Optimisation of Renewable Power-Hydrogen System for Decarbonising Heating

Eduardo Gonzalez *and* Hongjian Sun
Department of Engineering
Durham University, Durham, UK
eduardo.e.gonzalez-osuna@durham.ac.uk

Abstract—This paper presents an analysis of an integrated power-hydrogen system for an energy community, incorporating renewable energy sources as solar panels, battery storage, and grid interaction. This study focuses on optimizing energy consumption and minimizing CO2 emissions. Genetic algorithm techniques are implemented to find the optimal values for various parameters in the system such as battery usage and grid consumption. The analysis considers power load and hydrogen load for heating, with renewable energy sources meeting the power load and surplus energy used to produce hydrogen. The objective is to reduce CO2 emissions by minimizing grid consumption. The findings highlight the potential of integrated power-to-hydrogen systems for decarbonizing small communities.

Index Terms—Power-to-hydrogen system, optimization, genetic algorithms, decarbonization.

1 Introduction

Energy systems are presently undergoing a significant and profound transformation. This transformation is primarily driven by a confluence of scientific and technological advancements, as well as political initiatives, such as the concerns surrounding carbon emissions by first world countries and their efforts to reduce the carbon footprint within their respective nations. Such is the case of the United Kingdom which is currently developing different approaches of renewable energy systems and modern technologies to reduce the country's carbon footprint by 2030 [1]. Another example of power to hydrogen (P2H) inclusion for carbon emissions reduction is the case of Germany, which "By 2030, [. . .] aims to reduce greenhouse gas (GHG) emissions from the buildings sector by two-thirds relative to 1990 levels" [2]. A notable consequence of this ongoing transformation is the increasing interconnection and interplay among various energy vectors, encompassing electricity, natural gas, hydrogen, heating, and cooling [3]. Consequently, there is an increasing demand for energy storage and flexible demand mechanisms to accommodate the evolving dynamics of these energy systems. One such approach gaining prominence is P2H, wherein surplus energy of the renewable energy systems is employed to generate hydrogen. Given the intermittent nature of such systems, this hydrogen can serve as a means of storage for future utilization within the same system or for transportation to other applications [4].

Current energy systems are adopting diverse methods of integrating P2H to address prevailing challenges like intermittency and transportation. Nonetheless, certain obstacles remain concerning the utilization of hydrogen within renewable energy systems. Residential heating accounts for the majority of energy consumption in households, specifically 78% of the total energy usage [5]. A promising emerging technology that aims to reduce reliance on natural gas for heating is the blending of hydrogen with natural gas. It is feasible to replace up to 10% of natural gas with hydrogen using the current gas network infrastructure. Although hydrogen is abundant, it is primarily found in molecular form, mainly in covalent compounds with nonmetallic elements, due to its physical properties. The preferred method for extracting hydrogen involves using water and renewable electricity through the process of electrolysis. Research focused on the potential of hydrogen for energy storage, the financial profitability of this approach is not sufficient [6]. As a result, alternative uses of hydrogen, such as heating and transportation, are being explored. Evaluating hydrogen as a fuel in the transition to a low-carbon future is complex, as the viability and sustainability of its extraction through electrolysis are closely tied to the characteristics of the interconnected power system [7].

There are already different cases of blended hydrogen studies applied on real life scenarios such as the case of HyDeploy, a green energy trial, conducted at Keele University between 2019 and 2021 [8]. The achievement expected by the HyDeploy initiative is the establishment of a robust initial evidence base substantiating the seamless integration of hydrogen into the operational natural-gas network of the UK, upholding customer continuity and end-user safety. HyDeploy has effectively concluded Phase 1, marked by the authorization issued by the Health and Safety Executive (HSE) for the inaugural instance of hydrogen infusion into a gas network within the United Kingdom. Future data from the next two phases are required for a conclusive result.

Another example comes from the previously mentioned current trend of carbon reduction for 2030; a study from Longoria et al. (2021) [9] which proposes the deployment of electrolysers in Ireland in order to produce hydrogen for heating along the country, studying the energy required, hydrogen produced and cost of deployment and use. The conclusion of this research presents some interesting results:

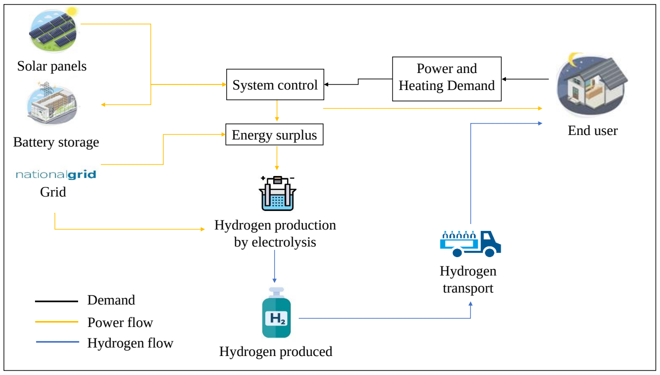

Fig. 1. Integrated power-hydrogen system operating model.

even if the electricity prices increase by around 1% to 2%, the policy of the United Kingdom for decarbonization to 2030 will result in a future price reduction when this technology is established. Also, the reduction of Greenhouse gas emissions will be an attractive incentive for investors and government. Finally, this research considers the future developments of P2H technologies that will benefit the use of such model for future energy systems.

As it can be attested, P2H is being widely researched for future medium-term implementation. However, there are still some gaps in the literature that are needed to be addressed. The production of green hydrogen with surplus from renewable energy systems still needs to have more research regarding the diverse types of energy systems, requirements, and constraints of such systems. CO2 production is a key factor to consider for optimal cost minimization of renewable energy systems and a balance between minimizing cost of production, grid consumption and CO2 produced will significantly improve system's performance and their appeal for investors and governments. Heating using hydrogen is beginning to take form and needs to be addressed as a future reality in future households. The use of computer science technologies to improve these systems such as Artificial Intelligence for load forecasting will be a necessity and needs to be more addressed.

This paper contributes with the following:

1) Propose an optimization model that reduces the grid consumption and CO2 production of a renewable energy system that satisfy power and heating necesities of an energy community.
2) The model uses a translation of natural gas for heating load to a H2 equivalent in order to propose an aproximation to a real world scenario.
3) The optimization minimizes grid consumption and CO2 production both while other aproximations tend to focus in just one objective to minimize.
4) This model also includes the costs of hydrogen transportation for heating in the energy community, considering energy required for compression and number of compressors aconrding to the distance between plant and community.

This research paper is going to follow the next structure: first, a description of the model, explaining the structure of the system and the interactions between the various parts of it. Next, an explanation of the methods used during this research and how the model was used for the research. Following, the results are going to be presented and explained. Finally, a conclusion will follow explaining a resume of this research and future implementations expected to improve the system.

2 Model and Objective

Assume there are two types of energy loads in a small village: power load and hydrogen load. The village deploys renewable energy sources, e.g., solar panels, to meet the power demand and use energy surplus (when supply is greater than demand) for generating hydrogen to meet hydrogen load. It can also use a set of batteries to store energy surplus. When the power demand cannot be met by renewable energy sources or and batteries, the village will consume energy from the power grid. The aforesaid system should consider the prices of buying energy from and selling energy to the grid, to run the system in an economic way. The hydrogen load is primarily met by the energy surplus from renewable energy sources. We also consider the cost of hydrogen compression for pipeline transportation. The main objective is to reduce CO2 emission generated from the integrated power-hydrogen system.

2.1 Power demand

The cost of energy consumption to meet power demand can be represented as:

$$P^G_{tot} = \sum_{t=1}^{24} C^G_t * P_t * \Delta t \tag{1}$$

where P^G_{tot} is the total cost of energy purchased from grid during 24 hours to meet the power load, C^G_t is the price to buy energy from the grid at time t, $G * P_t$ is the power needed from the grid in a moment t to meet the power load and Δt is the time interval, here assuming one hour in a 24-hour basis.

In order to find when and how much energy is required at a certain hour, we have a supply-load balancing model:

$$P^G_t = LP_t - RW_t + P^B_t \tag{2}$$

where P^G_t is the power required from the grid in a moment t to meet the power load, LP is the power load in a moment t, RW is the power from renewable energy in a moment t and P^B_t is the charging or discharging power of the battery during a moment t.

The solver aims to change the value of P^B_t in different iterations to find the best use of the battery and renewable energy to reduce the use of power from the grid. If the value of P^G_t is greater than zero during that moment, then the value is stored in an array P which represents that how much energy was purchased from the grid.

If $P^G_t < 0$

$$S_{t+1} = [S_t, -P^G_t] \tag{3}$$

$$P_{t+1} = [P_t, 0] \tag{4}$$

Else

$$P_{t+1} = [P_t, P^G_t] \tag{5}$$

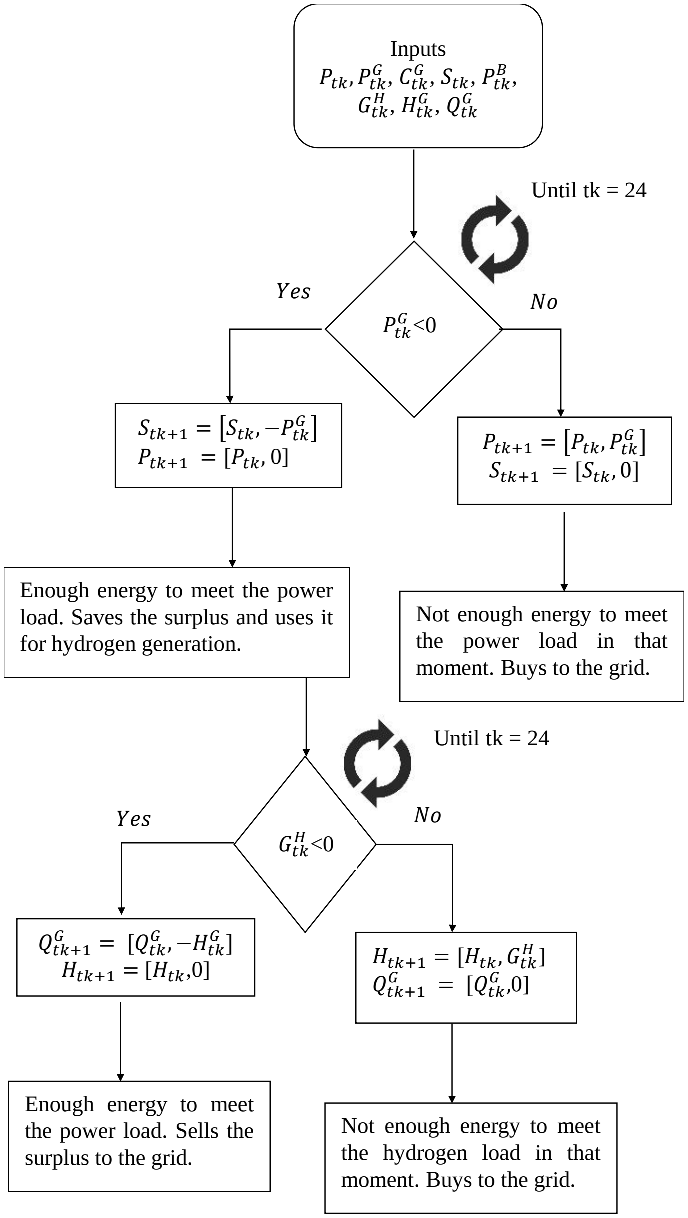

Fig. 2. Flow chart of the conditions to buy or sell to the grid.

$$S_{t+1} = [S_t, 0] \tag{6}$$

Otherwise, the value is stored in an array called S (surplus), meaning that the system is producing more energy than the need during that moment and is saving it for later use.

2.2 Hydrogen demand

We then consider the use of the energy surplus previously saved and sells the rest to the grid in case there is still surplus:

$$H^G_{tot} = \sum_{t=1}^{24}((-B^G_t * Q^G_t) + (C^G_t * H_t) + (P^{com} * n^{com}) * \Delta t) \tag{7}$$

where H^G_{tot} is the total cost of energy purchased for 24 hours to meet the hydrogen load, B^G_t is the cost the grid buys energy to the system in a moment t, Q^G_t is the quantity of energy that is going to be sell to the grid in a moment t, H_t is the amount of energy purchased to the grid in a moment t to meet the hydrogen load, P^{com} is the power the compressor requires to work and n^{com} is the number of compressors used in the hydrogen delivery process. An equation similar to (2) is used for this case but with a difference:

$$H_t = LH_t - (S_t + P^B_t) \tag{8}$$

where G^H_t is the energy required from the grid in a moment t, LH is the load of energy required to meet the hydrogen demand in a moment t and S is the surplus energy stored in a moment t.

If $G^H_t < 0$

$$Q^G_{t+1} = [Q^G_t, -H^G_t] \tag{9}$$

$$H_{t+1} = [H_t, 0] \tag{10}$$

Else

$$H_{t+1} = [H_t, G^H_t] \tag{11}$$

$$Q^G_{t+1} = [Q^G_t, 0] \tag{12}$$

Equations from (9) to (12) are similar as (3) to (6) with the difference that, instead of storing the surplus for later use, it is saved on Q^G_t to sell it to the grid.

2.3 Compressor

The power required for a compressor is calculated with the following equation:

$$P^{com} = Q(\frac{1}{24 * 3600})\frac{ZTR}{M_{H2}\eta}\frac{N\gamma}{\gamma - 1}((\frac{Press_{out}}{Press_{in}})^{\frac{\gamma-1}{N\gamma}} - 1) \tag{13}$$

Where P^{com} is the power required to compress the hydrogen. Q is an approximation of the hydrogen produced during the day in kg. Z is the hydrogen compressibility factor. T is the inlet temperature of the compressor in Kelvin. R is the universal constant of ideal gas $8.314 J/mol * k$ M_{H2} is the molecular mass of H2 $2.15 g/mol$. η is the compressor efficiency ratio at 75% N is the number of compressor stages. γ is the ratio of specific heat. $Press_{out}$ is the outlet pressure of the compressor. $Press_{in}$ is the inlet pressure of the compressor.

2.4 Battery

The battery of the system in a specific moment is represented by the following equation:

$$Stor_t = \sum_{t=2}^{25} Stor_{t-1} + P^B_{t-1} * \Delta t \tag{14}$$

where $Stor$ is the state of storage of the battery in a moment t.

2.5 CO2 emissions

The CO2 produced using the grid is represented by the following equation:

$$CO2^G_F = \sum_{t=1}^{24}(CO2^F_t * P^G_t) + (CO2^F_t * H^G_t) \tag{15}$$

where $CO2_F^G$ is the summatory of the CO2 generated during 24 hours in periods of 1 hour and $CO2_t^F$ is the CO2 factor in a moment t.

The goal of this study is to find the optimal values of a renewable energy system considering the minimization of two factors: grid consumption and CO2 generation. Both cost functions have the same priority in terms of minimization cost of the entire system. However, the system needs to address two necessities of a small village: power load and hydrogen load for heating, being this last one a proposed scenario for future heating technologies with hydrogen. The system consists on a renewable energy module which provides with energy produced by solar panels during 24 hours, a battery to store energy produced by the solar panels or bought to the grid for latter more convenient use, a hydrogen production module to meet the heating demand of the village in this proposed scenario where the hydrogen heating technology and transportation by pipeline is already deployed, compressors to maintain the hydrogen in an optimal compression state during the transportation by pipeline and finally the grid module to buy energy from the grid at hours when the energy produced and stored is not enough to meet both loads or when the energy is cheaper to purchase to use it in a convenient situation. To find the most optimal values to minimize both cost functions, Genetic Algorithms techniques were implemented to optimize the cost functions presented. The data used in these case studies was produced from the lectures of power required for heating obtained on the National Grid datasets and a calculation of the hydrogen equivalent to produce such energy, consiering the energy required from the electrolizer and the loss of energy in the process. Three profiles were created considering the following: profile 1 considers a small building with one to two rooms or a flat and using around 6-8kWh energy per day for heaing. Profile 2 considers a building of 3 to four rooms using around 8-10kWh of energy per day. Finally, profile 3 considers a building with four or more rooms and uses around 12-22kWh per day. After creating these three profiles, 30 buildings were proposed, randomly asigned one of the three profiles. This represents the small comunity of the case studies and with this, an aproximation of their energy and H2 load was finally created. Equations (1) and (7) are cost function that represents the quantity of energy required to be bought to the grid for 24 hours considering how much energy is buy or stored and the cost of buying energy to the grid during certain hours. (1) meets the power load and (7) the hydrogen load. The results of both cost functions are added to find the grid consumption, being this the first factor to minimize. Equations (2) and (8) works together with the previous one, representing the grid energy required in a moment t calculated by subtracting the renewable energy produced and the energy in the battery to the load of that moment in the case of energy load (2), and the same for hydrogen load (8) but changing the renewable energy produced in that moment for the surplus of energy on that moment. Finally, equations (3) to (6) and (9) to (12) are for assign the values depending on if the value is positive, which means that the system is buying to the grid, or if it is zero or negative, meaning that the system has more energy than needed, assigning the latter to surplus or to sell to the grid. Equation (13) is a cost function that represents the generation of CO2 for 24 hours. This value is calculated by the multiplication of the CO2 factor at a certain hour and the grid consumption during such hour. The result is the CO2 generated for 24 hours and is the second factor to minimize. Equation (14) represents the state of the battery storage during a certain hour. The equations skip the first hour and it calculates the difference between the current state of the battery and the previous one in order to find the change of state in the battery. This helps the system to keep track of the battery state to know the quantity of energy left for use in the current hour. The use of the battery is vital for the system to keep an external storage in case the system calculates that buying energy to the grid is convenient and both loads are meet during that hour. The optimization must consider the following constraints:

a The energy produced by solar panels always needs to be the primary source of energy to meet the power load.
b The hydrogen load needs to be meet primarily with the surplus after power load is meet.
c The battery cannot surpass the maximum capacity of storage.
d When one of the loads cannot be meet with the produced renewable energy, the remaining energy must be extracted from the battery.
e In case the produced renewable energy and the energy stored in the battery are not enough to meet the loads, energy from the grid must be purchased.
f Energy from the grid will be purchased if the price is convenient during certain hour and will be stored in the battery for later use.

3 METHODS

3.1 Hydrogen Load vector

The system proposed for this research solves two loads: power and hydrogen. For the power load, usage data from the national grid was selected to produce a vector of 24 hours of power load representing an autumn day in the northeast of UK [10]. On the other hand, for the hydrogen load there was not an existing example of hydrogen required for heating in the current grid. For this case, the natural gas required for heating in the northeast of UK was selected to produce an equivalent in terms of hydrogen, considering the heating potential of the hydrogen and the difference between hydrogen and natural gas quantity to produce the same heat [11]. After creating the hydrogen load vector, both load vectors were ready for minimization.

3.2 Model explanations

This model considers the following factors for minimizing: the cost of buying power to the grid, the price the energy can be sold to the grid, the CO2 produced by using energy from the grid in a certain moment, the power required for the electrolizer to work, the cost of power required for the hydrogen compressor, the number of compressors depending the distance between the energy community and the plant, the power produced by the renewable energy system and finally the state of the lithium batteries. This model uses the lithium batteries, charging and discharging

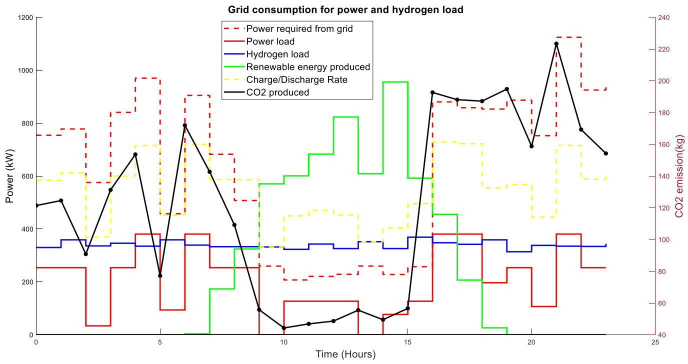

Fig. 3. No optimization applied.

them to distribute power to the system modules in certain moments depending on the cost of the energy from the grid at a certain hour, the level of charge of the battery, the load requirement during that hour and the CO2 factor during that hour, this in order to reduce the consumption of the grid and, in consequence, also reducing the CO2 production. However, reducing the grid consumption and the CO2 production are related but not entirely dependent one on the other. For example, at a certain hour the CO2 factor can be high but the cost to buy energy to the grid is low and the power produced by renewable energy is not enough to solve the power and hydrogen load. In a situation such as this one, the solver will evaluate the possibility of using the grid or to use the lithium batteries depending on the factors previously stated. The solver can prioritize the low cost of the grid consumption in that hour or the high CO2 factor during that hour which will result in a high CO2 production if the grid is used. Those two contrary options will be evaluated, and the result will be the one that satisfy the loads of the system but also reducing the two cost functions of the system, cost functions which have the same priority in this model.

3.3 Solver

A solver from the MATLAB software was applied for this research. MATLAB tools has been used in other research similar to [12] where a GA solver was applied to minimize cost functions to optimize a nuclear hybrid energy system. In this research the solver gamultiobj was applied to minimize the two cost functions. Gamultiobj finds the pareto front of the fitness functions using the Elitist GA algorithm to find the better fitness values. The upper bound and lower bound that the solver will consider are the capacity of the lithium batteries. The storage capacity serves as a limit to the solver to manipulate the use of the battery in order to improve the performance of the system. Finally, the solver will find the best results during a number of iterations and the best results are stored in a vector of results. This process is repeated 100 times and after this process, the best result among them is selected using an algorithm to find the best compromised solution. This algorithm is the Net Flow Method, an algorithm which evaluates the difference of ranks between this one and the others, then it does the same with the next objective and so on [13]. Using this algorithm, the solver finds the best option for this specific situation, minimizing both cost functions at the same time but ensuring that the criteria is meet.

4 RESULTS AND DISCUSSION

For this study, an energy community of 30 buildings with different power requirements is simulated. The data for these simulations is produced using the data of solar panel production in autumn days at the northwest of UK [10]. Since currently there is not a real-life scenario with massive hydrogen consumption for heating in regular communities, the data of natural gas used for heating in a community with similar characteristic was selected and such data was later used to calculate the equivalent of energy required to produce enough hydrogen to meet the heating demand. Also, in this simulated scenario, the hydrogen is delivered to the final users by pipeline and truck transportation, similar to how natural gas for heating is delivered, so it is needed to maintain a compressed state during the transportation, requiring a compression station around every one hundred miles approximately.

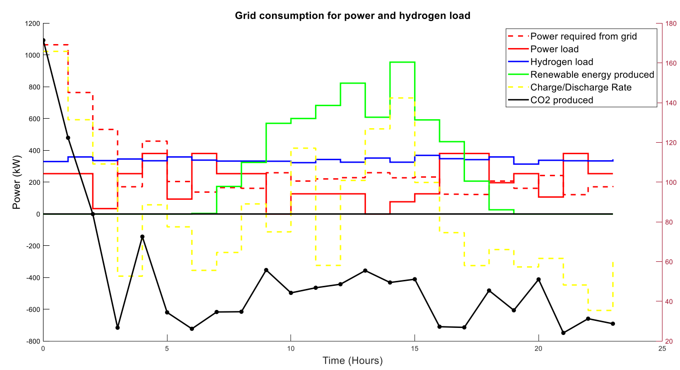

Fig. 4. Optimized results: Grid consumption and CO2 production minimized.

The cost functions of the system were optimized using a GA in order to find the most optimal use of the battery to minimize the grid consumption and CO2 production. Figure 3 represents an scenario where no optimization was made. The system used the battery just in specific moments where the price of buying energy to the grid was low and sold energy to the grid when the earnings were high not considering the production of CO2 and the intent to minimize the grid consumption at the same time. Meanwhile, Figure 4 represents the overall performance of the system by minimizing both cost functions with the same priority. During the first hours of the day, the system buys more energy to the grid to fill the batteries and to better distribute it during the rest of the day. A significant reduction in the CO2 emitted during the day can be observed alongside a better performance of the grid consumption.

The current real case scenarios such as the village of Winlaton [7] which implements H2 heating in the community are still very scarce. More research and time are needed to reach the goal of deploying this kind of systems in the communities, but as it is shown in this paper, the possibility of improving them and reduce their costs is doable. This research is going to be continued, improving the optimization, and including load forecasting from the end user to improve even more the optimization of the system and the reduction of cost and CO2 production.

5 CONCLUSION

This paper presents a comprehensive analysis of a small village energy system, considering two types of loads: power load and hydrogen load. The system incorporates solar renewable energy, battery storage, and grid consumption to meet the energy demands while minimizing CO2 emissions. The objective is to optimize the system's performance by reducing grid consumption and CO2 generation. Genetic algorithm techniques are implemented to find the optimal values for various parameters in the system such as battery usage and grid consumption. The cost functions representing energy purchased from the grid for power load and hydrogen load, as well as the CO2 generation, are minimized simultaneously with similar priority. The battery is required for storing excess energy and reducing reliance on the grid during peak demand periods when energy costs are generally high. The results demonstrate the effectiveness of the proposed system in reducing grid consumption and CO2 emissions. The simulations show that the algorithm efficiently manages the battery and strategically purchases energy from the grid at opportune times. The power and hydrogen loads are satisfactorily meet while the grid reliance is reduced. The findings suggest that this type of implementations can significantly contribute to reducing CO2 emissions and achieving energy sustainability in small communities. Further research of such systems is going to be made to validate the feasibility and scalability of this approach in diverse contexts, changing the data according to new case scenarios and eventually, when such technologies are finally deployed in real case scenarios, to use such data for better optimization results.

REFERENCES

[1] UK government, *The UK low carbon transition plan - gov.uk.*, (2019).

[2] Baldino. et al., *Hydrogen for heating? Decarbonization options for households in Germany in 2050*, International council on clean transportation, (2021).

[3] Fonseca, J.D. et al., *Trends in design of distributed energy systems using hydrogen as energy vector: A systematic literature review*, International Journal of Hydrogen Energy, 44(19), pp. 9486-9504, (2019).

[4] Hu, G. et al., *A review of technical advances, barriers, and solutions in the power to hydrogen (P2H) roadmap*, Engineering, 6(12), pp. 1364-1380, (2020).

[5] Eurostat, *Energy consumption in households*, (2020).

[6] Rath, R. et al., *Recent advances, unsolved deficiencies, and future perspectives of hydrogen fuel cells in transportation and portable sectors*, International Journal of Energy Research, 43(15), pp. 8931-8955, (2019).

[7] BAN, M. et al., *Integration of power-to-hydrogen in day-ahead security-constrained unit commitment with high wind penetration*, Journal of Modern Power Systems and Clean Energy, 5(3), pp. 337-349., (2017).

[8] Isaac, T., *Hydeploy: The UK's first hydrogen blending deployment project*, Clean Energy, 3(2), pp. 114–125, (2019).

[9] Longoria, G., Lynch, M. and Curtis, J., *Green hydrogen for heating and its impact on the Power System*, International Journal of Hydrogen Energy, 46(53), pp. 26725–26740, (2021).

[10] Our World in Data, *Solar Power Generation - United Kingdom.*, Our World in Data, (2023).

[11] Chae, M.J. et al., *The present condition and outlook for hydrogen-natural gas blending technology*, Korean Journal of Chemical Engineering, 39(2), pp. 251–262, (2022).

[12] Piotr D. and Wojciech K., *Development of the MATLAB Tool for Optimization of the Nuclear Hybrid Energy System Dedicated for Hydrogen Production*, 31th international conference of nuclear energy for new europe, (2022).

[13] Wang, Z. and Rangaiah, G.P., *Application and analysis of methods for selecting an optimal solution from the pareto-optimal front obtained by multiobjective optimization*, Industrial and Engineering Chemistry Research, 56(2), pp. 560–574, (2017).