technologies, their integration for this specific purpose presents daunting engineering challenges. The freezing heat exchanger and the low-ΔT heat engine are the primary technological bottlenecks. Scalability is conceptually feasible, with lake-based arrays representing a more near-term prospect and ocean-based systems remaining a long-term, high-risk ambition dependent on solving the brine rejection problem.

Table 3:   Comparison of deployment environments.

Factor	Lacustrine (Lake) Model	Maritime (Ocean) Model
Working Fluid	Freshwater (simpler)	Seawater (problematic) or closed-loop freshwater
Engineering Challenge	Moderate (seasonal ice, calm waters)	High (polar storms, sea ice dynamics, brine)
Resource Scalability	Limited to lake surface area	Virtually unlimited (ocean scale)
Operation Period	Seasonal (winter/spring)	Potentially year-round in high latitudes

Figure 4: Scalability analysis and deployment models. (**a**) Lacustrine (Lake-based) Deployment Model: Illustrates a modular approach using distributed floating *cryo-farms* on a seasonally frozen lake. This model leverages natural ice formation and is ideal for remote communities or research stations. (**b**) Maritime (Ocean-based) Deployment Model: Depicts a larger, centralized offshore platform designed to operate in polar maritime environments, utilizing sea ice as a feedstock.

4. Critical Feasibility Analysis and Outlook

A rigorous feasibility assessment for the Cryo-Thermal Cycle must contextualize its theoretical promise against fundamental physical limits and profound practical challenges (Table **4**).

Table 4:   Summary of key feasibility challenges.

Challenge	Description	Impact on Feasibility
Low Carnot Efficiency	Inherent thermodynamic limit (<10%) due to small ΔT.	Severely restricts maximum possible energy output.
Net System Efficiency	Low practical efficiencies of components (net ~1-2%).	Requires enormous solar input for modest electrical output.
Energy Density	Low power output per unit area of infrastructure.	Necessitates massive, costly scale-up (*cryo-farms*).
Technical Hurdles	Ice management, freezing kinetics, polar operations.	Increases complexity, cost, and maintenance challenges.
Niche Application	Only potentially viable in specific off-grid polar settings.	Extremely limited market and economic potential.

4.1. The Fundamental Thermodynamic Bottleneck

The most formidable constraint is imposed by the Second Law of Thermodynamics [25]. For a heat source at 0°C and a cold sink at -20°C, the maximum theoretical (Carnot) efficiency is approximately 7.3% (Section 2.2). Real-world ORC or Stirling engines achieve only 30-50% of this limit, yielding a practical η_{engine} of 2–4%. When compounded with realistic efficiencies for solar collection ($\eta_{solar} \approx 0.5$) and heat transfer ($\eta_{heat\_xfer} \approx 0.85$), the overall net system efficiency, *viz.*, the ratio of electrical output to solar input, falls sharply to a range of 0.85% to 1.7% [14, 16]. This stark figure underscores the cycle's core limitation: it is an inherently inefficient converter of solar energy into electricity, requiring nearly perfect component performance just to achieve a positive net energy balance ($E_{net} > 0$).

4.2. Consequential Challenges of Low Efficiency

This severe efficiency bottleneck directly creates secondary, equally critical challenges, i.e., massive scale and low energy density. Although the latent heat of fusion is high on a per-mass basis [6], the energy output is vanishingly low on a per-unit-area basis due to the poor net efficiency. This necessitates the deployment of sprawling arrays of modules, or *cryo-farms*, to generate meaningful power. For instance, to produce a modest 1 MW of continuous power at 1.5% net efficiency, the system must cyclically process approximately 718 metric tons

of ice per hour. The associated infrastructure, solar fields, heat exchangers, and handling systems, would be colossal and economically unviable for all but the most niche applications [26]. Viability is thus intrinsically linked to the availability of ample, inexpensive ice fields and the cost of constructing and maintaining such large-scale, distributed infrastructure in remote, harsh environments.

Beyond the core thermodynamic challenge, several significant engineering hurdles remain:

1) **Ice Management.** Automating the robust, low-energy handling, fracturing, and transport of solid ice presents significant mechanical challenges [27].

2) **Freezing Kinetics.** The power output is tied to cycle frequency, which is limited by freezing rate. In milder conditions (e.g., -5°C), freezing becomes impractically slow, crippling power generation without prohibitively large (surface areas) heat exchangers to maximize the transfer of latent heat to the cold sink [15].

3) **Extreme Environment Reliability.** All components must operate continuously under polar conditions, including vulnerability to icing, snow loading, extreme winds, and prolonged winter darkness, making maintenance difficult and costly [24].

4.3. Niche Viability and Conclusion

Given these compounded challenges, the Cryo-Thermal Cycle cannot be considered a competitor to mainstream renewables like solar PV or wind power [28]. Its potential, if any, resides in highly specialized, off-grid applications where its unique resource requirements align with local availability. Examples include providing supplemental power for autonomous polar research stations [29-32] or remote Arctic communities, where scarce winter sunlight and ice are the dominant, on-site resources.

From an environmental standpoint, the system offers the benefit of zero operational emissions. However, a full life-cycle assessment is necessary to evaluate the impact of its extensive material and installation footprint [33]. Further, potential local microclimate effects of large-scale deployments, such as altering albedo or disrupting local ice formation patterns, must be thoroughly studied to ensure ecological compatibility.

In conclusion, while the Cryo-Thermal Cycle is a thermodynamically valid concept, its practical feasibility for widespread renewable energy generation is severely limited. It may represent a fascinating scientific proposition and an ultra-niche solution for specific polar applications. However, it is not presently a viable energy technology. Future relevance would be conditional upon revolutionary breakthroughs in low-ΔT heat engine efficiency and heat exchanger design that are not foreseen by current engineering paradigms. This feasibility study therefore concludes that the concept, though intellectually compelling, holds limited near-term viability, but remains a promising long-term prospect for the global renewable energy portfolio.

5. Conclusion and Perspective

This study establishes the fundamental principles of the Cryo-Thermal Cycle, demonstrating the theoretical viability of harvesting latent heat from cyclical water phase changes for renewable energy generation. The thermodynamic analysis confirms that actively cycling water through freezing transitions can, in principle, yield net energy output through controlled release of fusion enthalpy. The feasibility assessment reveals that while positive energy balance is thermodynamically achievable, practical implementation faces substantial efficiency constraints. The technology's viability depends critically on developing specialized components: high-performance heat engines capable of operating at minimal temperature differentials and advanced heat exchangers optimized for maximum thermal transfer efficiency. Given the inherent Carnot limitations and systemic energy penalties, the Cryo-Thermal Cycle cannot be regarded as a broad-spectrum energy solution. Its potential appears restricted to carefully defined niche applications, particularly in remote cold-climate regions where conventional renewables face operational challenges. This work serves as a foundational proof-of-concept, establishing the theoretical framework while highlighting the considerable engineering challenges. Consequently, we propose a focused

research agenda prioritizing three priority pathways: experimental validation through laboratory-scale prototypes, development of novel materials engineered for enhanced thermal conductivity and cyclic freeze-thaw durability, and comprehensive techno-economic analysis to identify viable deployment scenarios. Only through systematic investigation across these domains can the practical potential of this unconventional energy concept be properly evaluated and harnessed.

Conflict of Interest

Funding

Acknowledgments

Data and Code Availability

All data used in this work has been incorporated within this paper.

References

[1]   IPCC. Climate change 2022: mitigation of climate change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press; 2022.

[2]   Mathy S, Menanteau P, Criqui P. After the Paris agreement: measuring the global decarbonization wedges from national energy scenarios. Ecol Econ. 2018; 150: 273-89. https://doi.org/10.1016/j.ecolecon.2018.04.012

[3]   Cromartie KA. Assessing the potential for renewable energy systems in remote Arctic communities as a means of reducing regional diesel fuel dependence (thesis). Reykjavík: Reykjavík University; 2021.

[4]   Ben A, Jordan R, Baring-Gould I. Distributed renewables for Arctic energy: a case study. Golden (CO): National Renewable Energy Laboratory; 2023. Report No.: NREL/TP-5000-84391. Available from: https://www.nrel.gov/docs/fy23osti/84391.pdf

[5]   Galimova T, Satymov R, Keiner D, Breyer C. Sustainable energy transition of Greenland and its prospects as a potential Arctic e-fuel and e-chemical export hub for Europe and East Asia. Energy. 2024; 286: 129605. https://doi.org/10.1016/j.energy.2023.129605

[6]   Çengel YA, Boles MA, Kanoglu M. Thermodynamics: an engineering approach. 9th ed. New York: McGraw-Hill Education; 2019.

[7]   National Snow and Ice Data Center. Sea Ice Today. Boulder (CO); 2023. Available from: https://nsidc.org/sea-ice-today

[8]   Sharma A, Tyagi VV, Chen CR, Buddhi D. Review on thermal energy storage with phase change materials and applications. Renew Sustain Energy Rev. 2009; 13(2): 318-45. https://doi.org/10.1016/j.rser.2007.10.005

[9]   Zalba B, Marín JM, Cabeza LF, Mehling H. Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. Appl Therm Eng. 2003; 23(3): 251-83. https://doi.org/10.1016/S1359-4311(02)00192-8

[10]   Farid MM, Khudhair AM, Razack SAK, Al-Hallaj S. A review on phase change energy storage: materials and applications. Energy Convers Manag. 2004; 45(9-10): 1597-615. https://doi.org/10.1016/j.enconman.2003.09.015

[11]   Tarascon JM, Armand M. Issues and challenges facing rechargeable lithium batteries. Nature. 2001; 414: 359-67. https://doi.org/10.1038/35104644

[12]   Heywood JB. Internal combustion engine fundamentals. 2nd ed. New York: McGraw-Hill Education; 2018. ISBN: 9781260116106.

[13]   Gleick PH. Water in crisis: a guide to the world's fresh water resources. Oxford: Oxford University Press; 1993. ISBN: 9780195076288.

[14]   Kim Y, Seo T. Thermal performances comparisons of the glass evacuated tube solar collectors with shapes of absorber tube. Renew Energy. 2007; 32(5): 772-95. https://doi.org/10.1016/j.renene.2006.03.016

[15]   Bergman TL, Lavine AS, Incropera FP, DeWitt DP. Fundamentals of heat and mass transfer. 8th ed. Hoboken (NJ): John Wiley & Sons; 2018.

[16]   Thulukkanam K. Heat exchanger design handbook. 2nd ed. Boca Raton (FL): CRC Press; 2013. https://doi.org/10.1201/b14877

[17]   Tchanche BF, Lambrinos G, Frangoudakis A, Papadakis G. Low-grade heat conversion into power using organic Rankine cycles—a review of various applications. Renew Sustain Energy Rev. 2011; 15(8): 3963-79. https://doi.org/10.1016/j.rser.2011.07.024

[18]   Kongtragool B, Wongwises S. A review of solar-powered Stirling engines and low temperature differential Stirling engines. Renew Sustain Energy Rev. 2003; 7(2): 131-54. https://doi.org/10.1016/S1364-0321(02)00053-9

[19]   Dixit P, Reddy VJ, Parvate S, Balwani A, Singh J, Maiti TK, *et al*. Salt hydrate phase change materials: current state of art and the road ahead. J Energy Storage. 2022; 51: 104360. https://doi.org/10.1016/j.est.2022.104360

[20]   ASM International. ASM handbook. Vol 13B, Corrosion: materials. Materials Park (OH): ASM International; 2006.

[21]   Quoilin S, Van Den Broek M, Declaye S, Dewallef P, Lemort V. Techno-economic survey of organic Rankine cycle systems. Renew Sustain Energy Rev. 2013; 22: 168-86. https://doi.org/10.1016/j.rser.2013.01.028

[22]   Weeks WF. On sea ice. Fairbanks (AK): University of Alaska Press; 2010.

[23]   Elimelech M, Phillip WA. The future of seawater desalination: energy, technology, and the environment. Science. 2011; 333(6043): 712-7. https://doi.org/10.1126/science.1200488

[24]   ISO. ISO 19906: petroleum and natural gas industries—Arctic offshore structures. Geneva: International Organization for Standardization; 2019.

[25]   Callen HB. Thermodynamics and an introduction to thermostatistics. 2nd ed. New York: John Wiley & Sons; 1985.

[26]   Khan S, Tao Z, Agyekum EB, Fahad S, Tahir M, Salman M. Sustainable rural electrification: energy-economic feasibility analysis of autonomous hydrogen-based hybrid energy system. Int J Hydrogen Energy. 2025; 141: 460-73. https://doi.org/10.1016/j.ijhydene.2024.09.063

[27]   Petrenko VF, Whitworth RW. Physics of ice. Oxford: Oxford University Press; 1999.

[28]   IRENA. Renewable power generation costs in 2022. Abu Dhabi: International Renewable Energy Agency; 2023. Available from: https://www.irena.org/Publications/2023/Jun/Renewable-Power-Generation-Costs-in-2022

[29]   Kang J, Wei Y, Liu L, Han R, Yu B, Wang J. Energy systems for climate change mitigation: a systematic review. Appl Energy. 2020; 263: 114602. https://doi.org/10.1016/j.apenergy.2020.114602

[30]   Lucci JJ, Alegre M, Vigna L. Renewables in Antarctica: an assessment of progress to decarbonize the energy matrix of research facilities. Antarct Sci. 2022; 34(5): 374-88. https://doi.org/10.1017/S095410202200030X

[31]   de Witt M, Chung C, Lee J. Mapping renewable energy among Antarctic research stations. Sustainability. 2024; 16(1): 426. https://doi.org/10.3390/su16010426

[32]   Gonçalves ACR, Costoya X, Nieto R, Liberato M. Extreme weather events on energy systems: a comprehensive review on impacts, mitigation, and adaptation measures. Sustain Energy Res. 2024; 11: 4. https://doi.org/10.1186/s40807-023-00097-6

[33]   Hertwich EG, Gibon T, Bouman EA, Arvesen A, Suh S, Heath GA, *et al*. Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. Proc Natl Acad Sci U S A. 2015; 112(20): 6277-82. https://doi.org/10.1073/pnas.1312753111