

Impact of Optimization Horizon on Techno-economic Performance of a PV-Driven Standalone District Cooling System

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Abstract. This study proposes a standalone photovoltaic (PV)-driven district cooling system integrated with multiple energy storage technologies, including battery storage, ice storage, and hydrogen storage. A techno-economic analysis is performed to optimize the system configuration and operation, with particular emphasis on the impact of the optimization horizon. The levelized cost of energy (LCOE) serves as the objective function, while component design and operational parameters are simultaneously optimized using a mixed-integer linear programming (MILP) approach. Key findings reveal that overly aggregated optimization horizons lead to underestimations of component capacities and LCOE. For instance, hydrogen storage is excluded when the optimization horizon is shorter than 90 days. However, extending the horizon beyond 90 days makes hydrogen storage essential to mitigate long-term solar energy scarcity. Furthermore, full-year optimization necessitates larger battery and ice storage capacities compared to aggregated time spans. The resulting LCOE under full-year optimization is 31.6% to 45.8% higher than those obtained using aggregated time spans, highlighting the importance of selecting an appropriate optimization horizon for accurate system design and cost assessment.

1 Introduction

Due to climate warming and rising living standards, global energy demand for space cooling is increasing at a faster rate than for heating, with projections indicating a surge from approximately 8 EJ to 19 EJ between 2022 and 2050 [1]. This growing cooling demand exacerbates global warming, creating a concerning feedback loop. District cooling systems (DCSs) have emerged as a promising solution to improve cooling efficiency and reduce carbon emissions [2]. For instance, the world's largest underground district cooling network has demonstrated energy savings of up to 40% compared to conventional standalone air-conditioning units [3]. Moreover, integrating renewable energy sources into DCSs presents further opportunities to enhance sustainability. Solar energy, in particular, is highly suitable

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for cooling applications in tropical and subtropical regions, where peak cooling demand often aligns with abundant solar irradiance [4].

However, a major challenge in renewable energy adoption is its inherent variability, which contrasts sharply with the controllability of conventional fossil fuels. This variability introduces new complexities in the design and operation of renewable energy systems. Currently, many such systems are optimized based on typical weather and demand profiles. While this approach may suffice for fossil fuel-based systems, it becomes inadequate for solar- or wind-powered systems due to their strong dependence on highly fluctuating weather conditions. For example, Liu et al.[5] optimized a renewable combined cooling, heating, and power (CCHP) system using averaged weather data and constant energy demands, ultimately excluding wind turbines and hydrogen storage from the optimal configuration due to perceived economic infeasibility. Similarly, when optimization is constrained to short time spans (e.g., a few typical days), hydrogen storage and batteries are rarely selected together [6,7]. This is primarily because hydrogen storage, despite its long-term balancing potential, is often deemed economically unviable in short-term analyses due to the high capital costs of electrolyzers, fuel cells, and hydrogen storage infrastructure. Therefore, the impact of optimization horizons on the renewable energy system design and operation has not been fully explored.

To address these limitations, this study proposes a photovoltaic (PV)-driven standalone district cooling system incorporating multiple energy storage technologies: batteries, ice storage, and hydrogen storage. We conduct a comprehensive techno-economic analysis to optimize system configuration and operation, with particular emphasis on the impact of the optimization horizon. The levelized cost of energy (LCOE) serves as the objective function, while component sizing and operational parameters are co-optimized using a mixed-integer linear programming (MILP) framework.

2 System description

Fig.1 presents the schematic diagram of the proposed renewable-driven standalone district cooling system. The system incorporates two types of chillers: conventional water-cooled chillers and dual-mode water-cooled chillers. While conventional chillers operate solely in chilled water production mode, the dual-mode chillers offer enhanced flexibility by functioning in both chilled water production and ice-making modes. This dual functionality is enabled through the use of glycol as the working medium.

The system's cold energy management operates through two key pathways: (1) glycol's cold energy can be transferred to chilled water via an intermediate heat exchanger, or (2) directed to an ice tank for thermal energy storage. Meanwhile, the ice tank can discharge its stored energy by transferring cold from ice to chilled water, again using glycol as the heat transfer medium through the intermediate heat exchanger. This configuration enables four distinct operating modes for the dual-mode chiller and ice storage combination: (1) Chilled water production mode, (2) Ice storage charging mode, (3) Ice storage discharging mode, (4) Combined ice discharging and chilled water production mode. Mode switching is achieved through automated valve control, ensuring operational flexibility.

The entire chiller system is driven by a PV farm, representing a complete transition from conventional fossil fuel-driven cooling. However, to address the inherent intermittency of solar energy, the primary challenge in renewable energy adoption, the system integrates multiple energy storage solutions. Specifically: (1) Battery storage and ice storage are employed to mitigate short to medium-term energy fluctuations, (2) Hydrogen storage is incorporated to address long-term energy variability. This multi-storage approach ensures reliable system operation across different timescales while maximizing renewable energy utilization.

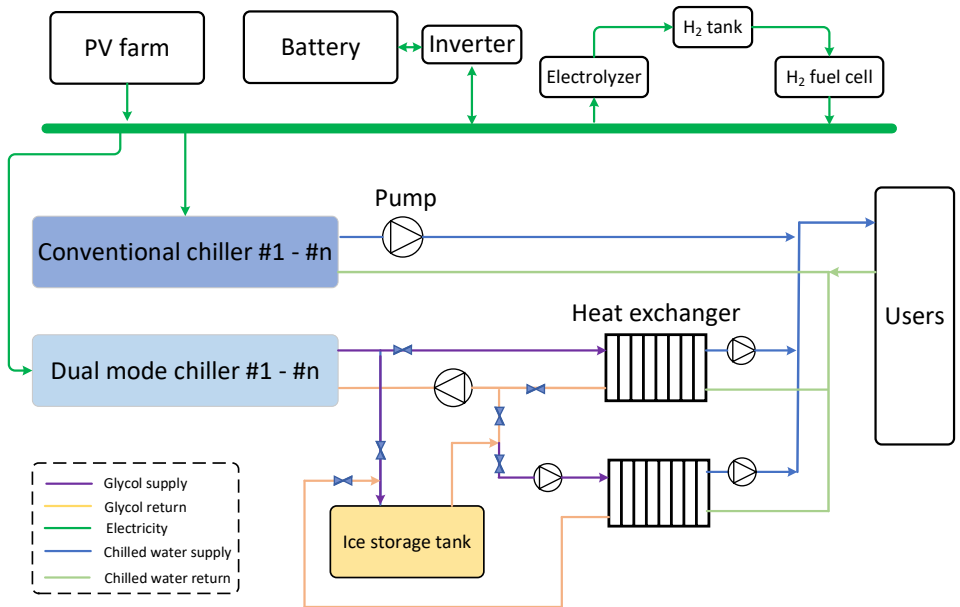


Fig.1. Schematic diagram of the PV-driven standalone district cooling system.

3 Results and discussion

In this study, the levelized cost of energy (LCOE) is defined as

$$LCOE = [CapEx + \sum_{y=0}^Y \frac{OpEx}{(1+r)^y}] / \sum_{y=0}^Y \frac{Q_{c,y}}{(1+r)^y} \quad (1)$$

In addition, annual greenhouse gas emission is written as

$$GHG = \sigma_{pv} P_{pv} + \sigma_{bat} E_{bat,char} + \sigma_{css} E_{css,char} + \sigma_{hss} E_{hss,char} + \sigma_{ec} CAP_{ec} \quad (2)$$

where *CapEx* is the capital investment, *OpEx* operation and maintenance cost, $Q_{c,y}$ is the cooling generation in year *y*, *Y* the project lifetime, *r* is the discount rate. σ_{pv} , σ_{bat} , σ_{css} , σ_{hss} , σ_{ec} are the carbon emission factor for PV, battery, ice storage, hydrogen storage and chiller. P_{pv} is the annual power generation from PV, $E_{bat,char}$, $E_{css,char}$, $E_{hss,char}$, are the annual energy storage for battery, ice and hydrogen, CAP_{ec} is the capacity of electric chillers.

Techno-economic performance across different optimization horizons is illustrated in Fig.2 (a)-(d). Fig.2 (a) demonstrates that component capacities exhibit a positive correlation with optimization horizon length, revealing that aggregated optimization horizons systematically underestimate required system capacities. Notably, hydrogen storage only becomes economically viable when the optimization horizon exceeds 90 days, highlighting its critical role in addressing long term solar variability. The full-year optimization scenario requires 31-46% larger battery and ice storage capacities compared to aggregated horizon approaches. This capacity expansion directly impacts system economics, with both capital investment and operation cost showing horizon-dependent growth, as shown in Fig.2 (b). While PV systems consistently dominate capital investments, hydrogen and ice storage investments are relatively small but are equivalent under full-year optimization, as shown in Fig.2(c). These capacity variations translate to a 31.6-45.8% higher LCOE for the full-year scenario, as shown in Fig.2(d), accompanied by a 20% - 31% increase in annual carbon emissions, from 290 to 380 equivalent tons/yr, due to missing long-term renewable energy fluctuation in shorter horizon optimizations.

The energy storage dynamics of the battery, ice tank, and hydrogen storage system are illustrated in Fig.3 (a)-(c). As shown in Fig.3 (a), the battery energy storage system exhibits pronounced diurnal cycling characteristics, with charging primarily occurring during peak solar irradiation periods (typically 12:00-16:00) followed by discharge after evening hours (about 20:00). This cyclical pattern manifests visually as alternating dark bands, indicating high state-of-charge (SOC) and light bands (low SOC), with complete discharge typically achieved by 08:00 the following day.

Fig.3 (b) demonstrates the ice storage system intermittent activation patterns, engaging primarily during periods of significant medium - term solar irradiance deficit. This selective operation stems from the relatively lower coefficient of performance (COP) associated with ice-making mode compared to direct chilled water production. However, during extended periods of solar energy, the combined ice output of battery and storage proves insufficient to meet cooling demand, necessitating hydrogen storage intervention Fig.3 (c).

This hierarchical response strategy reflects fundamental thermodynamic and economic considerations. While battery and ice storage systems offer superior round-trip efficiencies, their economic viability is limited to short to medium - duration applications due to inherent self-discharge characteristics. Conversely, hydrogen storage, despite its lower round-trip efficiency, provides critical long-term energy security through negligible self-discharge, making it indispensable for long-term energy balancing in renewable-powered district cooling systems.

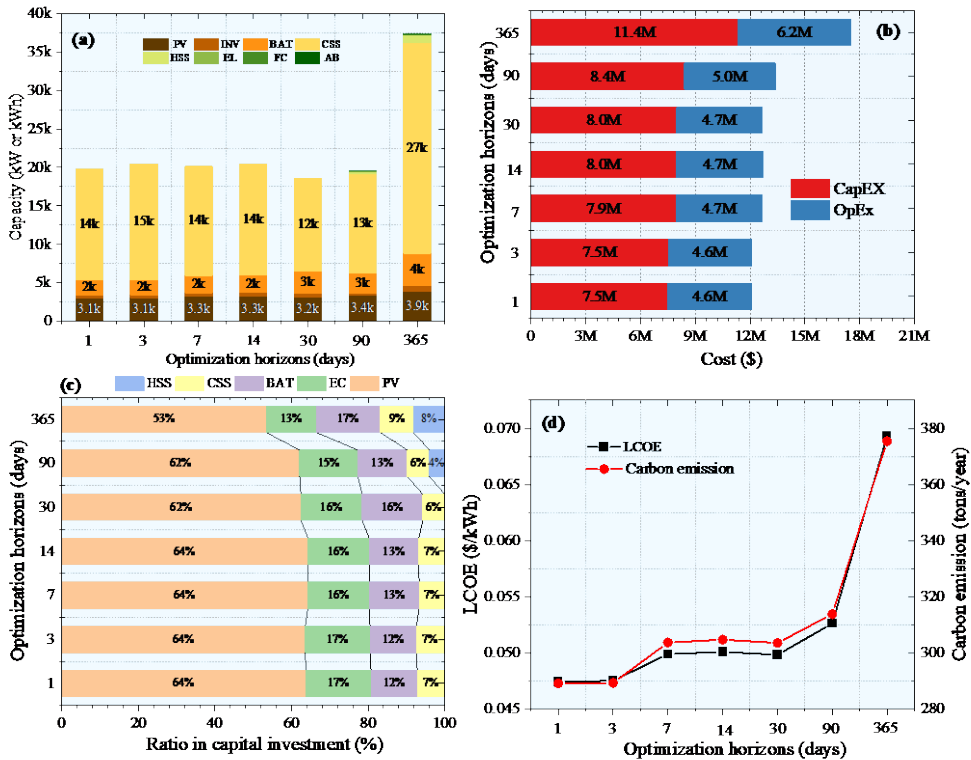


Fig.2. Techno-economic performance of the PV-driven standalone DCS considering various optimization horizons

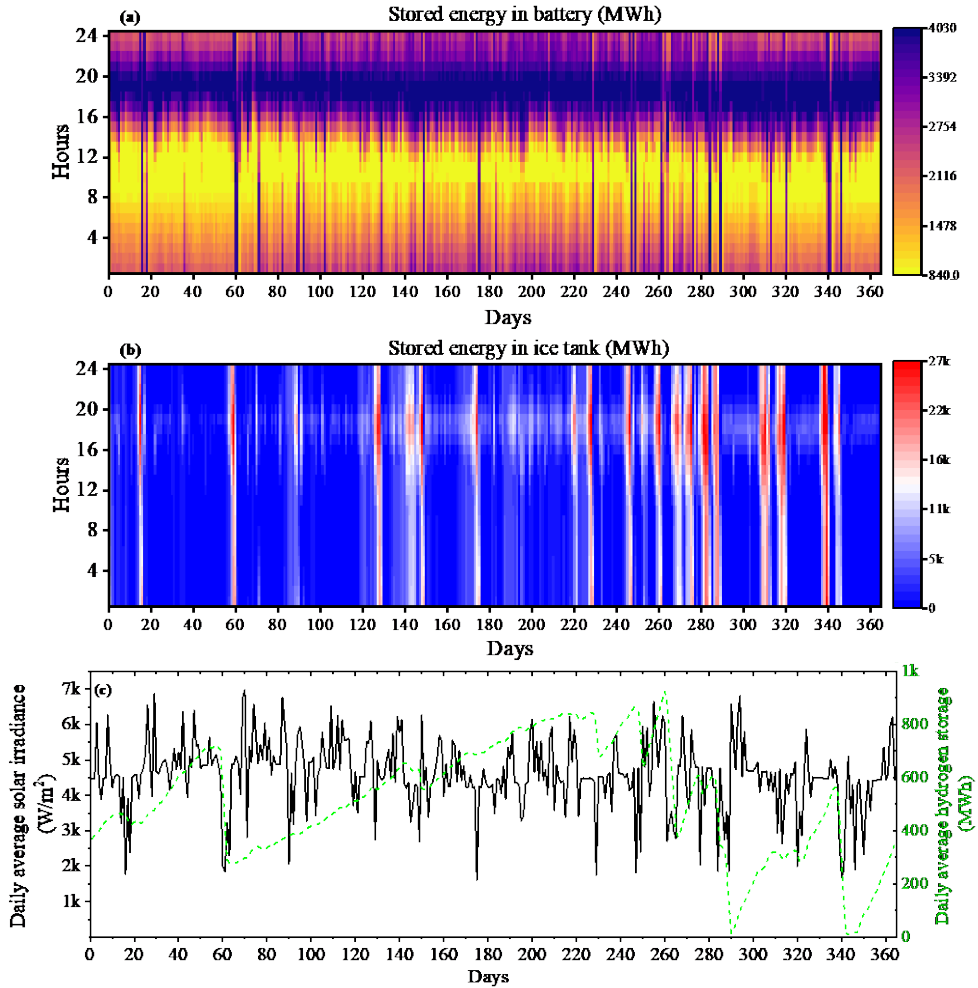


Fig.3. Variation of stored energy in battery, ice tank, and hydrogen tank.

4 Conclusion

This study systematically investigates the impact of optimization horizon on the techno-economic performance of a PV-driven standalone district cooling system incorporating hybrid energy storage (battery, ice, and hydrogen storage). The results demonstrate that aggregated optimization horizon significantly underestimate required component capacities and LCOE, with the full-year optimization horizon yielding 31.6-45.8% higher LCOE compared to aggregated optimization horizon. Hydrogen storage emerges as economically unviable for optimization periods below 90 days due to high capital costs but becomes essential for longer horizons to address long-term solar variability, despite its lower round-trip efficiency compared to battery and ice storage systems. While battery and ice storage combinations prove most economical for short-term energy balancing owing to their superior charge/discharge efficiencies, their effectiveness diminishes for long-duration storage due to inherent self-discharge characteristics. The findings underscore that full-year optimization necessitates 31.6-45.8% larger storage capacities to maintain system reliability across

yearlong variations, highlighting the critical trade-off between computational simplicity and design accuracy in renewable energy system optimization.

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