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The Storage Process of Electric Energy Produced from Renewable Sources from Hydrogen to Domestic Hot Water Heating

Dorel Stoica [1,*], Lucian Mihăescu [2], Gheorghe Lăzăroiu [3] and George Cristian Lăzăroiu [4]

[1] Department of Mechanics "Radu P. Voinea", National University of Science and Technology Politehnica Bucharest, 060042 Bucharest, Romania
[2] Department of Technical Thermodynamics, Engines, Thermal and Refrigeration Equipment, National University of Science and Technology Politehnica Bucharest, 060042 Bucharest, Romania; lucian.mihaescu@upb.ro
[3] Department of Energy Generation and Use, National University of Science and Technology Politehnica Bucharest, 060042 Bucharest, Romania; gheorghe.lazaroiu@upb.ro
[4] Electrical Systems Department, National University of Science and Technology Politehnica Bucharest, 060042 Bucharest, Romania; cristian.lazaroiu@upb.ro
* Correspondence: dorel.stoica@upb.ro

Abstract: The expansion of renewable electricity storage technologies, including green hydrogen storage, is spurred by the need to address the high costs associated with hydrogen storage and the imperative to increase storage capacity. The initial section of the paper examines the intricacies of storing electricity generated from renewable sources, particularly during peak periods, through green hydrogen. Two primary challenges arise: firstly, the complexity inherent in the storage technology and its adaptation for electricity reproduction; and secondly, the cost implications throughout the technological chain, resulting in a significant increase in the price of the reproduced energy. Electric energy storage emerges as a pivotal solution to accommodate the growing proportion of renewable energy within contemporary energy systems, which were previously characterized by high stability. During the transition to renewable-based energy systems, optimizing energy storage technology to manage power fluctuations is crucial, considering both initial capital investment and ongoing operational expenses. The economic analysis primarily focuses on scenarios where electricity generated from renewable sources is integrated into existing power grids. The subsequent part of this paper explores the possibility of localizing excess electricity storage within a specific system, illustrated by domestic hot water.

Keywords: green hydrogen; renewable electricity; storage processes; power grids

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1. Introduction

The issue of storage solutions for electric energy produced from renewable sources is already evident with the increasing share of renewables in energy microsystems, and it is expected to amplify over time until it reaches the level of the overall energy system.

The total installed capacity in renewable sources has doubled in the last 10 years, reaching over 3370 GW in 2022, of which hydro accounts for over 1390 GW, wind over 890 GW, solar energy over 1050 GW, bioenergy nearly 150 GW, and geothermal energy almost 15 GW. These capacities are connected to the electrical grid [1].

Renewable energy with power fluctuations comes from solar panel fields, wind farms, and biomass utilization. Power generation from solar sources varies over time based on the solar radiation flux, while wind energy depends on wind speed and duration. While the existence of diurnal maximums can be specified for solar energy sources, with values varying according to the annual period, the forecast for wind energy is completely variable [2].

Therefore, both wind and photovoltaic (PV) energy, being intermittent sources of energy, cannot meet the load demand at any given moment, 24 h a day, 365 days a year [3].

Electricity, being an ordered form of energy, is more versatile in its use than other types of energy, as it can be efficiently converted into other forms. However, a disadvantage of electricity is that it cannot be easily stored on a large scale.

Present and future energy storage technologies that can be considered for standalone wind or photovoltaic energy systems fall into the following broad categories: batteries; flywheels; compressed air; superconducting coils; pumped hydro storage; thermal energy storage; and gravitational storage [4].

This paper presents a global analysis for the option of storing electrical energy in thermal energy accumulated in water, dispersedly delivered to household consumers. Unlike most electric energy storage technologies, the proposed solution does not allow for the return to the initial energy, manifesting itself by satisfying a social need, in terms of the balance between electric energy costs and the cost of thermal energy produced from fossil fuels. The proposed solution comes as a capture of energy storage technology from renewable sources (solar and wind) in the form of hydrogen, also achieving environmental protection aspects.

This work focuses on the following conceptual aspects: In contrast to the analysis of storage in systems of a certain power of electrical and thermal energy (including cooling) presented in detail in [5], this study encompasses a summarization of local thermal energy accumulation.

Through the storage of this energy, the aim is to adapt the real-time balance between energy demand with a well-defined profile at the macro-energy system level and the variable supply over time. Initially, the storage of electric energy produced by these renewable energy sources (RES) only included the solution of manufacturing green hydrogen, which would be stored and later used to produce electric energy during periods of low production. This new energy chain leads to a relatively high leveled price of stored and subsequently reproduced electric energy. The newly created energy chain includes zero CO_2 emissions, and the costs must be included in this ecological matrix. It is projected that by 2030, this chain comprising RES-H_2 will reach an economically acceptable level. Therefore, the development of new standards, guarantees, and financial support schemes is necessary to cover the price difference in the energy chain [2,5].

The issue of energy storage has become increasingly critical with the rise of solar and wind renewable energy, characterized by variability over time. In contrast, energy in previous periods was marked by considerable stability, with technical solutions to enhance this stability. Studies on energy storage emerged in the 1970s, primarily in the theoretical and pilot stages. However, challenges emerged with energy storage using pumped hydro technology at large capacities, with few installations, especially after the increase in nuclear energy's share in many power systems. For instance, Romania planned a 100 MW storage plant in Târgu Jiu that was ultimately not realized.

Present and future energy storage technologies that can be considered for standalone wind or photovoltaic energy systems fall into the following broad categories: batteries; flywheels; compressed air; superconducting coils; pumped hydro storage; thermal energy storage; and gravitational storage [6].

An ecologically sustainable system with zero CO_2 emissions necessitates the inclusion of renewable energy sources such as solar, wind, hydroelectric, and geothermal energy. Some viewpoints also advocate for the incorporation of nuclear energy and biofuels, including biogas. Carbon capture solutions are now accessible for both combustion gases and atmospheric CO_2 at economically viable prices. Green hydrogen, the resulting cell being based on renewable, emerges as a pivotal solution for long-term energy storage and integration with hydrocarbon-based energy systems. This integration involves the conversion of captured CO_2 into methane or methanol through chemical reactors, thereby generating synthetic fuels that can be recycled within the production and CO_2 capture cycle.

CO_2 incorporated into liquid fuels, fuel substitutes, and fuel precursors for the transportation and energy production sectors is the correct direction for reducing it from the atmosphere [7].

Additionally, CO_2 conversion products have added value and can be used as fuels or precursors to produce more complex chemicals and fuels [8].

The introduction of CO_2 capture at hydrocarbon-consuming energy installations introduces a novel dimension to neutral energy production concerning CO_2 emissions, diverging from the current paradigm of total hydrocarbon elimination. The transition to a CO_2-neutral energy system hinges on economic variables, with the price of green hydrogen serving as a critical determinant.

It is worth mentioning that, in the year 2022, CO_2 emissions exceeded 37 gigatons globally, with the EU accounting for over 3 gigatons [9].

The imperative for storage solutions for electric energy derived from renewable sources is unmistakable, given the escalating proportion of renewables in energy microsystems, which is projected to escalate over time. Solar and wind energy display power fluctuations, influenced by factors like solar radiation flux and wind speed and duration. Solar energy exhibits diurnal peaks with fluctuating values corresponding to the annual period, while wind energy forecasts are wholly variable.

Energy storage endeavors to harmonize real-time energy demand with variable supply. Initially, storage solutions for electric energy from renewables centered on green hydrogen production were stockpiled for subsequent utilization during periods of low production. Nevertheless, this novel energy chain entails relatively elevated costs for stored and regenerated electric energy. Nonetheless, it boasts zero CO_2 emissions, with costs factored into the ecological framework.

It is anticipated that by 2030, this amalgamation of renewable energy and green hydrogen will attain an economically viable threshold.

There are multiple configurations of hydrogen energy storage systems (HESS) that can be useful in different scenarios, but the preferred one is bidirectional storage using fuel cells [6]. This configuration involves the additional use of a polymer electrolyte membrane (PEM) electrolyzer to generate hydrogen from water using an electric current (releasing oxygen as a byproduct) before compressing and storing the hydrogen until needed. The hydrogen is then re-electrified using fuel cells to produce electricity. HESS consists of three major components: the charging system, which includes electrolyzer modules, controllers, water treatment units, mass flow regulators, electrolyzer management system, compressor, and rectifier; the discharging system, which consists of stationary fuel cell modules, controllers, gas handling units, blowers, mass flow regulators, fuel cell management system, and inverter; and the storage system, which typically includes pipelines, tanks, or a cavern.

The main categories of costs are as follows: capital investment costs, operating costs, and decommissioning costs, which are often not taken into consideration. Investment costs, i.e., the installation costs of the storage system, include the costs of the system itself, design, construction, and integration into the grid, while operating costs include raw material costs, maintenance, and operation.

The formulation of new standards, assurances, and financial backing mechanisms Is imperative to offset disparities in the energy chain. The main solution for the future aims to minimize both investment and operating costs, as defined by the following relationship:

$$\text{Cost of green H}_2\text{ energy} \rightarrow \text{Minimize (investmentcost} + \text{operating cost)} \quad (1)$$

Operational minimization encompasses a multitude of variables, with fluctuations in interest rates during the amortization period and inflation exacerbating the complexity of the situation.

Different storage systems have varying lifespans, different life cycles, limitations in depth of discharge (DOD), and different maintenance and operating costs, with variable fees over time. A levelized cost of storage (LCOS) defined in USD/kWh is preferred in such cases. LCOS determined in this manner provides a USD/kWh value that can be interpreted as the average USD/kWh price at which the energy production from the storage system should be sold to achieve total cost profitability [6]. The relationship is as follows:

$$\text{LCOS} = (\text{FCR} \times \text{CAPEX} + \text{OM})/\text{AH} + \text{ECC}$$

where LCOS—levelized cost of storage (USD/kWh); FCR—fixed charge rate (%); CAPEX—present value of capital expenditures (USD/kW); OM—annual fixed OM (USD/kW-year); AH—annual hours discharged; ECC—electricity charging cost (USD/kWh-discharge) inclusive of costs due to losses (ECC—charging cost for purchased energy [USD/kWh] divided by system RTE [%]); RTE—round-trip efficiency

Despite the concerted effort to minimize the price of energy supplied by the hydrogen storage system, it is imperative that the cost of electric energy derived from renewable sources utilized in the storage operation remain below the levelized cost of energy derived from the overall energy mix during that specific period [2,10].

Considering these economic aspects regarding the storage of energy derived from renewable sources in green hydrogen, it becomes necessary to also explore other storage options, such as pumped hydro, compressed air, liquid salts, etc.

This paper proposes novel forms of energy storage at times through a local energy storage system in household hot water, distributed pointwise to household consumers, with the possibility of extension to the industrial sector. In this system, action will also need to be taken through minimum prices for excess electric energy during the storage period. Based on the resulting data, an estimation of expanding the capacity for storing hot water for industrial activities has also been made.

In Figure 1, a synthesis of the main electric energy storage technologies during peak production periods (excess production from renewable sources) is presented. This energy is intended to be reintroduced into the electric system or used in other forms of energy. Energy return can also be replaced with local utilization of electric energy from the storage system. This excess electric energy production will depend on both random opacity levels and seasonality.

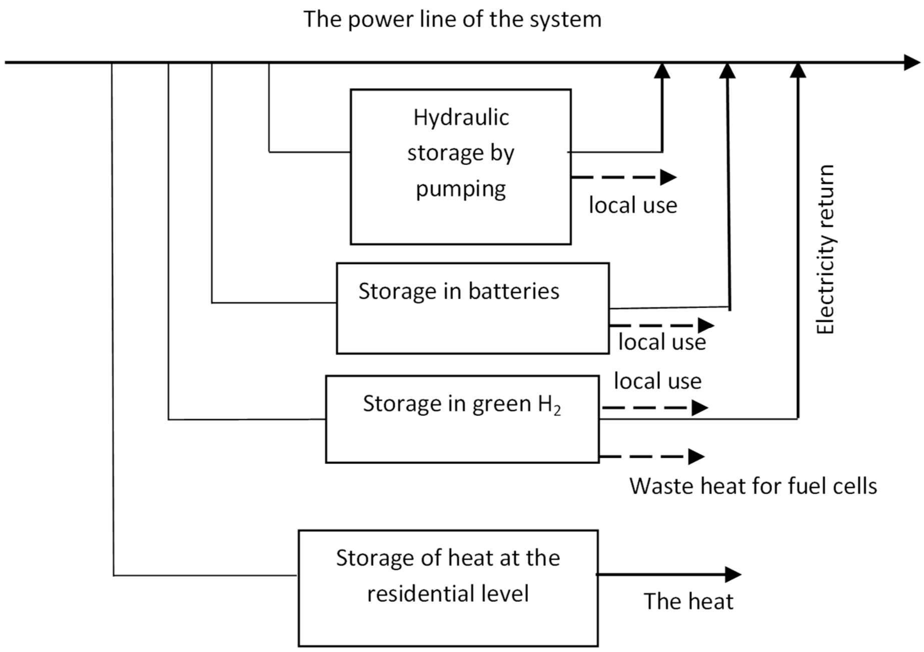

Figure 1. Schematic of the accumulation of electricity from the surplus period.

Taking into account these economic aspects regarding the storage of energy derived from renewable sources in green hydrogen, it becomes necessary to also consider other storage sources, such as pumped hydro, compressed air, liquid salts, etc.

This paper sometimes proposes new forms of energy storage through a local energy storage system in domestic hot water, distributed punctually to household consumers, with the possibility of extension to the industrial sector. In this system as well, action will need to be taken through minimal prices for surplus electricity during the storage period. Based on the resulting data, an estimation of the expansion of hot water storage capacity for industrial activities has also been made.

2. The Concept and Process of Storing Electric Energy from Renewable Sources Using Green Hydrogen

Electricity generation from renewable sources like solar and wind exhibits temporal variations. Solar sources show predictable patterns during the daytime, with fluctuations influenced by the season. In contrast, wind sources display entirely random variations. Despite the advancements, energy storage solutions in green hydrogen production are still in their nascent stages, with many unresolved questions regarding production, storage, and utilization methods. While the primary focus of hydrogen energy storage lies in the energy sector, particularly in electricity production, the concept can be expanded to encompass thermal energy production and transportation. It is crucial to highlight that hydrogen utilized in other industries, such as chemical and metallurgical sectors, operates outside the same comprehensive cycle of energy production, storage, and utilization.

Efficiently implementing green hydrogen production technologies demands innovative approaches and substantial investments in research and development. Furthermore, investigating sustainable and cost-effective methods of hydrogen storage is crucial for its seamless integration into both current and forthcoming energy systems.

As advancements in green hydrogen production and utilization technologies progress, it becomes paramount to identify and tackle challenges associated with efficiency, costs, and infrastructure. These endeavors will play a pivotal role in hastening the transition towards a sustainable and environmentally friendly energy landscape.

There are several configurations of HESS (hydrogen energy storage system), but bidirectional storage using fuel cells is preferred. This configuration involves the additional use of a proton exchange membrane electrolyzer (PEM) to generate hydrogen from water using an electric current and storing the hydrogen until needed. The hydrogen is then re-electrified using fuel cells to produce electricity.

A notable challenge arises when comparing the costs of grid-supplied energy with those of regenerating electricity from stored green hydrogen [11–13].

Figure 2 depicts a conceptual framework outlining the process of storing and utilizing energy from renewable sources in the form of green hydrogen. This approach presents a promising outlook for the future, given its advantages in terms of extended storage duration and the reliability of associated systems, which significantly differ from battery-based solutions. While various energy storage technologies exist, storing energy as green hydrogen stands out for its capability to manage prolonged storage periods and offer a dependable and consistent energy source.

In comparison to other storage alternatives like pumped hydro systems, green hydrogen presents notable advantages in flexibility and durability. However, it is important to note that currently, green hydrogen storage is still in its early developmental stages, and the infrastructure required for widespread implementation necessitates further refinement and optimization.

Another crucial aspect to consider when evaluating the effectiveness of green hydrogen storage is its environmental impact. While this approach holds substantial potential for reducing carbon emissions and fostering a sustainable energy transition, additional efforts are required to ensure that the entire process, from production to utilization, is sustainable and environmentally friendly.

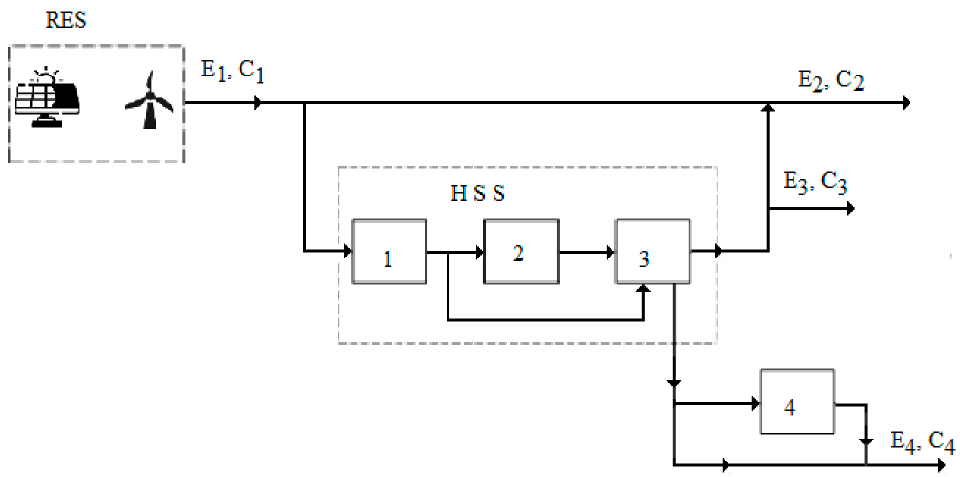

Figure 2. Schematic of the integration system in care: RES—renewable energy sources; HSS—hydrogen storage system; 1—electrolyser; 2—hydrogen storage; 3—fuel cell; 4—heat accumulator; E1—electric energy from renewable sources, in kWh; C1—the cost of electricity produced from renewable sources, in USD/kWh; E2—electric energy delivered to the network, in kWh; C2—the price of electricity delivered to the network, in USD/kWh; E3—electric energy delivered to the local grid network, in kWh; C3—the price of electricity delivered to the local grid network, in USD/kWh; E4—thermal energy delivered to consumers, kWh; C4—the price of thermal energy, in USD/kWh.

Ultimately, the efficient deployment of green hydrogen energy storage technologies will demand robust commitment from the scientific community, the private sector, and governments to support research and development, as well as to establish a conducive legislative and economic framework. This collective effort will contribute to solidifying green hydrogen's role as a central component of the future energy mix within an economy founded on renewable and sustainable energy sources.

The fuel cell produces electricity with power P_3 and cost C_3 but also thermal energy (heat) with power P_4 and cost C_4 (there may also be an RC heat accumulator inserted [2,4,14–16].

By generating electric power in the chain for hydrogen production, calling on the facilities shown leads to an increase in the price for the electricity delivered to the value C_3, higher than the price from the network C_1, ($C_3 > C_1$ [USD/(kWh)]).

Injecting this energy into the network will lead to a combined price $C_2 > C_1$. As illustrated in Figure 2, a portion of the electric power derived from the hydrogen storage line can be utilized locally without being fed back into the network.

The waste heat generated by the fuel cell can be utilized either locally or centrally if there is an accumulator. However, in certain cases and timeframes, it may result in losses [14–20].

An estimate of the current prices for the hydrogen storage system (HSS) indicates a price for electrolysis of about 1050–1060 USD/(kW), with a lifetime of 18 years [21,22]. Electrolyzers will have to have flexible behaviour to load variations but also frequent starts and stops. For 1 kWh consumed, electrolyzers will produce 1.2–0.23 $m_N^3/(h)$.

Technical but also economic problems also raise hydrogen storage, including for the compression process but also for the fuel cell, with all the recent technological evolution in this field.

This game of prices must be taken over by the energy system as a whole, including through subsidies for ecology. According to the data from the work [16], the average cost for the energy from an electric system is about 0.22 USD/(kWh), and for the energy delivered from the hydrogen storage system, it is about 0.41 USD/(kWh), the increase being about 1.8 times.

Given the current technological stage, alternative storage systems for electricity generated from renewable sources will need to be explored. Operational values fall within existing limits for power plants, including those utilizing fossil fuels. When considering the ratio between investment capital and operational costs relative to the electric power produced by installations using renewable sources and stored in green hydrogen, specific values can be identified [22,23].

Investment Securities
Photovoltaic panels: 1000–1100 USD/(kW); Wind energy systems: 850–950 USD/(kW); Electrolyser: 1050–1150 USD/(kW); Fuel cell: 1600–1700 USD/(kW)
Operational Values
Photovoltaic panels: 10.5 USD/(kW); Wind energy systems: 19–21 USD/(kW); Electrolyser: 30–40 USD/(kW); Fuel cell: 80 USD/(kW)

If you add the investment related to compression and storage (which can be of various technologies), along with that related to buildings, power lines, etc., you reach very high values, around 7000–8500 USD/(kW), with much over the investment in other electricity production systems or even its storage by using other technologies.

3. Results on the Proposed Energy Storage Technology

Regarding the adoption of green hydrogen in household consumption as part of the transition towards climate neutrality, there is a proposal to inject it into existing methane (CH_4) networks. However, it is essential to note that this approach only offers a partial solution to reducing CO_2 emissions. The strategy involves gradually increasing the proportion of green hydrogen in methane, with dosage ratios set at of $x = 0.05$; $x = 0.07$; $x = 0.10$, and $x = 0.15$, where x represents the volume of green hydrogen in (CH_4).

While this method presents a promising avenue for reducing carbon emissions, it also comes with its challenges. One significant drawback is the reduction in the calorific value of the resulting mixture. This decrease in calorific power, denoted as H_i and detailed in Table 1, raises concerns about the overall energy efficiency and performance of the blended fuel.

Table 1. Calorific power of methane–hydrogen blend.

x	0	0.05	0.07	0.10	0.15
$H_i\left[MJ/(m_N^3)\right]$	35.70	34.46	33.97	33.22	31.98

where x is the share of hydrogen mixed with methane $m_N^3/(m_N^3)$; H_i—the lower calorific value of the CH_4-H_2 mixture in $MJ/(m_N^3)$.

Therefore, while injecting green hydrogen into methane networks offers a transitional solution towards lower emissions, it is crucial to carefully consider the trade-offs involved, particularly in terms of energy output and efficiency. Further research and development may be necessary to optimize the blending process and ensure the effective integration of green hydrogen into existing infrastructure.

Therefore, a series of challenges emerge concerning the management of the flow rate as well as the measurement equipment and associated safety systems. Additionally, the resilience of the transportation and distribution networks to the changes brought about by the introduction of hydrogen raises significant concerns. Even the maintenance of the entire chain involved in the distribution and utilization of hydrogen will necessitate a different and innovative approach.

Another crucial aspect pertains to the specifications of the burners utilized in the process. These must consistently meet the Wobbe criterion to ensure the efficient and safe combustion of the hydrogen-methane mixture. Simultaneously, it is imperative to consider the impact on CO_2 emissions. Although introducing hydrogen into the methane network may result in a modest decrease in CO_2 emissions during the initial transition phase, this effect is limited, with an estimated reduction of less than 5%.

From an ecological standpoint, it is crucial to effectively evaluate the ways in which green hydrogen is utilized. While injecting hydrogen into the CH_4 network may serve as an initial step, it is evident that other applications for green hydrogen could make a more significant contribution to reducing carbon emissions.

Therefore, from a broader perspective, efficient electricity consumption emerges as a preferable option for energy production during the transition phase towards a society with reduced CO_2 emissions. It is imperative to seek innovative and sustainable solutions to ensure an efficient and environmentally friendly energy transition.

The utilization of hot water for storing electricity presents a viable alternative within the household energy consumption spectrum compared to hydrogen storage. This approach involves deploying a significant number of hot water storage devices, such as boilers, across the population. Unlike conventional methods where accumulated energy is redistributed as electrical power, this technique ensures an economic and societal remedy fpr the surplus electricity generated by centralized systems.

When considering the storage of electricity sourced from renewable outlets in domestic hot water for public consumption, it is crucial to assess its affordability during peak production periods. This entails ensuring that the associated cost remains economically feasible for this alternative. To encourage widespread adoption, the expense of utilizing electricity for water storage must undercut that of all other water heating solutions. Essentially, the cost per kilowatt-hour (kWh) of electricity should be lower than the cost of generating equivalent heat through the combustion of conventional fuels such as natural gas, LPG, or biomass [24].

The utilization of boilers with a 50 L capacity, powered by electricity with a rating of 2.3 kW, can effectively cater to the daily household demand for hot water. The water temperature within the boiler is set at 75 °C, as illustrated in Figure 3.

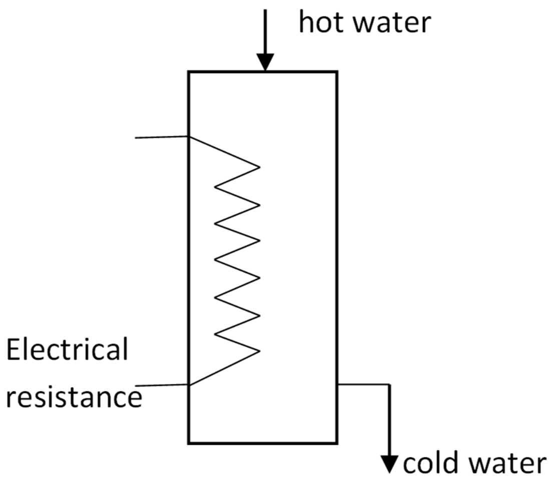

Figure 3. Schematic of the electric energy storage boiler in hot water.

The investment in this analysis mainly falls on the population and focuses primarily on the electric boiler, which keeps the cost within an acceptable range for each household. However, to enhance the attractiveness of this solution, besides the benefit of lower costs associated with producing hot water using electricity instead of traditional fuels, there may also be financial assistance available from the government. It is important to consider the appropriate timing for the implementation of this energy storage technology, which will largely coincide with the expansion of renewable energy sources.

The heat accumulated by the hot water will have the following value:

$$Q = m_a c_a \Delta t \; [KJ] \tag{2}$$

where m_a is the mass of water, (admitted to the value of 50 L); c_a—specific heat of water, $c_a = 4.18$ kJ/(kgK); and Δt—water heating rate (admitted Δt = 65 °C, hot water up to 75 °C).

For these values, the accumulated heat will have the value, $Q = 13,600$ [kJ]. The system considered involves boilers with direct electric resistance and advanced electronic control, allowing for setting the water temperature and programming the operating time.

For an electric power of 2.3 kW, the electric heating time will be 1.42 h (consumption of 3.266 kWh).

As an example, the ARISTON 100 L electric boiler with an electric power of 1.5–2 kW is considered, with a range of hot water temperature from 60–65 °C, and a water heating time to 65 °C of 4.2 h.

The takeover of electricity produced from renewable sources will be carried out during the period of maximum power, as shown in Figure 4. A period of accessing electric energy from renewable sources, especially solar, has been considered.

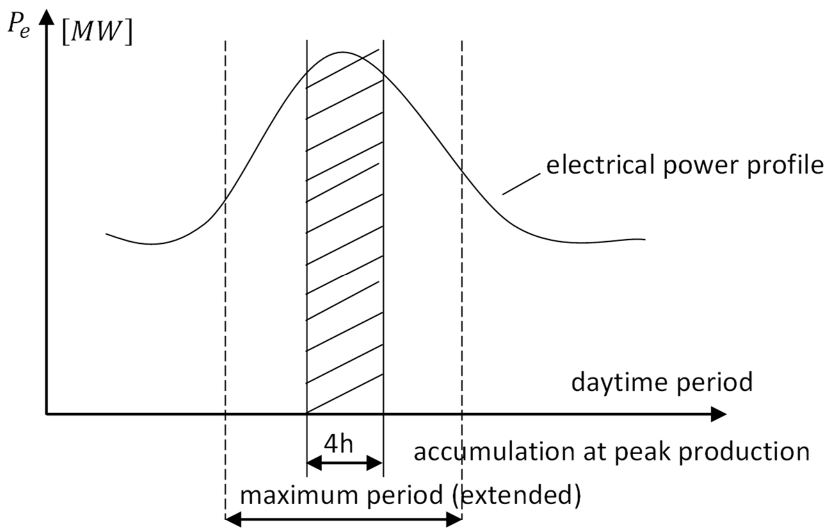

Figure 4. The period of electricity consumption from renewable sourcesd between heating the hot water storage.

It is considered 2.5 heating cycles per day, with the consumed electrical energy having the value (consumption period about 4 h, based on an average consumption of hot water for 3.5 people) $E_e = 8.165[\text{kWh}/(\text{year})]$.

The size of the extended period of use of electric water heating will depend on the structure of the power profile delivered to the network and its price.

A calculation for Romania, where there are approximately 7.5 million households, of which 2.5 million are considered potentially able to apply this storage solution. For an initial application aiming at maximum consumption, the following values are obtained. Assuming a period of 200 days per year during which the electric energy delivery curve is satisfied and the electricity price is attractive, for a number of 2.5 million households considered to be engaged in the operational program, the total accumulated energy will be as follows:

$$Q_{tot} = 2.5 \cdot 10^6 \cdot Q \cdot 200 \cong 4000 \text{ GWh}/(\text{year}), \tag{3}$$

with the quantity of heat Q determined by relation 2.

The thermal values presented represent a hypothetical capacity for capturing electric energy in the form of hot water in a set of installations (boilers) dispersed among the population. The data regarding the number, capacity, and costs are based on the authors' experience in this field, not on literature data. Additionally, the dynamics of water heating during operation must be taken into account, as presented further. Figure 5 schematically depicts the operation of an electric boiler.

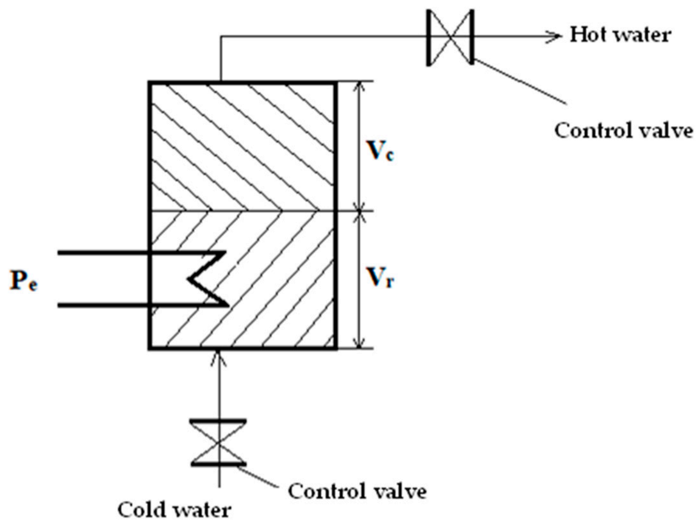

Figure 5. Scheme of the dynamic operation of the hot water accumulator.

The heater includes, through the stratification process, the cold zone, with a volume V_r (m^3) and water temperature t_r, and the hot zone with volume V_c (m^3) and temperature t_c (temperature being expressed in °C). According to the hypotheses in the paper [5], the cold water has the temperature from the supply network, while the hot water has the emperature from the consumer network.

The total volume of the boiler: $V = V_a + V_c$

The boiler will absorb energy by heating the volume of cold water.

$$E_e = V_a \cdot c_a \cdot \rho_a (t_c - t_r)\tau \quad [\text{kWh}] \tag{4}$$

where: V_a is the volume of cold water in m^3; c_a is the specific heat of cold water, kJ/(kgK); ρ_a is the density of cold water, kg/$\left(m^3\right)$; t_c is the temperature of hot water, °C; t_r is the temperature of cold water, °C; and τ is the operating time. The total volume of the boiler V in m^3 is the sum of V_a and V_c, m^3.

The time τ is determined by the duration of opening the hot water valve. There is a dependency between the volume of cold water admitted into the boiler and the duration of use of the installation, as well as a dependency between the flow rate of hot water and its temperature and the duration of use.

$$V_a = f_1(\tau);\ \tau = f_2(t_c) \tag{5}$$

Under the action of the flow rate of hot water used D_c in m^3/h, the volume of cold water in the boiler will be as follows:

$$V_a = V - D_c \cdot \tau \quad \left[m^3\right] \tag{6}$$

The heat accumulated in the boiler during operation will be less than the maximum accumulation. After the hot water consumption is closed, the installation enters a static heating process of the water until it reaches the nominal temperature value. These successive operations, for a possibly extended heating period, will lead, depending on the consumers, to the estimated accumulation values.

A reference to the thermal energy obtained through the combustion of natural gas indicates that the electrical energy accumulated for one day, in hot water Q, corresponds to 1 m_N^3 of natural gas.

For the 200 days expected to produce hot water from renewable electricity and for 2.5 million households, a natural gas equivalent of 0.5 billion m_N^3 results, which represents about 5% of the annual natural gas consumption for Romania.

For the reduction of CO_2 emissions by replacing the combustion of methane gas, it represents an average annual amount of 0.5 million tons.

The system of accumulating the electricity produced by SRE during peak surplus periods can be realized both in homes with thermal power plants and in those with heating in the centralized system. The investment is minimal, around EUR 400–500 for a home. The investment figure is minimal, covering the maximum range of (200–300) EUR/(kW).

Another possibility of storing electricity in hot water can exist in some residential houses that include individual installations with heating with fossil fuels and which are equipped with a water accumulator of 1000–1500 L. These accumulators will heat the water both from the hot water circuit of the plant and from an electric circuit with a power of 2–5 kW, depending on the value of the supply voltage; see Figure 6.

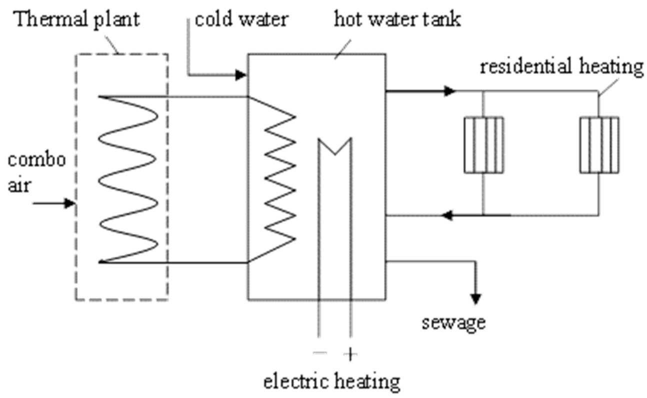

Figure 6. The scheme of electricity accumulation in hot water in a system equipped with a heat accumulator connected to the heating system.

Integrating electric heating into the hot water accumulator with thermal heating does not entail significant technical or investment difficulties. This solution can be achieved through a series of relatively simple and technically accessible modifications, without requiring complex equipment or technologies.

From an investment standpoint, the costs associated with introducing electric heating can be efficiently managed and incorporated into the existing budgets of households or building owners. Additionally, the long-term benefits of using electric energy for water heating, such as increased energy efficiency and reduced dependence on fossil fuels, can easily offset the initial costs.

Furthermore, introducing electric heating can provide increased flexibility and enhanced control over the heating system, allowing for precise adjustments to temperature and energy consumption based on individual needs and seasonal changes. Thus, this solution can be viewed as an accessible and efficient option for modernizing traditional water heating systems.

The heat accumulation process through the electric circuit overlaps with that obtained from fuel combustion. The total energy accumulated in the hot water will vary within a range between 5 and 20 kWh.

While electric heating contributes to accumulating a portion of the required thermal energy, fuel combustion adds an additional amount of heat to the system. This combination provides a high degree of flexibility and efficiency in providing hot water for various domestic or commercial applications.

Given the wide range of accumulated energy, this system can be adapted to meet the specific needs of different situations and user preferences. It also allows for adjusting the heat level according to usage requirements and environmental conditions, ensuring optimal comfort and increased energy efficiency throughout the process.

The advantage stems from the temporal flexibility of using electric heating, as well as the optimization of consumption involving both fossil fuel and electric heating for both household heating and hot water. An estimate of the potential for such energy accumulations in warm Romania indicates a range of 100,000 to 300,000 households. For an annual accumulation period of 200 days, the energy becomes the following:

$$Q_{tot} \cong (100 \div 600)[\text{GWh}/(\text{year})] \quad (7)$$

The accumulation of electric energy in hot water supplements that previously determined by boiler systems. The total estimated value reaches $(4.1 \div 4.6) \cdot 10^3 [\text{GWh}/(\text{year})]$, presenting a solution with easy applicability and relatively low investments.

If the cost of electricity ranges from \$24/MWh to \$96/MWh, and that of electricity produced from wind sources ranges from \$42/MWh to \$114/MWh, the cost range within this energy storage operation can be estimated at [25–28].

The proposed solution for storing energy in household water offers the advantage, as mentioned earlier, of requiring minimal investment, which can be undertaken by the population, and may also be considered for a certain degree of subsidization. This solution also considers household energy prosumers (self-producers) based on photovoltaic panels installed on homes, which can, for certain periods, serve as sources for storing energy in household hot water (for higher power, this can even extend to heating swimming pools). By involving household energy prosumers and integrating photovoltaic panels into the system for storing energy in hot water, a comprehensive and sustainable solution for managing energy consumption at both individual and community levels can be achieved. This approach provides an efficient means to utilize renewable energy and contributes to reducing the carbon footprint of households while also offering users increased autonomy and control over their energy consumption. The figures presented regarding the number of homes capable of achieving this accumulation of electricity in hot water were estimated, initially, based on housing space in Romania, taking into account the enthusiasm generated by investments in solar panels. The solution's applicability remains viable in situations where there is a reduced cost of electricity during peak production hours (thanks to contributions from renewable sources), lower than that achieved by burning natural gas or other fossil fuels or biomass.

For homes heated with wood, the use of domestic hot water through electric heating presents a tempting alternative, both economically and operationally.

The accumulation of excess energy in hot water can be successfully applied to homes equipped with photovoltaic panels [29,30].

Additionally, some commercial enterprises may find it feasible to implement hot water storage systems, given their significant consumption, either structurally or economically.

Among the potential sectors are as follows:

- Tourism, especially the hospitality industry, which includes both accommodation spaces and food preparation facilities.
- The food industry, which utilizes large quantities of hot water in production and cleaning processes.
- The agrochemical industry, which has production lines requiring hot water regularly.
- Agriculture and related industries, which may require hot water for various activities, from irrigation to primary processing of agricultural products.

To assess the capacity for hot water storage, it is relevant to consider natural gas consumption, which represents a significant portion of energy consumption in many sectors:

- Approximately 25% of total natural gas consumption is allocated to the residential sector.
- Approximately 18% of total natural gas consumption is allocated to the mentioned industrial sectors.

These figures suggest that a significant amount of electric energy can also be stored in industrial hot water consumption.

By implementing systems for storing electric energy in hot water, a reduction in natural gas consumption can be achieved, with significant implications for CO_2 emissions. Thus, the benefits of storing electric energy in thermal energy are twofold:

- Absorption of power variations generated by renewable sources of electric energy.
- Reduction of dependence on natural gas and, consequently, reduction of associated carbon emissions.

For a country like Romania, where natural gas is a significant component of the national energy mix, the implementation of hot water storage technology presents a promising opportunity for both economic and environmental benefits. In 2023, Romania's annual natural gas consumption reached approximately $10.65 \cdot 10^9$ m_N^3, indicating heavy reliance on this fossil fuel for various sectors, including residential, industrial, and commercial.

By adopting hot water storage systems on a widespread scale, Romania could significantly reduce its reliance on natural gas consumption. The estimated savings range from $(0.6 \div 1) \cdot 10^9$ $m_N^3/(\text{year})$ representing a substantial portion of the total consumption. This reduction in natural gas usage translates to significant environmental benefits, particularly in terms of reducing carbon dioxide (CO_2) emissions.

The projected decrease in CO_2 emissions is substantial, with an estimated reduction of $(1.2 \div 2) \cdot 10^6$ $t/(\text{year})$. This reduction aligns with Romania's commitments to mitigate climate change and transition towards more sustainable energy practices. By lowering CO_2 emissions, Romania can contribute to global efforts to combat climate change while also improving local air quality and public health.

Furthermore, the economic advantages of reducing natural gas consumption should not be overlooked. Decreasing reliance on fossil fuels can enhance energy security, reduce import dependency, and create opportunities for investment in renewable energy technologies. Additionally, the cost savings associated with lower natural gas usage can benefit households, businesses, and the overall economy by freeing up resources for other priorities.

The implementation of hot water storage technology offers Romania a valuable opportunity to achieve significant reductions in natural gas consumption and CO_2 emissions. By embracing this innovative approach, Romania can move towards a more sustainable and resilient energy future while simultaneously realizing economic and environmental benefits.

4. Conclusions

As the proportion of renewable energy resources, especially solar and wind, increases in energy production, the need for storage also rises for certain periods of time and for later use during periods of minimal production (production deficit). However, green hydrogen storage has shown some deficiencies related to technical and economic aspects, therefore, other energy storage technologies are being sought.

Like green hydrogen electricity storage, the applicability of the domestic water energy storage solution depends on the price of electricity and accessibility to storage (grid, metering, billing, etc.).

In general, the stock of electricity from renewable sources will follow a path of diversification of solutions, which will include all high power installations up to household installations [31–34].

This paper proposes a concept that can be applied, with the residential area becoming a factor in electricity storage. The current theoretical study will need to be supplemented with new data in the future to become the first solution for experimentation. Storing surplus electric energy from certain periods of the day, generated from renewable sources, in domestic hot water represents a solution in a preliminary analysis phase. In fact, the paper proposes an economic-social concept regarding the accumulation of surplus electric energy in residential punctual sources.

Storing energy in the form of residual hot water represents a simple and cost-effective technical and investment solution. It can become viable through a predictive policy on electricity production, reflected in the delivery price to the population. Skepticism in the analysis phase of this preliminary exhaustive proposal must consider that similar reservations existed for energy self-producers using solar panels, which are now witnessing a true explosion in their numbers. Accumulating energy in domestic hot water also assists energy self-producers by smoothing out the power curve offered to the energy system.

Storing energy in the form of hot water for residential and partial industrial consumption should be analyzed as a complementary solution to multiple storage solutions, which will likely operate in parallel for a viable energy system. The paper includes statistical references and a numerical application model under simplified ideal conditions for Romania, which is the sixth-largest economy in the European Union. The data presented can serve as a starting point for complex studies.

The paper presents a simplified comparative analysis, especially focusing on economic aspects of peak electricity storage, particularly during the daytime due to excessive production from renewable sources. In terms of reducing CO_2 emissions, it is mentioned that storing electric energy in domestic hot water ultimately leads to a reduction in the use of fossil fuels, with the corresponding environmental impact.

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