Using the Ecovat system to supply the heat demand of a neighbourhood

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***Abstract*—In this paper we present a demand side management control approach for a neighbourhood, which includes a seasonal thermal storage, called the Ecovat system. The Ecovat system is used to satisfy the heat demand of this neighbourhood instead of gas boilers, which are currently used in most Dutch houses for this purpose. We observe that an Ecovat system is capable of supplying the heat demand of such a neighbourhood throughout the year, even if the heat demand is unexpectedly high, for example due to a harsh winter. As benefits we observe an 86.8 to 91.8% reduction in electricity fed back to the grid as well as a reduction in the amount of CO_2 emitted yearly by 91.4 up to 138.8 ton, when using an Ecovat system instead of gas boilers to satisfy the heat demand of the neighbourhood.**

I. Introduction

In recent years the share of renewable energy sources in the energy system has increased significantly in an effort to reduce the amount of green house gas emissions, as well as to reduce the dependency on fossil fuels to satisfy our energy demands. This trend is expected to continue in the coming years. As these renewable energy sources can not be dispatched at will it becomes harder to match supply and demand when the share of renewables increases. Solutions to alleviate this mismatch include demand side management (DSM) and energy storage.

DSM involves measures taken at the demand side, such as demand shifting, to better match supply and demand. In [1] an overview of different DSM methods is presented, while [2] surveys DSM in a broader context, for example by also looking at monitoring and communication systems for DSM.

Energy storage in general can take many forms. In this paper we focus on thermal energy storage. Thermal energy storage technologies fall into three categories; sensible storage, which stores energy by heating the storage medium, latent storage, which stores energy by means of a phase change in the storage medium, and chemical storage, which stores heat by means of reversible chemical reactions. In [3] a general overview of thermal energy storage technologies is presented, while [4] gives an overview of seasonal thermal energy storage technologies specifically. The Ecovat system, the focus of this paper, is a seasonal thermal energy storage technology and falls in the category of sensible thermal energy storages.

Due to the increasing share of renewables on the grid, as well as the weather conditions in Western Europe there is an excess of (cheap) energy available in summer, while in winter when the demand is higher, especially for heating, there is less energy available from renewables. The Ecovat system is designed to take advantage of this fact, by storing thermal energy during summer, for use during winter. As such, the Ecovat system is designed to supply the heat demand of a neighbourhood of houses (50 to 500 houses, depending on the system size) throughout the entire year.

The Ecovat system is currently being developed, and a prototype has been realised in Uden, the Netherlands [5]. In previous research we have developed models for the Ecovat system itself [6]. However, the benefits of incorporating an Ecovat system in to a neighbourhood have not been investigated. As such, an investigation of the benefits of using an Ecovat system to supply the heat demand of a neighbourhood is the focus of this work. More specifically, the goals of this paper are: 1) to determine the benefits, in terms of CO_2 reduction and increased self-consumption, of using an Ecovat system instead of gas boilers (which is how most Dutch homes are currently heated), to supply the heat demand of a neighbourhood and 2) to determine the sensitivity of the system against major changes in heat demand. This goal is realised by combining a heuristic method to control an Ecovat system, developed in previous work [6], with the Decentralized Energy Management Toolkit (DEMKit) [7], which is designed to perform DSM simulations. More specifically, we modelled a neighbourhood of houses that is heated by gas boilers in the DEMKit simulator. DEMKit is then used to optimize the electricity consumption within the neighbourhood, in this case by flattening its electricity profile. In this simulation the control of the heat consumption is not optimized, since we assume that only gas boilers are used as heating sources, which simply run as soon as there is any heat demand. DEMKit gives as output the heat demand profile of the neighbourhood, along with a profile of the excess energy produced within the neighbourhood, e.g. through photovoltaic (PV) panels. This data is then used as input for the heuristic control method of the Ecovat system. Subsequently, the heuristic method determines the charging strategy of the Ecovat system while satisfying the requested heat demand from the neighbourhood. This allows us to quantify the benefits of using an Ecovat system instead of gas boilers to satisfy the heat demand.

Additionally, through considering different cases we study the sensitivity of the system with regards to an increased heat demand, both when this higher heat demand is planned, i.e. for a larger neighbourhood, or when it is unexpected, i.e. the winter months turn out to be colder than expected. In literature,

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similar setups considering both electrical and heat demand in a microgrid or neighbourhood, have been considered. For example, [8] presents a mixed integer linear programming model to minimize the operational costs of a microgrid considering both electricity and heat, while [9] formulates such a microgrid as a stochastic non-convex optimization model, which is then simplified to a linear programming model to be able to solve it. However, to the author's knowledge this is the first presented simulation case of a neighbourhood that includes an Ecovat system.

The remainder of this paper is structured as follows. In Section II the Ecovat system and the heuristic method developed to model its control are described, while in Section III the DEMKit simulator is described. In Section IV the inputs, components and outputs of the simulations are discussed, the different cases considered in this paper are presented in Section V. The results of the simulations are discussed in Section VI. Finally, in Section VII conclusions and avenues for future work are presented.

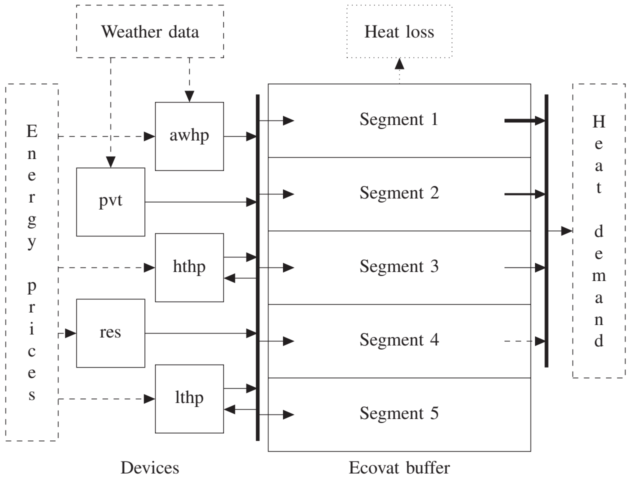

Fig. 1. Schematic overview of the Ecovat system. The system consists of the Ecovat buffer and a number of devices to charge the buffer. Figure reprinted from [6], reprinted with permission from the authors.

II. THE ECOVAT SYSTEM

The Ecovat system is a seasonal thermal energy storage technology that is currently under development in the Netherlands [5]. A schematic overview of the system is presented in Fig. 1. The main component of the system is the Ecovat buffer, which is a large underground, well insulated water tank. The buffer is divided into five segments, which can be charged individually through heat exchangers integrated in the buffer walls. This means that, contrary to most water tank designs, there is no water being pumped into or out of the buffer when it is charged or discharged. It should be noted that the buffer segments are not physically separated. Due to smart charging and discharging of the buffer the temperature stratification inside the buffer can be kept intact, which has been shown to improve the efficiency of water tanks [10], [11].

There are several devices in the Ecovat system to produce heat, which are used to charge the buffer. First, there are photovoltaic thermal (PVT) panels, which generate thermal energy, that can be used to charge the buffer, as well as electricity that can be used to power the other devices in the system. Second, there is a resistance heater (*res* in Fig. 1), which transforms electricity to heat on a one-to-one basis. As this is not very efficient, it is only used when energy prices are low and/or local energy is available, for example from the aforementioned PVT panels. Finally, there are a number of heat pumps included in the system. The air-water heat pump (*awhp* in Fig. 1) uses the ambient air as its heat source and one of the buffer segments as its heat sink. The two water-water heat pumps use one of the buffer segments as heat source and another buffer segment, that has a higher temperature, as heat sink. Since the possible range of temperatures in the Ecovat buffer is too large to be covered efficiently with one heat pump, one of the pumps covers the lower part of the temperature range and the other the higher part (*lthp* and *hthp* in Fig. 1 respectively).

In previous work [6] a heuristic method to control the Ecovat system was developed. It is based on an integer linear programming (ILP) model of the Ecovat system [12], [13]. In [13] we showed that the decrease in performance of the heuristic method compared to the ILP model is small, given the large decrease in computational time. In short the heuristic method works as follows. Initially, a very simplified model of the Ecovat system is used to determine useful energy content targets for every day of the year, where we define useful energy as energy that can be used to satisfy the heat demand of the neighbourhood, i.e. that is at a temperature that is higher than the demand temperature (60 °C in this research). After that a number of steps are performed for every time interval in the optimization horizon. First, the maximum energy price the model is willing to pay is determined, based on the pre-determined target for the useful energy content of the buffer and the actual useful energy content at that time. Based on this maximum accepted price and input for the weather conditions it is determined which devices will run during that interval. Then based on these decisions and the amount of heat lost by the buffer to its surroundings during the given time interval, the new temperature values of the buffer segments and the operational costs incurred during this time interval are determined. By iteratively considering all time intervals the total operational costs of the system throughout the year are determined. Next to the operational decisions the evolution of the temperature distribution inside the buffer throughout the year is a valuable outcome of this method. For a more detailed description of the heuristic method we refer to [6].

III. DEMKIT

To perform DSM simulations of a neighbourhood of houses the Decentralized Energy Management Toolkit (DEMKit) simulator, developed at the University of Twente [7] is used as this simulator considers integrated energy systems combining various energy carriers such as e.g. heat and electricity. This open source simulator allows the user to define a model of a neighbourhood, build up of houses with individually modelled devices. To this end, DEMKit includes a library of device components, such as; washing machines, dishwashers, batteries, heat pumps, PV panels and electric vehicles. Furthermore, DEMKit includes components to control these devices by means of various optimization algorithms.

As mentioned, DEMKit can optimize the consumption of multiple commodities, such as electricity and heat. However, in our research we only use DEMKit to optimize the electricity consumption within the neighbourhood, while taking the requirements of the heat demand into account. The used optimization approach in this work is the profile steering algorithm [14], which uses a desired power profile (in this case a flat profile) as steering signal instead of electricity prices. More specifically, DEMKit uses the extended version of this algorithm presented in [15], which uses a two-phase approach. In the first phase it uses predictions to make a planning for the neighbourhood synchronously, while in the second phase profile steering is used to schedule the individual devices. This second phase happens asynchronously and is event driven.

The output of the DEMKit simulator consist of, among others, the consumption and generation of energy on both a device and neighbourhood level, and the amount of electricity imported from and exported back to the grid.

IV. Simulation setup

As discussed in Section I we first use DEMKit to optimize the electricity consumption of the simulated neighbourhood. In the second step we use the Ecovat heuristic to satisfy the heat demand of the neighbourhood. Fig. 2 shows the relations between the used models, as well as their inputs and outputs. The required inputs consist of 1) weather data, more specifically ambient temperature and solar irradiation, used by both DEMKit and the Ecovat heuristic, 2) load profiles of the houses in the neighbourhood, used by DEMKit and 3) energy prices used by the Ecovat heuristic.

For the generation of the load profiles we used the Artificial Load Profile Generator (ALPG) described in [16]. This open-source tool uses a bottom-up approach to obtain an occupancy profile for a given house, by modelling the behaviour of its occupants. The ALPG models when the occupants are at home, and based on this the usage pattern of devices (e.g. a device that requires input of an occupant never runs when no one is at home). The generated profiles include electrical devices, but also consumption of heat used for space heating and hot water. The profiles that the ALPG gives as output consist of an electrical load profile for all uncontrollable devices (such as lighting), vectors specifying constraints for any controllable smart devices, such as the time range in which a washing machine is required to run, a vector with temperature setpoints for the thermostat, which specify the desired temperature inside the house, a ventilation profile of the house and a hot water consumption profile. This means that the load profiles also include the flexibility provided by the smart devices present in the neighbourhood.

To create the load profiles, the ALPG requires some parameters of the neighbourhood, such as the types of households in the neighbourhood and the devices available in those households. In our case we take a neighbourhood with a mix of single worker households, dual worker households, households of families with children and households of retired persons. With regards to the devices present, we consider a future scenario with a higher penetration of emerging technologies such as electric vehicles and PV panels than is currently common. More specifically, we consider a neighbourhood where 13% of the households have an electric vehicle and a further 32% have a plug-in hybrid electric vehicle. Furthermore, 50% of the households has PV panels and 10% has a battery. Additionally, 25% of households uses induction cooking and between 20% to 60% of the households has a dishwasher, based on the type of household, with households consisting of more persons having a higher chance of owning a dishwasher. Finally, we assume that every household has common devices such as a washing machine, oven and refrigerator.

For the weather data we use the ambient temperature and solar irradiation profiles measured by weather station Twenthe in Enschede, the Netherlands of the year 2014. For the energy prices we use the prices on the Dutch imbalance market of the year 2014.

Based on the load profiles and the weather data DEMKit optimizes the electricity profile of the neighbourhood, i.e. it flattens it as much as possible given the flexibility provided by smart devices. It outputs the heat demand profile of the neighbourhood, as well as the excess local energy produced within the neighbourhood. In our model this excess local energy can be consumed by the Ecovat heuristic at zero cost. This could be in exchange for a lower heating bill, as well as from a desire to improve the degree of self-consumption of the neighbourhood. The outputs generated by DEMKit are fed into the Ecovat heuristic together with the weather data and energy prices. The output of the Ecovat heuristic consists of the operational costs of the Ecovat system, the temperature distribution inside the Ecovat buffer throughout the year and the electricity fed back to the grid.

V. Case descriptions

To investigate the benefits of using an Ecovat system instead of gas boilers for satisfying the heat demand of the neighbourhood, as well as determining the influence of a higher heat demand on the performance of the system we consider five different cases. The base case consists of a neighbourhood of 50 houses which tries to maximize its self-consumption of energy (we call this case **h50**). In the base case we assume any excess electrical energy from the neighbourhood is offered for free to the Ecovat system, where it can be converted to heat and stored for later use by the neighbourhood. In this case self-consumption is preferred even if the energy price is negative. Fig. 3 shows the heat demand profile of the neighbourhood for this case.

The second case differs only from the base case in its objective, which switches from maximizing self-consumption to maximizing profit (we call this case **h50-profit**). In this case electrical energy might be fed back to the grid by the

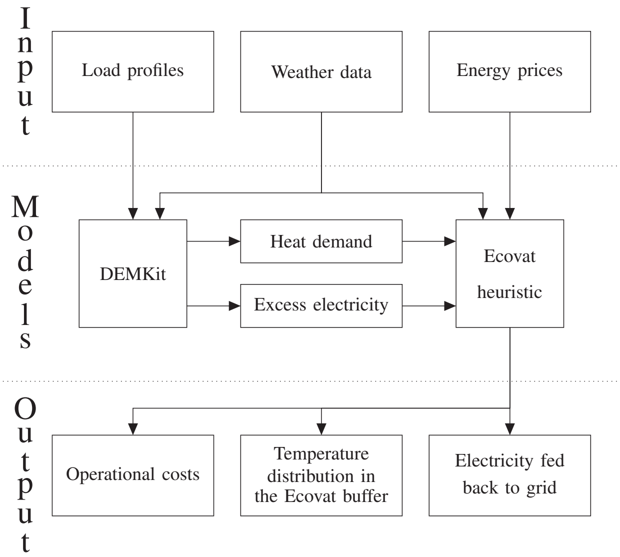

Fig. 2. Overview of the used models and their inputs and outputs.

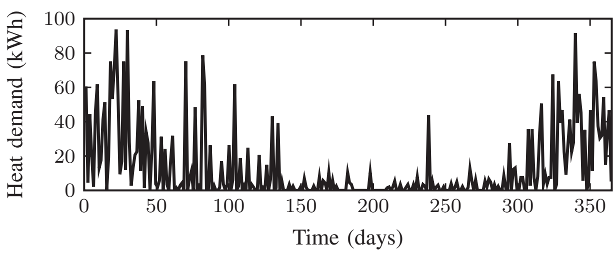

Fig. 3. Heat demand throughout the year for the h50 case.

neighbourhood, while simultaneously energy is bought on the energy market for a negative price by the Ecovat system. This assumes that the neighbourhood is not penalized for feeding back energy to the grid even though the energy price is negative, or that the neighbourhood and the Ecovat system operate on different markets. In other words the consumers would still receive the normal feed-in tariff from the supplier in this case. It should be noted that while maximizing profit in this way is sound from an economical perspective, it may not be preferable from a social standpoint.

The third case is again similar to the base case with the exception that the heat demand during the winter months is increased by an average of 30%. This will give us an indication how robust the Ecovat system is in handling heat demands which are higher than was expected, for example due to a colder winter than expected (we call this case **h50-winter**). To do this, the previously discussed heat demand profile is taken and the value for the heat demand in every time interval in the months December, January and February is multiplied by a random number between 1 and 1.6 taken from a uniform distribution. To model that the increased heat demand is unexpected, and thus not known on beforehand, this case uses the same targets for the useful energy content of the Ecovat buffer at the end of every day (see Section II), as those used for case **h50**.

The fourth case is the same as the base case but instead of a 50 house neighbourhood we consider a 65 house neighbourhood, we call this case **h65**. The fifth case combines the third and fourth cases, in other words we consider a neighbourhood of 65 houses with increased demand in winter, we call this case **h65-winter**. The case **h65-winter** uses the same targets for the energy content of the Ecovat buffer at the end of every day as case **h65**, for the same reasons as for the **h50-winter** case.

Because of the randomness introduced in the heat demands of the **h50-winter** and **h65-winter** cases we have simulated each of these cases five times and determined the average result from these five simulations for both cases. In the next section we present the simulation for both cases that gave the result closest to the determined averages. It should be noted that even though some randomness was introduced in the heat demand, the results for all the simulations were close to the average (all within 5% from the average).

VI. Results

The goal of this research is to investigate the benefits of using an Ecovat system to supply the heat demand of a neighbourhood of houses instead of the heating being done using gas boilers, which is by far the most common way of space heating in the Netherlands currently. We first look at the temperature evolution inside the Ecovat buffer throughout the year, the operating costs of the Ecovat system and the useful energy of the buffer at the end of the year for the different cases described in Section V. This gives a good indication about how well the Ecovat system is capable of supplying the heat demand of the neighbourhood for different circumstances. Fig. 4 shows the temperature distribution of the Ecovat buffer throughout the year for the cases **h50**, **h50-winter**, **h65** and **h65-winter**. The **h50-profit** case is not included since the temperature distribution is the same for that case as for the **h50** case. This is due to the fact that the decisions whether and how to charge the buffer do not change between these cases, merely the preferred energy source (excess neighbourhood energy versus energy bought on the energy market) changes. Table I shows the operational costs of the Ecovat system (with negative costs meaning profit) as well as the useful energy at the end of the simulated year. For reference, the initial useful energy content of the buffer and thus the target at the end of the year is 54246 kWh. The costs only include operational costs and do not include costs associated with maintenance, connection to the grid etcetera. Also, this does not include any profit made from supplying heat to customers in the neighbourhood.

We can see from Fig. 4 that in the base case, **h50**, the Ecovat buffer is low on useful energy ($T_2 = 60$°C and T_1 is close to 60 °C) at the end of February (around day 60) and almost full during summer (all segments are close to their maximum temperatures), as one would expect. From Table I we can see that for this case the useful energy content at the

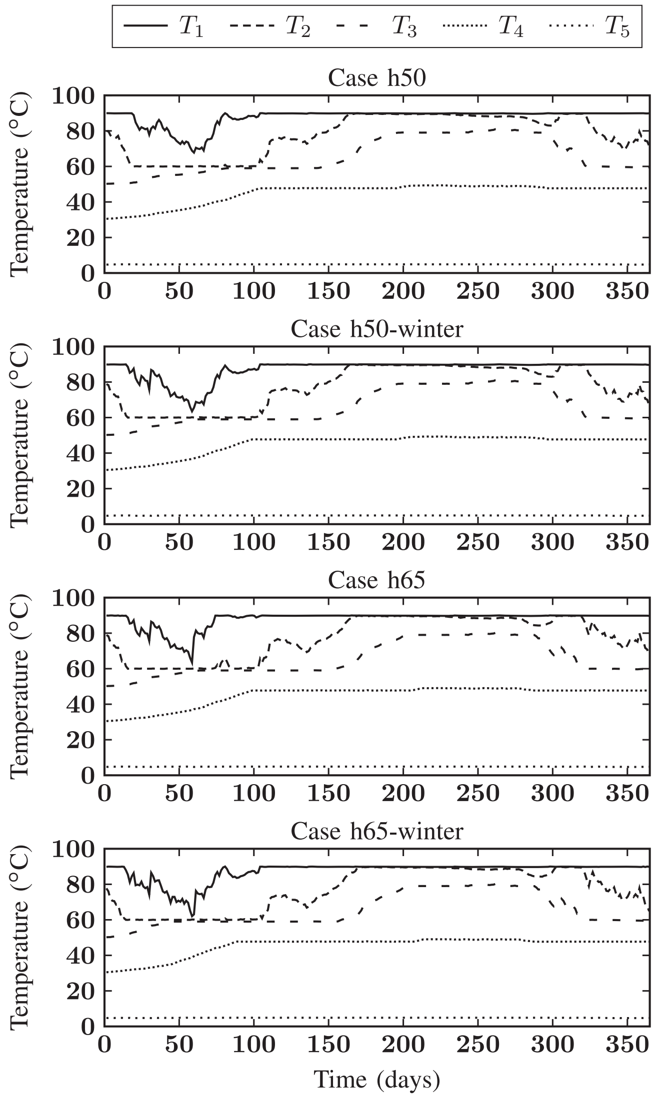

Fig. 4. Temperature evolution inside the Ecovat buffer for the different simulation cases. T_i is the temperature of buffer segment i.

TABLE I
COMPARISON SIMULATION CASES

Case	Costs Ecovat system (€)	Useful energy (kWh)
h50	-19946	49702
h50-profit	-20021	49702
h50-winter	-18357	43636
h65	-17939	44470
h65-winter	-16576	42071

end of the year is about 10% lower than the aforementioned target of 54246 kWh. To make up this difference in useful energy the costs would increase due to extra charging being required during the year. When operating a real Ecovat system this deficit would cause the costs to increase in the following year due to starting the year at a lower useful energy content. The costs for the **h50-profit** case are only slightly lower than for the **h50** case. This is due to the fact that the amount

TABLE II
ELECTRICITY FED BACK TO THE GRID

Case	Electricity fed back (kWh)	Decrease (%)
No Ecovat, 50 houses	44596	-
No Ecovat, 65 houses	55778	-
h50	3655	91.8
h50-profit	4596	89.7
h50-winter	3843	91.4
h65	7072	87.3
h65-winter	7366	86.8

of extra electricity that is bought on the energy market (at negative prices) in this case is only small compared to the base case, **h50**. For the **h50-winter** case we see that the buffer is a little closer to empty at the end of February, but otherwise the temperature evolution inside the buffer is very similar. As expected, the operational costs are higher than for the **h50** case due to the increased heat demand. Finally, the useful energy content of the buffer at the end of the year is lower than for the **h50** case, again due to the increased demand.

When looking at the **h65** case we see similar results as for the **h50-winter** case, costs are higher and useful energy at the end of the year is lower than for the **h50** case as expected. Finally, for the **h65-winter** case we see the same trend as for the previous cases, where a higher demand leads to higher costs and lower useful energy content at the end of the year. In this case the costs to compensate for the lack of useful energy would be even larger than for the previous cases. We observe that for all cases considered the Ecovat system is capable of supplying the year round heat demand of the connected neighbourhood of houses. However, by adding more houses to the neighbourhood the operational costs of the Ecovat system increase. On the other hand, the profit made by supplying the heat demand will of course increase for a larger neighbourhood. Where the optimum is in this trade-off is a question for further research, but outside the scope of this paper.

One of the benefits of using an Ecovat system to supply the heat demand of a neighbourhood of houses instead of using gas boilers is that part of the excess electricity produced in the neighbourhood, for example from PV panels, can be used to charge the Ecovat system instead of being fed back to the electrical grid. Table II shows the amount of electricity fed back to the grid over the entire year for the considered cases. The 'No Ecovat' cases give the amount of electricity fed back to the grid if gas boilers are used instead of the Ecovat system. The second column gives the decrease of electricity fed back to the grid compared to the 'No Ecovat' case for the same number of houses. We can see that for all the considered cases the amount of electricity fed back to the grid is decreased significantly if an Ecovat system is used instead of gas boilers to satisfy the heat demand. Even for the **h50-profit** case we see a large decrease in electricity being fed back, the decrease being only slightly smaller than for the base case **h50**. In the **h50-profit** case extra electricity, compared to the **h50** case, is fed back to the grid during times where there is both excess local production as well as negative energy prices on the

TABLE III
CO_2 EMISSION REDUCTION COMPARED TO GAS BOILERS

Case	Total heat demand (kWh)	Reduction CO_2 (ton)
h50	$4.5 \cdot 10^5$	91.4
h50-winter	$5.3 \cdot 10^5$	107.2
h65	$5.9 \cdot 10^5$	118.6
h65-winter	$6.9 \cdot 10^5$	138.8

energy market. This happens only for a small number of time intervals, as such the majority of the excess local production is used to charge the Ecovat system. This extra feedback of electricity would translate to some extra profit in the **h50-profit** case compared to the **h50** case. However, this is only a small amount (about 41 € if we assume a price of 0.04 €/kWh). Combined with only a small decrease in operational costs in the **h50-profit** case compared to the **h50** case the total increase in profit is relatively small, which means that even a small incentive to increase self-consumption is enough to disregard the **h50-profit** option. Finally, we note that most of the electricity that is still fed back to the grid in all the considered cases is fed back during summer when the Ecovat buffer is at its capacity.

Another benefit of using the Ecovat system to supply the heat demand instead of using gas boilers is the reduction in CO_2 emissions. The Ecovat system has zero emissions, assuming the energy used to charge the buffer is generated in a sustainable way. This means that using an Ecovat system instead of gas boilers causes a CO_2 emission reduction equal to the total emission of the gas boilers. Table III lists the total heat demand during the year for each case, as well as the amount of CO_2 reduction that can be achieved by replacing the gas boilers by an Ecovat system. The CO_2 reduction is calculated using the emission factor of 56 ton CO_2/TJ for natural gas in the Netherlands [17].

VII. Conclusion

In this paper we have presented a DSM control approach for a neighbourhood of houses with an Ecovat system. We have used the DEMKit simulator in combination with a previously developed heuristic method for controlling the Ecovat system. The objective of DEMKit is to flatten the electricity profile of the neighbourhood, while the Ecovat system is used to satisfy the heat demand of the neighbourhood.

The results show that the Ecovat system is capable of supplying the heat demand of the neighbourhood throughout the year for all considered cases, even if the heat demand was unexpectedly larger such as in the winter cases. While the Ecovat system is always capable of supplying the heat demand the operational costs increase for increasing heat demand. Furthermore, the useful energy content of the buffer at the end of the simulated year decreases for increased heat demand, which in turn leads to potentially higher operational costs in the subsequent year.

Benefits of using the Ecovat system instead of gas boilers for satisfying the heat demand of the neighbourhood include a reduction in the electricity fed back to the grid by 86.8 to 91.8% (increased self-consumption), as well as a reduction in CO_2 emission by 91.4 to 138.8 ton.

Options for future work include determining the number of houses which leads to the best trade-off between operational costs and profit from supplying the heat demand to the neighbourhood. Another interesting option is investigating other sources of cheap local energy, such as the waste heat produced by industry or agriculture, which can be used to charge the Ecovat system. Finally, the integration of a model of the Ecovat system into the DEMKit simulator, such that it can be incorporated into a multi-commodity optimization of the neighbourhood, would be an improvement over the method presented here where we first simulate the neighbourhood using DEMKit, before considering the Ecovat system to satisfy the heat demand of the neighbourhood.

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