Decarbonising Heating with Power-Hydrogen Optimisation

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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 optimising energy consumption and minimising CO_2 emissions. Genetic algorithm techniques are implemented to find the optimal values for various parameters in the system such as battery usage and grid utilisation. The analysis considers power and heating loads, with renewable energy sources meeting the power load and surplus energy used to produce hydrogen. The findings highlight the potential of integrated power-to-hydrogen systems for decarbonising small communities.

Keywords: Keywords: Power-to-hydrogen · Optimisation · Decarbonisation.

1 Introduction

Energy systems are currently 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 utilisation 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 utilisation 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. 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.
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: even if the electricity prices increase by around 1% to 2%, the policy of the United Kingdom for decarbonisation 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. As it can be attested, P2H is being widely researched for future medium-term implementation. However, 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. CO_2 production is a key factor to consider for optimal cost minimisation of renewable energy systems and a balance between minimizing cost of production, grid consumption and CO_2 produced will significantly improve system performance and its 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.
This paper contributes with an optimisation model to reduce grid power consumption and CO_2 emissions while meeting power and heating needs. It will be structured as follows: a description of the model and model interactions, an explanation of research methods, presentation and discussion of results, and a conclusion summarising the research and future work.

2 Model

2.1 Power Demand

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

$$Cost_E = \sum_{t=1}^{24} C_{buy}(t) \cdot P_{\text{grid},E}(t) \cdot \Delta t \tag{1}$$

where $Cost_E$ is the total cost of energy purchased from the grid during 24 hours to meet the power load, $C_{buy}(t)$ is the price to buy energy from the grid at moment t, $P_{\text{grid},E}(t)$ is the power needed from the grid at moment t to meet the power load and Δt is the time interval, assuming one hour in a 24-hour basis. To calculate the power to buy from the grid at a certain hour, we define the following power demand and surplus balancing model:

$$P_{\text{grid},E}(t) = P_{\text{LE}}(t) - P_{\text{pv}}(t) + P_{\text{bat}}(t) \tag{2}$$

where $P_{\text{grid},E}(t)$ is the power required from the grid in a moment t to meet the electricity load, $P_{\text{LE}}(\text{t})$ is the electricity demand of the village to supply their electricity requirements (light, electric devices, etc.) at moment t, $P_{\text{pv}}(t)$ is the electricity produced from solar panels at moment t and $P_{\text{bat}}(t)$ is the charging or discharging power of the battery during moment t. If $P_{\text{grid},E}(t) < 0$, it indicates that there is a surplus of energy. This surplus is used for hydrogen production, and no electricity is purchased from the grid. If $P_{\text{grid},E}(t) > 0$, energy is purchased from the grid to meet the demand. The following model captures this dynamic: If $P_{\text{grid},E}(t) < 0$:

$$S_{t+1} = -P_{\text{grid},E}(t) \tag{3}$$

$$P_{\text{pur}}(t) = 0 \tag{4}$$

where S_{t+1} is the energy surplus at time $t + 1$ after using surplus energy to produce hydrogen. Otherwise, if $P_{\text{grid},E}(t) > 0$:

$$P_{\text{pur}}(t) = P_{\text{grid},E}(t) \tag{5}$$

$$S_{t+1} = 0 \tag{6}$$

In this case, $P_{\text{pur}}(t)$ represents the power purchased from the grid to meet the electricity demand at moment t, and no surplus is available for hydrogen production.

2.2 Heating Demand

The energy surplus previously saved will be used for hydrogen production to meet the heating demand and natural gas will be used to meet heating demand when hydrogen is insufficient. Additionally, if there is still surplus energy after heating demand is satisfied, the remaining energy will be sold to the grid. To allocate the surplus energy and calculate the hydrogen and natural gas usage, the following equations are used:

$$P_{\text{load,Hydrogen}}(t) = P_{\text{S}}(t) \tag{7}$$

where $P_{\text{load,Hydrogen}}(t)$ is the power required from the grid in a moment t to supply the demand by hydrogen and P_{S}(t) is the surplus avaliable in a moment t. However, for hydrogen to supply the heating demand, the general cost of electrolisis process is considered:

$$P_{\text{heating},H_2}(t) = P_{\text{load,Hydrogen}}(t) \cdot \eta_{\text{el}} \tag{8}$$

where $P_{\text{heating},H_2}(t)$ is the power required from the grid in a moment t to supply the demand by hydrogen and η_{el} is the electrolisers efficiency factor. The remaining heating demand after using hydrogen is:

$$\text{R}_{\text{LH}}(t) = P_{\text{LH}}(t) - P_{\text{heating},H_2}(t) \tag{9}$$

where $R_{\text{LH}}(t)$ is the remaining heating demand in a moment t after using hydrogen to supply some of the demand and $P_{\text{LH}}(t)$ is the total heating demand of the village in a moment t. If the remaining heating demand is positive, natural gas is used to meet the rest. If there is still surplus energy after meeting the heating demand:

$$P_{\text{sale}}(t) = -P_{\text{grid},E}(t) \tag{10}$$

Otherwise:

$$P_{\text{pur}}(t) = P_{\text{grid},E}(t) \tag{11}$$

where $P_{\text{sale}}(t)$ is the surplus power sold to the grid at time t. The total cost of heating can be represented as:

$$\begin{aligned} Cost_H = \sum_{t=1}^{24} [(C_{\text{buy,grid}}(t) \cdot P_{\text{heating},H_2}(t)) \\ -((C_{sell}(t) \cdot P_{\text{sale}}(t))) \\ +(C_{\text{buy,NG}}(t) \cdot P_{\text{heating,NG}}(t)) \cdot \Delta t] \end{aligned} \tag{12}$$

where $Cost_H$ is the total cost of heating over 24 hours, $C_{\text{buy,grid}}(t)$ is the cost of buying electricity from the grid at time t, $C_{\text{sell}}(t)$ is the price at which surplus energy is sold back to the grid at time t, $P_{\text{heating},NG}(t)$ is the power for natural gas used to meet the remaining heating demand after hydrogen, calculated as:

$$P_{\text{heating,NG}}(t) = \frac{\text{R}_{\text{LH}}(t)}{\eta_{\text{ng}}} \tag{13}$$

where $\text{R}_{\text{LH}}(t)$ is calculated in (9) and η_{ng} is the efficiency of the natural gas boiler. $C_{\text{buy,NG}}$ is the cost of natural gas and Δt is the time interval, assumed to be one hour in a 24-hour period.

2.3 CO_2 emissions

The CO_2 emissions produced by using the grid and natural gas for heating are represented by the following equation:

$$
\begin{aligned}
CO_{2_{\text{tot}}} = \sum_{t=1}^{24} & (CEI(t) \cdot P_{\text{grid},E}(t) \cdot \Delta t) \\
& + (CEI(t) \cdot P_{\text{heating},H_2}(t) \cdot \Delta t) \\
& + (CO_{2,\text{ng}} \cdot P_{\text{heating,NG}}(t)) \cdot \Delta t
\end{aligned}
\tag{14}
$$

where $CO_{2_{\text{tot}}}$ represents the total CO_2 emissions generated during 24 hours, $CEI(t)$ is the CO_2 Emissions Intensity (CEI) of the grid in a given hour t, $P_{\text{grid},E}(t)$ is the power drawn from the grid at time t to meet electricity demand, $P_{\text{heating},H_2}(t)$ is the power to produce hydrogen for heating in time t, $P_{\text{heating,NG}}(t)$ is the power for natural gas to supply the rest of the demand at a moment t, $CO_{2,\text{ng}}$ is the emission factor of natural gas in gCO_2/kWh, and Δt is the time interval (assumed to be 1 hour).

3 Methods

3.1 Overview and Optimisation Goals

Consider a village that requires energy for both electricity consumption and heating demand. The village utilises renewable energy sources, specifically solar panels, to meet the electricity demand and generates hydrogen from surplus energy when the supply exceeds the demand. To enhance energy management, a battery is employed to store the surplus energy for future use and to buy and store energy to the grid when is economically convenient. When the renewable energy and battery storage are insufficient to meet the power demand, the system draws energy from the grid. The system is designed to operate economically by considering the prices for buying energy from and selling energy to the grid. The primary goals are to minimise grid consumption and reduce CO_2 emissions.

3.2 Multi-objective optimisation

For this optimisation problem, a multi-objective genetic algorithm (MOGA) was applied. This type of algorithms can be used at optimisation problems with more than one objective by creating mulitiple solutions and subjecting them to a process similar to the natural selection process in real life, ranking the performance of every solution, selecting the best ranked ones, mixing them, mutating them and creating new solutions (childrens of the previous ones) to repeat the process until the difference of performance between results is too small to consider an improvement between them or when the stipulated time or number of iterations is reached [10]. The algorithm presents random values of the battery charge and discharge during 24 hours. Then, it evaluates the results and starts to rank the solutions to find the most optimal ones to reach the goal (minimisation). It chooses the best results and starts to mix them and evaluate the "childs" in order to get closer and closer to the best result possible acording to the constraint of the battery storage and rate capability. In the end, it finds the best possible results of battery use during 24 hours in order to use the grid as minimum as possible and also to reduce the CO_2 production. It is important to consider that in some hours it can be cheaper to buy energy to the grid, being a more convenient option than using energy stored in the battery, but also in that same hour the CEI can be high producing high CO_2 emissions, so the algorithm will evaluate which one ponders heavier in the final result and finally deciding if it will use battery or buy energy. This action is repeated 10 times to have a variety of different optimised results which are going to be evaluated by a decision making technique to find the best compromised solution.

3.3 Net Flow Method (NFM)

The Net Flow Method (NFM) is a making-decision tool designed to select an optimal solution in multiobjective optimisation. It ranks a set of results and evaluates them acording to their rank between how much this alternative outranks the others and how much is outranked by others (the Net Flow). The alternative with the highest net flow is considered the best option [11]. For this work, the NFM takes the 10 results obtained after the optimisation and generates a pareto front (a set of non-dominated solutions). It compares the solutions in the pareto front and ranks them acording to the criteria (Grid consumption and CO_2 emissions), calculating how better or worse those solutions are compared to others untill it finds the best ranked one and chooses it as the best compromised solution.

4 results and discussion

For this study, a day in June and a day in Decembe of 2019 were simulated to compare the performance of the model with different environmental characteristics. The non-optimised results were produced by a model that does not use a lithium battery and hydrogen production is not considered, resulting in a total dependency of grid consumption and the solar power produced during that same hour, wasting any surplus produced. On the other hand, our model proposed the use of surplus storage by lithium battery in order to use it for hydrogen production designed to supply the heating demand, proposing a more optimised use of the power produced but also adding electricity cost in form of electrolisers. As it can be atested in Figures 1 and 2, our model presents significant reductions in terms of grid consumption and $\mathrm{CO_2}$ emissions in comparison to the non-optimised scenario. During the moments of the day where solar power is more prominent, the grid consumption drops in both optimised scenarios, even having earnings during the summer scenario, storing the surplus and reducing $\mathrm{CO_2}$ emissions at the same time that it sells the surplus after power and heating is supplied, in contrast to the non-optimised scenarios where the grid consumption is still reduced during midday but with a considerable grid consumption and waste of surplus in order to supply the power for both power and heating loads.

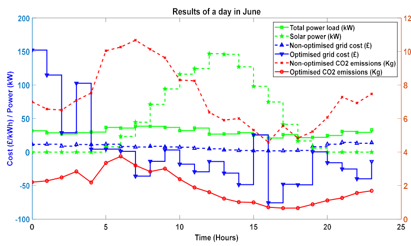

Fig. 1: June results.

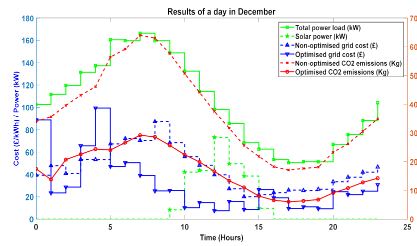

Fig. 2: December results.

Table 1: Optimisation Results: Power Load, Solar Power, Grid Cost, and CO_2 Emissions

Day of the year	Total Power Load (kWh)	Solar Power (kWh)	Non-Optimised Grid Cost (£)	Optimised Grid Cost (£)	Non-Optimised CO_2 Emissions (kg)	Optimised CO_2 Emissions (kg)
June	718.87	1138.90	192.87	-27.76	173.59	45.67
December	2501.47	265.52	1075.88	793.61	896.28	395.03

As it is shown in this paper, the possibility of applying a hybrid solution using hydrogen heating with grid power and NG heating at the same time is doable. Given the proper time and research, with more efficient methods and materials for a more optimised electrolisis process and hydrogen storage with less power demand and constraints, this proposal can be adapted from a hybrid system to a fully hydrogen-based heating system and considering the current developments in the matherials sector, these kind of optimisation models will be very demanded in a forseable near future. This research is going to be continued, including water supply optimisation and amplifying the scope from days to months in order to have a better control of the optimisation process.

5 Conclusion

This paper presents an optimisation model for an energy system. The system incorporates solar renewable energy, battery storage, and grid consumption to meet the energy demands while minimising CO_2 emissions. The objective is to optimise the system's performance by reducing grid consumption and CO_2 generation. Genetic algorithm techniques are implemented to find the optimal values for lithium battery usage in the system in order to minimise the aforesaid objectives. The cost functions representing energy purchased from the grid for power load and heating load, as well as the CO_2 production. Those are minimised 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 algorithm runs 10 times and the results of every iteration are stored. Then, NFM is used to find the best compromised solution. The results demonstrate the effectiveness of the proposed model in reducing grid consumption and CO_2 emissions. The simulations show that the algorithm efficiently manages the battery and purchases energy from the grid at opportune times. The power and hydrogen loads are satisfactorily meet while the grid reliance is reduced and battery constraints are considered. The findings suggest that this type of implementations can significantly contribute to reducing CO_2 emissions and achieving energy sustainability in small communities. Further research is going to be made to validate the feasibility and scalability of this approach in diverse contexts, optimising water supply to the system and changing the data according to new case scenarios and with improved electrolisis and PV technologies.

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