Applied Energy 216 (2018) 348–357

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Techno-economic feasibility of integrating energy storage systems in refrigerated warehouses

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HIGHLIGHTS

- Integrating energy storage systems can effectively shift the electricity consumption of refrigerated warehouses.
- The capacity of enery storage needs to be optimized to maximize the benefit.
- Integrating a cold energy storage system has a lower capital cost but a higher O&M cost than batteries.
- Batteries will be more attractive when the price is lower than 0.7 kRMB/kWh.

ARTICLE INFO

Keywords:
Refrigerated warehouses
Electricity consumption shifting
Cold energy storage
Battery
Dynamic simulation and optimization
Payback period

ABSTRACT

This work evaluates the techno-economic feasibility of integrating the cold energy storage system and the electrical energy storage system in a refrigerated warehouse for shifting the power consumption. A dynamic model has been developed in TRNSYS®. Based on the dynamic simulation, the performance and benefit of those two types of energy storage systems were compared. Results showed that, the integration of a cold energy storage can reduce the electricity consumption and operational cost by 4.3% and 20.5%, respectively. Even though integrating a battery system will increase the electricity consumption by 3.9%, it can reduce the operational cost by 18.7%. The capacity of the energy storage systems, the battery price and the peak electricity price had been identified as key parameters affecting the performance and benefit. To achieve a payback period less than 3 year, for the integration of a cold energy storage system, the peak electricity price should be increased by 25% from the current level, while for the integration of a battery system, the battery price should drop to 0.7 kRMB/kWh.

1. Introduction

According to the Postharvest Education Foundation, 40% of fruits and vegetables are lost from the harvest in developing countries, 23% of which can be attributed to the lack of cold storage [1]. With the improvement of the living standards, more and more refrigerated warehouses have been built, resulting in a fast increase of the electricity consumption for refrigeration, which accounts for approximately 16% of the electricity consumption of the food industry [2]. Refrigerated warehouses consume much more electricity in the daytime than in the evening as the ambient temperature is higher. To reduce the peak load and balance the grid load, dynamic electricity price schemes have been widely used, and high prices normally appear in the daytime [3,4]. If the electricity consumption can be shifted from the peak time to valley time, or from daytime to evening, the operational cost can be significantly reduced.

Therefore, energy storage systems, which can shift energy consumptions, have attracted more and more attentions [5–7]. For refrigerated warehouses, two types of energy storage systems can be applied: the cold energy storage system and the electrical energy storage system, which store the cold energy in thermal reservoir by using high sensible heat materials or phase change materials and electricity in batteries, respectively.

Cold energy storage systems have been widely used in the building sector. Rismanchi et al. [8] integrated a cold energy storage system using ice into office buildings and found the annual cost can be reduced

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https://doi.org/10.1016/j.apenergy.2018.01.079
Received 30 October 2017; Received in revised form 2 January 2018; Accepted 24 January 2018

Nomenclature

V	volume [m^3]
P	battery capacity [kWh]
m	mass flow [kg/h]
t	time [hour]
i	discount rate [%]
C	cost [kRMB]
E	electricity demand per hour [kWh]
DM	design margin
DOD	depth of discharge
N	year N
h	enthalpy [kJ/kg]

Greek symbols

ρ	density [kg/m^3]
η	battery efficiency [%]

Subscripts

Tank	tank
w	cooling water
out	outlet
in	inlet
air	air
Battery	battery
I/C	inverter/charger
capital	capital cost
O&M	operation and maintenance

Acronyms

LCC	Life cycle cost [kRMB]
PBP	Payback period [Year]
NPV	Net present value [kRMB]
CF	Cash flow [kRMB]
ROI	Return on investment [%]

up to 35%. Boonnasa et al. [9] evaluated a cold energy storage system using chilled water for a university building. The application of the storage system can move 35.7% of the energy consumption from the peak to the off peak periods. Zhou et al. [10] conducted a case study about integrating a cold energy storage system using chilled water in a refrigerated warehouse located in Hunan, China. The results showed that the energy consumption and cost can be reduced by 19.2% and 26.6%, respectively. Chen et al. [11] used ammonia/lithium nitrate as working fluid for a cold energy storage system integrated in a refrigeration system and found the energy consumption was reduced by 10.65% compared to the refrigeration system without cold energy storage, and the dynamic payback period was shorten from 1 to 0.72 year. The application of an ice-on-coil storage system in an office building was simulated by Chaichana et al. [12]. Based on Thailand's electricity tariff, the monthly operational cost can be saved by up to 55% and the total energy consumption can be reduced by around 5%. Habeebullah [13] assessed the economic feasibility of thermal cold energy storage system using ice in Saudi Arabia, advising that the operating cost can be saved up to 363 $/day. Integrating a cold energy storage using ice slurry in a typical library building was conducted by Yau and Lee [14]. The overall cost can be reduced by 24% based on the electricity tariff of Malaysia; however, the total energy consumption was increased by 20%. By using an optimal strategy based on the ice-based energy storage system, Luo et al. [6] found the operational cost can be saved up to 11.3% per day and 9.3% per month. By using the ice thermal energy storage system in a commercial buildings, Wu et al. [15,16] found that the annual operation cost can be reduced by 37%.

With the development of battery technologies, electrical energy storage systems have been widely applied [17]. Particularly, when a lot of second life batteries become available as a result of the rapid development of electrical vehicles, the capital cost of electricity energy storage are decreasing quickly [18,19]. A prediction of the lithium-ion battery price had been made, implying that the price would decrease from 1.70 kRMB/kWh to 0.7 kRMB/kWh, from 2015 to 2025 [20]. Leadbetter et al. used batteries to shave the peak residential electricity demand [21]. Results showed that a reduction of 42–49% can be achieved in general. Oudalov et al. [22] presented a method to optimize the capacity of battery for peak load shaving based on customer load profiles. After optimization, the annual electricity bill was reduced by 4%. Shi et al. [23] proposed a joint optimization framework for the battery storage system used for peak shaving, which can reduce up to 12% of the customers' electricity bill.

There are also some studies comparing the feasibility of thermal and electrical energy storage systems, most of which focus on the integration with intermittent renewable energy, such as solar and wind power in order to improve the penetration. For example, Comodi et al. studied the multi-apartment residential micro-grid with electrical and thermal storage devices. A photovoltaic (PV) plant, a solar thermal plant, and a geothermal heat pump were used to provide the heat demand. Results showed that the thermal energy storage system was more profitable, while the batteries were still less competitive in the residential market [24]. Thygesen et al. [25] analyzed a solar assisted heat pump system with thermal and electrical energy storage systems for high levels of PV electricity self-consumption. Results showed that the battery system had a levelized cost two times higher than the thermal energy storage system. Comodi et al. [26] compared different energy storage systems for cooling demand management in tropical climates, including sensible heat thermal energy storage, phase change material thermal energy storage, compressed air storage, liquid air storage and Li-Ion battery. Results showed that the thermal energy storage system was the best solution for small and medium-scale applications due to the low capital cost and short payback time. Though the high capital cost and long payback time, the electrical energy storage has the advantages in terms of efficiency, flexibility and safety. However, the cooling demand and the production of cooling were not simulated in details and the energy storage systems were not optimized. In addition, Bianchi et al. [27] compared the feasibility of thermal and electrical energy storage systems at the side of energy production, through the integration with a combined heat and power (CHP) plant. Based on the various production cost of at different loads, the capacity of energy storage systems were optimized. In order to be feasible for the adoption of battery, the cost of electrical energy storage system should be below 200€/kWh.

The literature review shows that using energy storage to shift the load is highly feasible and promising. However, there is not a systematical comparison about the cold and electrical energy system for the application of power shifting in the cooling applications. Meanwhile, when a cold energy storage system is employed, the system optimization should not only be done regarding the capacity of the energy storage system. In addition, the capacity of the cooling or the refrigeration system should also be considered in order to store more cold energy. Nevertheless, this has been rarely considered in previous studies. This work is to conduct a techno-economic comparison about the cold and electrical energy storage systems for power shifting. The details of the dynamic variation of both demand and cooling production have been considered. By doing sensitivity analyses, the key parameters affecting the system performance have been identified and optimization was also conducted to minimize the payback period. This work intends