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Latent heat thermal energy storage for sport facilities with photovoltaic overproduction

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ABSTRACT

With increased renewable energy sources such as photovoltaics and an increased need for decarbonization, investing in energy storage methods will be vital. In this paper, a thermal energy storage for sport facilities with photovoltaic overproduction was examined to investigate the economic and heat decarbonization potential. A MATLAB model for a latent heat thermal energy storage was created with hourly input data of heat demand, electric demand, and PV production. The storage uses a phase change material for converting electricity to heat from overproduction of PV and from an auxiliary heater connected to the grid to cover a heat demand. The system became most profitable with 100% auxiliary compensation from the electric grid, due to utilization of grid electricity during the colder months which has more costly heat prices. With an optimal storage size of 510 kWh, it was able to utilize 82% of the annual PV overproduction, reduce the heat demand by up to 12%, mitigate 304 tons worth of CO2 emissions, and generate a profit of 23 200 EUR. With these results, LHTES has the potential to be a feasible option for energy storage with the rise of variable renewable energy sources.

Keywords: Latent heat thermal energy storage, phase change material, Thermal energy storage, Latent Heat, High-Temperature PCM

NONMENCLATURE

Abbreviations	
Al-Si	Aluminum Silicon
LCOE	Levelized Cost Of Energy
LHTES	Latent Heat Thermal Energy Storage
NPV	Net Present Value
PV	Photovoltaics
PCM	Phase Change Material
TES	Thermal Energy Storage
VRE	Variable Renewable Energy
Symbols	
C_p	Specific heat of the PCM (kJ/kg °C)
L_{PCM}	Latent heat of fusion of PCM (kJ/kg)
m_{PCM}	Mass of the PCM (kg)
$Q_{storage}$	Energy in storage unit (kWh)
T	Temperature (°C)

1. INTRODUCTION

To fulfil the Paris agreement of limiting global warming below 2°C, one of the changes the world must face is to transition from fossil energy sources to renewable ones. As of 2018, about 10% of the world's power was generated from variable renewable energy (VRE) sources, primarily solar and wind, and this share is predicted to grow to 35% by 2030 and to 60% by 2050 [1]. The problem with VRE is the large mismatch that can occur between the energy supply and the demand on the consumers side. To tackle this issue, thermal energy storage (TES) can be utilized to store the surplus energy from VRE and have it used later during high demand hours. TES is utilized for heating applications in the building sector, district heating sector, and industry sector, with sensible heating of water tanks currently being the dominant technology for these sectors [1] [2]. This paper aims to investigate the potential of a short-term high-temperature latent heat thermal energy storage (LHTES) by analyzing how it would affect four sport facilities with PV overproduction in Rocklunda (Västerås, Sweden) by creating a MATLAB model of the system and cover the facilities heat demand.

Sensible heat is the heat exchanged by a system which changes the temperature of a storage medium but doesn't change its phase, and on the other hand, latent

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heat is the heat occurring due to the phase change of a material [3]. Materials which are specifically used for latent heating is usually known as phase change materials, or PCM for short. Compared to sensible heating, latent energy storage has higher energy density and operates more isothermally [3]. When selecting a PCM, the most important characteristics to consider are the phase change temperature range, latent heat of fusion, and thermal conductivity [1] [4]. There are also other important characteristics to consider such as market availability, thermal cycling stability, corrosiveness, toxicity, flammability and ease of handling [5].

To summarize the state of art with LHTES, it can be said that the technology has been demonstrated [6] [7] and is nearing commercial use and implementation [1]. A lot of the focus is on the PCM themselves and increasing their heat transfer through encapsulation, heat pipes, metal foams, extended surfaces or other complex geometries [8] [4]. There is not a lot on case study investigations involving direct conversion of PV or wind power to heat with a LHTES. There are though experiments and demonstrations with LHTES systems to support space heating and hot water supply to buildings [6] [7]. Most studies about LHTES are focused on modelling the internal workings of the temperature change and phase change boundary of the PCM with methods such as Finite Difference Method and Volume Difference Method [9].

2. METHOD

In this paper, a case study of four facilities in Rocklunda area was conducted, the methodology involved data collection, analysing of the data, MATLAB modelling of the LHTES system, an economical investigation of its profitability, and calculations of saved CO2 emissions. From the authors knowledge, this is one of the first techno-economical case studies within the area of absorbing VRE with a LHTES and covering a heat demand as well as relying on grid electricity during times of low PV production.

2.1 Data & Analysis

For the four facilities at Rocklunda area, the heat use, electricity use, and PV production, on an hourly time resolution for the year 2020, as well as the monthly electric prices, were gathered. The data was treated as demand data for the MATLAB model and was analysed to observe a pattern of PV overproduction and heat demand. Data from the 1st of June to the 31st of August was analysed and an average PV overproduction and heat demand for each hour during the day. This was to determine suitable charging and discharging hours for the storage, as shown in Figure 1. From the average, it was determined to charge the storage between 03:00-16:00 in the presence of PV overproduction and discharging it between 17:00-23:00 where there is high heat demand.

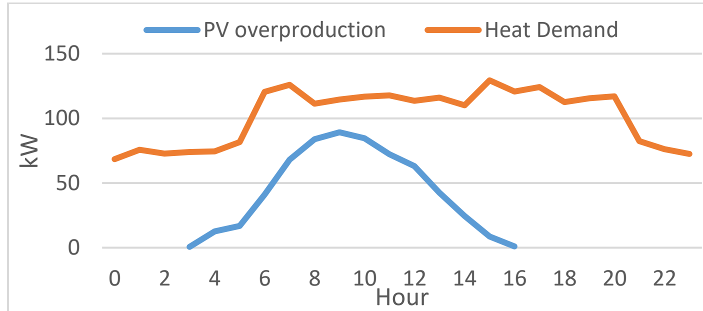

Fig. 1. Average PV overproduction and heat demand per hour for the summer

2.2 MATLAB Modelling Calculations & Optimization

The system is based on high-temperature heat storage with a PCM. The system schematic can be seen in figure 2, the facility's electric demand is supplied by its own PV production and electricity from the electrical grid. The heat demand is supplied via district heating and the LHTES. The storage is charged by PV overproduction, converting it to heat with an electric heater. During times of insufficient PV overproduction, auxiliary heat from the electricity grid is also provided at the last charging hour (16:00) of the storage. Five different levels of auxiliary heat compensation were investigated: 0, 25, 50, 75, and 100%. For a given compensation level, the storage would be supplied with auxiliary heat if the remaining energy required to fully charge the storage would be equal to or less than the listed level relative to the maximum storage capacity. For instance, 25% compensation level will supply heat if the storage is missing 25% or less of its maximum energy capacity.

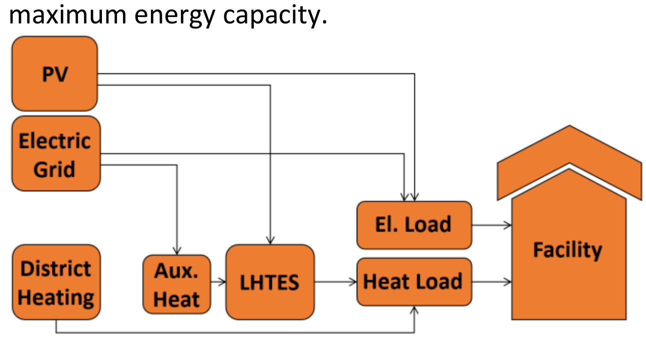

Fig. 2. Schematic of High temperature system

The model is based upon hourly energy balances of charging, discharging and stored energy of the LHTES.

Figure 3 shows a flow-chart map of how the MATLAB model operates. It begins by comparing the electric demand and the production from the PV. If the PV production is greater than the demand, the LHTES is not fully charged, and the time is within the charging hours, the excess electricity is converted into heat and stored. If the time is the last charging hour (16:00) and the excess PV meets the set auxiliary compensation level, it also converts and stores the energy. If the auxiliary compensation level is not met during this hour, the auxiliary unit will use grid electricity to cover the missing difference to fully charge the storage. For all different paths, the hourly energy demand can be affected, and those changes are recorded and then compared with the energy demand without storage. The difference between with and without storage result in the saved heat, which is combined with an energy price model to yield the saved profit.

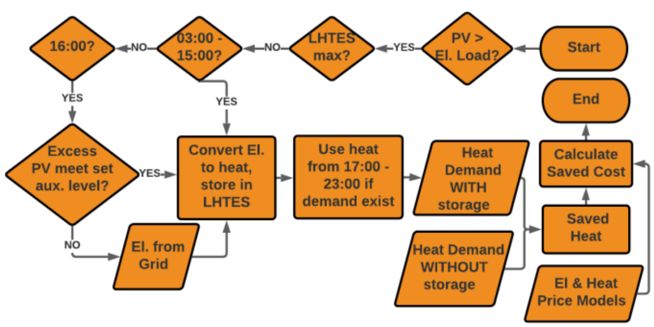

Fig. 3. Flow-Chart of the model

2.3 Further model assumptions & simplifications

Firstly, the lifetime of the system was assumed to be 30 years in the MATLAB model. The energy usage and PV production of the year 2020 for the four facilities is assumed to be the future demand and PV production for every year in the simulation. There is no account for geometry of the storage container, thus the charge and discharge rate are not determined from geometry, but instead a set charge of 3 hours and discharge time of 4 hours [10]. There is no sensible heating of the PCM after melting in the liquid phase, efficiency losses are neglected, and a constant specific heat is assumed. It is also assumed that the LHTES can be completely discharged, and at midnight the residue heat in the storage is set to zero to prevent it from being stored to the next day. Lastly, for simplicity's sake, rather than having a storage unit at each facility which operates based on its own hourly energy data, the model used a single storage unit based on the hourly energy data for all facilities combined.

Table 1 shows characteristics of aluminum silicon (Al-Si) which was the PCM used for the model. Al-Si has many advantages such as high latent heat, high thermal conductivity, suitable phase change for high temperature TES applications, and being cost effective [11] it is also one of the most studied high temperature PCMs [12].

Table 1 List of Al-Si PCMs properties; melting temperature, latent heat of fusion and specific heat [12]

Melting Temperature T_{Melt}	552 °C
Latent heat L_{PCM}	515 kJ/kg
Specific heat C_p	1.49 kJ/kg °C

The main equation for the model is used to determine the maximum energy storage capacity in kWh and how much heat it takes to completely melt the PCM. The model assumes there is no sensible overheating in the liquid state so that the storage is determined to be full when the sensible heat for the solid phase and the latent heat are reached.

$$Q_{storage} = m_{PCM} * C_p * (T_{Melt} - T_{Amb}) + m_{PCM} * L_{PCM}$$

Where m_{PCM} is the mass of the PCM, C_p is the specific heat of the PCM, T_{Melt} the temperature at which the PCM melts, T_{Amb} the ambient temperature assumed to be 20 °C and L_{PCM} the latent heat of energy.

The hourly savings with the LHTES were calculated using a district heating price model from Mälarenergi and electric prices based on Rocklunda's monthly electric prices. The investment and operational costs were based of the literature study by Chiu et al (2009) [13]. The economic success was measured in NPV, payback period and LCOE. From the main equation an iteration of the PCM mass to find the highest NPV was done while keeping everything else in the equation constant for the different auxiliary compensation levels. The generated CO2 emissions were calculated using a ratio for CO2 emissions per kWh from the district heating system.

3 RESULTS & DISCUSSION

The NPV throughout the implemented system's lifetime, based on optimal storage size and the level of the auxiliary compensation, can be seen in figure 4. For each auxiliary compensation level, the optimal storage was 510 kWh, with the exception for 50% compensation where it was 470 kWh.

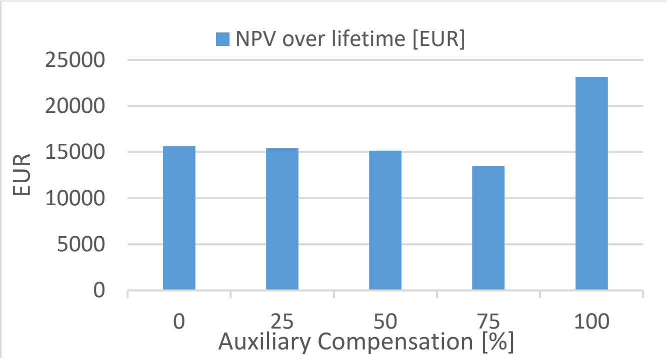

Fig. 4. The NPV of the system based on the auxiliary compensation level and optimal storage size of 510 kWh (470 kWh for 50% compensation)

The result showed that the NPV decreased with an increase in auxiliary compensation with the exception for 100% compensation where the system became most profitable. This was due to that the system, mostly during colder periods where there was little to no PV generation, could only charge itself if the compensation level was 100% since it would then charge the storage even if it had no energy stored. In this case, since the heat was more costly than electricity during the colder periods, the electricity which was purchased and converted from the grid to the storage during those periods yielded saved costs in the form of heat. The decrease in NPV for the other compensation levels was due to the storage charging unnecessarily during sunnier periods where the storage was partly charged due to the PV generation.

Figure 5 shows the NPV, used Auxiliary energy, and the utilized portion of the PV overproduction, based on storage size with 100% auxiliary compensation level.

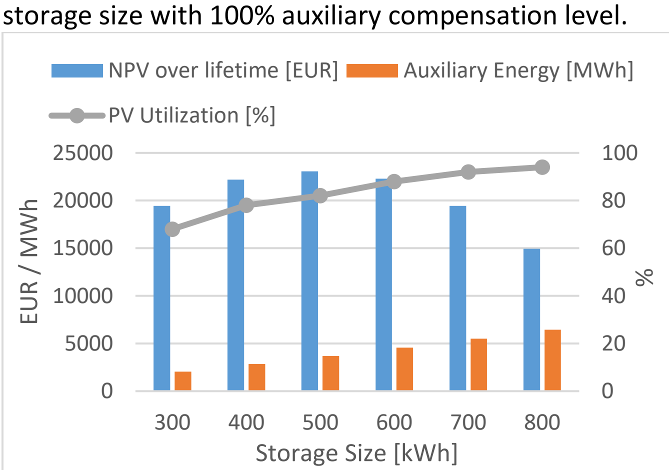

Fig. 5. The NPV, PV utilization, and auxiliary energy usage throughout the lifetime of the system based on storage size for 100% auxiliary compensation level

It is reassuring that the PV utilization was around 80% at the optimal storage size.

The final part of the results, summarized in table 2, show the saved heat, LCOE, payback period, and mitigated CO2 emissions of the system, based on the optimal compensation level and storage size.

Table 2 Saved heat, payback period, LCOE, and CO2 mitigation, based on 100% auxiliary compensation level for optimal storage size of 510 kWh

100% Auxiliary Compensation, 510 kWh Storage Size	
Saved Heat [MWh]	4 990 (or 1 360*)
Saved Heat/Demand [%]	11,6 (or 3,5*)
Payback Period [Years]	5
LCOE [EUR/kWh]	0,02
CO2 saved [Ton]	304

* = result for 0% auxiliary compensation

From an economic standpoint, the LHTES system shows promise since its attained LCOE is lower compared to certain VRE technologies. For offshore wind power, onshore wind power, solar PV, and thermal solar, the LCOE respectively ranges between 0,003-0,18 EUR/kWh, 0,06-0,24 EUR/kWh, 0,05-0,3 EUR/kWh, and 0,15-0,43 EUR/kWh [14]. Considering that solar PV will likely have the largest growth of renewable electricity production within the coming years, investing in LHTES to utilize its potential overproduction could prove beneficial.

4 CONCLUSIONS

LHTES has the potential to be a feasible option for energy storage in the future as VRE systems become more prominent and the need to decarbonize the energy sector will further increase. This paper investigated the potential of a short-term latent heat thermal energy storage by developing a model for four sport facilities in Rocklunda. For the optimal case, the results showed that the storage would be able to save ~4 990 MWh worth of heat, utilize ~82% of the annual PV overproduction, reduce the heat demand by up to ~12%, mitigate ~304 tons worth of CO2 emissions, and generate a profit of ~23 200 EUR. Furthermore, based on the results, having complete auxiliary compensation and buying electricity from the grid during periods of higher heat prices generated the highest NPV.

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