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Dynamic simulation of an HP-ORC-Heat Storage pilot plant for an economic evaluation and necessary cost reduction

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ABSTRACT

A novel pumped thermal energy storage (PTES) system with a heat pump (HP) and an Organic Rankine Cycle (ORC) is built and investigated at the Energie Campus Nürnberg, Germany. The basic idea is that surplus electricity available during the day is converted into heat with the HP and stored in a sensible hot water thermal storage. This enables a shift of e.g. photovoltaic electricity from day to night, as the stored heat can be converted back into electricity with the ORC at night. In order to examine the economic efficiency of the system, a dynamic simulation was set up using the AnyLogic simulation software. For a small community of 40 houses, it was shown that under current german market conditions, no economic use is possible without a significant cost reduction of the PTES. However, taking into account current trends in the development of feed-in tariffs in Germany, an economic use will be possible within the next few years.

Keywords: energy storage, carnot battery, pumped thermal energy storage, dynamic simulation, economic evaluation

NOMENCLATURE

Abbreviations	
HP	Heat Pump
ORC	Organic Rankine Cycle
PTES	Pumped thermal energy storage
CAPEX	Capital expenditures
TOTEX	Total expenditures
PV	Photovoltaic

1. INTRODUCTION

For the German “Energiewende” to succeed, it is necessary that electricity from photovoltaics can also be used at night. This shift of surplus electricity from day to night can be managed with storage systems. In the search for suitable storage systems, PTES are receiving more and more attention as a possible solution for grids with increased feed-in from renewable energy sources [1]-[5]. They represent an alternative to battery systems as the scalability of thermal storage is easier and cheaper compared to batteries. Another advantage is the lower environmental impact, as [6] clearly shows that a sensible hot water storage is less toxic to the environment.

The “i7-AnyEnergy” software library developed at the Lab of Computer Science 7 contains important components for energy systems in the form of individual modules. This modular character allows the components to be flexibly assembled to models of complex energy systems, which reduces the development time of simulation models [7],[8]. A dynamic simulation of the PTES system with a HP, heat storage, and ORC was developed. This paper investigates the influence of the storage system in a small community of 40 houses with different photovoltaic (PV) plant sizes. The research focuses on how the total expenditures (TOTEX) of the system would have to develop in comparison to the pilot plant, in order for the system to become economical.

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2. THE HP-ORC STORAGE SYSTEM

As part of the "Speicher A" project, a PTES is built and researched on a laboratory scale at Energie Campus Nürnberg [9]. It essentially consists of a HP, a sensible heat storage and an ORC (see Figure 1).

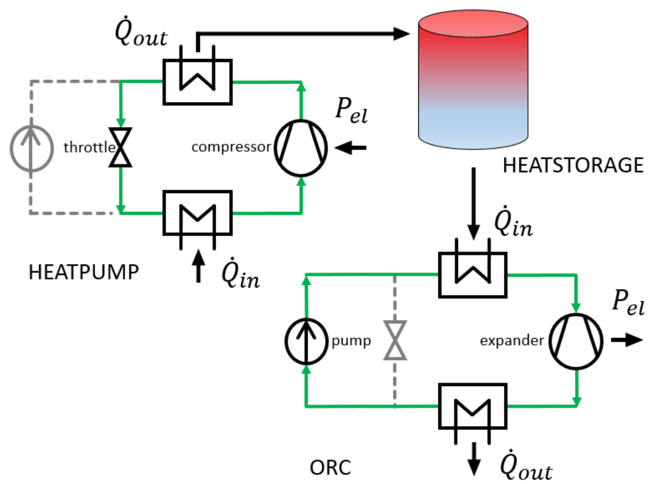

Figure 1: Overview of the PTES with a HP, sensible hot water storage and ORC

Instead of converting excess electricity directly into heat, the HP is used to exergetically upgrade existing waste heat at a lower temperature level. The heat is stored in a sensible hot water storage at a temperature of 120°C. The ORC is used to convert the heat back into electricity. As seen in Figure 1, the basic structures of the heat pump and ORC share many similarities. Therefore, components such as the heat exchangers can be used for charging and discharging the heat storage, thus reducing investment costs.

Based on the temperature level of the system, a coefficient of perfomance of 5 is obtained for the HP and an efficiency of 10% for the ORC, which corresponds to a power-to-power efficiency of 50% [10]. Furthermore, the knowledge and data gained from the pilot plant serves as input for the simulation.

3. SIMULATING THE SYSTEM

The dynamic simulation of the PTES is performed with the AnyLogic simulation software. Based on the i7-AnyEnergy library, a model was developed which represents the components of the PTES in detail. Since both HP and ORC share as many system components as possible, the ratio of maximum electrical input of the heat pump to maximum electrical output of the ORC is 3:1. For the simulation, the maximum electrical power of the HP is set to 20 kW and the ORC to 6.7 kW. For the HP and the ORC, a warm-up phase of 10 minutes is implemented if their start-up threshold of 50% of the maximum electrical power is exceeded. In addition, an almost linear course of the system efficiencies in partial load operation is also implemented.

The aim of the simulation is to show economic aspects of the PTES in small community. For this purpose, standard load profiles were included to represent the demand of a house. Depending on the scaling of the profiles, a different number of houses can be evaluated. For this study, a community size of 40 houses with an average of 3 persons per household was chosen. The last necessary aspect is the supply of excess electricity from PV. Using the weather data for global radiation of the Erlangen-Nuremberg region in Germany, the electricity production can be calculated depending on the PV size and a pessimistic system efficiency of 15%. The yield of the PV system is used to cover the electricity demand of the entire community, not just individual houses.

In order to show the influence of the amount of excess electricity on the economic efficiency of the PTES, the PV size was varied in the simulation. With the assumption that each house can have a maximum PV size of 50m², which corresponds to approx. 7kWp on its roof, the number of houses with PV is the varied parameter. "10 houses with PV on the roof" therefore corresponds to a PV size of 500m², which belongs to the entire community.

The scenarios considered are either 10, 20 or 30 houses in the community are equipped with PV plants on their roofs. A whole year is simulated, whereby the most important aspect of the control algorithm is the coverage of the own demand. The storage system can only be charged with PV electricity, once the demand of all houses has been covered by the PV plants. The storage is discharged when the PV plants are no longer able to cover the electricity demand and the state of charge of the heat storage is greater than zero.

For the economic evaluation, electricity costs, feed-in tariffs and the investment costs of the system are taken into account. An average household in Germany pays 30 ct/kWh for electricity. Owners of PV systems receive a feed-in tariff, if they feed their electricity into the grid. This feed-in tariff was 10 ct/kWh in 2019, but has been steadily reduced to just about 8 ct/kWh at the end of 2020.

4. RESULTS

The total savings achieved by the system (S_{PTES}) are calculated by subtracting the lost profit for not selling the PV electricity (C_{PV}) from the savings the community has, by discharging the PTES instead of paying for electricity from the grid (C_{GRID}). By varying the thermal capacity of the storage in 100 kWh steps, the potential savings for the community were analysed. The electrical power parameters for HP and ORC are constant for all simulations.

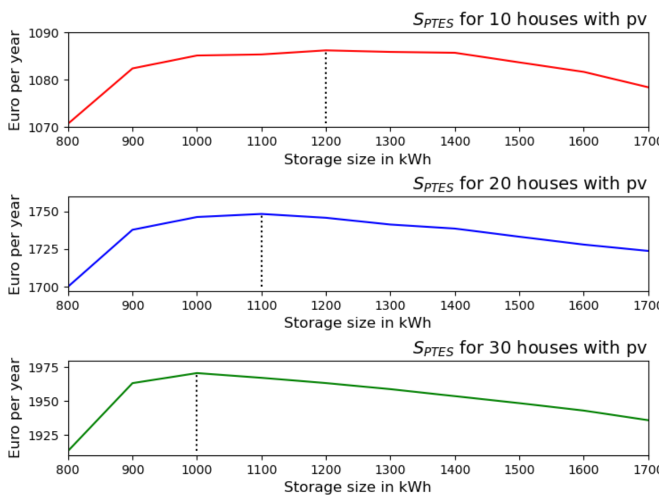

Figure 2: Possible savings per year with the PTES for different storage sizes and a fixed feed-in tariff of 10 ct/kWh

In Figure 2, S_{PTES} for the community is plotted for different storage sizes and different PV scenarios with a constant feed-in tariff of 10 ct/kWh. The general shape of the graphs show, that simply increasing the storage size further and further won't increase S_{PTES} for the community. For a positive slope of the graph, $\Delta C_{GRID} > \Delta C_{PV}$ between two storage sizes, whereas a negative slope is the result of $\Delta C_{GRID} < \Delta C_{PV}$. A reason for this reversal is the increasing loss of stored energy with increasing storage sizes. Less stored energy to satisfy the own demand reduces C_{GRID}, while C_{PV} increases as more energy can be stored.

As the maximum electrical input of the HP during all simulations is constant, more PV increases the full load hours of the HP. The simulations show, that especially during summer the HP is largely utilised to its full capacity and the storage is fully charged. Further increasing the PV size therefore yields more electricity to charge the storage during morning and evening operation. A fully charged heat storage has bigger thermal losses, which amplifies the negative effect of a bigger storage size on C_{GRID}.

Table 1: Best fitted storage sizes and resulting costs for the PTES

		Storage in kWh	CAPEX in €	TOTEX in €/a
Houses with PV	10	1200	115,623	6937
	20	1100	114,733	6884
	30	1000	113,759	6826

The investment costs (CAPEX) of the plant are based on the expenditures for the pilot plant. Table 1 shows the storage sizes responsible for the biggest S_{PTES} for the community and the resulting investment costs of the whole PTES, including the HP and ORC. Assuming that the system has a lifespan of 20 years and operating costs (OPEX) of 1% of the CAPEX per year, the total costs (TOTEX) per operating year can be determined.

The feed-in tariff is significantly more volatile compared to the electricity price, which makes it largely responsible for the savings achieved with the system. In Figure 3, S_{PTES} is shown for the three scenarios as a function of the feed-in tariff in.

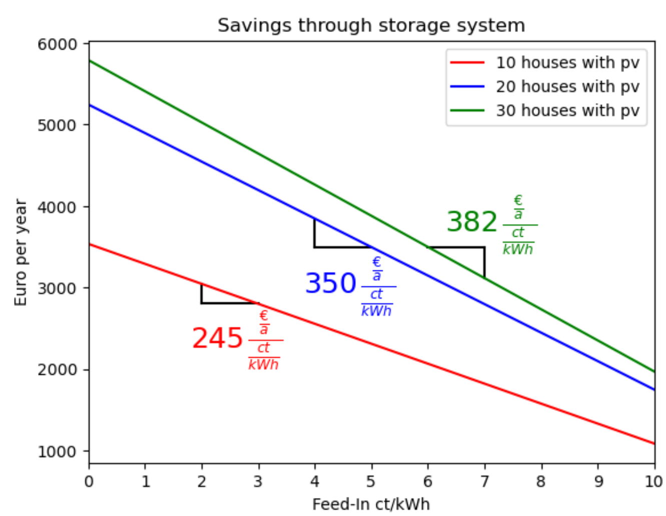

Figure 3: Possible savings for the community with different PV sizes

First of all, it can be seen that savings are a linear function. The slopes show the difference in savings per cent feed-in tariff. While a clear difference can still be seen between scenario "10" and "20", a further increase in the PV size has only a minor impact. The reason for this is the already mentioned utilisation of the system, with the heat pump as a limiting factor.

For the system to be economical, S_{PTES} must at least cover the TOTEX. A more detailed representation is given with Figure 4 for scenario "20".

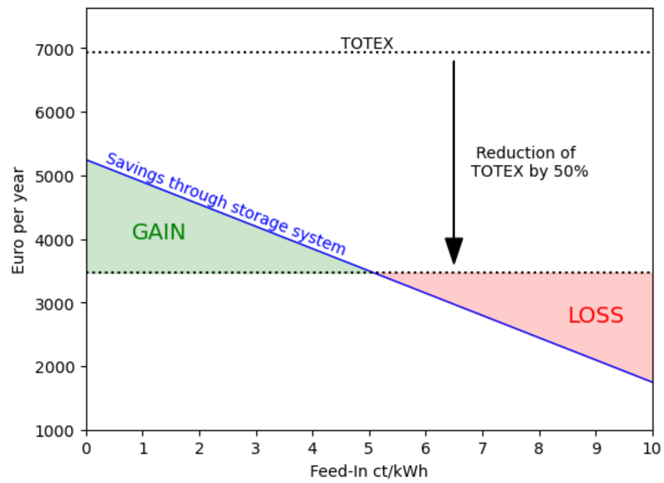

Figure 4: Influence of reducing the TOTEX on the economic evaluation of the PTES

The dotted line at just under 7000 €/a represents the TOTEX of the system. These costs have to be paid each year for the 20 years lifespan of the PTES. It can be clearly seen that even with a feed-in tariff of 0 ct/kWh (maximum savings) the TOTEX cannot be covered. The calculation of the TOTEX is entirely based on the pilot plant, which is, for example, equipped with considerably more sensors for research purposes than actually necessary. If such aspects are taken into account, a lower TOTEX results for a plant with market maturity. With an exemplary reduction of 50 %, it can be seen that already at a feed-in tariff of about 5 ct/kWh the annual costs are covered and the storage system becomes profitable.

Analogous to the linear course of the savings, a necessary reduction of the TOTEX can also be determined in % per cent feed-in tariff. The results are shown in Table 2 for selected feed-in tariffs as well as the slope of this linear function.

Table 2: Necessary reduction of the TOTEX in % for different feed-in tariffs

		8 ct/kWh	6 ct/kWh	4 ct/kWh	Slope (% / ct/kWh)
Houses with PV	10	-77.2	-70.2	-63.2	-3.5
	20	-64.5	-54.3	-44.1	-5.1
	30	-59.9	-48.7	-37.5	-5.6

Here, too, it can be seen that overdimensioning the PV plant does not bring any significant advantage. It will not be possible to reduce the costs by almost 80 %, therefore no economic use is achievable for the current market situation. However, if the current trend is taken into account, a feed-in tariff of 6 ct/kWh in the near future is not impossible, as is the necessary reduction of costs of ~ 50%, e.g. in scenario “20”.

5. CONCLUSION

The dynamic simulation of a PTES presented in this paper shows that although no economic scenario exists yet under current market conditions, possible applications can be found for the near future taking into account current market trends. The study is also limited to a fixed community size and fixed parameters for HP and ORC. An additional restriction is the chosen location. Since the focus is purely on electricity generation with PV, Southern Germany is not necessarily the first choice as a location for this system compared to countries such as Egypt, Australia or India. In a future work, a wide variation of community and plant sizes as well as different locations with different PV sizes will be simulated. In order to be able to make a more precise statement about the price development of the system, a detailed analysis of the costs is also planned.

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