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Feasibility evaluation of hydrogen as seasonal energy storage for energy-neutral neighborhoods

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ABSTRACT

The decarbonization of the European Union energy sector is associated with large-scale integration of renewable energy sources (RES) and a transition toward decentralized electricity supply architectures. While residential energy storage systems (ESS) based on electrochemical batteries enable short-term balancing of renewable generation, their limited energy capacity and high cost make them unsuitable for seasonal energy storage, leading to significant curtailment of renewable energy production. Hydrogen-based energy storage is considered a promising alternative due to its high specific energy capacity and suitability for long-term storage, despite low round-trip electrical efficiency and infrastructural challenges. This paper evaluates the feasibility of hydrogen technologies for electrical energy storage in RES-based residential power systems in Estonia. The analysis is based on a real Estonian household dataset and considers metrics such as near-zero energy consumption, grid-support capability, and RES energy utilization. A comparative assessment of daily and seasonal ESS configurations together with a techno-economic comparison of battery and hydrogen-based storage systems is performed. Special attention is given to the utilization of waste heat generated during hydrogen-to-electricity conversion for residential heating, which is identified as a key condition for achieving economic feasibility and improving overall system efficiency.

Introduction

The decarbonization of the EU energy sector is a cornerstone of achieving climate neutrality by 2050, as established by the European Climate Law [1]. Guided by the European Green Deal, the EU aims to cut net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels [2]. The Renewable Energy Directive (EU) 2018/2001 [3] further supports this transition by promoting the large-scale deployment of renewable energy sources (RES).

Deep penetration of RES into electric public grids should be accompanied by a transition from a centralized to a decentralized principle of electricity supply, which is supported by the installation of an energy storage system (ESS). An ESS is intended for compensating fluctuations of RES generation and is based on lead-acid or lithium-ion technologies. Considering the cost and specific energy capacity limitations, a modern electrical ESS can balance the system from several hours to several days and is not intended for balancing seasonal weather variations [4]. Therefore, in power supply systems based on RES, a considerable portion of the generated energy remains unused locally [5].

This issue is particularly important for the residential sector, where each household with renewable energy technologies can become a prosumer – both a producer and consumer of electricity [6]. By integrating distributed generation with residential-scale energy storage, households can help balance the overall power system, reduce peak loads, and enhance local energy resilience. In this way, widespread adoption of RES at the household level contributes to the formation of a decentralized electricity supply architecture, strengthening system flexibility and resiliency, and reducing dependence on centralized generation sources [7].

In this context, the concepts of a near-zero energy building (nZEB) and a zero-emission building (ZEB) are playing an increasingly important role as

integral elements of decentralized energy systems. nZEBs are designed to achieve a balance between annual energy consumption and on-site renewable energy generation, typically through photovoltaic (PV) systems, often combined with local energy storage and intelligent energy management [8]. By minimizing energy demand through advanced building construction, high-efficiency systems, and smart control strategies, nZEBs aim to significantly reduce reliance on external energy supply while increasing the self-consumption of locally generated renewable electricity [9].

However, achieving an annual net-zero balance does not eliminate the inter-seasonal mismatch between renewable generation and demand. In residential nZEBs dominated by rooftop PV arrays, electricity production typically peaks in summer (particularly in the Nordic climate zone), while electrified space-heating demand (heat pumps, resistive backup) increases in winter, leading to summer surpluses and winter deficit, which can substantially increase seasonal variability of net demand [10]. While local electric batteries can be effective for daily shifting, the seasonal component remains the most challenging and requires medium-/long-duration storage and system-level flexibility measures [11]. Addressing inter-seasonal imbalance motivates the integration of seasonal storage options (e.g., hydrogen-based power-to-gas-to-power or seasonal thermal energy storage) and coordinated operation / energy sharing at the community or district level [12,13].

Despite its potential, the state-of-the-art hydrogen storage technology for electrical energy faces several significant limitations, primarily due to its low round-trip electrical efficiency of 25–40% and the high energy demand for compression or liquefaction. Safe storage requires specialized high-pressure or cryogenic systems because hydrogen has low volumetric energy density and can leak through materials or cause embrittlement, while large-scale deployment also demands costly new infrastructure. Additionally, fuel cells used to convert hydrogen into electricity experience gradual degradation, which further reduces overall system reliability and economic feasibility [14].

This paper examines the feasibility of hydrogen for electrical energy storage in residential power systems in Estonia through the development of evaluation metrics for near-zero consumption, grid-support capability, and RES utilization. To design efficient seasonal hydrogen energy storage, a comparative techno-economic and infrastructural assessment of daily and seasonal storage configurations is performed, including the round-trip efficiency of the conversion cycle and the compatibility with distributed generation. Particular attention is given to hydrogen's potential as a long-term energy storage solution capable of enhancing an nZEB household's energy autonomy and system flexibility under the conditions of the Estonian energy market and local climate characteristics.

Daily and seasonal cycles of balancing and grid-support functions provided by household-level power supply systems

Regardless of whether the power supply is centralized or decentralized, the grid must include maneuverable capacities that can be quickly connected to or disconnected from the network to balance generation and consumption. In centralized networks, this function is typically performed by fossil-fuel thermal power plants. Meanwhile, a universal and environmentally friendly method of balancing both centralized and decentralized grids is the use of an ESS. Nowadays, electric batteries are widely used for this purpose.

ESS is a key element in the transition from a centralized power-grid concept based on high-power fossil-fuel power plants to distributed power generation based on RES [15]. The implementation of ESS helps increase the share of RES and ensures sustainable and resilient operation of the power grid. Moreover, increasing the capacity of ESS provides grid-support functions during peak consumption hours and allows for the gradual reduction of the peak power of centralized high-power plants [16]. Under these conditions, energy from centralized sources is used whenever the household's local grid lacks sufficient power. Therefore, an intermediate goal in the transition to distributed power supply is achieving the near-zero consumption, where the average amount of energy drawn from the central grid over a given period is equal to zero [17]. It is desirable for such a system to include additional capacity that can be dispatched upon request from the central grid during peak-load hours, thereby providing ancillary services.

The period of zero consumption should naturally follow the power generation and consumption cycles: daily in the short-term perspective and annually in the long-term perspective. The principle of near-zero consumption in short- and long-term perspectives is illustrated in Fig. 1.

Effective power grid balancing with achieving near-zero consumption and grid-supporting function is shown in Fig. 1a for daily balancing and in Fig. 1b for annual balancing. Near-zero annual energy consumption can be achieved using a high-capacity ESS capable of utilizing all generated RES energy. During peak-load hours, the ESS can supply energy to the centralized power grid, thereby supporting grid stability. Conversely, during nighttime periods with surplus energy in the centralized grid, the ESS can operate as an additional controllable load. In the case of insufficient ESS capacity, periods of low renewable generation, such as reduced PV output during winter, require peak-hour energy demand to be supplied by the power grid, thereby increasing grid loading. Conversely, during periods of maximum RES generation, surplus energy cannot be fully utilized and is therefore curtailed, as shown in Fig. 1c,d.

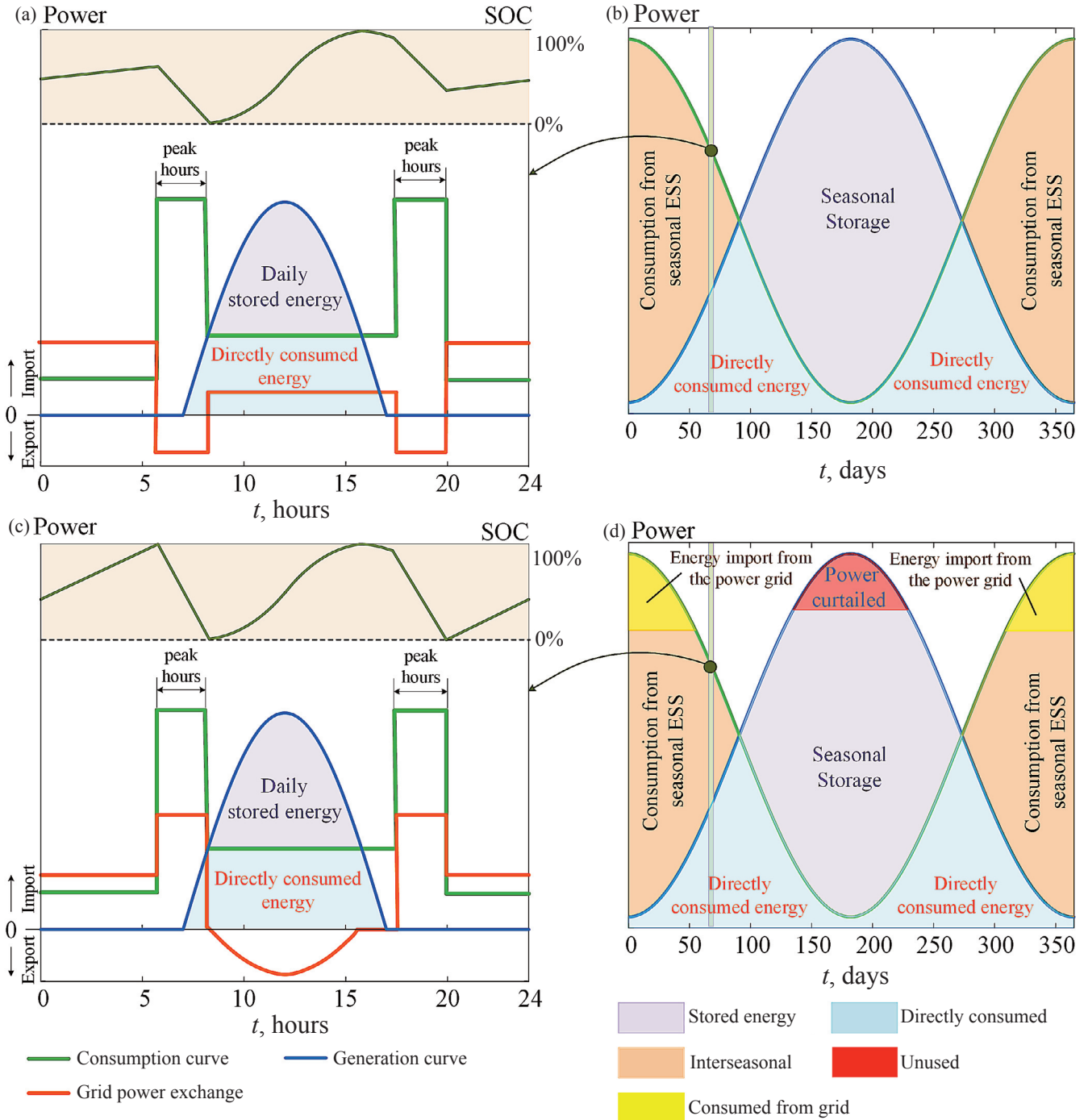


Fig. 1. Principle of grid balancing: (a) daily balancing with high-capacity ESS, (b) annual balancing with high-capacity ESS, (c) daily balancing with low-capacity ESS, and (d) annual balancing with low-capacity ESS.

Power system design for daily and annual energy balancing

The design aspects of a residential power system with balancing and grid-support functions are analyzed using real consumption and generation datasets from a grid-connected household equipped with a PV array [18]. The energy flow data are obtained using two Camile Bauer PQ1000 electricity meters [19], as illustrated in Fig. 2. Household electricity demand is supplied jointly by the power grid and the PV system.

The analyzed configuration does not include a physical energy storage system and instead uses the power grid as a virtual storage, which has a negative impact on grid operation, particularly during peak-load periods. Moreover, due to seasonal variations in energy generation and consumption, this configuration imposes additional stress on the grid during winter, when generation is minimal and consumption is at its maximum. In contrast, during summer periods, PV-generated energy may remain partially unused to avoid grid destabilization. Logged data illustrating electricity consumption and generation in June and January, which support these observations, are shown in Fig. 3a and Fig. 3b, respectively.

As shown in Fig. 3a, PV generation is drastically reduced during the winter period, while power consumption remains high due to the increased electricity demand of the household heat pump for space heating. Consequently, a significant negative energy imbalance with respect to the power grid occurs during this period. In contrast, during June the situation is reversed: high PV generation combined with low household consumption results in a predominantly positive energy balance with the grid. Due to such imbalances, a power system without an ESS can be connected to a centralized power grid only at low levels of RES penetration, typically up to 10–15% [20]. For higher shares of RES, an ESS is required to redistribute generated and consumed energy, thereby reducing the energy exchange with the power grid.

To assess the positive impact of the ESS on the power grid, including grid-support operation and near-zero grid electricity consumption, a numerical evaluation of these options should be performed.

The near-zero consumption ratio N_{zc} is estimated as the integral of the difference between the generated P_{gen} and the consumed P_{con} , normalized by the consumed power P_{con} :

$$N_{zc} = \frac{\int (P_{gen}\eta_{en} - P_{con})dt}{\int P_{con}dt}, \quad (1)$$

where η_{en} is the energy conversion efficiency, $\eta_{en} = 0.95$.

For the short-term analysis, a daily integration time interval is used, whereas an annual period is considered for the long-term analysis.

A positive value of N_{zc} indicates near-zero energy consumption and the ability of the system to support the grid. If the annual value of N_{zc} is negative, the power system does not generate sufficient

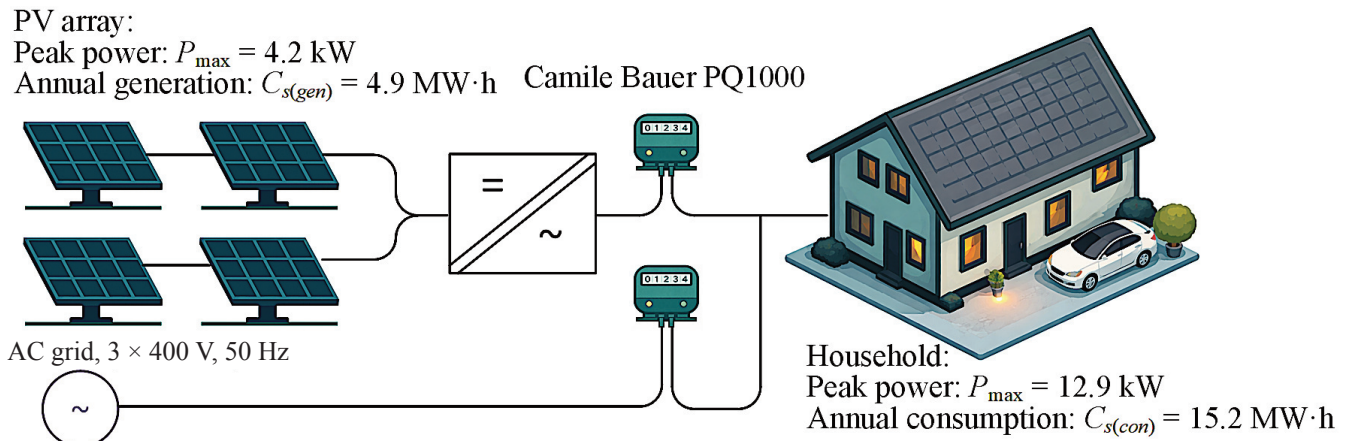


Fig. 2. Generalized representation of the tested household's power electric system.

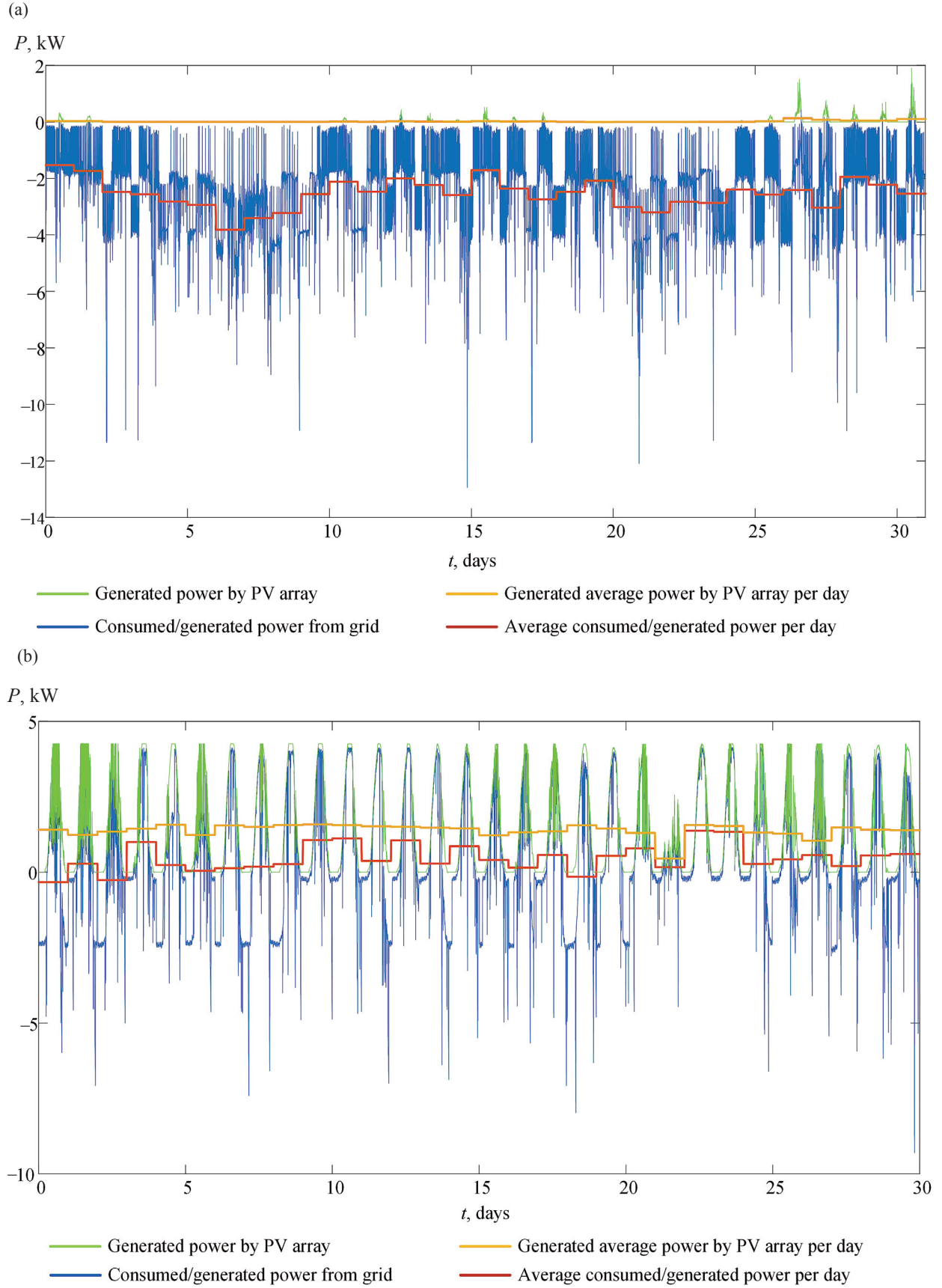


Fig. 3. Logged consumption and generated power with their averaged curves: (a) for January and (b) for June.

renewable energy to achieve an annual nearly zero energy balance. In this case, the RES-generated power from the reference dataset P_{gen} needs to be scaled by a factor k_{sc} to obtain a slightly positive corrected value of N_{zc_b} , $N_{zc_b} = 0.05-0.1$:

$$k_{sc} = \frac{N_{zc_b} + 1}{N_{zc} + 1}. \quad (2)$$

The grid supporting capability index N_{gs} may be assessed by normalizing the average grid power P_g during peak-load intervals t_p with respect to the average consumed power per day over the interval t_d :

$$N_{gs} = \frac{\frac{1}{t_p} \int_{t_p} P_g dt}{\frac{1}{t_d} \int_{t_d} P_{con} dt} = \frac{\frac{1}{t_p} \int_{t_p} P_g dt}{P_{con(av)}}. \quad (3)$$

Depending on the value of N_{gs} , the residential power system can be classified as follows:

- Grid-supporting power system $N_{gs} > 0$. A higher value of N_{gs} indicates stronger grid-support capability.
- Neutral power system $-1 < N_{gs} < 0$. Lower values of N_{gs} correspond to increasing loading of the power system on the grid.
- Grid-burdening power system $N_{gs} \leq -1$. Decreasing values of N_{gs} indicate progressively worse loading effects on the grid.

As an additional parameter characterizing renewable energy utilization in grids with medium-to-high RES penetration is the cut-off (curtailed) energy W_{cf} illustrated in Fig. 1d. The energy W_{cf} is not utilized and is lost due to excess energy in the grid. The cut-off level K_L depends on factors such as RES penetration and ESS capacity. Lower values of K_L indicate worse operating conditions, as a larger share of renewable energy is curtailed. The level K_L may be normalized by the average daily energy consumption $P_{con(av)}$:

$$K_L = \frac{P_{gen(av)}}{P_{con(av)}}. \quad (4)$$

For nZEBs with low ESS capacity that are connected to power grids with high RES penetration, the parameter K_L does not exceed unity. In more stable grids with medium RES penetration, K_L typically lies in the range of 1–5. For centralized power grids, the value of K_L is constrained by the allowable peak power and may reach values as high as $K_L = 20$, which is estimated for a lower level of the average consumed power $P_{con(av)} = 1$ kW with the peak-power limitation of a three-phase power grid 3×32 A [21,22].

The next step is to investigate the impact of ESS on the aforementioned parameters and to identify the conditions required to achieve a power system with medium-to-high RES penetration, near-zero energy balance, and grid-support capability.

First, the parameter values are evaluated for the system without an ESS to establish a baseline. The near-zero consumption index N_{zc} for the daily and annual reference dataset periods is shown in Fig. 4a. Due to the negative annual value $N_{zc,y} = -0.69$ of the reference household, the PV array-generated power is scaled by a factor of $k_{sc} = 3.42$ to achieve the boundary value $N_{zc,b} = 0.05$, in accordance with (2). Fig. 4b presents the daily and annual profiles of N_{zc} after applying the scaling factor.

Based on the data presented, N_{zc} remains negative from October to April even after PV scaling. Therefore, in the absence of an ESS, the residential power system imposes a significant load on the power grid during this period.

A more accurate assessment of power system loading is provided by the grid-support capability index N_{gs} . For the peak-load intervals $t_p \in (6;9) \cup (18;21)$, the distribution of N_{gs} is shown in Fig. 5.

According to Fig. 5, even after scaling, the index N_{gs} has a positive value and thus provides grid support only for 130 days a year. For 20 days, the power system has a neutral impact on the grid, while for 215 days it imposes a significant load during peak hours.

Another drawback of a power system without an ESS is the low utilization of RES energy when a power cut-off is implemented. In this case, the maximum power exported to the grid is constrained. During peak-load hours $(6;9) \cup (18;21)$, the generated power is normalized by the factor K_L , whereas during night hours $(0;5)$, the generation is not possible. During the remaining hours, the generated power may be limited to $0.33K_L$. Figure 6 shows the ratio of utilized RES energy W^* as a function of K_L .

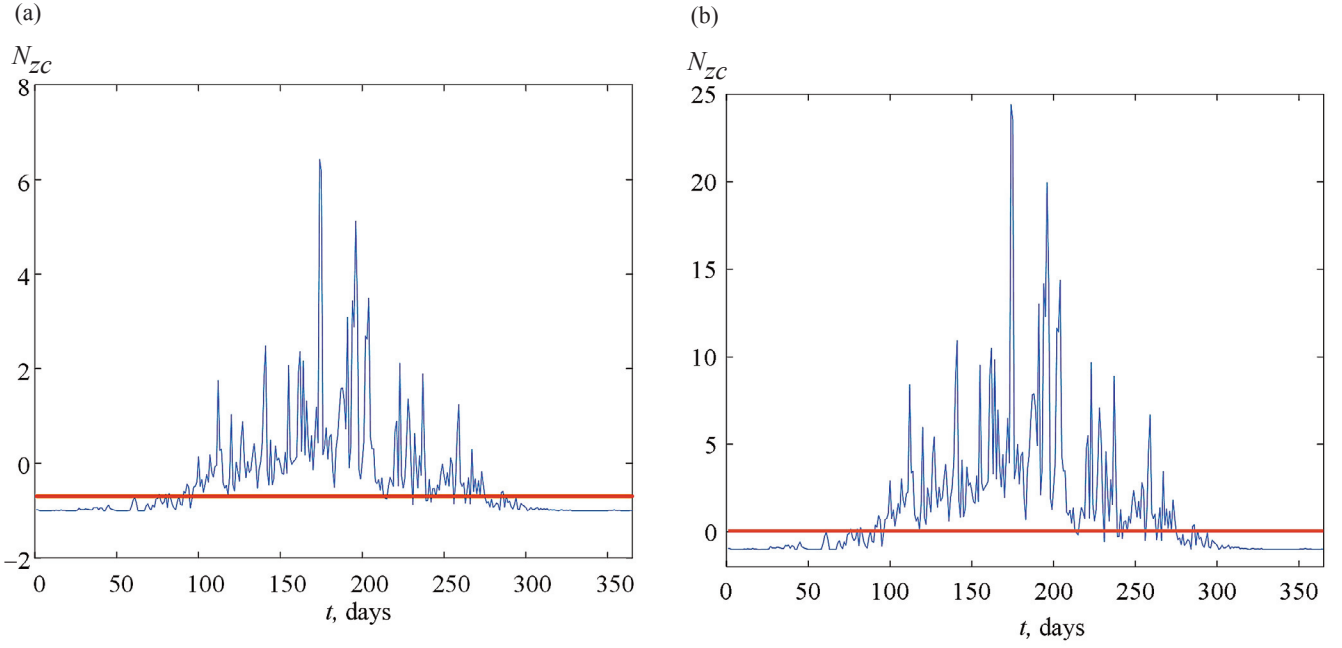


Fig. 4. Daily and annual distribution of N_{zc} : (a) before scaling and (b) after scaling.

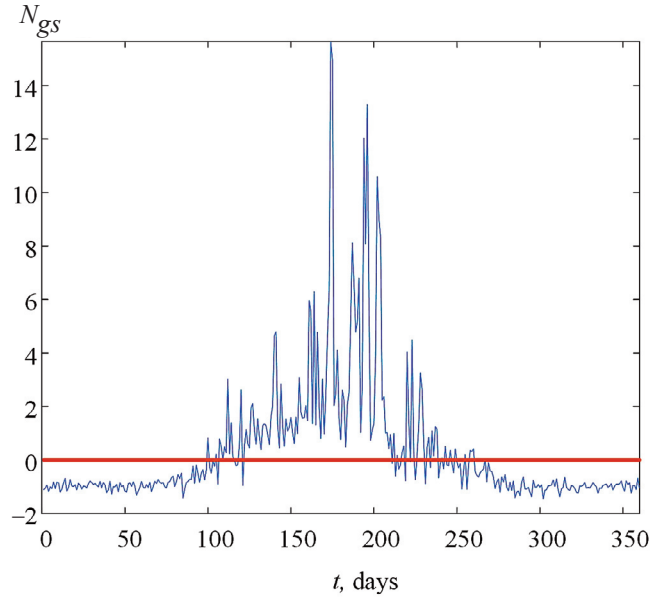


Fig. 5. Estimation of the grid-supporting possibility option N_{gs} .

According to Fig. 6, a typical value of K_L allows the utilization of only 20–40% of RES with a power cut-off, whereas in the centralized power grid this value may reach 80%.

The integration of ESS storage into the power system significantly improves the analyzed parameters. Daily balancing using an ESS has a strong impact on the grid-support capability index and partially increases the ratio of utilized renewable energy. However, achieving near-zero daily energy consumption throughout the entire year, along with full utilization of RES energy, is possible only with a high-capacity ESS suited for seasonal energy storage, especially in regions such as Estonia with a high seasonal variation of RES generation.

The daily energy storage capacity C_{daily} is estimated assuming the grid-supporting $N_{gs} > 0$ for each day of the year. Due to additional ESS power losses, the PV scaling factor is increased to $k_{sc(ESS)} = k_{sc}/\eta_{ESS} = 3.8$, where η_{ESS} is energy storage efficiency, $\eta_{ESS} = 0.9$. As a result of the simulation, the minimum battery capacity required to provide grid-support functionality for the particular case study is $C_{daily} = 11.6 \text{ kW}\cdot\text{h}$. The annual profile of daily $N_{gs(ESS)}$ values for this ESS configuration is shown in Fig. 7.

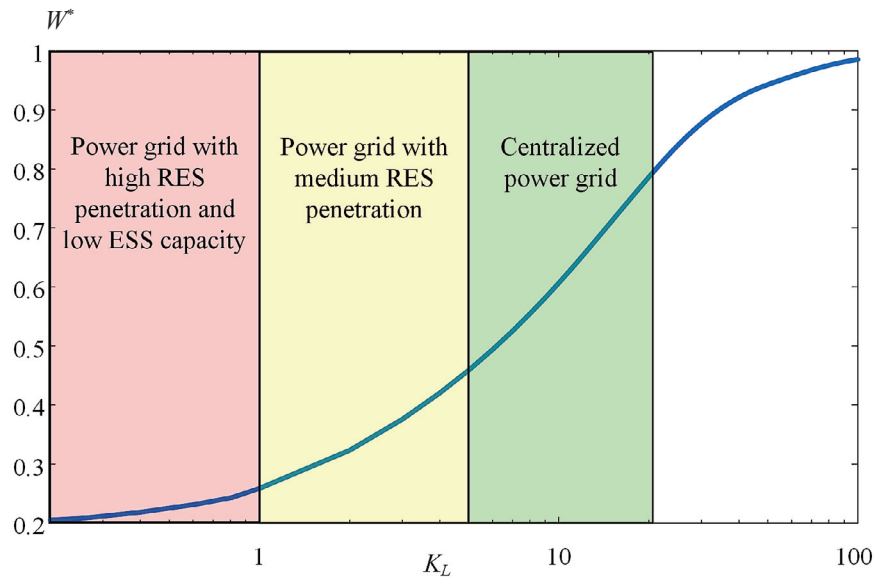


Fig. 6. Ratio of utilized RES energy W^* as a function of K_L .

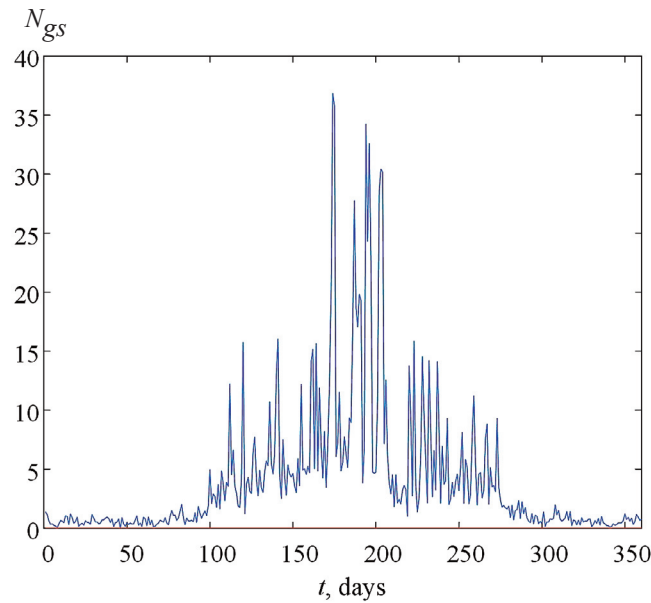


Fig. 7. Annual curve of daily $N_{gs}(ESS)$ values with ESS capacity $C_{daily} = 11.6$ kW·h.

Table 1. Improved RES energy utilization K_L

	Low-penetration, $K_L = 20$	Moderate-penetration, $K_L = 5$	High-penetration, $K_L = 1$
without ESS	76%	43%	24%
with ESS	83%	53%	33%

As shown, during the summer period, the value of $N_{gs}(ESS)$ significantly exceeds unity. Such levels of exported energy are not permissible for power grids with medium- and high-RES penetration. Therefore, to ensure efficient utilization of RES energy, an ESS charging–discharging control algorithm should be adopted that accounts for the RES penetration level, the value of N_{gs} without the ESS, and the objective of minimizing ESS charging energy, as described in the Appendix.

After implementing the proposed algorithm, the grid-support criterion is satisfied for every day of the year, and RES energy utilization is improved, as summarized in Table 1.

For the estimation of the total system efficiency η_Σ , the share of the stored energy δ_{ESS} is assessed at $\delta_{ESS} = 19\%$ of the consumed energy, which allows the overall system efficiency η_Σ to be improved to the value

$$\eta_\Sigma = \eta_{en}((1 - \delta_{ESS}) + \eta_{ESS}\delta_{ESS}) = 0.93, \quad (5)$$

where the parameter definitions and values are provided in Table 2.

As a result, the PV array area with the ESS must be increased by at least 7.5% compared with the system without the ESS.

The seasonal balancing ESS capacity is calculated as the difference between the generated and consumed energy over the warm (May–September) and cold (October–April) seasons, denoted as C_{seas_gen} and C_{seas_con} , respectively. The calculation accounts for additional losses during long-term storage caused by battery self-discharge, typically 2–3% per month, corresponding to a round-trip efficiency of $\eta_{rt} = 0.88$.

$$C_{seas_gen} = \frac{\int (\eta_{en}P_{gen} - P_{con})dt}{\eta_{en}\eta_{ESS}\eta_{rt}}, \quad (6)$$

$$C_{seas_con} = \frac{\int (P_{con} - \eta_{en}P_{gen})dt}{\eta_{en}\eta_{ESS}\eta_{rt}}. \quad (7)$$

Accordingly, the PV scaling factor for seasonal energy storage is also increased to $k_{sc(s)} = k_{sc(ESS)}/\eta_{rt} = 4.3$. Under these conditions, the required seasonal ESS capacities for generation and consumption are $C_{s(gen)} = 14 \text{ MW}\cdot\text{h}$ and $C_{s(con)} = 8.8 \text{ MW}\cdot\text{h}$, respectively. The difference between these capacities arises from the approximation of warm and cold seasons and from cumulative power conversion losses between generation and consumption. Given an annual household energy consumption of $W_{s\Sigma} = 15.2 \text{ MW}\cdot\text{h}$, the share of energy stored in the seasonal ESS $\delta_{s(ESS)}$ is:

$$\delta_{s(ESS)} = \left(1 - \frac{C_{s(con)}}{W_{s\Sigma}}\right) \cdot 100\% = 42\%. \quad (8)$$

Thus, in this case, approximately 42% of the energy is stored in the ESS for about six months, 19% is stored for short-term balancing, and only 39% is directly consumed by the load. Consequently, the overall system efficiency η_Σ is calculated as follows, where all used parameters and their values are described in Table 3.

$$\eta_\Sigma = \eta_{en}((1 - \delta_{ESS} - \delta_{s(ESS)}) + \eta_{ESS}\delta_{ESS} + \eta_{ESS}\eta_{rt}\delta_{s(ESS)}) = 0.85, \quad (9)$$

where the parameter definitions and values are provided in Table 2.

Table 2. Parameters for equations (5), (9), (11)

Parameter	Notation	Value
Energy conversion efficiency	η_{en}	0.9
Electric battery ESS efficiency	η_{ESS}	0.9
Hydrogen ESS efficiency	$\eta_{hs(ESS)}$	0.6
Round-trip efficiency, Eqs (5), (9)	η_{rt}	0.88
Round-trip efficiency, Eq. (11)	η_{rt}	0.98
Compressor efficiency	η_{com}	0.9
Share of daily stored energy	δ_{ESS}	19%
Share of seasonal stored energy	$\delta_{s(ESS)}$	42%
Fuel cell degradation factor	η_{deg}	90%

Table 3. Energy cost for different configurations of the power system

Parameter	Power system without ESS, $k_{sc} = 3.42$	Power system with daily ESS, $k_{sc(ESS)} = 3.8$	Power system with seasonal ESS, $k_{sc(s)} = 4.3$
PV array power, kW	14.4	16.0	18.1
PV array generated energy W_g , kW·h	16 756	18 618	21 067
ESS storage capacity C_{ESS} , kW·h	—	11.6	14 000
Utilized gross energy for $K_L = 20/5/1$, W_{gr} , kW·h	12 735/7205/3854	15 453/9868/6144	21 067
Utilized net energy for $K_L = 20/5/1$, W_{net} , kW·h	12 098/6845/3661	14 371/9177/5714	17 907
Total cost for 25-year cycle, \$	28 800	53 750	10 536 200
Cost per 1 kW·h generated energy, \$	0.10/0.17/0.31	0.15/0.23/0.38	23.5

As a result, the PV array area in the configuration with seasonal ESS must be increased by at least 18% compared with the baseline configuration without ESS.

The implementation of seasonal ESS would undoubtedly have a significant positive impact on power supply stability and RES utilization. However, it requires an approximately three-orders-of-magnitude increase in ESS capacity, which substantially raises the system cost. Therefore, the total cost of ownership per 1 kWh of generated energy is further evaluated. The cost analysis is based on the following input parameters: a normalized cost of \$2000 per kWp for the PV system, including supplementary equipment, with an operational lifetime of 25 years; and a lithium-ion battery system with a grid inverter at a total cost of \$750 per kW·h, with an operational lifetime of 10 years for daily ESS and 25 years for seasonal ESS [23]. The resulting energy cost for this configuration is summarized in Table 3.

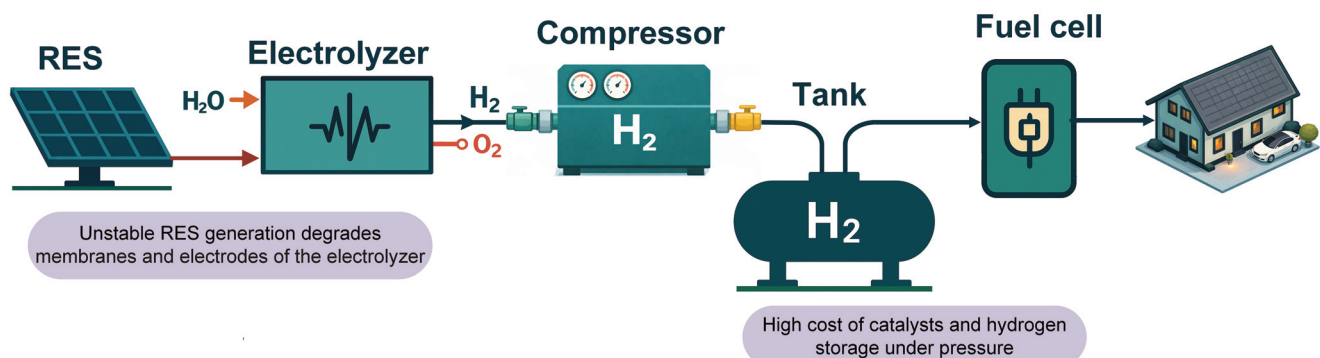
As follows, the cost of energy in power systems with daily ESS is 20–50% higher than in the baseline case, whereas the use of seasonal ESS increases the cost by a factor of 75–230. This clearly indicates the economic infeasibility of using electrochemical batteries for large-scale seasonal energy storage. In contrast, hydrogen could be a more attractive energy carrier for seasonal energy storage applications.

Analysis of hydrogen as an energy storage carrier

The reaction of hydrogen with oxygen releases approximately 120–140 MJ of energy per kilogram and produces water as the only reaction product. Owing to its high specific energy (approximately 200 times greater than that of lithium-ion batteries) and its reduced environmental impact, hydrogen may become one of the key elements of sustainable energy systems in the near future. However, a hydrogen energy system has a more complex structure, comprising an electrolyzer that produces hydrogen from water using RES-generated electricity, a compressor, a hydrogen storage tank, and a fuel cell for electricity generation, as shown in Fig. 8.

This increased system complexity and the associated costs must be carefully addressed to ensure the efficient and safe utilization of hydrogen [24]:

- Gaseous hydrogen has a low volumetric energy density, which requires storage in compressed form (350–700 bar) or in liquid or solid states.

**Fig. 8.** Basic topology of hydrogen ESS.

- The high cost of catalysts such as platinum and its analogues, together with hydrogen storage systems, significantly increases the overall system cost.
- Membranes and electrodes are subject to degradation over time, especially under conditions of fluctuating RES generation.
- The service life of hydrogen energy systems remains limited compared with conventional energy storage technologies.

The challenges mentioned reduce the competitiveness of hydrogen-based energy systems compared with conventional battery-based solutions. However, the need for long-term energy storage could partially mitigate the disadvantages of hydrogen storage due to its better suitability for large-scale applications [25]. Additionally, the hydrogen system's performance may be improved by:

- providing stable power output from RES through the use of an auxiliary electric battery;
- utilizing the heat generated by the fuel cell reaction for household heating;
- transitioning from household-level ESS to community-level ESS, enabling further cost reductions of hydrogen storage tanks due to economies of scale.

The following analysis considers a residential neighborhood of around 60 households with a community PV array of 10 000 m², with a peak power of 1 MW and an annual generation of 1.2 GW·h. This corresponds to a scaling factor $k_{sc} = 238$, related to the initial dataset. The neighborhood structure is illustrated in Fig. 9.

As shown in Fig. 9, the community power system incorporates a mixed ESS architecture, consisting of an individual daily ESS based on electrochemical batteries and a shared hydrogen-based seasonal ESS. The seasonal ESS comprises an electrolyzer that converts unused electrical energy into hydrogen, which is then compressed and stored in a hydrogen tank. A fuel cell is used to convert the stored hydrogen back into electrical and thermal energy. Due to the low dynamic response of the fuel cell, the generated energy is first accumulated in an electric battery buffer and then distributed to the load. The heat generated in the fuel cell is recovered via a heat exchanger and used for water heating.

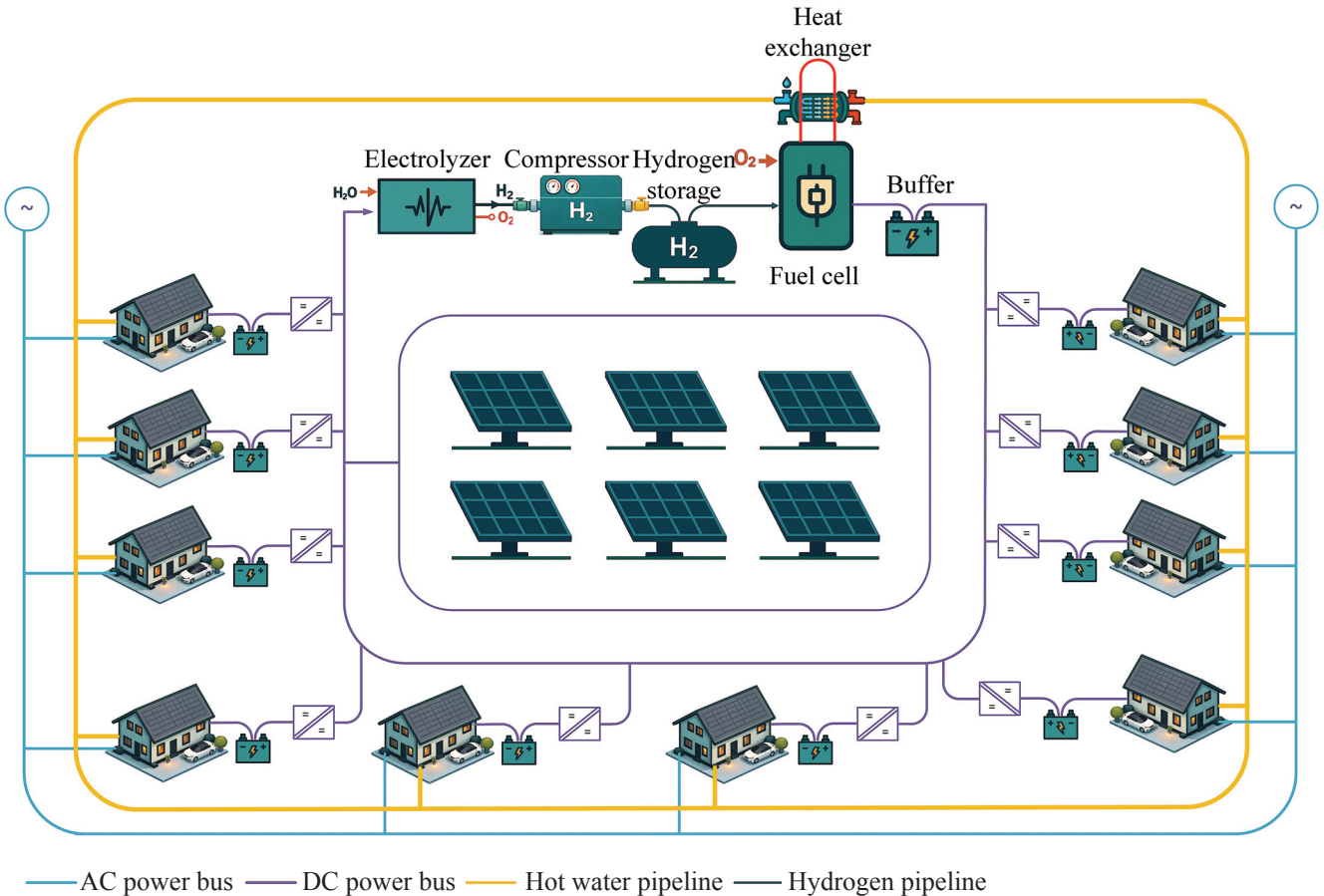


Fig. 9. Community power system with hydrogen ESS and combined heat and electricity generation.

The required buffer capacity at the fuel cell output is determined by the dynamic characteristics of both the fuel cell and the load. Fuel cell response times range from seconds for proton exchange membrane fuel cells (PEMFCs) to hours for solid oxide fuel cells (SOFCs) [26,27]. Since the houses (loads) include daily ESS, the consumed power can be effectively stabilized. Consequently, the buffer capacity C_b can be designed to provide autonomous operation for the time $t_{aut} = 10$ minutes and can be calculated as follows:

$$C_b = t_{aut} P_{fc(max)}, \quad (10)$$

where $P_{fc(max)}$ is the maximum power of a fuel cell.

Fuel cell efficiency with heat utilization usually varies in the range of 70% to 90% [28]. Taking into account the efficiency of an electrolyzer, the total efficiency of the electrolyzer–fuel cell pair is 60–70% [29]. Additionally, the energy consumed by the compressor must be considered. Furthermore, due to the degradation of a fuel cell, its efficiency is reduced with time [30]. Typically, the compressor consumes 5–10% of the energy located in hydrogen [31]. Therefore, we can assume that the compressor efficiency η_{com} is equal to 90–95%.

Let us define the total hydrogen ESS efficiency as $\eta_{hs(ESS)} = 60\%$, the compressor efficiency as $\eta_{com} = 90\%$, the fuel cell degradation factor as $\eta_{deg} = 90\%$, a hydrogen loss of 2%, and the round-trip efficiency as $\eta_{rt} = 98\%$ [32]. Then the total system efficiency may be calculated as follows:

$$\eta_{\Sigma} = \eta_{en} ((1 - \delta_{ESS} - \delta_{s(ESS)}) + \eta_{ESS} \delta_{ESS} + \eta_{hs(ESS)} \eta_{rt} \eta_{com} \eta_{deg} \delta_{s(ESS)}) = 0.68, \quad (11)$$

where the parameter definitions and values are provided in Table 2. The power loss components according to (11) are shown in Fig. 10.

For cost assessment, both the individual and community hydrogen-based ESS power systems are analyzed. The component parameters of the hydrogen ESS power system are listed in Table 4.

The cost assessment for individual and community power systems is given in Table 5. For the individual ESS, a hydrogen tank operating at 350 bar is considered. For the community ESS, additional low-cost, ready-to-use storage options, such as porous media or depleted fields, are considered due to their significantly lower storage costs. As a result, the individual power system with a hydrogen ESS is more expensive than the system based on electrochemical batteries, mainly due to the extensive set of additional components required. For the community-level system, economies of scale reduce the total cost; however, it remains relatively high, at approximately \$15.9 per kW·h for conventional tank storages and \$8.5 per kW·h for natural storages.

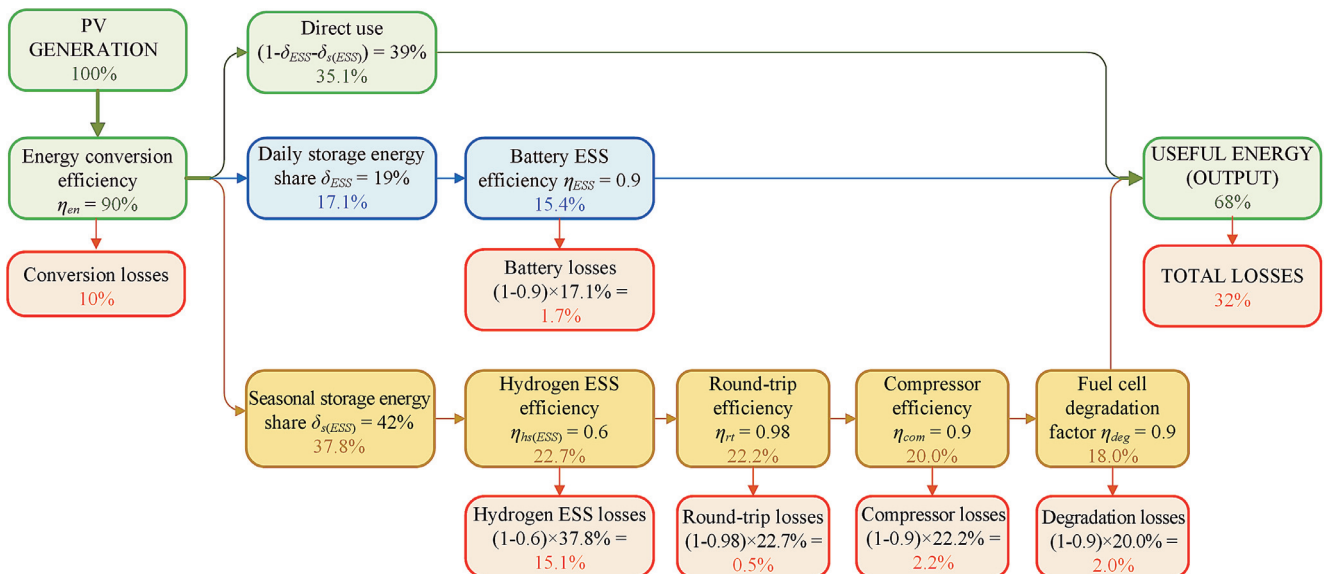


Fig. 10. Visualization of power loss in a power system with hydrogen ESS.

Table 4. Component parameters of the hydrogen ESS power system

Parameter	Household power system, $k_{sc(s)} = 4.3$	Community power system, $k_{sc(s)} = 238$
PV array power, kW	18.1	1000
PV array generated energy W_g , MW·h	21	1166
PV array operational period, years	25 [33]	25 [33]
Seasonal ESS capacity $C_{s(ESS)}$, MW·h	14	775
Seasonal ESS operational period, years	30 [34]	50 [35]
Daily storage capacity C_{daily} , kW·h	11.6	696
Daily ESS operational period, years	10	10
Electrolyzer power P_{el} , kW	18.1	1000
Electrolyzer operational period, years	12 [36]	12 [36]
Compressor power P_{com} , kW	1.8	100
Compressor operational period, years	15 [37]	15 [37]
Fuel cell power P_{fc} , kW	4	240
Fuel cell operational period, years	9 [38]	9 [38]
Buffer capacity C_b , kW·h	0.67	40
Buffer operational period, years	10	10
Total system efficiency	0.68	0.68

Table 5. Main cost parameters for individual and community power systems

Parameter	Household power system, $k_{sc(s)} = 4.3$	Community power system, $k_{sc(s)} = 238$
PV array cost per 1 kW C_{stpV} , \$	2000 [23]	1600 [23]
Seasonal ESS cost per 1 kW·h $C_{st_s(ESS)}$, \$	20 [39]	10/1 [39,40]
Daily ESS cost per 1 kW·h $C_{st_d(ESS)}$, \$	800 [23]	800 [23]
Electrolyzer cost per 1 kW $C_{st_{el}}$, \$	3000 [41]	1000 [42]
Compressor cost per 1 kW $C_{st_{com}}$, \$	7500 [43]	3500 [43]
Fuel cell cost per 1 kW $C_{st_{fc}}$, \$ (with heat power)	4500 [44]	1200 [44]
Buffer cost per 1 kW·h $C_{st_d(ESS)}$, \$	800 [23]	800 [23]
Total cost for 25-year cycle, \$	480 000	13 000 000/6 900 000
Cost per 1 kW·h generated energy, \$	33.6	15.9/8.5

Discussion and conclusions

In this paper, a dataset from a residential house located in Estonia is used to analyze the parameters of a household operating under near-zero energy consumption and grid-support functionality. The analysis is carried out under the assumption that an increasing share of RES reduces grid flexibility and decreases the rate of RES energy utilization. Although local battery storage within buildings can partially address this issue during warm seasons with high PV output on a daily basis, the mismatch between seasonal generation and demand peaks requires cross-seasonal energy storage solutions.

For the seasonal ESS design, key factors include the near-zero consumption ratio, grid-support capability, and the RES utilization cut-off level, which characterize system stability, overload capability, and the effectiveness of RES utilization. The analysis of these values showed that the parameters of a power supply system with seasonal energy storage significantly depend on climatic conditions and are not always economically feasible. Under Estonian climatic conditions, with significant variations in solar irradiation throughout the year, the storage capacity required for full utilization of solar energy exceeds the capacity required for daily balancing by three orders of magnitude, ranging from 11.6 kWh for daily balancing to 14 000 kWh for full seasonal utilization. Therefore, the cost of seasonal ESS based on conventional electric battery technologies increased approximately from 0.1–0.4 \$ to 23.5 \$ per kW·h.

Hydrogen ESS becomes more attractive for large-scale storage applications due to the scaling effect and thus may be implemented for seasonal ESS. A comparative analysis of residential power systems with conventional battery-based seasonal ESS and hydrogen-based ESS shows that hydrogen systems are even more expensive for individual applications. For community-scale

hydrogen ESS, costs are reduced to about \$15.9 per kW·h for high-pressure tanks and \$8.5 per kW·h for natural storage (porous media or depleted fields) when cogeneration of electricity and heat is taken into account. Although this cost remains relatively high to provide clear economic benefits, it is potentially more promising for practical implementation compared to batteries due to the large storage capacity achievable. Therefore, it can be concluded that hydrogen energy storage technologies are still relatively expensive at the current stage of development; however, as the costs of individual components gradually decrease, their deployment could become more suitable for shared use at the energy community level.

Data availability statement

The dataset used in this study is publicly available in the TalTech Data Repository: <https://data.taltech.ee/records/6hayh-x0h25>.

The dataset “PV Generation and Consumption Dataset of an Estonian Residential Dwelling” contains one year of high-resolution measurements (January–December 2023) of aggregated household electricity consumption and photovoltaic (PV) generation recorded at 10-second intervals. The measurements were obtained from a residential building in Estonia using power-quality monitoring devices installed on the PV system and the main electricity meter.

The repository includes raw time-series data organized by months and supporting Python scripts for data preprocessing and missing-value imputation.

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Appendix

ESS charging–discharging algorithm for efficient RES energy utilization for day = 1 to 365:

Calculation of generated energy in morning peak-consumption hours, $W_{gs1} = \int_6^9 P_g dt$.

Calculation of average daily consumed power hours, $P_{con(av)} = \frac{1}{24} \int_0^{24} P_{con} dt$.

Calculation of morning grid supporting parameter, $N_{gs1} = W_{gs1} / (3P_{con(av)})$,

if $N_{gs1} < K_L$,

 if $N_{gs1} > 0.1$,

 if $C_{daily} > 0.3 \cdot P_{con(av)} / (\eta_{en} \cdot \eta_{ESS}) - W_{gs1}$.

 Generated power P_g is reduced over time interval $t \in (0;6)$:

$P_g = P_g - 0.05P_{con(av)} / (\eta_{en} \cdot \eta_{ESS}) + W_{gs2}/6$.

 Residential power system supports power grid in morning peak hours $t \in (6;9)$:

$P_g = 0.1 \cdot P_{con(av)}$.

 else

 Generated power P_g is reduced over time interval $t \in (0;6)$:

$P_g = P_g - C_{daily} / (6\eta_{en} \cdot \eta_{ESS})$.

 Residential power system reduces consumption in morning peak hours $t \in (6;9)$:

$P_g = P_g + C_{daily} / 3$.

 end

end

Continued on the next page

Appendix. Continued

else

Maximum grid supporting level is provided on evening of previous day $t \in (21;24)$:

$$P_g = K_L \cdot P_{con(av)}/3$$

and zero generation in night hours of current day is provided $t \in (0;6)$:

$$P_g = P_g - (1 - SOC)C_{daily}/3$$

for reducing generated power P_g to allowed level in morning peak hours $t \in (6;9)$:

$$P_g = K_L \cdot P_{con(av)}.$$

end

Calculation of generated energy in evening peak-consumption hours, $W_{gs2} = \int_{18}^{21} P_g dt$.

Calculation of evening grid supporting parameter, $N_{gs2} = W_{gs2} / (3P_{con(av)})$,

if $N_{g1} < K_L$,

if $N_{g1} > 0.1$,

if $C_{daily} > 0.3 \cdot P_{con(av)} / (\eta_{en} \cdot \eta_{ESS}) - W_{gs2}$.

Generated power P_g is reduced over time interval $t \in (9;18)$:

$$P_g = P_g - P_{con(av)} / (\eta_{en} \cdot \eta_{ESS}) / 30 + W_{gs2} / 9.$$

Residential power system supports power grid in morning peak hours $t \in (6;9)$:

$$P_g = 0.1 \cdot P_{con(av)}.$$

else

Generated power P_g is reduced over time interval $t \in (9;18)$:

$$P_g = P_g - C_{daily} / (9\eta_{en} \cdot \eta_{ESS}), t \in (9;18).$$

Residential power system reduces consumption in evening peak hours $t \in (18;21)$:

$$P_g = P_g + C_{daily} / 3, t \in (9;18).$$

end

end

else

Maximum grid supporting level is provided during midday period $t \in (9;18)$:

$$P_g = K_L \cdot P_{con(av)}/3$$

for reducing generated power P_g to allowed level in evening peak hours $t \in (18;21)$:

$$P_g = K_L \cdot P_{con(av)}.$$

end

Calculation of average midday generated power hours, $P_{g_md(av)} = \frac{1}{9} \int_9^{18} P_g dt$,

if $P_{g_md(av)} > K_L P_{con(av)}/3$;

Maximum generation is defined from night hours of previous day $t \in (21;24)$:

$$P_g = K_L \cdot P_{con(av)}/3,$$

zero generation in night hours of current day is provided $t \in (0;6)$:

$$P_g = 0, t \in (0;6),$$

and maximum generation in morning peak hours $t \in (6;9)$:

$$P_g = K_L \cdot P_{con(av)}$$

for maximum battery discharging before midday PV generation.

end

end

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Hooajalise vesinikupõhise energiasalvestuse teostatavuse hinnang

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Euroopa Liidu energiasektori dekarboniseerimine on seotud taastuvenergiaallikate ulatusliku integreerimisega ja üleminekuga detsentraliseeritud elektrivarustussüsteemidele. Kuigi elektrokeemilistel akudel põhinevad kodused energiasalvestussüsteemid võimaldavad taastuvenergia ületootmise lühiajalist tasakaalustamist, ei sobi need piiratud mahutavuse ja suure maksumuse tõttu hooajaliseks energiasalvestuseks. Sellest tulenevalt tuleb taastuvenergia tootmist märkimisväärselt piirata. Hoolimata madalast salvestustsükli kasutegurist ja infrastruktuuriga seotud väljakutsetest peetakse vesinikupõhist energiasalvestust paljulubavaks alternatiiviks tänu vesiniku suurele erienergiale ja sobivusele pikaajaliseks salvestiks.

Käesolevas töös hinnatakse vesinik-energiasalvesti teostatavust taastuvenergiaallikatel põhinevates elamute elektrisüsteemides Eestis. Analüüs põhineb reaalse Eesti majapidamise andmetel ning arvestab selliseid näitajaid nagu liginullenergia tarbimine, võrgu toetamise võimekus ja taastuvenergia kasutamise määr. Võrreldakse nii päevase kui ka hooajalise energiasalvestussüsteemi konfiguratsioone ning akudel ja vesinikul põhinevaid salvestussüsteeme tehnilis-majanduslikust aspektist. Erilist tähelepanu pööratakse vesinikust elektri tootmisel tekkiva jääksoojuse kasutamisele elamute kütmiseks, mida käsitletakse peamise tingimusena majandusliku tasuvuse saavutamiseks ja süsteemi üldise efektiivsuse parendamiseks.