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Research Papers

Feasibility study of energy storage options for photovoltaic electricity generation in detached houses in Nordic climates

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A B S T R A C T

Energy storage is an emerging solution to mitigate the intermittency of solar photovoltaic (PV) power generation and includes several technologies that could also be applied in small-scale residential applications. However, energy storage systems have not yet seen wide-scale integration into the energy systems of buildings, due to the inherently high investment costs of energy storages. Nevertheless, as new EU policies suggest stricter climate targets for 2030, including proposals to increase the share of renewable energy in the building sector to 49 %, a potential widescale integration of solar PV systems combined with various energy storage technologies in many types of buildings could follow. Subsequently, this paper models the use of lithium-ion battery storage (LIB), hydrogen storage, and thermal energy storage (TES) in detached houses in southern Finland, in order to evaluate the cost-effectiveness of utilizing energy storages to enhance residential photovoltaic electricity generation.

This study found that solar PV systems without selling surplus electricity to the grid were profitable up to a renewable fraction of 10 % with 2019 market prices and up to 35 % with the 2021 unusually high market prices. The possibility of selling the surplus electricity to the grid improves the profitability further, up to a renewable fraction of 20 % with 2019 market prices and up to 50 % with 2021 market prices. Out of the examined energy storage technologies, LIB storage turned out to be the most financially feasible storage option with costs relatively close to stand-alone solar PV systems in many scenarios, whereas utilizing either hydrogen storage or TES and HP in combination with solar PV systems turned out to be multiple times more expensive than using grid electricity to power detached houses. Consequently, this paper found that integrating energy storage systems with photovoltaic power generation in individual detached houses would require either sustained high electricity market prices or subsidies to be economically viable in the Nordic climate.

1. Introduction

Increasing the share of renewable energy sources while mitigating greenhouse gas emissions has become a key challenge currently facing nations worldwide, a dilemma which is reflected in the climate targets of the European Union (EU). These climate targets mandate a 32 % renewable energy target for the union by 2030, promoting alternative renewable energy sources such as wind, solar and biomass, and have been realized through the EU renewable energy directive [1]. In addition to this, individual member states are also encouraged to set even more progressive goals, like the pledge of the Finnish government to reach carbon neutrality by 2035 [2]. In July 2021, the European Commission further proposed a mandate to adopt a more ambitious renewable energy target of 40 %, as well as to increase the share of renewable energy in residential buildings to 49 % by 2030 [1], a policy change that would increase the demand for renewables in the building sector significantly. As the building sector accounts for 40 % of the energy consumption and 36 % of greenhouse gas emissions in the EU, improving energy efficiency in buildings will play an important role in reaching European climate targets [3].

One approach to achieve a more sustainable building sector is to integrate solar photovoltaic (PV) systems more extensively into

Abbreviations: COP, Coefficient of performance; DC, Direct current; DH, District heating; DR, Demand response; EES, Electrical energy storage; EU, European Union; FC, Fuel cell; GSHP, Ground source heat pump; HP, Heat pump; IRES, Intermittent renewable energy source; LCC, Life cycle cost; LCOE, Levelized cost of energy; LCOS, Levelized cost of storage; LIB, Lithium-ion battery; O&M, Operation and maintenance; P2X, Power-to-X; PEM, Polymer electrolyte membrane; PV, Photovoltaics system; RF, Renewable fraction; TES, Thermal energy storage.

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residential buildings. While the worldwide installed capacity of solar PV systems has increased considerably as the prices of solar panels have fallen consistently over the last decade [4–6], residential buildings with solar PV systems still remain a minority in Nordic climates [7,8]. Photovoltaic power generation is directly dependent on the amount of solar irradiation available, which is affected by multiple factors, such as the time of day, cloudiness, and season. As a result, solar PV power generation is non-coincident with the energy demand of most buildings, limiting the extent of which photovoltaic power can be utilized, since with larger residential much energy PV systems would be wasted. At present, most commercially sold residential solar PV systems in Finland only yield a renewable fraction (RF) around 20 % of the building total consumption [9], mainly because solar PV systems are an intermittent renewable energy source (IRES), with very small production in wintertime.

Consequently, a number of solutions have emerged to overcome these intermittency issues. One of these solutions includes implementing energy storage systems to store the surplus electricity generated by the solar PV system during its peak production hours for use during low production hours, an approach that would effectively balance the variable power generation with the power and heat demand of the building [10]. Conversely, another option would be selling the surplus photovoltaic electricity to an existing power grid. While conveying excess electricity to the power grid would be an easy solution for the end-user, only around 1/3 of the purchase price can be obtained for the sold electricity after considering transmission costs, taxes and markups [11,12]. For this reason, it is desirable to use as much energy as possible locally, and thus, implementing energy storage systems for this purpose might be a reasonable alternative compared to discarding surplus photovoltaic electricity or selling it at a fraction of the electricity purchase price in detached houses.

Residential solar PV systems could be enhanced by employing a number of different energy storage technologies, such as electrical energy storage (EES), chemical energy storage, and thermal energy storage (TES). Examples of these technologies include Li-ion batteries (LIB) for EES, the use of fuel cells (FC), electrolysers, and hydrogen tanks for power-to-hydrogen conversion and chemical energy storage, as well as the use of water tanks or boreholes for TES [10]. Of these technologies, LIB storage has become one of the most common methods to store energy presently in buildings, largely due to the fact the technology is already mature and widely used in a number of different applications, such as electronics and electric vehicle batteries [10,13]. Another reason behind the popularity of LIB storage is the relatively high energy density and cycle life of the battery chemistry [14], which has outweighed the drawbacks associated with LIB storage, such as its high costs and limited raw material availability [15].

Conversely, in H_2 energy storage systems, excess solar power is converted to hydrogen and oxygen using an electrolyser, which can be stored and converted back to electricity at a later point with a FC. Storing electricity in an energy carrier such as hydrogen has its own advantages and disadvantages. One advantage is that H_2 energy storage is better suited for seasonal energy storage than LIB storage, since the storage size can more easily be scaled by increasing the amount of hydrogen tanks in the system [13]. Another advantage includes hydrogen being a highly versatile gas, which can also be used for a number of other purposes [16], such as in future FC powered vehicles. Some disadvantages of H_2 energy storage include the high costs of the Power-to-X (P2X) components, i.e., the electrolyser, storage tanks and FC, the low efficiency of the overall process, as well as the low volumetric density of hydrogen [14], which increases the number of H_2 tanks needed. As such, storing energy as hydrogen in small-scale applications is still in its development phase [14,17], but could become a promising alternative if hydrogen takes a more central role in sector coupling.

Furthermore, like power-to-hydrogen systems, excess solar power can also be converted to heat using various power-to-heat technologies, after which it can either be directly used for heating purposes or stored for later using TES systems [13,14]. Stored thermal energy is typically not converted back into electricity since the heat can be more efficiently used for the heating of buildings, especially when considering that heating can make up around 75 % of the energy demand in a single-family house in southern Finland [18]. For this purpose, common power-to-heat conversion methods include the use of heating resistors and heat pumps (HP), however, HPs are more commonly used in combination TES systems due to their higher power-to-heat ratio [19]. For example, a typical ground source heat pump (GSHP) with a seasonal coefficient of performance (COP) of 3.0 produces on average 3 times as much heat as the electricity it consumes throughout the year [20]. Notably, heat could also be produced directly using solar thermal collectors in combination or instead of solar photovoltaic systems [21,22]. However, this paper focuses on the comparison of implementing different energy storage and energy conversion technologies combined with solar photovoltaic generation. Furthermore, similar to the multiple available power-to-heat methods, several TES technologies also exist [13]. Of those, sensible heat storage systems, i.e., storing heat by increasing the temperature of a material, is the most mature technology for residential buildings; where using either water tanks or boreholes are the most common alternatives due to their relatively low costs compared to other TES technologies [23].

As installing solar panels becomes an increasingly popular alternative for sustainable power generation in buildings worldwide, several methods to manage their intermittency are simultaneously being promoted. For example, many companies are marketing LIB packs between 5 and 20 kWh for residential use together with solar PV systems [24,25], whereas other solutions include the use sellback of surplus solar power to the electricity grid. For instance, Helen Oy, the energy company owned by the city of Helsinki, offers spot prices for excess solar power sold to the grid to incentivize investments in solar PV systems [11]. While the consumer would only receive roughly 1/3 of the typical electricity purchase price for their sold solar power after considering both distribution costs and taxes using this approach [12], it does allow the consumer to install a larger solar PV system and to increase the sustainability of the building without much effort from the consumer, while not suffering any losses from unused solar power. Thus, comparing the costs of different storage systems with other methods that can enhance solar PV utilization in residential applications becomes an important consideration when installing a solar PV system.

Despite of the relevance of this topic, not much research has been published on the financial feasibility of residential energy storage systems, mostly due to the inherently high costs of many energy storage systems. To this end, a study from 2017 by Uddin et al. showed how there is no economic benefit from integrating LIB storage with residential photovoltaic systems even before including the costs of battery degradation [26] with the price levels at the time. Nevertheless, as solar PV system prices continue to drop and nations worldwide implement policies to reach sustainability in the building sector as part of new climate targets, energy storage systems could also quickly become relevant in small-scale residential applications. The rapid worldwide development of energy storage systems also highlights this possibility, as the costs of different storage systems fall every year. Consequently, this paper aims to evaluate the financial feasibility of employing energy storage systems in residential applications to accompany the increasing intermittent solar electricity production, which would create insight on whether these technologies could effectively be used to accelerate the transition towards a sustainable building sector.

To this end, the present study estimates the costs of integrating energy storage and P2X technologies to more efficiently utilize solar PV systems in detached houses, including LIBs, H_2 energy storage, and sensible heat storage. Based on these cost estimates, this study also assesses the potential benefits of energy storage technologies and evaluates their current financial feasibility in residential buildings. To achieve these objectives, the present paper develops a computational model to simulate the operation of such a system, to optimize the capacity of different components, as well as to determine the life cycle cost (LCC) and levelized cost of storage (LCOS) for the different energy storage methods. Furthermore, the model includes a separate demand response (DR) function to evaluate the potential impact that a DR system could have on the costs and required storage capacity of detached houses. Consequently, this paper presents different ways of combining photovoltaic energy production with energy storage, thus facilitating the integration of small-scale solar PV systems in residential buildings, while simultaneously increasing the self-sufficiency and sustainability of the building sector.

The remainder of this paper is organized as follows. Chapter 2 starts by presenting the methodology of the paper by illustrating the structure of the energy storage model, including the methods used for capacity optimization, sensitivity analysis, storage utilization and DR. Furthermore, the chapter introduces the economic indicators used to evaluate the feasibility of the energy storage systems. Afterward, Chapter 3 presents a case study with the modelled scenarios and used input values of the feasibility study, followed by results and discussion in Chapter 4. Chapter 5 then concludes the study by evaluating the financial feasibility of using energy storage systems in small-scale residential applications, while also giving suggestions for further research on the topic.

2. Methodology

To evaluate the financial feasibility of implementing energy storage systems in residential buildings in Nordic climates, the use of energy storage technologies in combination with a solar PV system was modelled for detached houses employing different heating methods in Southern Finland. The model design presented in Fig. 1 illustrates how several combinations of energy supply, energy storage, and energy demand were modelled in relation to one another. The considered energy supplies included district heating (DH), grid electricity and solar photovoltaic generation, whereas energy demand was modelled for houses with direct electric heating, DH, and HP heating as their heating method. The modelled energy storage technologies included LIB storage, H_2 storage, and TES, which were integrated into detached houses in combination with rooftop solar PV systems. These energy storages were used to store photovoltaic electricity from hours with surplus generation to hours with a production deficit, thus increasing the effectiveness of the solar PV system and facilitating a higher RF in the end-energy use of the building. Notably, the use of solar PV and energy storage systems were modelled using an hourly resolution over a 1-year period in the simulations, resulting in 8760 individual timesteps.

In this paper, the financial feasibility of LIB storage, H_2 storage, and TES was estimated through economic calculations for several scenarios, with differences in the energy supply, used storage technology and energy demand of the building. Life-cycle cost (LCC) and levelized cost of energy (LCOE) were used as the primary economic indicators in this study and were calculated for the end-energy use of the building, in addition to the levelized cost of storage (LCOS) which was calculated for each of the modelled energy storage systems.

Furthermore, to evaluate the potential synergies between DR, energy storage and PV electricity generation, the model also included different scenarios where an additional DR parameter impacted the energy demand of the building. Based on these simulations, the paper then estimated the difference in cost, RF and storage capacity utilization achieved by employing a generic DR system. Similarly, a sensitivity analysis was conducted on the discount rate employed in the economic calculations, to further determine how feasible energy storage systems would be in detached houses in Finland with other economic conditions.

2.1. Model structure

To accurately simulate the use of energy storage and solar photovoltaic panels in residential houses, the model used in this paper was developed in the MATLAB software environment. Fig. 2 illustrates the structure of this model by showing the code logic and how most of the results were derived from different from different data sources and input values. In short, the model matched the energy supply profile of a solar PV system with the demand profile of a detached house in Finland to calculate the surplus photovoltaic electricity of the application. This data was then used in combination with technical input data to calculate the required capacity of several energy storage methods, as well as to model the total energy consumption of the application for each storage method. Based on the desired size of the solar PV system, the capacity of the energy storage system, the annual energy demand of the building, as well as the LCC, LCOE and LCOS indicators were calculated for each scenario.

2.1.1. Capacity optimization and sensitivity analysis

The cost of employing energy storage systems in detached houses largely depends on the RF of the system. This is because the RF varies according to how much electricity the solar PV system generates, which again has a significant impact on the required energy storage capacity

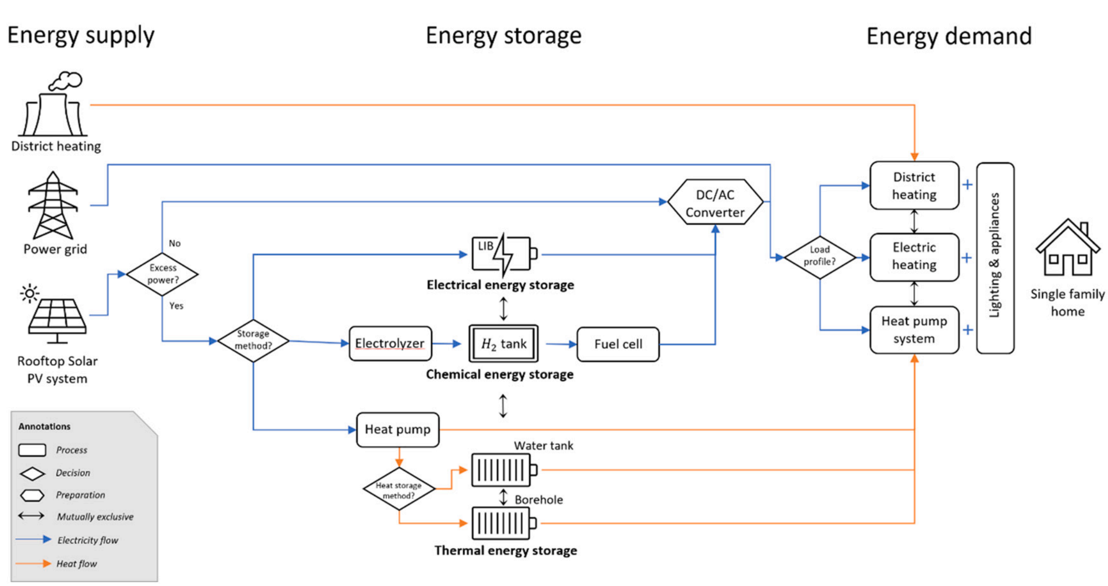

Fig. 1. Design of the feasibility model.

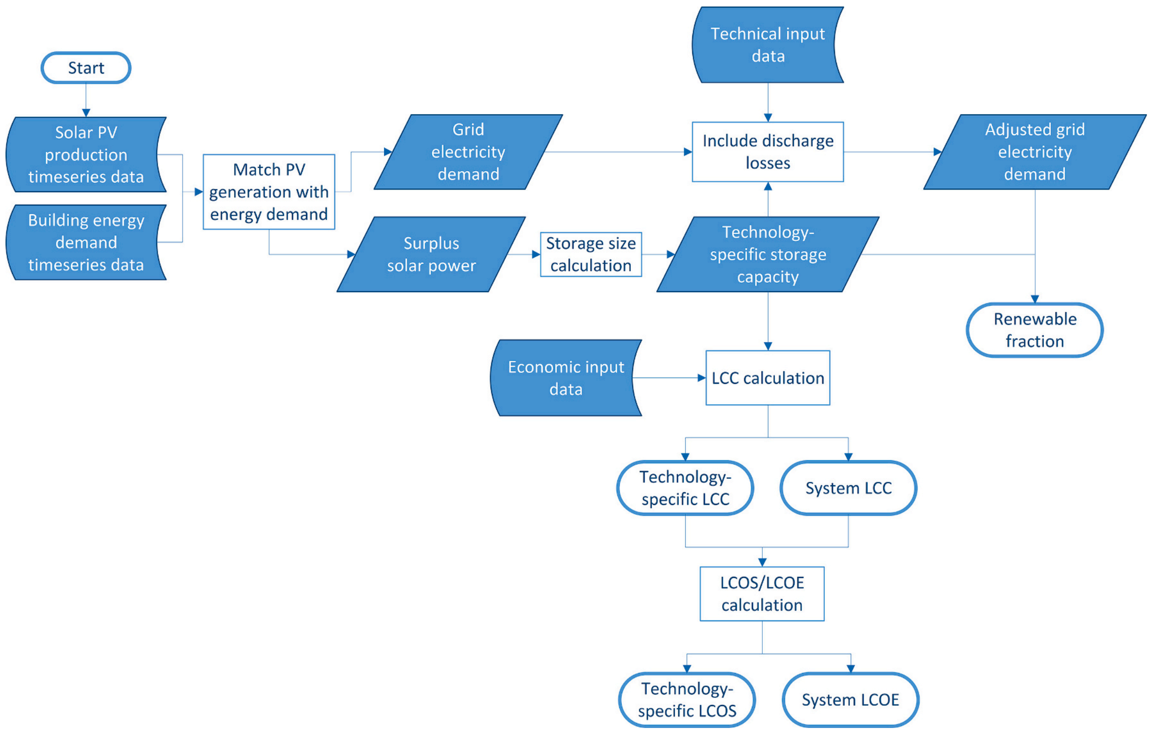

Fig. 2. Structure and logic of the MATLAB energy storage model

and the costs of the system. For this reason, the energy storage model included a function to simulate both the LCOE of the detached house compared to the RF of the system, as well as the LCOS of the storage technologies compared to their capacity, which allowed for capacity optimization of both the solar PV and energy storage systems.

Although linear optimization methods are effective at solving similar functions, a previous study on the feasibility of small-scale energy storage systems concluded that using linear optimization to determine the most optimal size of financially unfeasible storage systems is not always the best approach [27], as the optimal storage size can often be equal to the lowest allowed capacity constraint. For this reason, this study instead opted for graphical capacity optimization, illustrating how the LCOS of the storage system developed as a function of the storage capacity, and how the solar PV capacity and RF developed in relation to the LCOE of the energy use in the application. Furthermore, this function also included a sensitivity analysis, which illustrated the cost development of the modelled scenarios when calculated with other discount rates.

2.1.2. Storage utilization and impact of DR

Besides optimizing the storage capacity of the different energy storage systems, the storage utilization of the modelled system was also simulated for the various scenarios, allowing for further insight in how effectively the energy storage systems were employed. For the LIB storage system, the battery was charged during hours with surplus photovoltaic electricity and available storage capacity and discharged during hours with lower solar generation than energy demand, resulting in some surplus electricity being discarded.

However, for the H_2 and TES systems, all of the surplus electricity was utilized and stored until the next timestep with enough demand to discharge the storage. Notably, the H_2 storage also included a startup requirement for the FC component, so that hydrogen is only converted back into electricity when the energy load from the building reaches a set limit. Furthermore, the discharged electricity from the modelled storage systems was used to cover both the electricity demand of appliances and lighting, as well as any possible heating demand. Consequently, the function was able to display how the capacity level of the different energy storage systems varied throughout the year with an hourly resolution, as well as to show the average storage level over a 3-day period.

Additionally, to compare how the required seasonal storage capacity changes if the discharge conditions are altered, an alternative function was included to analyze the storage capacity of H_2 storage and TES systems when all the surplus energy instead is stored until the 4th quarter of the year. This alternative approach for discharging the seasonal storage allowed for further insight on the potential benefits of discharging all the stored energy during the colder months in Finland, when the energy use of buildings and electricity prices can be significantly higher.

Furthermore, the model also included a function to simulate the impact of a DR system on the costs and RF of a detached house with an energy storage system. DR systems may become more widespread in the coming years as they are a lucrative option to both save energy and decrease costs only by adjusting the energy demand profile of the building. Accordingly, the impact of a DR system was estimated by evaluating the effects such a system would have on the energy demand profile of the building, by shifting the energy demand of hours with low solar PV generation to hours with peak PV generation, lowering the total solar PV surplus by a selected percentage. Hence, this modelling approach would be representative of an automatic DR system installed in the detached house able to shift certain energy loads, such as the loads of heating or household appliances, between hours on a daily cycle. Subsequently, the DR function calculated the hourly storage capacity level throughout the year for two different demand response degrees and estimated the effect the DR system would have on the costs and RF of the detached house.

2.2. Economic indicators

In order to evaluate the financial feasibility of integrating energy storage systems with solar PV system in detached houses, economic indicators able to compare the costs of the different storage scenarios with one another are needed. For this purpose, this study opted to use multiple different economic indicators in the cost analysis part of this paper, such as the life cycle cost (LCC), the levelized cost of energy (LCOE), and the levelized cost of storage (LCOS) for each model scenario. Using these parameters, it was then possible to compare the financial feasibility of different energy storage options for photovoltaic electricity generation in detached houses with both houses using only grid electricity, as well as with houses connected to the grid with a solar PV system.

2.2.1. LCC

The first economic indicator, the LCC, is a frequently used indicator in several academic disciplines. It depicts the entire discounted cost of a given system over its lifetime. Hence, when estimating the costs of energy storage systems, the LCC accounts for both technical and economic parameters, including the round-trip efficiency, lifetime, capital costs and operation and maintenance (O&M) costs of each storage system. For this reason, the LCC can be a valuable indicator when seeking to estimate the total costs of an investment and can thus also be of much value in this study when comparing the costs of different energy storage systems with one another and the with the selected reference cases.

$$LCC\ [€] = Investment\ cost + \sum_{t=1}^{T}\left(\frac{O\&M\ cost + Charging\ cost}{(1+r)^t} + \frac{End-of-life\ cost}{(1+r)^{T+1}}\right) \quad (1)$$

Eq. 1 depicts how the LCC was calculated for the different scenarios modelled in this paper. Eq. 1 is comprised of the initial capital costs of the investment, the recurring costs of the system, including operation and maintenance (O&M) costs as well as possible charging costs, in addition to any residual value or end-of-life costs of the system. Notably, this paper excluded both the charging costs and the end-of-life costs when calculating the LCC for the modelled scenarios, as a lack of accurate data on the costs of employing various energy storage systems with solar PV systems in small-scale residential applications would have made comparison between storage systems unreliable.

2.2.2. LCOE and LCOS

In addition to the LCC, this study also used the levelized cost of the system, or in this case the levelized cost of storage (LCOS) and the levelized cost of energy (LCOE) as economic indicators to analyze the feasibility of energy storage systems in residential application. This is because one significant shortcoming of the LCC is its inability to forecast whether an investment will be economically successful on its own, given that it only depicts the total costs over the lifetime of a system. In short, the LCOS is defined as the discounted cost per unit of discharged energy of an energy storage system [28], and it reflects the internal average price of electricity in the system. As such, the LCOS is directly comparable to other levelized costs, such as the LCOE, which is the discounted cost per unit of energy employed in a system. Consequently, the LCOS can be used to compare the costs of an energy storage system with the costs of only purchasing electricity and can thus be used to evaluate the financial feasibility of the selected energy storage system at different price levels.

$$LCOS\left[\frac{€}{kWh}\right] = \frac{LCC}{\sum_{t=1}^{T}\frac{E_{disch}}{(1+r)^t}} \quad (2)$$

Subsequently, Eq. 2 describes how the LCOS was calculated for the different energy storage systems in this study. Eq. 2 is comprised of the total investment costs of the system, the discounted O&M costs over the lifetime of the system including charging costs, the discounted end-of-life costs including the disposal and recycling costs of the system, all divided by the discounted total discharged energy of the storage system over its lifetime. In its simplified state, the numerator of the LCOS formula is the LCC of the storage technology, and the denominator the discarded energy from the storage system during its lifetime.

The final economic indicator in this study is the LCOE, which is defined as the discounted price per unit of generated electricity for the system to break even at the end of its lifetime. Therefore, the LCOE was calculated in the same way as the LCOS, as showed in Eq. 3, but instead substituting the numerator with the LCC of system and the denominator with the discounted lifetime energy production of the system. Similar to the LCC calculations, charging costs and end-of-life costs were also excluded from the final LCOS and LCOE calculations to account for incomplete data on the costs of various energy storage systems.

$$LCOE\left[\frac{€}{kWh}\right] = \frac{LCC}{\sum_{t=1}^{T}\frac{E_{gen}}{(1+r)^t}} \quad (3)$$

3. Case study

Based on the model introduced in Chapter 2, the use of suitable energy storage methods combined with a solar PV system in detached houses was simulated as different scenarios. These scenarios were: a) a house powered by grid electricity, b) a house with a solar PV system, c) a house with a solar PV system able to sell surplus power to the grid, d) a house with a solar PV system combined with short-term battery storage, e) a house with a solar PV system combined with long-term H_2 storage, and f) a house with a solar PV system combined with a HP and a seasonal TES system. To evaluate the current feasibility of these technologies in detached houses, the scenarios were modelled using current technical and economic data for the technologies when applied in small-scale buildings. Additionally, all the modelled scenarios were simulated for grid-connected detached houses in Southern Finland, only with differences in the employed heating method, load profile, and in the size of the used solar PV system.

3.1. Energy supply and demand

While the weather in southern Finland is not as cold as that of the rest of the country, the average yearly temperature in Helsinki is still only 6.3 °C, with an average temperature below −0 °C from December to March [29]. Consequently, buildings in Finland consumed the 3rd most electricity in Europe in 2019, only after Sweden and Norway, a number largely affected by the high heating demand of buildings compared to many other European nations [30]. To accurately represent existing detached houses in Finland, the model simulated detached houses with common heating methods utilized in Finnish building, including direct electric heating, DH, and GSHP heating. Fig. 3 shows the hourly electricity load over a one-year period for a detached house with each heating method, in which the electricity needed for both appliances and lighting, as well as the electricity used for heating purposes is included.

As can be observed from Fig. 3, the electricity demand profile of a house with district heating is much lower and relatively even across the year compared to the other heating methods, as no electricity is needed for heating purposes. Conversely, houses with electric and heat pump heating follow a more seasonal demand profile with higher energy

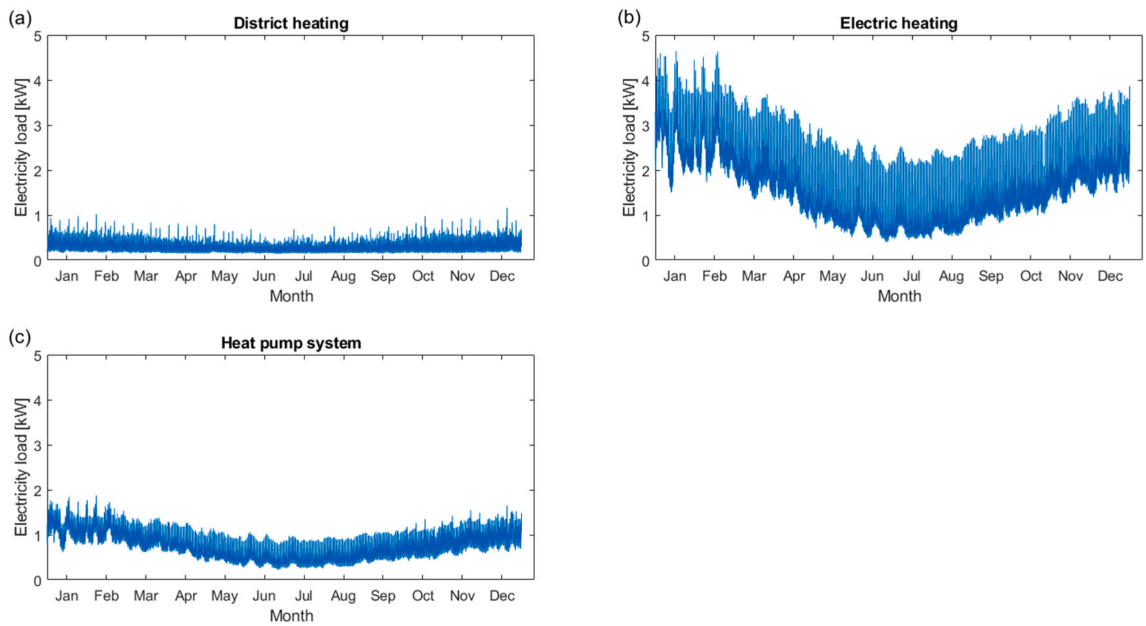

Fig. 3. Hourly electricity load profile in a detached house with a) district heating, b) electric heating, and c) a HP system.

demand in wintertime. As can be observed from Fig. 3, the electricity consumption of a house with electric heating is the highest of all the alternatives, due to the lower power-to-heat conversion efficiency of heating resistors compared to GSHP systems. Subsequently, the house with electric heating presented in Fig. 3 had a yearly energy consumption of 14,100 kWh, which amounts to a daily average energy consumption of 38.7 kWh, whereas a house with DH only had an annual electricity consumption of 2800 kWh/year, which amounts to a daily average electricity consumption of 7.6 kWh, equal to the electricity need of appliances and lighting in a detached house. Consequently, it was estimated that a house with a GSHP system with an 75 % thermal load in a Nordic climate would have an annual electricity consumption of 5600 kWh resulting in a daily average demand of 15.4 kWh [18].

Furthermore, another factor that affects the capacity and subsequently the financial feasibility of energy storage systems is the size and location of the modelled solar PV system. Thus, to simulate the use of solar PV systems in Nordic climates, the model included scenarios with both a fixed solar PV capacity of 5 kW, representative of a typical residential solar panel in Finland [9], as well as with a fixed RF of 49 % for the house, with the solar PV capacity determined accordingly. This fixed RF was selected as it is in line with the revision proposal for the EU renewable energy directive, indicative of the Union target of renewables in buildings by 2030 of 49 % [1]. Hence, the modelled results with a fixed 5 kW solar PV system can be used as a cost estimate for retrofitting existing smaller solar PV installations with energy storage systems, whereas the modelled results with a fixed 49 % RF better depict how energy storage systems can be used to enable larger solar PV systems in accordance with the current climate targets.

Fig. 4 illustrates the hourly electricity generation over a one-year period for a 5-kW rooftop solar PV system installed in a residential building in Southern Finland, calculated using a typical-year weather file representing a multi-year historical period for the location [31]. As can be observed from Fig. 4, the annual electricity generation from a solar PV is highly intermittent throughout the year, but also follows a clear seasonal profile with peak production in the summer, contrasted by little generation in the winter.

3.2. Technical parameters

Furthermore, a number of technical input parameters were employed in the model to simulate the use of energy storages and to calculate their costs. These parameters included a 4 % discount rate and a 20-year lifetime for the modelled system, constraints that could be used to describe integrating energy storage and solar PV systems in detached houses. Additionally, the grid electricity price present in the model was calculated from the hourly electricity spot prices in Finland for 2019, combined with electricity distribution costs and taxes for the Helsinki region as shown in Fig. 5. Electricity prices from 2019 were selected over other years for modelling purposes as the year historically described the hourly spot price in Finland more accurately than e.g.,

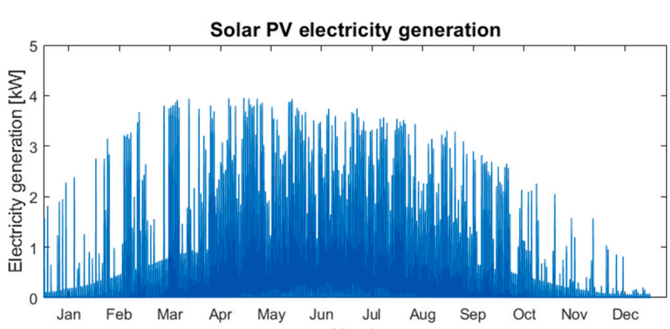

Fig. 4. Hourly electricity generation throughout the year from a 5 kW Solar PV system in a detached house in Southern Finland.

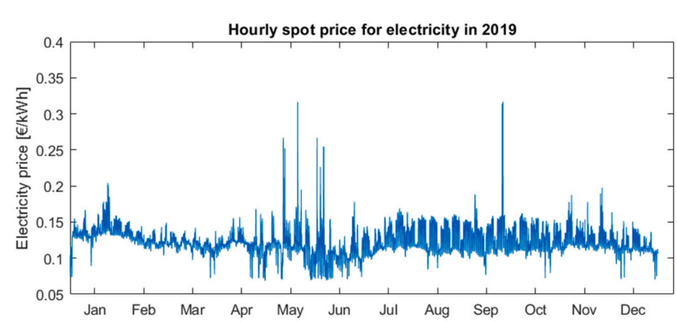

Fig. 5. Hourly spot price of electricity for Finland in 2019 (including spot price, electricity distribution fee, and tax).

2020 and 2021 [32], both years affected by the coronavirus pandemic and unusual weather [33]. Accordingly, the average electricity price employed in the model was 0.123 €/kWh, as the average spot price for 2019 was 0.044 €/kWh [32], combined a value-added tax of 24 %, a flat distribution fee of 5.51 €/month and a distribution rate of 0.041 €/kWh in the Helsinki region [34]. For the scenario where electricity could also be sold to the grid instead of using energy storage systems, hourly spot prices were used as the sellback rate, i.e., the same price that Helen, the energy company owned by the city of Helsinki, offers its customers [11].

Furthermore, the technical parameters in the model also included component specific efficiencies for the different energy storage systems. For the battery storage system, a 90 % round-trip efficiency was used, representing the use of a generic LIB [15,35]. For the H_2 energy storage system, a 30 % round-trip efficiency was used, a value that could also be lower for small-scale energy storage applications. This selected round-trip efficiency was a combination of the 75 % efficiency that can be achieved by a PEM electrolyser and the 40 % electrical efficiency of a PEM FC [35–40]. Hence, this study did not consider the possible losses or energy consumption of pressurizing and storing hydrogen, nor the possibility of utilizing thermal waste energy produced by the FC for heating purposes. Notably, the FC component in the H_2 energy storage system also included a minimum energy demand requirement of 500 W to discharge energy. Lastly, the round-trip efficiency of the TES system was set at 50 %. Although the efficiency of TES systems can reach up to 90 % for larger applications [23], a lower 50 % round-trip efficiency was selected since it more accurately demonstrates the heat losses to the surroundings of a small-scale heat storage system, such as water tank or borehole storage, with a larger surface area relative to the storage volume resulting in more heat losses. This 50 % efficiency also considered the electricity use of auxiliary devices, such as water pumps, and was estimated to be the same regardless of a water tank or borehole was used for the TES system [23]. Additionally, the HP system in the model used a coefficient of performance (COP) of 3.0, descriptive of the yearly average COP of a generic GSHP system in a Nordic climate [20].

3.3. Economic parameters

In addition to the technical parameters presented in the previous section, a number of economic input values were required to calculate the LCC and LCOS of the modelled scenarios. These cost parameters included the investment costs, operation and maintenance (O&M) costs, and the replacement costs of different technologies, as well as the estimated module lifetime of each component. End-of-life costs and charging costs were excluded from the calculations as the cost data on small-scale residential energy storage systems is inconclusive. Table 1 illustrates the used cost variables for the small-scale applications of the considered energy storage related technologies.

Out of these cost parameters, the costs of the solar PV system are roughly equal to the average market prices in Finland including inverter costs. Likewise, the battery storage costs are based on the median price of LIBs currently on the market, similarly to the FC and electrolyzer costs, which are representative of commercially available products. For the thermal energy storage, the cost estimates are derived from the costs of presently installed thermal energy storage systems in larger applications, whereas the HP costs are an estimate of the total price of installing a GSHP system in a detached house in Finland. Additionally, scenarios with DH as the modelled heating method also included the costs of the DH, which for a typical residential house in the Helsinki region includes a yearly fee of 1000€, in addition to a cost of 0.0685 €/kWh according to the heat consumption of the building [46]. Notably, the DH charge did not include the one-time fee to join the district heating network, which can be substantial depending on the location of the building.

4. Results and discussion

Section 4.1 presents the results of this study, including a cost analysis for detached houses employing energy storage systems combined with either a fixed 5-kW solar PV system, or a variable solar PV power rating corresponding to a 49 % RF in the energy demand of the building. Furthermore, the cost development compared to the RF of the various scenarios and their respective storage capacities are illustrated graphically in Section 4.2, showing both the optimal energy storage capacity for different systems and a sensitivity analysis on the used discount rate, followed by an assessment of the storage utilization and impact of demand response in Section 4.3.

4.1. Cost analysis

Table 2 presents the costs for of a detached house where the installed solar PV system has a fixed power rating of 5 kW. The scenarios presented in the table include a detached house fully powered by grid electricity (Grid electricity), a grid-connected house with a solar PV system (Solar PV), a grid-connected house with a solar PV system able to sell surplus photovoltaic electricity to the grid (Solar PV – sell), a grid-connected house with a solar PV system and a LIB storage system (LIB storage), a grid-connected house with a solar PV system with a PEM FC, PEM electrolyzer and tanks for hydrogen storage (H_2 storage), as well as a grid-connected house with a solar PV system combined with TES using either a water tank or a borehole to storage the surplus electricity as heat (TES). All the aforementioned scenarios considered grid-connected houses employing electricity rates based on hourly spot prices for 2019, with either electric heating, HP heating or DH as the primary heating method of the building. Table 2 also presented the RF in the end-energy use of the building for each scenario, as well as the RF for houses with a HP system (RF-HP), if 2/3 of the heat released by the GSHP is considered renewable, as specified in EU legislation [47].

As can be observed from Table 2, the LCC and LCOE of detached houses with a typical 5-kW solar PV system able to cover around 20 % of the building energy demand are very close to the LCC and LCOE of the reference case of a house only employing grid-electricity, with slightly higher LCOE values between 0.003 and 0.039 €/kWh. However, when any type of energy storage system is added to the house, the overall costs increase significantly in all the scenarios regardless of the used heating method. Moreover, it can be observed that the most cost-effective energy storage option is LIB storage, at 0.05–0.12 €/kWh, whereas H_2 storage and TES increases energy related costs by 0.13–0.21 €/kWh and

Table 1
Cost parameters [9,23–25,37,41–45].

Variable	Technology	Solar PV	LIB	PEM Electrolyzer	PEM FC	H_2 tank	TES	HP
Investment costs [€/kW]		1250	500[1]	1000	1700	85[2]	10[1]	20,000[3]
O&M costs [€/year]		10	10	0.085[4]	0.1[4]	0	0	0
Replacement costs [€/kW]		1250	500[1]	850	1700	85[2]	10[1]	20,000[3]
Module lifetime [years]		25	15	10	10	25	25	25

[1] €/kWh.
[2] €/kg.
[3] €.
[4] €/h.

Table 2
Renewable fraction (RF), life cycle cost (LCC), and levelized cost of energy (LCOE) for different heating methods in a detached house with a 5 kW solar PV system, including an alternative RF for the HP heating scenarios where 2/3 of the energy produced by the HP system is considered renewable, according to the EU guidelines [47].

Heating method	Electric heating			Heat pump heating				District heating		
Scenario	RF [%]	LCC [€]	LCOE [€/kWh]	RF [%]	RF-HP [%]	LCC [€]	LCOE [€/kWh]	RF [%]	LCC [€]	LCOE [€/kWh]
Grid electricity	0 %	24,570	0.128	0 %	53.5 %	11,950	0.134	0 %	29,790	0.155
Solar PV	18.2 %	26,460	0.138	25.7 %	65.5 %	15,390	0.173	37.6 %	34,340	0.179
Solar PV - sell	18.2 %	25,090	0.131	25.7 %	65.5 %	13,430	0.151	37.6 %	31,970	0.167
LIB storage	28.2 %	34,370	0.179	50.1 %	76.8 %	22,970	0.258	78.0 %	42,610	0.221
H_2 storage	22.6 %	48,720	0.254	39.2 %	71.8 %	30,220	0.339	53.6 %	62,700	0.327
TES	48.2 %	64,120	0.719	48.2 %	75.9 %	44,120	0.495	48.2 %	88,270	0.363

0.21–0.59 €/kWh, respectively. Subsequently, relying on grid-electricity for the entire energy use of the building is still the most affordable option at present when considering electricity prices from 2019 and employing a 5-kW solar PV system.

Furthermore, the results also show how the LCC of grid-connected houses with electric heating and DH are much higher than those of a heat pump. However, it should be noted that in the HP heating scenario the storage and solar PV systems are installed in a house with an existing GSHP system, and thus the LCC of a new GSHP system are only included in the scenarios with TES combined with electric heating and DH. As a consequence of the transition to HP heating, the RF of the TES scenario in houses with electric heating is also substantially higher than the RF of the reference cases, as the high COP of the GSHP system decreases the overall energy demand. Conversely, in houses with HP heating and DH, battery storage conveys the highest RF, as LIB storage has the highest round-trip efficiency of the considered storage technologies.

However, to reach the climate targets proposed in the revised EU renewable energy directive for 2035, the final renewable energy consumption of the building sector should reach 49 %, which if implemented locally in individual detached houses without considering any renewable energy from the grid, would require substantially larger solar PV systems to be installed. Notably, in this assumption we analyze that solar PV generation would cover the entire 49 % RF target, whereas renewable energy from other sources, such as heat produced by heat pumps, is not considered towards this target. Accordingly, Table 3 shows the costs obtained from modelling detached houses with a fixed 49 % RF, with a variable solar PV power rating depending on the used storage method.

The modelled results now instead show how a larger solar PV system up to 13.5 kW would be needed to meet the renewable energy demand of detached houses without energy storage, whereas a 5.1–10.8 kW solar PV would be sufficient with an energy storage system. In comparison to the previous results in Table 2, the results in Table 3 now show how the LCC and LCOE values generally increase as larger solar PV systems are implemented into the buildings. Notably, installing a 13.5 kW solar PV system in houses with electric heating and DH would cost between 0.03 and 0.06 €/kWh more than the LCOE of grid electricity, whereas in houses with a GSHP system would increase this cost to 0.10 €/kWh as the lower energy need achieved by the GSHP would lead to a higher storage need and subsequently higher costs. However, detached houses with a solar PV system able to sell surplus power to the grid remains the most cost-effective option when installing larger solar PV systems similar to the results displayed in Table 2, as installing a large solar PV system able to sell excess electricity to the grid only increased the overall LOCE of the building by 0.18–0.29 €/kWh compared ordinary grid-powered houses.

While the costs of all energy storage systems remain too high to be considered financially attractive without further support mechanisms, LIB storage is clearly the best storage alternative in all scenarios with a LCC 1000–7500 € higher and a LCOE 0.005–0.04 €/kWh higher than the costs of a 13.5 kW stand-alone solar PV system. Compared to installing a H_2 energy storage or TES system, which would increase the LCC up to 29,000 € and 52,000 € respectively compared to the solar PV scenario, combined with an 180 % – 245 % increase in the LCOE of the building, LIB storage quickly becomes the most feasible option if an energy storage system is needed in individual houses. Furthermore, it can also be observed how the costs of LIB storage and H_2 storage in houses with electric heating increase as larger storage systems are installed, whereas the LCOE for TES decreases as the initial HP investment substantially increased the LCOE of TES previously presented in Table 2.

In addition to the LCC and LCOE of the entire energy of the house presented so far, Table 4 further shows the LCC and LCOS of each modelled storage technology. The component specific LCCs for the energy storage technologies show how the LCC of each storage system contributes substantially towards the total LCC in the end-energy use of the building, as previously shown in Table 3. The LCOS values in Table 4 further emphasize this, as the relative cost of the discharged energy from the storage systems is substantially higher than the LCOE of grid electricity as presented in Table 3, regardless of the employed energy storage system, further highlighting the presently high costs of small-scale energy storage systems.

4.2. Capacity optimization and sensitivity analysis

Furthermore, this section presents results on the capacity optimization of this paper, as the previous cost analysis did not consider the

Table 3
The life cycle cost (LCC), levelized cost of energy (LCOE), solar PV size, and storage system size for different heating methods in a detached house with a 49 % RF in its energy demand covered by PV production.

Heating method	Electric heating				Heat pump heating				District heating			
Scenario	LCC [€]	LCOE [€/kWh]	PV size [kW]	Storage size [kWh]	LCC [€]	LCOE [€/kWh]	PV size [kW]	Storage size [kWh]	LCC [€]	LCOE [€/kWh]	PV size [kW]	Storage size [kWh]
Grid electricity	24,570	0.128	–	–	11,950	0.134	–	–	29,790	0.155	–	–
Solar PV	35,490	0.185	13.5	–	20,630	0.231	9.6	–	36,160	0.188	6.5	–
Solar PV - sell	29,500	0.154	13.5	–	16,050	0.180	9.6	–	32,880	0.171	6.5	–
LIB storage	43,200	0.225	8.7	17.4	22,670	0.254	4.9	9.8	37,080	0.193	3.1	6.3
H_2 storage	64,610	0.337	10.8	690	36,500	0.409	6.2	1280	59,380	0.309	4.6	4920
TES	64,220	0.335	5.1	3110	44,220	0.496	5.1	3110	88,360	0.461	5.1	3110

Table 4
The LCOS for LIB storage, H_2 storage and TES in detached houses with a 49 % RF in its energy demand employing different heating method.

Heating method	Electric heating			Heat pump heating			District heating		
Scenario	LCC [€]	LCOS [€/kWh]	Storage size [kWh]	LCC [€]	LCOS [€/kWh]	Storage size [kWh]	LCC [€]	LCOS [€/kWh]	Storage size [kWh]
LIB storage	17,510	0.453	17.4	9922	0.461	9.8	6414	0.517	6.3
H_2 storage	35,240	1.270	690	21,640	1.320	1280	26,340	4.350	4920
TES	51,100	2.540	3110	31,100	1.540	3110	51,100	2.540	3110

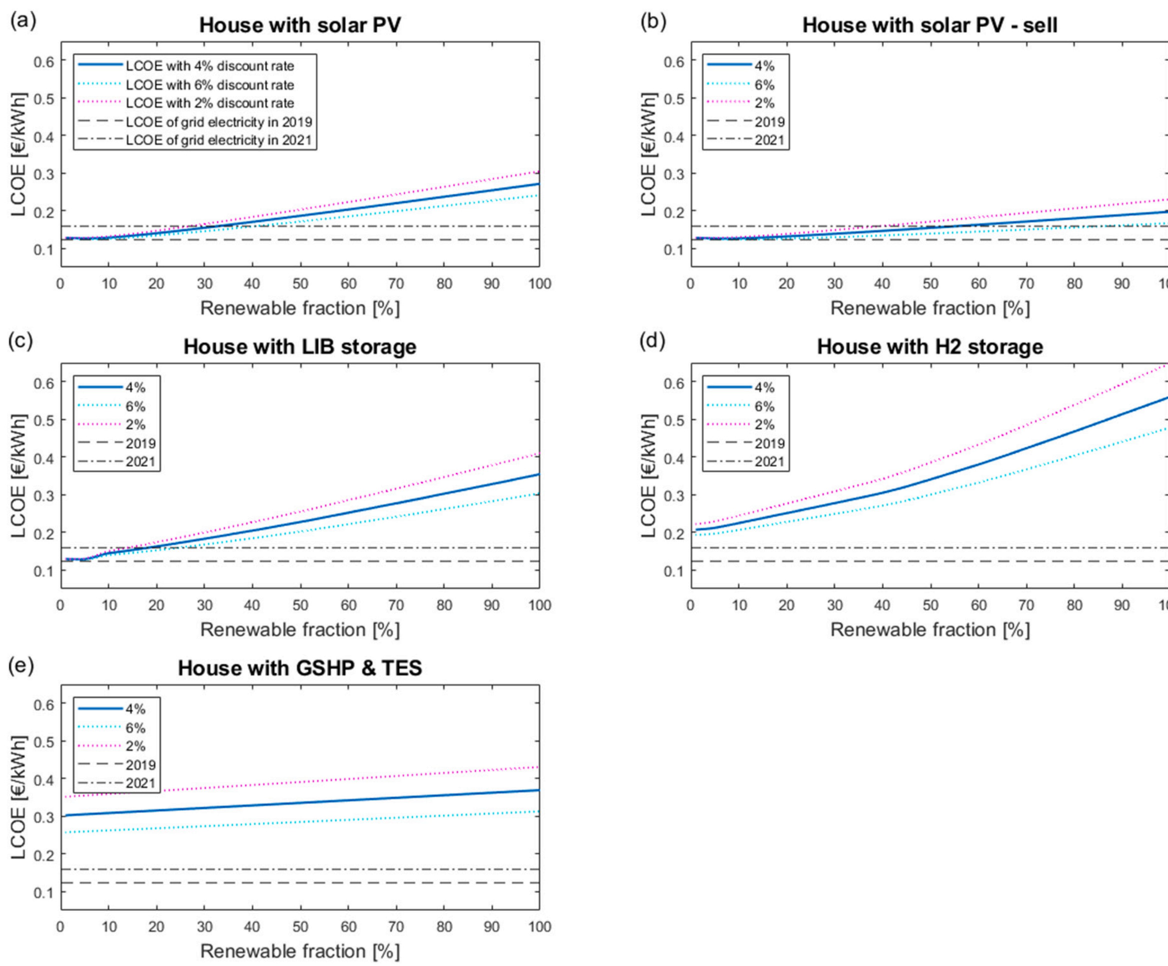

Fig. 6. The LCOE as a function of the RF of the end-energy use in a detached house with electrical heating with a solar PV system combined with different storage technologies with a) a solar PV system, b) a solar PV system able to sell excess electricity to the power grid, c) a solar PV system combined with LIB storage, d) a solar PV system combined with H_2 storage, and e) a solar PV system with a GSHP and TES system.

optimal size of the solar PV system or the optimal storage capacity to minimize the costs of the system. However, since the results in Table 2 and Table 3 show how the energy storage systems are not currently cost-effective solutions to reduce the intermittency of residential solar PV systems, linear optimization would not necessarily be an effective approach in determining the optimal system size, as the minimum costs would be situated at the minimum size constraints of the system in most scenarios. For this reason, this paper instead conducted a graphical analysis on the optimal RF and capacity of the employed energy storage systems, as illustrated in Fig. 6 and Fig. 7, including a sensitivity analysis on the used discount rate.

Accordingly, Fig. 6 illustrates how the LCOE of the end energy consumption of the modelled detached house with electrical heating develops compared to the RF of the system, whereas Fig. 7 illustrates the LCOS compared to the capacity of LIB storage, H_2 storage, and TES with a fixed 49 % RF. The LCOE of grid electricity based on the hourly spot prices in 2019 and 2021 is also included in the F igures, which is shown as the two black lines. Furthermore, Figs. 6 and 7 also include the results of the sensitivity analysis with two different discount rates, which is illustrated as the colored dotted lines. Hence, the cost developments presented in Fig. 6 and Fig. 7 allow for the optimal capacity of energy storage systems to be determined graphically, while also illustrating the costs of larger systems with more functional properties.

The LCOE as a function of the RF of the system presented in Fig. 6 supports the previous conclusions in Section 4.1, as the LCOE increases significantly as the solar PV system size and storage capacity is increased regardless of the employed energy storage technology. Fig. 6 c) shows how the costs of a battery storage system increases rapidly when combined with a larger solar PV system in a small application with a fixed energy demand, as a much larger LIB is needed to store the increasing amounts of excess electricity produced by the solar PV system. Fig. 6 d) and e) illustrate how the LCOE in a detached house with a H_2 storage or TES system is generally much higher than in other scenarios. Additionally, it can be observed that the LCOE development of the TES

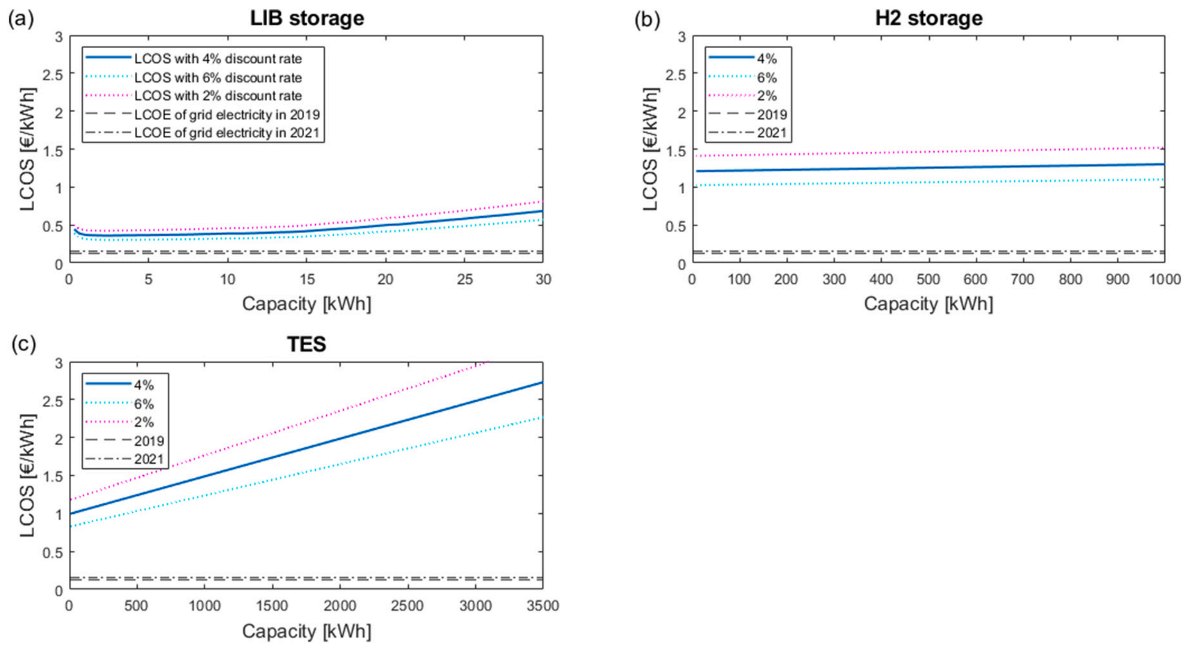

Fig. 7. The LCOS as a function of the storage capacity of the battery storage (a), hydrogen storage (b) & thermal energy storage systems (c) in a detached house with electrical heating with a solar PV system with a constant 49 % RF in its end-energy use.

system starts at a substantially higher level compared to the H_2 storage system, as the initial investments including a GSHP system increases the overall costs. However, as the RF and storage capacity of the system increases, TES becomes the more affordable option as H_2 storage comes with higher reoccurring costs.

Likewise, Fig. 6 a) also shows how the LCOE of a rooftop solar PV system increases with as the PV system becomes larger, as more and more surplus solar PV cannot be utilized during peak generation hours. While the ability to sell surplus electricity to the grid notably lowers the overall costs when comparing Figs. 6a) and 6b) with one another, the low sellback price of electricity limits the effectiveness of this approach. Hence, the optimal capacity of all the energy storage systems is zero, whereas the feasible solar PV size is limited to below 20 % when using the 2019 electricity prices as comparison. However, if the results are compared to the higher electricity prices of 2021, solar PV systems with a renewable fraction up to 50 % would be economically feasible by selling excess electricity to the grid. With 2021 electricity market prices, also a battery storage would be economically beneficial up to a renewable fraction of about 20 %. Furthermore, Fig. 6 also shows how increasing the discount rate from 4 % to 6 % increases the profitability of energy storage systems, as higher rates of return can be expected from the investments, whereas a lower discount rate of 2 % results in a higher LCOE in the energy use of the detached house in all of the scenarios.

While Fig. 6 presented much insight into the LCOE of detached houses with energy storage system at different RF values, the modelled results were comprised of values in which both the solar PV size and energy storage capacity increased significantly. Thus, to examine the technology specific cost development of each energy storage method, Fig. 7 shows how the LCOS for LIB storage, H_2 storage, and TES changes as the storage capacity is increased. As can be observed from Fig. 7, the LCOS presented further supports the previous conclusions in this chapter regarding the low-cost effectiveness of energy storage systems at present price levels, as all of the storage technologies have a LCOS significantly higher than the price of electricity. While LIB storage clearly remains the most feasible energy storage technology with a LCOS of 3–5 times higher than the LCOE of grid electricity, the LCOS of the discharged energy from the H_2 storage and TES system is between 5 and 20 times higher than that of grid electricity.

In contrast to the cost development presented in Fig. 6 d) and 6 e), the LCOS of H_2 storage increases at a lower rate than the LCOS of TES in Fig. 7. This is because only additional hydrogen tanks need to be added to increase the capacity of the H_2 storage, as the dimensions of the fuel cell and electrolyser can be kept the same as the solar PV capacity is not increased. On the contrary, the total volume of the TES system has to be increased to reach a larger storage capacity, which would require a larger water tank to be installed or the drilling of more boreholes to store the energy, resulting in a higher relative increase in the LCOS. Similar to the sensitivity analysis presented in Fig. 6, employing a higher discount rate also decreases the LCOS of each storage technology as illustrated in Fig. 7, and increases the LCOS at lower discount rates, however, not enough to make substantial impact on the cost-effectiveness of the storage technologies.

From these results, we can see that selling surplus photovoltaic electricity to the grid is the best alternative to mitigate the intermittency of solar PV systems in individual household and would be an effective approach that could be implemented right away. Conversely, employing energy storages for this purpose is still very costly at current price levels, but could become a lucrative alternative in the near future as a result of higher electricity prices, considering the wholesale electricity price in Finland reached an all-time high in December 2021 [33]. Similarly, we can see that seasonal storage systems would be more cost-effective if utilized in larger energy communities where the initial investment cost of the system can be shared.

An interesting possibility for further research would be using solar thermal collectors in combination with TES in small-scale residential applications, as direct heat production would increase the efficiency and reduce the complexity of TES systems substantially [21,22]. For instance, Hirvonen et.al have shown that a combination of solar thermal collectors, solar PV systems and TES could achieve a RF close to 90 % in Finnish detached houses with life cycle costs of 250–480 €/m^2 when implemented in community sizes [48]. Additionally, the use of other TES methods, such as of phase change materials, could be explored further, as sensible heat storage systems, such as water tanks and boreholes, are not the most efficient TES methods available despite their lower cost and common usage in many TES applications. Future research could also consider utilizing waste heat produced by the FC, to improve the low round-trip efficiency of the H_2 storage system and subsequently make H_2 storage more cost-efficient.

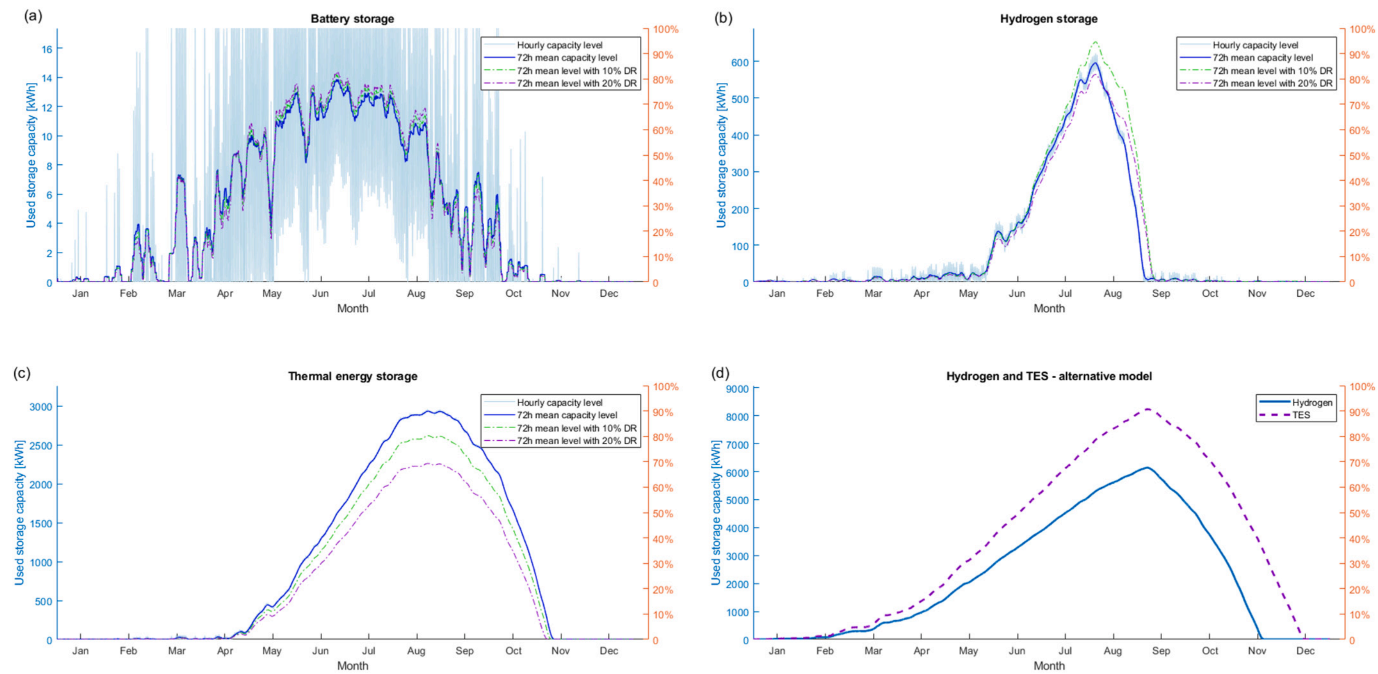

Fig. 8. Storage capacity utilization of a) the used LIB storage system, b) the H_2 storage system, c) the TES system, and d) the H_2 and TES systems calculate with an alternative method for a detached house with electric heating and a 49 % RF in its energy use. Additionally, the capacity level of each storage method with a DR system is shown in each figure.

4.3. Storage utilization and impact of demand response

To further analyze the capacity optimization of the different energy storage technologies and to evaluate the impact of demand response system in the detached house, this paper also included a model on the utilized storage capacity for each energy storage technology. Subsequently, Fig. 8 illustrates the hourly capacity level of the LIB storage, the H_2 storage and TES, in addition to the 72-h mean storage capacity level for the aforementioned storage technologies, as shown in Fig. 8 a) – c). Furthermore, Fig. 8 also includes the 72-h mean storage capacity level with a 10 % and 20 % demand response degree for the different energy storage systems over 1 year, whereas Fig. 8d) shows the seasonal capacity level of the H_2 and thermal energy storage systems using an alternative method, where the stored energy is only released in the colder months of the year, with higher heat demand and spot electricity prices. In Fig. 8, the x-axis shows the month of the year, while the left and right y-axes show the used capacity in kilowatt hours and percentages, respectively.

The hourly capacity usage of the battery storage system in Fig. 8 a) shows how even though the battery storage is charged until its maximum capacity during several timesteps during the year, with additional excess electricity being discarded due to the limited capacity of the LIB, most of the annual excess solar energy is still captured and stored in the LIB. This observation is also in line with the previous results in Section 4.2, where Fig. 7 shows how the costs of the battery storage system only reach feasible levels as the storage capacity is limited, with some excess solar power being discarded.

Furthermore, compared to daily discharge cycle of the battery storage system, the capacity usage of the seasonal storage develops more linearly, with the overall capacity increasing throughout the summer months before being discharged later in the year. It should also be noted that some energy is still discharged throughout the entire year during timesteps where the hourly energy demand is above the minimum discharge constraint. This significantly lowers the needed storage capacity compared to a model where the stored energy is only discharged in the colder months of the year, as shown using an alternative model (Fig. 8 d). Consequently, this alternative method for seasonal energy storage does not appear to be a reasonable approach to store energy as the costs resulting from the required storage capacity would outweigh any slight benefits achieved from only discharging stored energy during colder months at higher electricity prices.

Additionally, Fig. 7 also illustrates the potential impact that a DR system could have on the required storage capacity level, by including scenarios with 10 % DR and 20 % DR in the plotted figure. These DR percentages indicate the percentage decrease in peak solar PV production, which would be lowered by shifting some of the electricity load from hours with low solar generation to hours generating the most photovoltaic electricity. It can be observed from Fig. 8 that a 10 % or 20 % DR system would substantially decrease the require storage capacity of the TES system, as less surplus photovoltaic electricity is available to be stored. However, the same DR system does not decrease the required H_2 storage capacity, and surprisingly, even increases the total capacity slightly (Fig. 8 d). This is because the DR system shifts surplus photovoltaic electricity from peak generation hours to other timesteps during the day, simultaneously reducing the number of hours each day during which the FC can discharge energy from H_2 storage, as the minimum energy demand to meet the discharge requirement of the FC is not met as frequently.

Table 5
Impact of a demand response system on the LCOE and the required solar PV capacity to reach a 49 % RF in the energy use of a detached house with electric heating.

Scenario	Demand response, 10 % LCOE change [%]	Demand response, 10 % PV size change [%]	Demand response, 20 % LCOE change [%]	Demand response, 20 % PV size change [%]
Grid electricity	0.0 %	0.0 %	0.0 %	0.0 %
Solar PV	−7.0 %	−7.5 %	−7.0 %	−14.0 %
Solar PV - sell	−4.7 %	−7.5 %	−4.7 %	−14.0 %
LIB storage	−3.2 %	−3.7 %	−3.2 %	−7.0 %
H_2 storage	−3.4 %	−4.4 %	−3.4 %	−8.4 %
TES	−6.1 %	−4.5 %	−6.1 %	−8.6 %

Nevertheless, a DR system would still have a significant impact on the overall costs and energy consumption profile of the building in most scenarios, as shown in Table 5. More precisely, Table 5 presents the percentage change in the LCOE and required solar PV size to meet the 49 % RF target of proposed by the EU, with either a 10 % or 20 % demand response degree for detached houses with electrical heating. Notably, it can be observed that both the LCOE and required PV size to meet the set RF target decrease as a higher DR degree is employed in the mode, as more energy demand is shifted to hours with surplus solar PV generation. Although the LCOE decrease is only a few percent in most of the scenarios as the LCOE is comprised of several factors, implementing a DR system still had a positive impact in all scenarios, with notable benefits especially in the TES and solar PV cases.

5. Conclusion

This paper evaluated the costs of integrating LIB storage, H_2 storage and TES into detached houses with a solar PV system in southern Finland, as energy storage systems are emerging as a potential solution to mitigate the intermittency of residential solar PV systems. For this purpose, a computational model was developed to simulate the energy demand, supply and storage need of detached houses for a number of scenarios, with differences in the employed heating method, the storage technology used and renewable power generation.

This study found that energy storage systems without any economic support mechanisms require high electricity markets prices to be profitable with solar PV systems in detached houses in Nordic climates, as the LCC and LCOE of such applications are substantially higher due to high capex costs of the energy storage systems. Solar PV systems without selling surplus electricity to the grid were profitable up to a renewable fraction of 10 % with 2019 market prices and up to 35 % with the 2021 unusually high market prices. The possibility of selling the surplus electricity to the grid improves the profitability considerably further, up to a renewable fraction of 20 % with 2019 market prices and up to 50 % with 2021 market prices. It was also shown that out of the considered energy storage technologies, LIB storage is the most financially feasible storage technology in small-scale applications with a LCOE close to the that of solar PV systems in some scenarios. With 2021 electricity market prices, also a battery storage would be economically beneficial up to a renewable fraction of about 20 %. Both H_2 storage and TES turned out to be economically unfeasible option to integrate into individual detached houses with solar PV systems, as the costs of these technologies far exceeded their benefits.

Moreover, sensitivity analysis showed that a discount rate increase from 4 % to 6 % would improve the expected rate of return for all the applications notably, but not adequately to make seasonal energy storage systems cost-effective for unsubsidised use in detached houses. Additionally, this paper showed how the most cost-effective storage approach for seasonal storage systems requires the stored energy to be discharged at the first possible timestep, to minimize to required storage capacity and costs of the system, as seasonally storing large quantities of excess photovoltaic power in individual houses for use during months with high energy prices increased the required storage size and costs excessively.

Consequently, this paper concludes that some type of change in either technology costs, electricity prices or policy execution is required if residential buildings are to reach a 49 % RF in their end-energy use by integrating solar PV and energy storage systems by 2030 in accordance with the EU guidelines, when not considering renewable energy supplied by the electricity grid. For example, in order to make solar PV systems with integrated LIB storage a cost-effective alternative for detached houses with various heating methods while reaching a 49 % RF in the end-energy use of the building, the LCOE of grid electricity would need to be increased from approximately 0.13 €/kWh in 2019 to at least 0.26 €/kWh, whereas H_2 storage and TES systems with HP would require the levelized cost of grid electricity to reach between 0.3 and 0.5 €/kWh or higher to be feasible.

Another approach to reach a higher RF in residential buildings could be employing energy storage in a community scale instead, where the high capex costs of energy storages can be shared between multiple households. Future research could also calculate the costs of energy storages with other electricity prices, as all detached houses do not necessarily use spot prices for their electricity contracts, and as the price of electricity has varied substantially in the Nordic spot market recently. Additionally, future research could consider energy storages in other building types, as the EU climate targets encompasses the entire building sector. For example, the overall costs could be quite different for applications such as apartment buildings, office buildings or public and communal spaces, as these buildings have different load profiles combined with a higher energy demand. Similarly, also other geographical locations in the Nordic countries could be considered, as the cost of energy and energy consumption vary between countries.

CRediT authorship contribution statement

Johannes Hyvönen was the main author, who created the model, performed the calculations, and wrote the paper. Concept planning was done jointly by all authors. Comments and review were conducted by Annukka Santasalo-Aarnio and Sanna Syri.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

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