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A model for triple generation of cooling, heating and electrical power with a seasonal pumped thermal energy storage

Scharrer D[1*], Eppinger B [2], Bazan P[1], Zigan L[2], Will S[2], German R[1]

1 Lab of Computer Networks and Communication Systems, Friedrich-Alexander University

Erlangen-Nürnberg (FAU), Martensstr 3, 91058 Erlangen, Germany (Corresponding Author)

2 Institute of Engineering Thermodynamics, Friedrich-Alexander University Erlangen-Nürnberg (FAU), Am Weichselgarten 8, 91058 Erlangen-Tennenlohe, Germany

ABSTRACT

In this work the possibility of a triple generation system for a seasonal pumped thermal energy storage (PTES) is investigated. Residential cooling via a heat pump (HP) is used to load a simple seasonal thermal storage during the summer season and unload it when the requirement of residential heating occurs. While unloading the high temperate, heat is used to power an Organic Rankine Cycle (ORC), whose low temperature condensation heat is then used to heat the building. Therefore, power and heat is stored in the summer and used during the winter. This combines the usage of increased renewable power generation during the summer, especially from photovoltaic and the reduction of fossil or power intensive heating requirements during the winter. Power to power efficiencies of up to 29.2 % with latent and 25.4 % with sensible storages were achieved.

Keywords: energy storage, residential heating, residential cooling, seasonal storage, pumped thermal energy storage, triple generation

NONMENCLATURE

Abbreviations

HP	Heat pump
PTES	Pumped thermal energy storage
ORC	Organic Rankine Cycle
SOC	State of Charge

1. INTRODUCTION

Pumped thermal energy storages are getting more and more attention in the current search for a solution to the demand of energy storage in grids with an increasing penetration of renewable energies [1–5]. Besides the main goal of storing electricity via heat, a combined effort to use the stored heat for residential heating is also often discussed [6,7]. The combined use of PTES for power generation and heating leads to a decrease in the power to power efficiency η_{P2P} due to the higher condensation temperatures during the discharging cycle [6].

A further common attempt in the application of thermal storage in the modern demand side management is the use of seasonal thermal storage units like pit thermal energy storages with water below 100 °C as simple and cheap storage medium [8–10]. These are often combined with a heat pump or direct solar thermal heating.

In this study, the feasibility of an over the year energy balance of a triple generation system with a seasonal thermal energy storage is modeled and simulated. For the model, a generic building with a total area of 12,600 m² over 7 floors was applied. During the operational hours in the summer, the required cooling load of the building determines the load of the heat pump, which cools the building and charges the seasonal storage. As soon as the outside temperature drops below 15 °C, the heating mode of the system is used to discharge the stored heat in the seasonal storage via an

Organic Rankine Cycle and use the condenser to heat the building. The system therefore reduces the heat output of the building during the summer, stores power and heat seasonal and reduces the required heating and power load during the winter.

2. THE HP-ORC STORAGE SYSTEM

The PTES with its different components and operation modes is displayed in Fig 1. Cooling during the hot season is achieved by the evaporation of the working fluid at 15 °C in the evaporator of the heat pump. By using power from photovoltaics or other renewables, the heat is upgraded in the heat pump by the compressor and then stored in the thermal energy storage. For this paper, several temperature levels are considered as well as latent and sensible storage behaviors are also taken into account. The storage temperatures are between 55 °C and 95 °C for the sensible hot water storage and between 65 °C and 95 °C for the latent storage systems. After charging the seasonal thermal energy storage with the heat pump, the cycle is reversed with an expander instead of the compressor and a feed pump instead of a throttle to switch to the heating and power generation mode. The ORC provides the required heating for the building with its condensation temperature of 35 °C. Therefore, the heating and cooling requirements of the building are mostly provided by this system with the additional benefit of seasonal electricity storage. Rather low power-to-power efficiencies of the storage system are compensated by the combined use of cooling, heating and power.

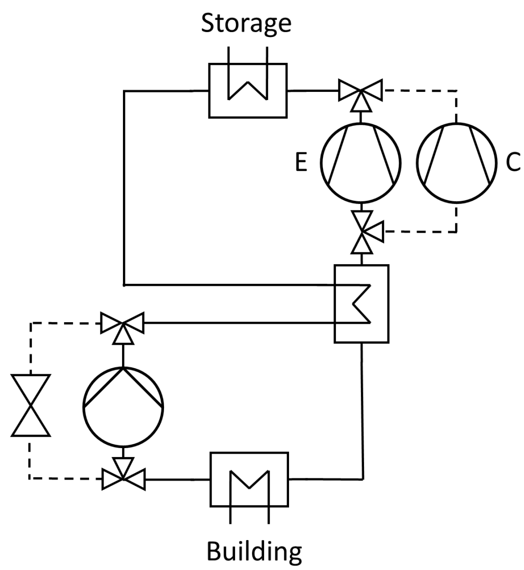

Fig 1. Flow chart of the PTES with heat pump mode as dotted lines and the compressor C, as well as the ORC in full lines with the expander E

3. THERMODYNAMIC LAYOUT

Earlier studies have already pointed out, that R1233zd(E) is an optimal candidate for a PTES in a low temperature range [3]. Together with the required temperature levels for cooling and heating, in this case the assumed 15 °C in the cooling mode and 35° C in the heating mode, the cycles are mostly dominated in their design by the storage temperature characteristic. The isentropic efficiency of the compressor and the expander is assumed as 80% for both working machines. The pinch point temperature in all heat exchangers is assumed with 5 K, this includes the air heat exchanger, the storage heat

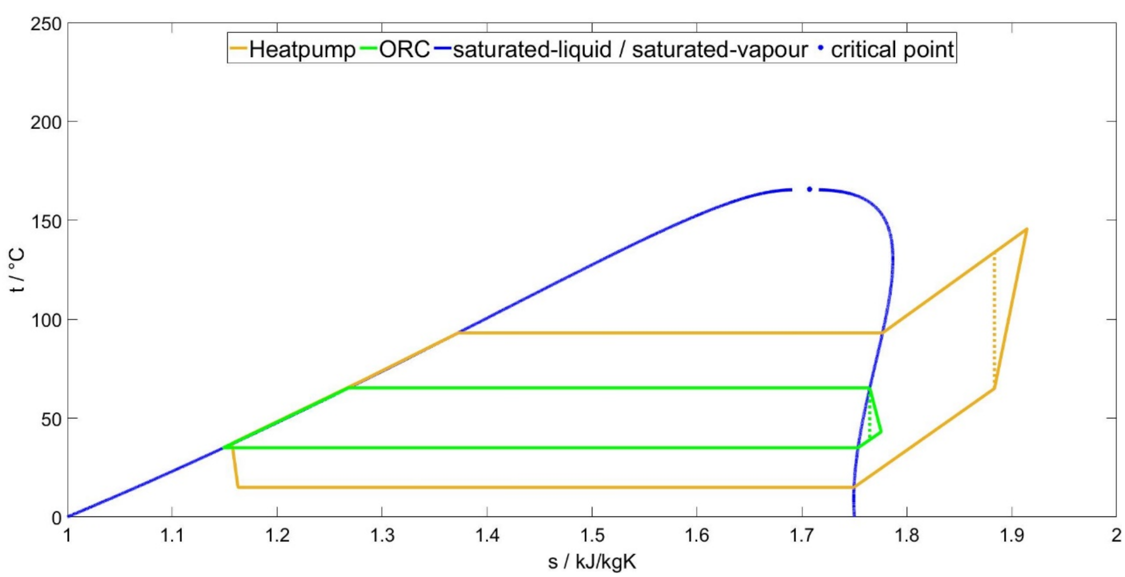

Fig 2. t-s-Diagram for R1233zd(E) with the heat pump and the Organic Rankine Cycle

exchanger and the internal heat exchanger. Both cycles are displayed in an example case in Fig 2. The small temperature difference in the ORC may cause problems in a realistic setup and might require more fine tuning in the engineering process than usual ORCs require. The heat pump on the other side has, for currently available technologies, a very high compression end temperature and might limit the selection of fitting parts. All heat exchangers can be used in both modes and reduce therefore the investment costs of the system. The oversizing of the internal heat exchanger for the ORC mode is considered with a reduced pinch point temperature of 3 K. In Fig 3 is an overview given of the achieved efficiencies and COPs for lower storage temperatures of the sensible storage between 55 °C and 75 °C. The upper storage temperature is always 95 °C to make simple unpressurized hot water storages a cheap option as a seasonal thermal storage.

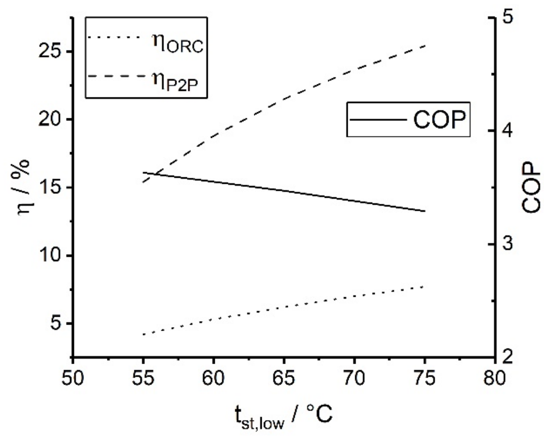

Fig 3. Efficiencies and COPs for various lower storage temperatures of a sensible storage with 95 °C upper storage temperature

In addition to the sensible storages, latent storages were also investigated as shown in Fig 4. This is a general approach to latent storages and only melting temperatures and no real storage medium was considered to achieve the comparative results. Nevertheless, there are some storage media which are suitable for this application like, Ba(OH)2·8H2O with 78 °C melting temperature, Mg(NO3)2·6H2O with 89.3 °C and (NH4)Al(SO4)2·12H2O with 95 °C as reviewed by Mohamed et al.[11]. For higher temperatures with a energy balance towards the energy input MgCl2·6H2O with 117 °C would be an option [11,12].

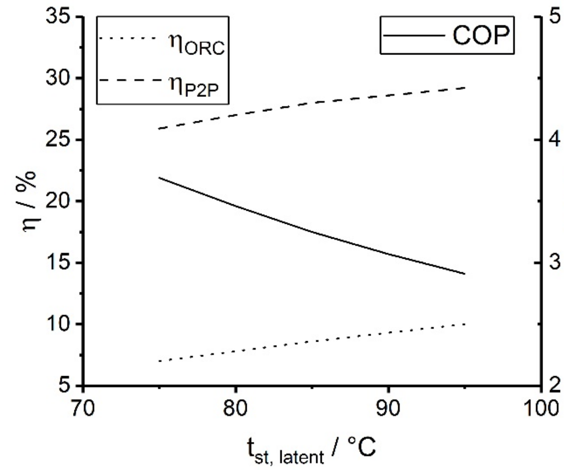

Fig 4. Efficiencies and COPs for various storage temperatures of a latent storage

4. HEATING AND COOLING OF AN OFFICE BUILDING

The use of cooling as well as heating with the storage system is most suitable for an office building, as the demand for heating as well as cooling energy can be predicted most easily due to the working hours. In order to determine the exact load, we take the outside temperature as a basis. The data used here is the temperature profile for the city of Nuremberg in southern Germany. If the outside temperature exceeds 25 °C, the building is cooled, if it falls below 15 °C, the building is heated.

The cooling power per square meter can be determined as 175 W/m². Furthermore, the average heating power is in a range between half or even a third of the cooling power, which is why the heating power is chosen as 75 W/m². To obtain results that are as representative as possible, a building with a floor area of 90 m x 20 m is considered. Furthermore, it is assumed that the office building has 7 floors, which means that 12,600m² must be heated or cooled. This results in a necessary heating power of 0.95 MW and cooling power of 2.2 MW. These maximum powers must be provided on the hottest or coolest day of the year. In order to take a certain part load behaviour into account, the outputs are scaled linearly between the threshold temperatures and maximum values of the outside temperature.

Three scenarios can be defined as time periods for the office building. The first time period is the so-called core working time between 9 am and 4 pm. At this time, most employees are usually in the office building. The time period 7 am to 7 pm corresponds to the time when people in general are in the office building to work. The last scenario is the time period between 12 pm and 2 pm to investigate the possibility of using the system for peak shaving. The resulting energy quantities for one year are shown in Fig 5. hp_{q_in} corresponds to the cooling energy provided, orc_{q_out} corresponds to the heating energy.

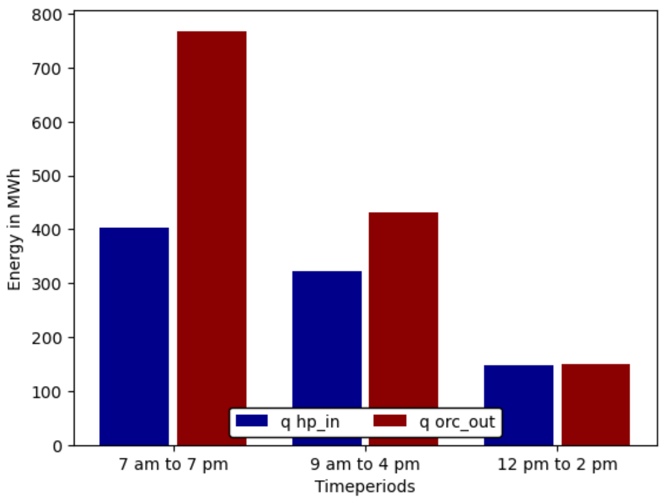

Fig 5. Cooling energy and heating energy for different working times

It is noticeable that the greatest difference between the amounts of energy is during the largest time period. The number of hours with an outside temperature above 25 °C throughout the year is usually only around noon, whereas in the morning and evening hours the temperature can fall below 15°C. If the time period is successively reduced, the two energy balances gradually converge.

5. RESULTS

For the sensible heat storage, only the lower storage temperature is varied between 55 °C and 75 °C, while the upper storage temperature is kept constant at 95 °C. In order for an application of the storage system to be considered positive, more heat must be loaded into the storage by the heat pump (q_{hp_out}) in the course of a year than is unloaded by the ORC (q_{orc_in}). A change in the temperature difference between the upper and lower storage temperature also results in a change in the efficiency of HP and ORC. Fig 6 shows the total energy quantities as a function of the lower storage temperature of the sensible heat storage for the time period 9 am – 4 pm.

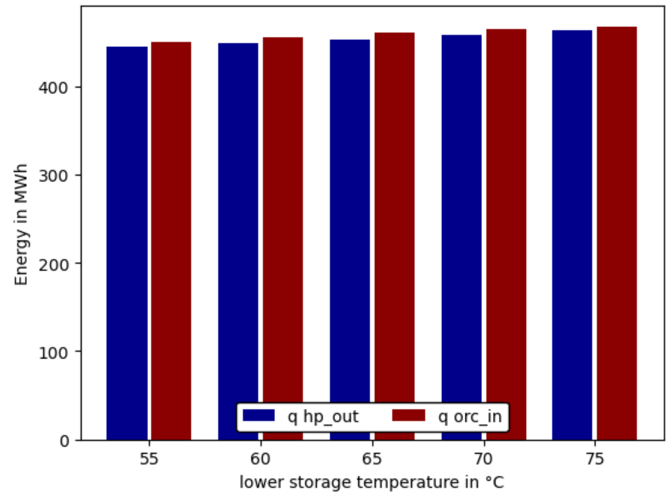

Fig 6. Heat input and output during a year for a sensible heat storage for the time period 9 am – 4 pm

Regardless of the lower storage temperature, both amounts of heat are very similar, but more heat is taken out of the storage than is put in. The average difference of approx. 4 MWh can be compensated in later operation by a more efficient management of the system.

In the case of a latent heat storage (Fig 7), larger differences can be seen across the storage temperatures. Only at temperatures above 90 °C, more heat is loaded into the storage than unloaded.

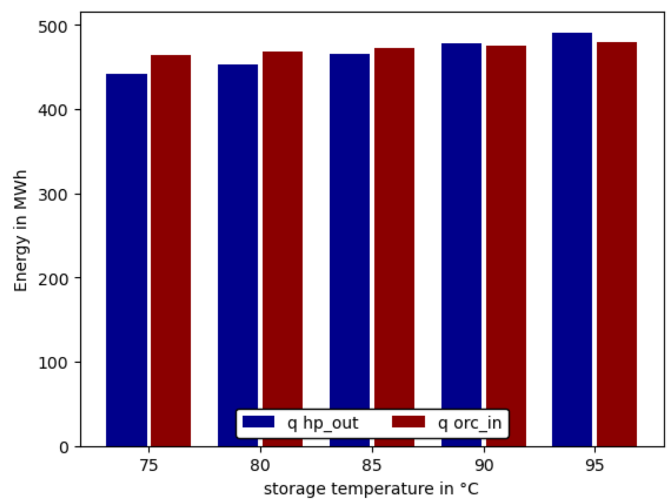

Fig 7. Heat input and output during a year for a latent heat storage for the time period 9 am - 4 pm

The ratio between q_{hp_out} and q_{orc_in} gives a first evaluation at different time periods. A value of 1 means that exactly as much heat is extracted as is added. If the value is less than 1, there is not enough heat in the storage. If the value is larger than 1, there is still heat in the storage left after one year, which has not been used. Table 1 and Table 2 give an overview of the different time periods and storage types. It can be seen that of the three scenarios considered, the time period 9 am – 4 pm would be the most suitable for an application.

Table 1. Ratio of input and output for a sensible heat storage for different timeperiods and storage temperature

		Time periods		
		7 am – 7 pm	9 am – 4 pm	12 pm – 2 pm
Temp. in °C	55	0.69	0.98	1.31
	60	0.69	0.98	1.31
	65	0.69	0.98	1.31
	70	0.69	0.99	1.31
	75	0.7	0.99	1.32

Table 2. Ratio of input and output for a latent heat storage for different timeperiods and storage temperature

		Time periods		
		7 am – 7 pm	9 am – 4 pm	12 pm – 2 pm
Temp. in °C	75	0.67	0.95	1.27
	80	0.68	0.97	1.29
	85	0.69	0.99	1.31
	90	0.71	1.00	1.34
	95	0.72	1.02	1.36

However, a purely balance approach is not sufficient for an evaluation of the system. In order to ensure that at no time the storage tank runs empty, an important factor is the state of charge (SOC) of the heat storage. In Fig 8, the SOC curve for the maximum temperatures of the latent as well as the sensible heat storage is shown. The system was chosen to start operation in mid-April, as from this time on the cooling demand exceeds the heating demand in our simulation. During summer, the stored energy triples in just a few days as seen between hours 2500 and 2700, whereas during fall, the SOC does not change drastically, as charging and discharging are balanced. In winter, the SOC decreases steadily as the system is constantly using the stored energy to power and heat the building. The latent heat storage contains energy at all times, which ensures a continuous operation of the entire system. After one year of operation, the SOC of the sensible storage becomes negative in the last few days.

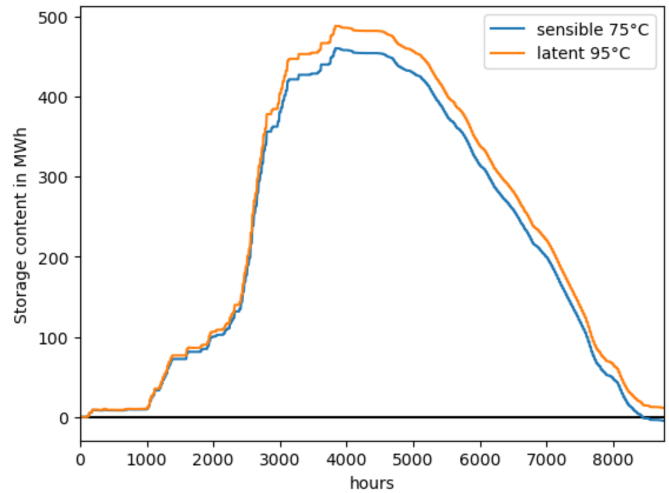

Fig 8. SOC for a latent and sensible heat storage for 1 year

In addition to providing heating energy, the ORC also produces electricity. Depending on the time periods and the type of storage, it is possible that more heat is extracted than is available. Therefore, the analysis of the potential for electricity production must be based only on the amount of energy actually available.

Table 3. Possible power output of the orc for a sensible heat storage for different time periods and storage temperature in MWh

		Time periods		
		7 am – 7 pm	9 am – 4 pm	12 pm – 2 pm
Temp. in °C	55	24.41	18.68	8.59
	60	29.80	23.78	10.93
	65	35.18	28.07	12.91
	70	40.15	32.04	14.73
	75	44.68	35.65	16.40

As the storage temperature rises, the temperature level of the ORC also increases, which improves the efficiency of the system and therefore produces more electricity. The difference between the time periods can again be attributed to the different number of hours. The longer the heat pump can run and charge the storage, the more heat is available for the ORC for electricity production.

Table 4. Possible power output of the orc for a latent heat storage for different timeperiods and storage temperature in MWh

		Time periods		
		7 am – 7 pm	9 am – 4 pm	12 pm – 2 pm
Temp. in °C	75	38.78	30.95	14.23
	80	44.31	35.36	16.26
	85	50.17	40.04	18.41
	90	55.71	44.46	20.45
	95	61.53	49.11	22.59

6. CONCLUSION

This paper demonstrates how a triple generation of cooling, heating and power is possible with a PTES. The application is best suited for office buildings, where the demand curves change little and can therefore be predicted well. Both sensible and latent heat storages can be used for this purpose, even if the latent heat storage shows better results. The core working time period from 9 am to 4 pm, which is typical for Germany, proves to be the optimal time window for the application. It can be cooled or even heated all year long with the system. A further advantage of the system is the support of the building's power consumption. Up to a quarter of the electricity used for cooling in summer can be recovered in the winter days.

All calculations were done for Nuremberg in Germany. The energy balance will significantly change depending on longitude and latitude, for example the cooling demand will surpass the heating demand in equatorial areas due to higher ambient temperatures.

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