EXPLORING THE FLEXIBILITY POTENTIAL OF RESIDENTIAL HEAT PUMPS COMBINED WITH THERMAL ENERGY STORAGE FOR SMART GRIDS

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ABSTRACT

In the coming years, an increased electrification in the residential sector is expected, leading to new challenges for the electricity grid. The Linear project aims at optimally integrating residential electrical applications to obtain a smart grid that can deal with a high share of renewable energy resources. This paper focuses on the flexibility potential of residential heat pumps (HPs) combined with thermal energy storage (TES). Firstly, the general context and the Linear project are introduced. Secondly, a definition of flexibility is proposed. Afterwards, a concept of a residential HP with flexible TES for space heating (SH) is discussed. The flexibility potential of this concept has been assessed, taking into account determining factors. An individual residential HP of 10 kW_{th} combined with a SH water storage tank of 400 litres could offer about 1 hour flexibility on a day with an average heat demand for a domestic dwelling with a total annual heat demand of 10,600 kWh.

INTRODUCTION

In the coming years, an increased electrification in a number of domains in the residential sector such as transport (introduction of electric vehicles, (plug in) hybrid vehicles, …) and building HVAC systems (HPs with high Coefficients of Performance) is expected. Major drivers for this trend are technology developments and an increasing interest in the (decentralized) production of electricity based on renewable energy sources in order to reduce CO_2 emissions. The latter leads to increasing shares of less predictable intermittent energy resources such as wind and solar energy in the power system. To guarantee grid stability, a so-called paradigm shift from “production following loads” to “loads following (intermittent) production” is needed, leading to the development of a smart(er) grid.

The upcoming decentralized production of electricity, together with increasing shares of (relatively) heavy consumers on distribution level (HPs, electric vehicles, …) could lead to an additional burden on the grid when they are connected in the traditional way (“fit-and-forget”). Given the abovementioned paradigm shift and the need for smart(er) grids, existing flexibility or the creation of additional flexibility in the power system could play a major role in the grids of the future.

This paper studies the possibilities and constraints of HPs in combination with TES at residential level (distribution network) from a flexibility perspective: how much flexibility can be expected from HPs combined with different capacities of TES? Although HPs are seen as a future “threat” for the distribution grid, they might offer interesting flexibility opportunities when combined with TES [1].

The research was conducted within the framework of the Linear project [2], a Flemish smart grid breakthrough project. One of the main objectives of this collaborative project is to design and assess different concepts for matching electricity supply and demand in an intelligent way while taking into account aspects such as the flexibility of users, local producers, communication, grid constraints, controlling strategies, etc. The focus is on the residential level and distribution network. From 2012 on, a large residential field test will be implemented, transposing the theoretical concepts into practice.

DEFINITION OF FLEXIBILITY

The flexibility of a HP in smart or intelligent grids can be seen in two different ways.

Delay of (a part of) the electricity consumption of the HP over a limited period, although there is a demand for SH and/or domestic hot water (DHW): the heat demand is higher than the (delayed) heat production of the HP. This situation takes place when electricity demand is higher than the production injected in a (local) grid.

Forced electricity consumption of the HP over a certain period although there is no or low demand for SH and/or DHW: the heat demand is lower than the forced heat production of the HP. This situation happens when electricity demand is lower than the production injected in a (local) grid.

In both cases, the use of TES can lead to flexibility, defined as the ability to shift the consumption of a certain amount of electrical power in time (number of hours or kWh). The flexibility of a HP depends on different parameters but the most important ones are the expected heat demand of the building (depending not only on the building characteristics but also on the behaviour of the inhabitants and the climate) and the stored energy in the storage system. During colder days, the flexibility in delay of the electricity consumption is normally lower compared to warmer days (for the same storage capacity) due to a relatively higher heat demand resulting in a faster consumption of the stored heat. On the other hand, during colder days the flexibility in forced electricity consumption is normally higher compared to warmer days for the same reason.

Finally, determining the flexibility depends on the time of the snapshot, while the amount of the available flexibility changes over time because it results from actions taken in the past (e.g. exploiting an amount of flexibility 1 hour before leads to less stored energy and thus flexibility at a given time) and predictions for the future energy demand.

THERMAL ENERGY STORAGE CONCEPTS

When considering concepts for HPs in combination with a TES, several aspects have to be taken into account.

First of all, the scope of the Linear project is the distribution network and more specifically residential or small commercial applications. From this perspective, it has been chosen to focus on individual residential HPs (at household level) with TES although HPs are also applied in commercial buildings, offices, multiple residences etc.

Secondly, in preparation of the Linear field test, the analysed concepts are implemented and tested in a laboratory environment to verify theoretical conclusions by experiences in practice. With an eye on the controllability of the different external parameters to be imposed on the HP with TES, and taking into account the existing test infrastructure at VITO premises, a water-water HP was chosen for the practical implementation. As there are other HP technologies (e.g. air/air, air/water, brine/water, ...) [3], this might result in differences regarding the available flexibility between different HP technologies (e.g. the influence of electrically defrosting the evaporator in the case of air/water HPs). These differences will be assessed later in the Linear project.

Thirdly, the chosen TES technology is a water storage tank because it is currently the most feasible option for TES from a technical and economic point of view. Water storage tanks are already frequently used in combination with HPs (although not in a smart grid context) and are the least expensive solution compared to other storage technologies, e.g. phase change materials (PCMs) [4]. It should be kept in mind that the designed concepts will be implemented in practice during the Linear field test.

Having determined the boundaries for the HP concept, still some conceptual choices have to be made. Although there are a lot of variations possible when coming down to the practical and detailed design of the concept, two basic core concepts can be distinguished: 1) A HP combined with a flexible TES on the DHW side and 2) a HP combined with a flexible TES on the SH side.

The first concept is graphically presented in Figure 1. In this concept, the HP delivers the heat for SH directly to the building while using the storage tank for DHW by keeping the water between a certain temperature bandwidth. An advantage is that only one storage tank is needed which is favorable for limiting thermal losses of the tank but also investment costs. Moreover, the flexibility is available throughout the whole year (also in summer). On the other hand, the total amount of flexibility is rather limited as only DHW is considered (heat demand for DHW is limited compared to SH in current dwellings). If in the future this storage tank would also be combined with thermal solar power, then the available flexibility will be even less.

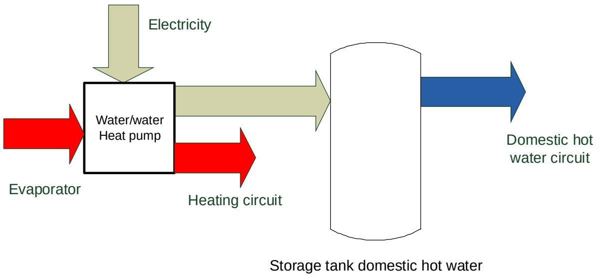

Figure 1: Schematic view of the HP concept with DHW storage tank

The second concept is graphically presented in Figure 2. In this concept two water storage tanks are used: one for DHW and one for SH. The main advantage of this concept compared to the previous one is the fact that a lot more flexibility can be offered because both storage tanks can be used for flexibility purposes and SH requires in general a lot more heat than DHW, although the ratio depends strongly on the building characteristics (the insulation level in particular). The main disadvantages are the higher investment costs in addition to the higher complexity when controlling both storage tanks in an intelligent way, and more energy losses due to an additional circulation pump and the use of two water storage tanks.

For the Linear project, the second concept was chosen with the higher amount of flexibility as the main reason. However, for the practical implementation in the laboratory and the field test, the focus in the first stage is on an intelligent control of the SH water storage tank, implying almost no flexibility during the summer.

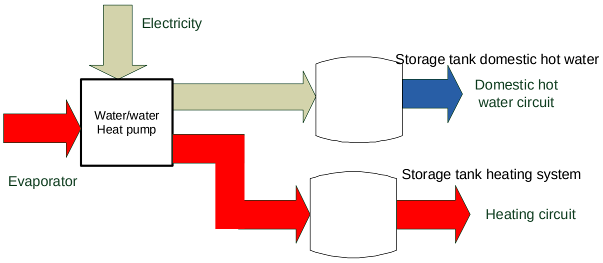

Figure 2: Schematic view of the HP concept with SH and DHW storage tanks.

OBJECTIVES AND ASSUMPTIONS

Assessing a HP concept with TES requires more than just a theoretical calculation of the available. When carrying out the analysis in detail, technical and practical issues arise, related to size and weight of the storage tank, scalability of the concept, stratification issues, temperature levels, Coefficient Of Performance (COP), definition of state of charge (SOC), control etc.

In this study the aim is getting a first view on the expected flexibility of different combinations of HPs with TES and determining the most relevant theoretical parameters. This analysis is conducted while keeping a number of technical and practical challenges in mind in order to obtain practically feasible solutions that will be further investigated in a laboratory environment.

Although the HP simulation model allows the flexibility assessment to be carried out on different scenarios by changing the input parameters, a reference scenario will be discussed in this paper for the sake of clarity and comparability. For this reference scenario, a day with an average heat demand (average hourly varying heat demand profile of a heating season) and the day with the highest heat demand of the heating season were selected to present the flexibility assessment results. The building for which the simulation results are presented, is a semi-detached building with a heated surface of 166 m². Following insulation levels were applied: 5 cm EPS in the walls, 5 cm PUR on the floor and 18 cm of mineral wool in the roof. The U-value for windows was determined at 2.83 W/m²K, and for the doors at 1.1 W/m²K. Night setback is applied. Temperature settings are 21°C during the day and 15°C during the night. These assumptions result in a total SH demand of 10,600 kWh/year. The HP in the reference scenario has a thermal output power of 10 kW.

This scenario shows a rather low annual heat demand compared to the average heat demand of a Flemish domestic dwelling (20.000-25.000 kWh). The latter is a consequence of the relatively old average housing stock (poor insulation) [5]. However, the target markets for HPs are mainly buildings with a low heat demand (well-insulated), preferably equipped with energy systems designed with low heat distribution systems such as floor heating systems or low temperature radiators to guarantee high efficiencies of the HP. In the future, it is expected that this average heat demand will come down due to the renovation of existing buildings and a higher proportion of new well-insulated buildings. An example of an electrical load profile of a HP without TES and without night setback but including day-night tariff for a typical day in March is shown in Figure 3.

FLEXIBILITY ASSESSMENT RESULTS

Different results of flexibility are obtained for the case of a delayed start up of the HP compared to the forced operation of the HP. Moreover, the most relevant parameters impacting the amount of available flexibility are the volume of the TES and the difference between the temperature levels of the in- and outlet of the water storage tank (ΔT).

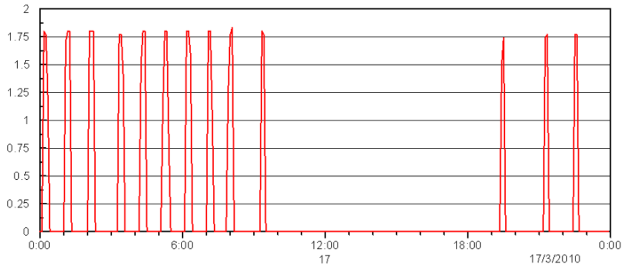

Figure 3: Electrical load profile of a HP without TES (kW)

Flexibility by delayed start up

When a certain heat demand is present and the HP is requested not to start up but to provide the heat by relying on the TES, flexibility is created by a delayed start up. In a smart grid context, this could happen in a situation in which only very few electricity is injected in the grid due to a limited amount of renewable energy sources such as wind or solar power.

In the simulation, the depletion time of the TES is calculated for an imposed heat demand profile when no heat is supplied to the TES and for different combinations of ΔT and volume of the water storage tank. This is the maximum time to delay the start up of the HP. The water storage tank is modelled to be fully stratified and heat losses are neglected (ideal buffer). The buffer is assumed to be full at the beginning of the day and the simulation time step is 1 hour. Although this simulation is rather rough and leaves out certain technical complexities (see section about objectives and assumptions), it gives sufficient insight in the expected flexibility.

Varying the volume of the TES (ΔT = constant)

Figure 4 shows the simulation results for a varying volume of the TES. Temperature difference between inlet and outlet temperature of the storage system is considered to be constant at 10 K. Flexibility is defined as the maximum number of hours between start of the heat demand and start-up of the HP. The TES tank is assumed to be fully charged at the beginning of the day (0 h). Figure 4 shows that with a storage tank volume of 1,000 l the flexibility is 1.25 hours on the worst day of the year (highest heat demand) and about 2 hours for an average day. Furthermore, a storage tank volume of 750 l can bridge a heat demand of 1 hour on the worst day of the year while about 350-400 l at an average heat demand should be sufficient. It should be recalled that this flexibility is the maximum: at the beginning of the day the storage tank is considered to be fully loaded. Finally, it should be kept in mind that the size and weight of the storage tank in residential buildings should not violate architectural limitations.

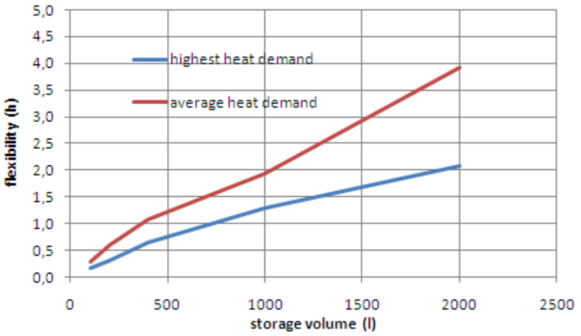

Figure 4: Flexibility as a function of the TES volume (ΔT = 10 K)

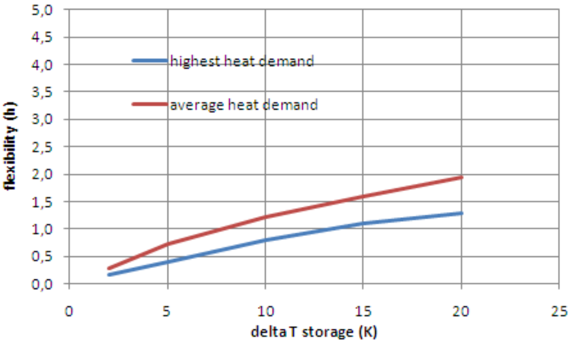

Figure 5: Flexibility as a function of the ΔT over the storage tank (volume = 500 l)

Therefore, a water storage tank with an acceptable level of flexibility of 1 hour during a day with an average heat demand seems to be feasible.

Varying ΔT (volume of the TES = constant)

In the simulation described above, the ΔT over the storage volume was kept constant at 10 K. This might be not always realistic as often a heating curve is applied . Therefore, also the effect of ΔT over the storage volume is simulated. The results of a varying delta T are shown in Figure 5. It can be seen that the flexibility is more or less proportional to the delta T over the water storage tank.

Flexibility by forced operation

When there is no or very few heat demand, flexibility can be created by forcing the HP to operate (and consume electricity) by delivering its heat to the TES. This can happen when a lot of electricity of less predictable renewable energy sources is available in the grid while the electricity demand is rather low. The maximum flexibility created by the TES in this case can easily be derived. The time period a HP still can run starting from an empty storage volume and with no heat demand, is the capacity of the storage tank divided by the power of the HP, e.g. a storage tank of 1,000 l with a ΔT of 10 K has a capacity of 11.6 kWh. When the HP has a thermal output power of 10 kW, the resulting maximum flexibility is 1.16 hour. In the reference scenario and assuming a water storage tank of 400 l, this results in a capacity of 4.65 kWh and a flexibility of 0.5 hour for the considered HP.

CONCLUSIONS AND FUTURE RESEARCH

A continuous growth of the number of HPs connected to the distribution grid is expected in the coming years and could lead to a supplementary burden on the distribution grid, being the reason why distribution grid operators are observing this trend closely. However, HPs combined with TES and controlled in an intelligent way might also offer opportunities in the form of flexibility to the grid, reflected by a delayed or forced operation and thus an electricity consumption pattern that can be shifted in time. This paper assesses this flexibility for a given reference scenario, being a domestic dwelling with a total annual SH demand of 10,600 kWh. The analysis resulted in a flexibility of about 0.5 to 1 hour flexibility for forced and delayed operation respectively for the reference scenario and a practically feasible water storage tank for SH of about 400 l. Future research will focus on the practical implementation of a HP concept in laboratory environment and field test, the development of intelligent control algorithms for HPs with TES and a further assessment of the theoretical and practical complexities of TES (e.g. temperature and stratification issues, size and weight, SOC, ...).

MISCELLANEOUS

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