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RESEARCH ARTICLE

Increasing Self-Sufficiency of Energy Community by Common Thermal Energy Storage

ELAHE DOROUDCHI, HOSNA KHAJEH, (Graduate Student Member, IEEE), AND HANNU LAAKSONEN, (Member, IEEE)
School of Technology and Innovations, Flexible Energy Resources, University of Vaasa, 65200 Vaasa, Finland

Corresponding author: Elahe Doroudchi (elahe.doroudchi@uwasa.fi)

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ABSTRACT Customers energy consumption pattern affects directly the grid burden, especially during peak hours. In recent years, many different control methods have been proposed to shift the energy consumption to off-peak hours through demand response (DR) management. In order to have effective DR energy management, optimization has a key role. Thus, increasing the benefits for the customers and encouraging them to consider the new controlling approaches in their daily energy consumption pattern is needed for increased customer participation. On the other hand, renewables are integrated with the buildings to decrease the buildings' energy costs and dependency on the grid utilities. This study moves a step further and considers a few numbers of neighboring houses as an energy community. The community commits to sharing their produced energy from the individual distributed solar system with each other and increasing their energy self-sufficiency by minimizing the import and export of power from/to the grid. This research focuses on applying common electric heat energy storage when community's own solar PV generation is used to thermal energy generation/storing in heat storage and compares it with the case in which each house has its own distributed thermal energy storage. Then, different sized thermal storages are tested for the community to find the best solution. The results are compared in terms of import and export of energy, annual costs and the payback-time. It is concluded that the community with common thermal energy storage could decrease the energy exchange with the grid and the payback-time of the investments could be reduced for the community members.

INDEX TERMS Demand response, energy community, renewable energy resources, sustainable energy community, thermal energy storage.

NOMENCLATURE

P^i_{exp}	Export power of house i.
P^{max}_{exp}	Maximum allowable export power.
P^i_{imp}	Import power of house i.
P^{max}_{imp}	Maximum allowable import power.
P^i_{load}	Energy consumption of house i.
P^i_{solar}	Solar generated power of house i.
C_{sto}	Storage total capacity.
E_{sto}	Storage cumulated energy.
n	Length of the analysis period.
P_{exp}	Export power.
P_{imp}	Import power.
P_{load}	Energy consumption.
P_{solar}	Solar produced energy.
P_{sto}	Storage charging/discharging power.
r	Discount rate.
S	Net present worth of the cumulated cost. savings
S_a	Annual savings in euros.
SOC	State of charge.
SOC_{max}	Maximum allowable state of charge.
SOC_{min}	Minimum allowable state of charge.
w_{exp}	Export energy price.
w_{imp}	Import energy price

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I. INTRODUCTION

A. MOTIVATION

Renewable integration to power grids has many advantages for the future of the power systems while raising a lot of new challenges. Fossil fuels are increasing the CO_2 emissions and the earth atmosphere is polluted due to the harmful effects of carbon emissions. Besides, fossil fuels could not be permanent sources of energy as they are limited. Thus, renewable sources of energy could be a suitable substitute for these old resources of energy. Furthermore, renewables are compatible with the sustainable solutions that the United Nations is targeted to be achieved by 2030 by most of the member countries [1]. In this agenda, goal seven focuses on providing affordable and clean energy that highlights the need for renewables and new methods of applying them. Renewables can be of any size and of any kind depending on the application. Residential customers are a huge portion of energy consumers and replacing traditional energy systems with renewables is of great help in decreasing the environmental effects of fuels [2], [3]. Thus, in many countries, governments have started investments in increasing the use of these new sources of energy. In the very beginning, the idea was to have the same methodology as in conventional power plants, meaning that creating huge power plants of e.g. solar panels and wind turbines. Having power plants of this kind is required; however, having access to large free spaces is also necessary to install the plants. The equipment is expensive and this method might not be beneficial for every country.

Thus, distributed generation (DG) has been introduced as a solution to make the use of renewables more accessible and much easier. This means that every single house could have its own generation system while consuming on-site produced power. Applying photovoltaic (PV) panels in residential buildings is the easiest way of involving customers in the process of generating power rather than being a mere consumer [4], [5]. Therefore, this research considers single residential buildings that have PV panels installed on their roofs. As the solar energy is intermittent and the major part of the building consumption is during the evening, applying storage in the building system would benefit to increase the use of on-site energy fraction. Then, each house has its own panels and separate storage in its premise. This system is efficient as approved in the research, however, usually surplus energy from the building should be exported to the grid.

As each house has a unique energy generation and consumption pattern, the demand and supply matching is different in neighboring buildings. Thus, it would be a possible solution to consider several neighboring houses together as a community in terms of energy generation and consumption. In this regard, several prosumers and consumers voluntarily join together to follow the same energy-related objective [6]. The communities could be small or large depending on the number of houses and the number of energy supply sources. Creating such communities in rural and urban areas requires studies, economic analyses, changes in policies and proper designs for the system installation.

B. LITERATURE REVIEW

Energy communities were thoroughly introduced and discussed in [7]–[12] and the fans of such solutions are growing. Recently, the topic has been developed considerably and researchers evaluated different aspects of energy communities. Ref. [13] conducted a societal study to obtain a vision of future energy community-based energy systems. The work highlighted the importance of government actions and policymakers, both at national and local levels, in order to develop future energy communities. Therefore, governments should start planning for such changes and try to consider the challenges regarding these new energy networks in their future energy management policies. Otherwise, it would not be possible to implement these models in practice. As one example, in the UK the government has already started studies on these types of energy hubs [9].

In this regard, the benefits of energy communities need to be clarified to motivate individuals to join energy communities. For example, the authors of [14] proved that forming energy communities can reduce the risk of blackouts. It also stated that energy communities, in some cases, can be environmentally and economically efficient. In this concept, [15] conducted an ex-post study to guarantee the benefits of the prosumers within a community through a novel two-stage mechanism. Ref. [16] discussed in what ways energy community-based power systems increase the flexibility of future power systems and compensate for a high share of intermittent renewable resources. The paper also reviewed the power-electronic devices and potential flexible energy resources that can be deployed in future energy communities.

Some research considered communities with different resources and discussed their optimal operations. For instance, Ref. [17] considered prosumers with PV panels and a battery energy storage system forming a local energy community. The focus of that work was on the prosumer-to-vehicle concept and it assessed how this approach can benefit the community. Ref. [18] studied the interaction between prosumers in an energy community. For this purpose, it developed several trading modes including traditional, agent-based, peer-to-peer, as well as two hybrid ones. Ref. [19] tried to obtain the coordinated operation of a storage device and conversion devices in a multi-energy community. In another work conducted by [20], the authors presented a model to dispatch energy within the energy community that has multiple distributed energy resources. The aim was to minimize carbon emissions and net daily energy. The mentioned articles did not devote their study to long-term economic analyses. The authors of [21] assessed scenarios in which prosumers trade electricity within an energy community and compared it with the case where prosumers trade electricity with the retailer. The focus of that work was on the electricity trade between prosumers.

Zero-energy community is one type of energy community that can be useful for urban areas. This type of community tries to increase the self-sufficiency of its members. In this regard, [22] presented coupled distributed energy resources consisting of PVs, hybrid storage, and electric vehicles in a form of a zero-energy community. Similarly, a zero-energy community for urban areas has been designed by [23]. The community was equipped with a battery as well as hydrogen vehicle storage. The model was proven to bring substantial environmental benefits by reducing carbon emissions. Ref. [24] presented a "zero-energy neighborhood" model. The paper assessed the possible mutualization choices that match the excess energy of some buildings with the demand of neighboring buildings. In another work proposed by [25], fog-computing retrofit architectures were utilized for community infrastructures to manage flexible consumption, and enhance service delivery within the community. Ref. [26] designed a nearly zero-energy community with hybrid energy storage. It concluded that the scenario in which the community has equal numbers of residential and public buildings obtains optimal energy saving as well as carbon reduction. However, this scenario might not be possible in locations with a greater number of residential buildings. In spite of their interesting works, the reviewed articles' focuses were not on the operation of the community's resources and the economic outcome obtained by forming communities.

One of the important points in the energy community's studies is to analyze the community's shared asset(s) and the benefits obtained by forming the community. In this regard, [27] contributed significantly to this topic and evaluated the investment of an energy community in energy assets including a wind turbine and a battery. It quantified the saving of the members accordingly. The research has focused on the economic outcome of the community and did not consider the self-sufficiency aspect of the community. The authors of [28] presented a community of residential customers that has the potential to be responsive. Also, the community's electric vehicles can be charged according to the transformer's operational constraints. Ref. [29] scheduled a battery energy storage system as a shared asset of the community's members. The community was designed to provide frequency services. The mentioned studies, however, failed to conduct an economic analysis and to evaluate if forming a community benefits an individual prosumer.

As the reviewed articles indicated, storages are an essential asset in energy communities. Thermal energy storages are one economical option and a flexible solution that enhances the integration of intermittent solar power [30], [31]. Short-term thermal energy storage is utilized to provide peak-shifting flexibility and encounter short-term variabilities due to renewables while medium-term and long-term thermal energy storage can add weekly and seasonal energy flexibility into the systems [32]. In spite of their benefits, less attention has been given to the application of thermal energy storage in local energy communities [33].

C. CONTRIBUTION AND ORGANIZATION

To remedy the shortcomings of the existing literature, this research considers common thermal energy storage for the whole community and studies the energy sharing between the community units and the storage at the same time. To the best of the authors' knowledge, thermal energy storage has not been considered for energy-community-level systems. In addition to the application of thermal storage in energy communities, our work aims to highlight the benefits of forming an energy community by residential area household customers / members. The main contribution of our paper can be listed as follows:

1- It studies a group of houses with different living areas and PV panel sizes. The energy consumption and cost of these houses are assessed for two cases. In the first case, each unit has its own separate distributed thermal / heat energy storage. The second case considers a community of houses with common centralized thermal energy storage. The houses' and the community's objective is to increase their self-sufficiency by minimizing the import and export power.

2- The paper assesses the annual import and export, energy cost, and the payback time of different cases. In this regard, different sized thermal energy storages are checked for the community and compared with the case in which the house has its own distributed thermal storage. Thus, it analyzes whether forming an energy community is beneficial for households. Also, the paper determines the size of storage that fits the best for the case study.

The rest of the paper is organized as follows. Section III describes the system modelling and presents the problem formulation in both study cases for individual houses study and for the community. The results are presented in Section IV while discussing the pros and cons of the cases compared with each other. Finally, the paper is concluded in Section V.

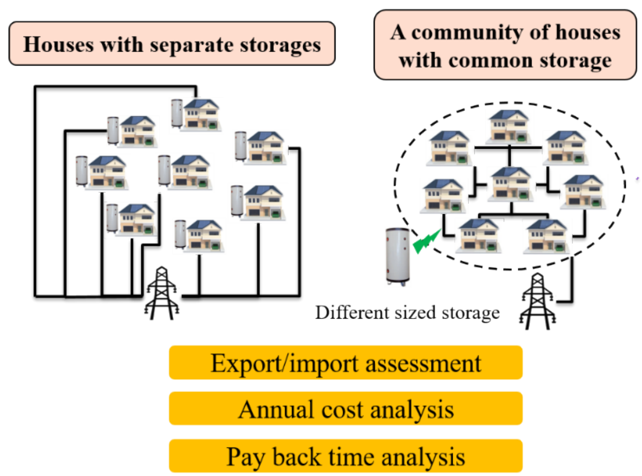

FIGURE 1. The main architectures of two cases that are modeled in the paper.

II. SYSTEM MODELING

This section explains the system modelling in the cases of individual houses and the community network. Fig.1 summarizes the main architectures of the models considered in this paper. The paper assesses two cases including houses with individual thermal storage and a community of houses with common thermal storage.

A. CASE I: INDIVIDUAL HOUSES

In this case, individual houses are modeled. Each house is assumed to have a specific gross floor area and PV panel's size and they have separated energy generation and consumption. The storage is considered thermal energy storage (TES). When storage is applied a demand response control system is required to implement the supply and demand matching. Thus, (1) is introduced to minimize the import and export power while considering the electricity price as a weighting factor in this function.

$$\min \sum_{t=1}^{8760} \left(P_{imp}(t) w_{imp}(t) + P_{\exp}(t) w_{\exp}(t)\right) \tag{1}$$

The objective function (1) considers the imported power, P_{imp}, and exported power, P_{exp}, separately as the price model that is applied has different values for buying electricity price, w_{imp}, and selling electricity price, w_{exp}. The price of selling is considered about one-third of the purchasing price. The balance equation that completes the model of this case is presented in (2) where P_{solar} is the power generated by the PV panels, P_{load} is the energy consumption at home at each hour and P_{sto} represents the charging/discharging power of the storage at each hour.

$$P_{\text{imp}}(t) + P_{\text{solar}}(t) - P_{\text{load}}(t) - P_{\text{exp}}(t) + P_{\text{sto}}(t) = 0 \tag{2}$$

The storage has always losses and considering them in the system modelling would cause the results that are more realistic. Thus, (3) and (4) show the inclusion of the losses, α, in the storage model and the storage state of charge (SOC) minimum and maximum limits, SOC^{min}, SOC^{max}, respectively to extend its lifetime [34].

$$E_{sto}(t) = (1-\alpha) SOC(t-1) C_{sto} \tag{3}$$

$$SOC^{\min} < SOC(t) < SOC^{\max} \tag{4}$$

In (3), $E_{sto}(t)$ shows the storage cumulated energy at each hour and C_{sto} represents the total capacity of the storage. The TES model used in this study is based on the thermally stratified TES tanks in [35].

Thermally stratified TES tanks with water as a storage medium are common in heating and air-conditioning applications. The thermal stratification is affected by the temperature, size and shape of the tank and flow rate during charging and discharging of the storage. Different types of stratified water tanks with direct and indirect heating modes are illustrated in Fig. 2 [36].

This study considers a direct heating mode of the storage medium, which is water.

The imported and exported power are also restricted based on the grid policies in maximum allowable import, $\boldsymbol{P}_{exp}^{max}$ and export, and export, $\boldsymbol{P}_{exp}^{max}$ power. In (5) and (6), this limitation

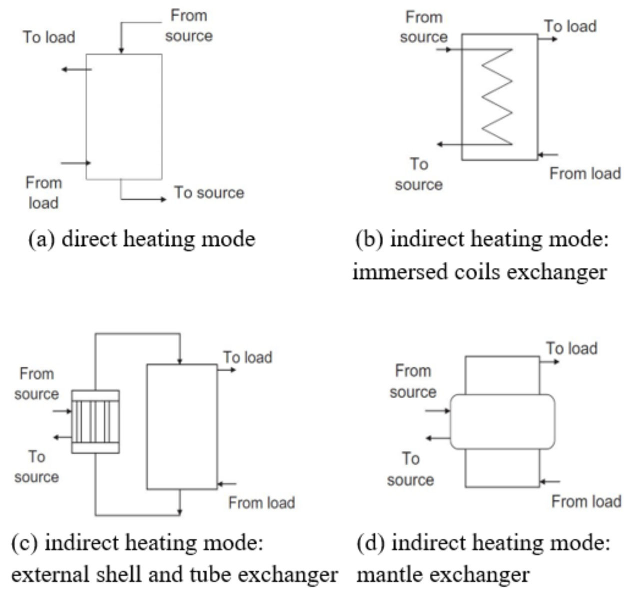

FIGURE 2. Different type of stratified water tanks with direct (a) and indirect (b), (c) and (d) heating mode [36].

is shown.

$$0 \le P_{\text{imp}}(t) \le P_{\text{imp}}^{\max} \tag{5}$$

$$0 \le P_{\text{exp}}(t) \le P_{\text{exp}}^{\max} \tag{6}$$

The aforementioned model is tested for each house separately in this case and the results are discussed in Section IV.

B. CASE II: ENERGY COMMUNITY

In this case, the neighboring houses in case 1 are considered as a community network together. It is assumed that each house, as in case 1, has its own PV system and the consumption pattern is the same as before. However, one common thermal storage is considered for the community area instead of individual storages. The common thermal storage size should be optimized to provide the suitable balance between the supply and demand of the community units. In our case study, different sizes are checked to examine the operation of the community network. The current model considers the storage installation in the vicinity of the neighboring buildings which minimizes the energy transfer losses.

To manage the energy flow in the community network the objective function (7) is applied where i is the house number index, $\boldsymbol{P}_{imp}^{i}$ is the import power at each hour for house i and $\boldsymbol{P}_{exp}^{i}$ is the export power at each hour for house number i. This equation minimizes the import and export of energy from the grid for one year and considers all the houses. As the calculations are implemented on an hourly basis the energy exchange is considered at each hour for all the houses and then the next hour's calculations are implemented.

$$\min \sum_{t=1}^{8760} \sum_{i=1}^{8} \left(P_{imp}^{i}(t) w_{imp}(t) + P_{\text{exp}}^{i}(t) w_{\text{exp}}(t)\right) \tag{7}$$

The balance equation and the constraints for the grid power and the storage charging/discharging manner are represented in (8) – (12) where P^i_{imp}, P^i_{exp}, P^i_{solor}, and P^i_{load} represent each house import, export, PV generated power and the energy consumption at each hour, respectively.

$$\sum_{i=1}^{8} P^i_{imp}(t) + P^i_{\mathrm{solar}}(t) - P^i_{\mathrm{load}}(t) - P^i_{\mathrm{exp}}(t) + P_{sto}(t) = 0, \forall t \in [1, 8760] \quad (8)$$

$$E_{sto}(t) = (1-\alpha)SOC(t-1)C_{sto} \quad (9)$$

$$SOC^{\min} < SOC(t) < SOC^{\max} \quad (10)$$

$$0 \le P^i_{imp}(t) \le P^{\max}_{imp} \quad (11)$$

$$0 \le P^i_{\mathrm{exp}}(t) \le P^{\max}_{\mathrm{exp}} \quad (12)$$

The import and export power of each house at each hour, P^i_{imp} and P^i_{exp} are restricted within the limits that are provided from the grid utilities. The balance equation is defined to consider the energy exchange within the houses and the grid at each hour.

Applying the equations in this part provides solutions for the community energy sharing possibility. Therefore, the priority in providing the energy for each house is with the installed solar system of that house. Then, if excess power is still required it is taken from the solar-generated power of the neighbors. Any surplus is provided from the storage and then the grid. In this case, the houses considered in the community network are capable of internal energy buying and selling and the revenue of the system is shared between the members of the community. Results of the study and more discussion are provided in the next section.

III. RESULTS AND DISCUSSION

Based on the presented models in Section III, the optimization problems have been solved and the results are presented in the form of figures and tables in this section. In the case study, eight houses are considered to voluntarily form a community. The houses are selected from the database in [17] and their generated energy and consumption are based on the measured data. These residential houses are located in Austin, Texas. The houses have different total square footage between 1842 to 2934. All of the houses have their own PV panels and electrical appliances such as refrigerator, microwave, dishwasher, etc. Fig. 3 represents the average energy consumption and the average solar production for each house.

The data are provided on an hourly basis and for one calendar year. In the reference case (case 1), each house owns storage of 10 kWh and it is responsible to provide its on-site generated power.

Regarding the community case, the common storage size is optimized and different storage sizes are checked to examine the operation of the community network. A thermal storage of the capacity of about 190 liters can provide about 73% of the 8.3 kWh of daily average residential water heater use [37].

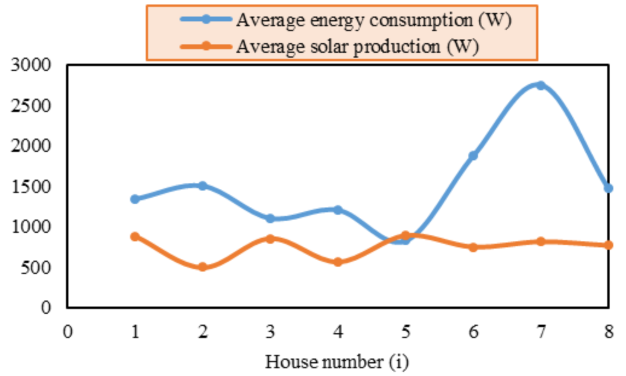

FIGURE 3. Hourly average energy consumption and solar production for each house within a year.

The sizes for the common storage are determined to be within the range of 22.5 kWh to 40 kWh, which is of the size of a 450 to 800 liters of water heater [38]. The minimum size is selected based on the possible matching of the supply and demand and the maximum size is chosen based on the half of the size of the summation of all the storages in the case 1. Other storage sizes up to 80 kWh are also tested, however larger storage size does not provide much saving differences financially. Considering this range, 22.5 to 40 KWH, the common sizes for thermal energy storage are 22.5 kWh. 25 kWh, 30 kWh, and 40 kWh.

A. ENERGY ASSESSMENT

Applying the duration curves assist to analyze the numbers of hours that a building is eliminating its export/import with the grid to zero. Using this method shows that a common energy storage would approach better to the nZEB definition as Table 1 confirms that the numbers of non-transitional hours with the grid improves when a larger storage for the community is applied.

TABLE 1. Number of hours the community energy transition with the grid is zero.

Cases	Number of hours
Reference case	5319
Storage size_22.5 kWh	6950
Storage size_25.0 kWh	6960
Storage size_30.0 kWh	6970
Storage size_40.0 kWh	6979

Considering Table 1 as a basis for duration curves, Fig. 4 compares the normalized net export curve of the reference case, case 1 in Section III, with the case of installing one common storage of the size of 40 kWh for the community network. The normalized net exports are duration curves that present the cumulative amount of hours that power is exported or imported during a calendar year [39]. Thus, if the number

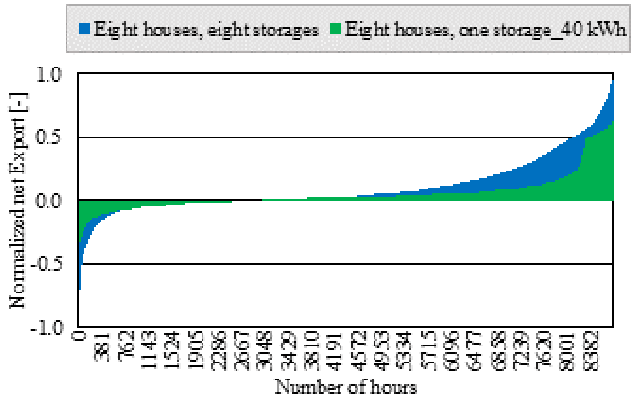

FIGURE 4. **Normalized net export comparing the reference case with common storage 40 kWh.**

of hours for export/import is reduced or if the normalized net export value is less in Fig. 4 compared to the reference case, the proposed model is more efficient in terms of the use of on-site energy fraction and the on-site energy matching. Furthermore, when the number of hours that the normalized net export axis approaches zero increases, the community could achieve closer to the nZEB definitions.

As can be seen in Fig. 4, the duration curve for the community model with the energy storage size of 40 kWh is below the duration curve of the reference case. This shows that the community model could implement the energy management among the members of the community with a remarkable reduction in the overall hourly import/export power as summarized in Table 1.

To study the community network energy cost savings for the community members, further analysis is performed. The annual energy payments for each house in all five cases are compared in Fig. 5. The first case is the reference case that every house has its separate 10 kWh storage and the four others are cases when common storage is applied for the whole community. The energy cost shown in the figure is the annual cumulative cost that is provided by the objective functions (1) and (7).

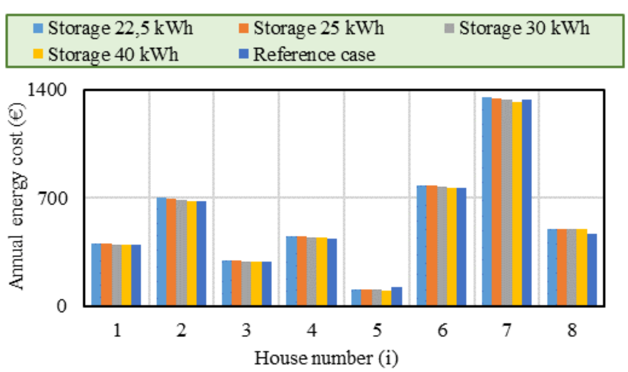

FIGURE 5. **Annual energy costs comparison for each house.**

The comparison between the results illustrates a very small difference between the annual energy costs in different cases for each house. The energy cost difference manner is not the same for all the houses. Each house has its unique energy cost's change when the common storage is applied. For instance, for house 5, the energy cost of the house for one year is reduced when the common storage is applied, while in house 7 the amount is variable with the storage size.

However, in all the cases the building's owner energy payments do not change significantly. The minor increase in the energy cost is acceptable as in the reference case; each house owns storage that in total 80 kWh storage size could be considered for the community. However, in the community network study, smaller storage is applied. The annual energy cost may increase a bit for some houses this way but the investment cost reduces significantly, which causes a shorter payback time. This issue is studied in part B of this section.

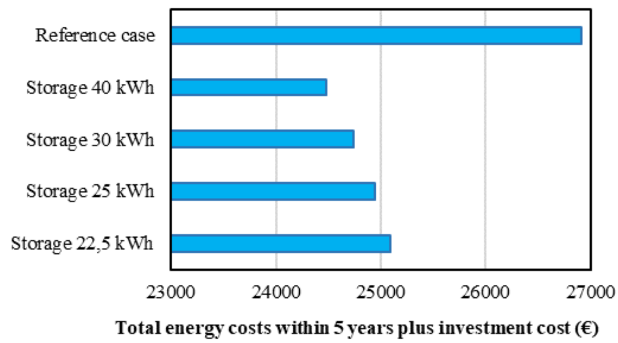

FIGURE 6. **Accumulated 5 years energy cost of the community plus the initial investment cost.**

To make the comparison more explicit accumulated 5 years energy cost of the community plus the initial investment costs for the five aforementioned cases is presented in Fig. 6. This figure shows clearly total cost difference in the reference case with the cases of common storage is significant. Besides, by the change of the storage size, this discrepancy is reduced and minimized for the storage size of 40 kWh.

B. ECONOMIC ASSESSMENT

In order to study the revenue and the payback time of the community network, the initial investment of the building owners and the savings in each case should be studied separately and be compared with the case where no storage is installed in the system at all.

To study the payback time of the discussed cases with the condition that no storage is installed in the system (13) is applied. This equation represents the net present worth of the cumulated savings that indicates the maximum allowable capital cost of the advanced power management system for each analysis period. In other words, the analysis period is an indicator of the period by the end of which the investment pays itself back. The economic viability is assessed by comparing the cumulated cost savings with the known prices of the system components.

$$S = \frac{(1+r)^n - 1}{r(1+\mathrm{r})^n} \cdot S_a \tag{13}$$

In (13), S represents the net present worth of the cumulated cost savings, Sa is the annual savings in euros, n shows the length of the analysis period in years and r is the discount rate [39], [40]. The discount rate is calculated based on the cost of the capital employed in the innovation. The typical discount rate is between 10 to 30 percent depending on the risky nature of the ventures.

TABLE 2. Payback time for different cases of the storage size in accordance to the case without any storage.

Cases	r = 0.2	r = 0.3
Reference case	2,5 years	3,6 years
Storage size_22.5 kWh	1,8 years	1,6 years
Storage size_25.0 kWh	1,74 years	1,54 years
Storage size_30.0 kWh	1,7 years	1,5 years
Storage size_40.0 kWh	1,6 years	1,4 years

Applying (13) to analyze the payback period provides an overview of the economic viability of the community network proposal in this research. The results are summarized in Table 2. In this table the payback time is tested for $r = 0.2$ and $r = 0.3$. These discount rates are considered typical values for solutions with higher risk is usually considered higher in the defined range for r.

The number of years for the community to get their investments back based on the savings that the new system has for them is variable and it is different in the reference case compared to the community network case. Table 2 clearly shows that applying the common storage results in shorter payback period and the storage size affects it only for few months. However, the difference between the reference case and the community model is up to two years. Thus, applying common storage has environmentally and financially positive benefits for the building owners of the neighborhoods that commit to shared energy consumption.

IV. CONCLUSION

The integration of renewables in residential buildings is of great importance nowadays. In future power grids, residential buildings are active participants in the power generation process and play a significant role in balancing the market supply and demand chain. To approach this system, studies should be performed from one house and be expanded to a few numbers of houses, called an energy community. In addition, at the upper level, communities are connected with each other. This research focused on the community study when common thermal energy storage is applied for a few houses instead of individual thermal storages for each house. The research analysis was implemented through optimization models for single-family home and the community. The houses and the community are considered to enhance their self-sufficiency. Also, the economic and energy assessments were conducted for the community with different-sized thermal / electric heat energy storages.

Finally, the duration curve of the community with common thermal storage was compared with that of the houses with individual thermal storage. The results represented overall less import and export energy with the grid in the community network. It was concluded that common energy storage helps to approach the nZEB definition. Also, larger storage leads to the increased numbers of non-transitional hours with the grid. Thus, the community has improved the self-sufficiency of the houses. Besides, applying common storage would benefit the community members for some savings in the initial investment costs and this provided the payback period to be shorter than the case that each house has a separate storage. According to the results of our case study, forming an energy community with the neighborhoods and sharing common thermal storage can have financially positive benefits for the building owners.

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