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Developing an effective capacity sizing and energy management model for integrated hybrid photovoltaic-hydrogen energy systems within grid-connected buildings.

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DEVELOPING AN EFFECTIVE CAPACITY SIZING AND ENERGY MANAGEMENT MODEL FOR INTEGRATED HYBRID PHOTOVOLTAIC-HYDROGEN ENERGY SYSTEMS WITHIN GRID-CONNECTED BUILDINGS

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Abstract

The ongoing energy transition has accelerated renewables integration within many sectors requiring addressment of their intermittency challenges. Implementing hydrogen energy storage with renewables is a solution; however, Renewable-Hydrogen hybrid systems come with their effective sizing and energy management challenges. This paper reports the development of an effective capacity sizing and energy management model of hybrid Photovoltaic-Hydrogen energy system for grid-connected buildings to ensure reliable buildings sector decarbonization. The developed model was implemented on one of Robert Gordon University buildings, on the North-East coast of Scotland, as a case-study. From the results the best-suited PV system size was found to be 4.31-MW, designed using 14368 PV modules each rated 300-W and 4 inverter units each rated 1-MW, with 23.5 km^2 installation area required. Simulation results showed the output energy from this PV system allowed supplying around 38% of building demands with green energy. The size of the hydrogen energy storage system components suited to support this PV system intermittency was found to be 2.28-MW electrolyser, 500-kW fuel cell and 1331 kg gaseous hydrogen storage tank. Mathematical modelling was developed for simulating this hydrogen energy storage system operation. An energy management model was then developed within MATLAB environment to schedule the operation of the proposed hybrid PV-H2 system components and the grid in supplying the building demands. Results have indicated that integrating the proposed hydrogen energy storage system with the PV system has improved the solar energy utilization by about 57% and raised the building green energy supply to around 59% resulting into reduction of grid power import equivalent to 612,005.76 kgCO2e/year.

1 Introduction

With the increasing concern about the catastrophic climate change and the continuous increase in global energy demands, there is an increasing pressure towards achieving Net Zero-Carbon ambitious goals [1, 2]. The large-scale integration of renewable energy can play an increasingly important role in tackling climate change. However, their intermittent nature and uncertainty in addressing the load demands can result in a huge imbalance between generation and consumption, thus threating the renewable potential and introducing a key barrier against the energy system security and the reliability of the power system operation. Green Hydrogen, as a free-carbon energy storage medium, offers a greater flexibility in maximizing the capacity of renewable energy, providing peak-demand support and helping to realize the decarbonization goals [3, 4]. A green Hydrogen Energy Storage System (HESS) mainly consists of a hydrogen electrolyser, storage system and fuel cell facility. The hydrogen electrolyser is used to convert the electrical energy output from renewable resources into green hydrogen by water electrolysis. The green hydrogen generated can be stored in form of pressurized gas, liquid or solid-state, then the fuel cell technology is used to retrieve the chemical energy stored back into electricity when needed [5]. While HESS represents a sustainable solution towards the green energy transition, its usage when integrated with renewables, adds complexity in terms of capacity sizing, operation scheduling and energy management. Among the commercially-available software tools used for sizing renewable energy systems incorporating HESS, is the HOMER software [6-11], however this tool only provides the ability to size the system components from a financial perspective before taking an investment decision. Other energy modelling software tools include ANSYS, which can simulate and assess the performance of hydrogen electrolysers and fuel cell stacks, however cannot simulate the entire operation of green hydrogen-based energy systems [12], and thus cannot guarantee the energy balance between renewable power input and load consumption. A detailed mathematical modelling and simulation of green hydrogen-based energy systems can be found in HYDROGEMS software, available as part from TRANSYS 16, however it is not capable of sizing the overall energy system [13]. Thus, developing a model that can size and simulate the entire operation and energy management of HESS when integrated with renewables is a challenging task. This paper reports the development of a model that can size and simulate the entire operation and energy management of the hybrid HESS with integrated renewables, and the utility grid. The developed system model allows the capacity sizing of a Photovoltaic-Hydrogen (PV-H2) hybrid energy system for reducing the carbon footprint of grid-connected buildings, and develops an effective energy balancing mechanism between the system components that ensures meeting the building load demands while increasing the green energy proportion. The capacity of the proposed PV system has been sized and its output energy generation was simulated using PVsyst software. The hourly PV output power results from the PVsyst simulation were then used in the developed energy management model to allow scheduling the operation of the PV system with the integrated HESS and the grid in feeding the building load demands. The developed hybrid energy system scenario has been applied on a case study building within the Robert Gordon University (RGU) campus, located in Aberdeen city on the North-East coast of Scotland, to support the university ongoing campaign towards green energy transition and the Scottish government goals in achieving carbon-neutrality by 2045 [14]. The rest of the paper is organized as follows: Section 2 provides an overview of the proposed hybrid PV-H2 energy system within grid-connected building scenario. Section 3 shows the capacity sizing of the PV system proposed for the case study building. Section 4 shows the component sizing and mathematical modelling of the proposed HESS. Section 5 presents the energy management model developed for scheduling the operation between the proposed system components. Section 6 discusses the results and demonstrates the effectiveness of the developed model in maintaining reliable system operation while reducing the building carbon footprint. Section 7 provides concluding remarks.

2 The Proposed PV-H2 System Description

The proposed hybrid PV-H2 Energy System consists of solar PV arrays integrated with HESS which includes a hydrogen electrolyser, H2 storage tank and fuel cell. During the hours of excess PV production, the surplus electricity is utilized to power the hydrogen electrolyser producing green hydrogen as a form of energy storage. The produced green hydrogen is then stored under high pressure in a gaseous hydrogen storage tank to be used later in the fuel cell for producing electricity during the hours of PV production deficit. Finally, any remaining load demand that cannot be met by the proposed PV system and the green H2 fuel cell facility, is met by the utility grid while ensuring energy balance between all system components. The schematic diagram of the proposed “Hybrid PV-H2 system within a grid-connected building scenario” is shown in Figure 1. Figure 2 (a) shows the hourly load demand profile for the case study building over one-year timescale based on actual data collection for year 2020-2021. The building average hourly load demand is 515.77 kW, peak hourly load demand is 738 kW, minimum hourly load demand is 340 kW and the total annual load energy consumption is around 4518 MWh. Figure 2 (b) shows the hourly solar irradiation at the building location over one-year timescale using PVGIS web interface, with an average hourly solar irradiation of 119.66 W/m^2.

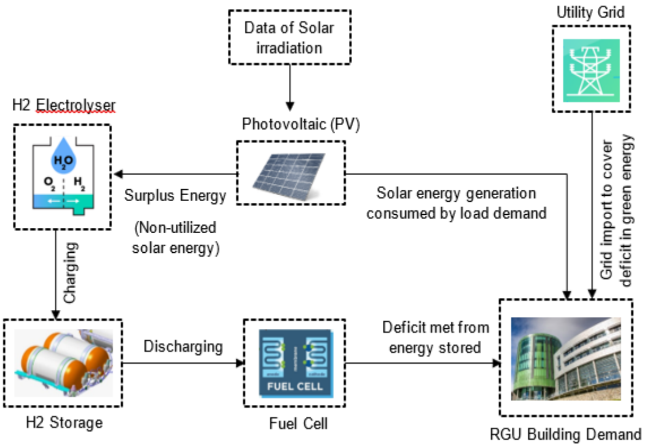

Figure 1 The Proposed Hybrid PV-H2 Energy System within Grid-connected Building Scenario

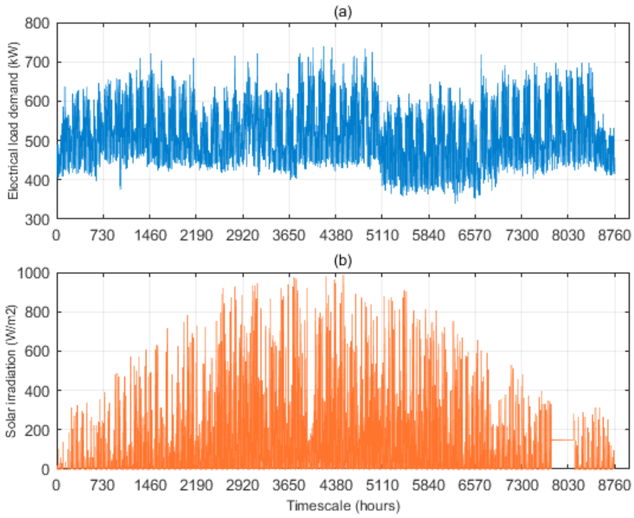

Figure 2 (a) Hourly load demand profile, (b) Hourly solar irradiation at the case study building location

3 Sizing the Proposed PV System and Simulating its Output Energy Generation

The proposed PV system is considered the primary energy source used to feed the building load demands during the hours of sun availability. Using the load demand data of the case-study building, the rated capacity of the proposed PV system given by equation (1) was found to be 4.31 MW where the PV capacity factor was calculated as 11.966% based on the average hourly solar irradiation as percentage to the solar irradiation at Standard Test Conditions (1000 W/m2) [15].

$$\boldsymbol{P_{PV\,rated}} = \frac{\boldsymbol{P_{PV}}}{\boldsymbol{CF_{PV}}} \tag{1}$$

Where; $\boldsymbol{P_{PV\,rated}}$ is the rated capacity of PV system, $\boldsymbol{CF_{PV}}$ is the PV capacity factor, $\boldsymbol{P_{PV}}$ is the PV average output power which should equal the average hourly load demand over the year.

The capacity of the sized PV system was then used as input to the PVsyst software together with the building geographical location coordinates of 57.2° N and -2.2° W, tilt angle of 45° with the system orientation facing South, Azimuth of 0°, and the PV system design parameters listed in Table 1.

Table 1 Design parameters of the proposed PV system

Parameter	Value / Type
Total PV installed capacity	4310 kW
Total number of PV modules	14368
Total Area requirement	23.5 km^2
Each PV Module Type and nominal power rating	AE 300M6-60, Si-Mono, 300 W
PV Modules connection	449 strings x 32 in series
Total number of PV inverters	4 units
PV inverter Type and nominal power rating	Sinacon PV1000, 1000 kW

Finally, the monthly energy production from the sized PV system capacity was simulated using the PVsyst software to demonstrate the monthly PV energy fed to the building load demands and the monthly PV energy excess. Simulation results are shown later in Section 6.

4 Component Sizing and Mathematical Modelling of the Proposed HESS

4.1 Sizing the Hydrogen Electrolyser and Modelling its Output H2 Generation

The hydrogen electrolyser is sized to absorb any energy excess available from the sized PV system capacity after meeting the building load demand and thus sized based on the maximum PV excess which is identified by evaluating the mismatch between the rated power of the proposed PV system and the minimum building load demand [15]. However, hydrogen electrolysers are expensive and thus desirable to operate them with a high level of utilization to enhance their economic viability. Therefore, the size of the proposed hydrogen electrolyser is calculated as shown in equation (2) to compensate for underutilization during the hours of low PV production [15].

$$\boldsymbol{P_{ele}} = \frac{\boldsymbol{P_{PV\,rated} - P_{l\,min}}}{\boldsymbol{2}} \tag{2}$$

Where; $\boldsymbol{P_{ele}}$ is the rated capacity of hydrogen electrolyser, and $\boldsymbol{P_{l\,min}}$ is the minimum hourly load demand.

The hourly power fed to the electrolyser is then modelled using equations (3) and (4), where the hourly power fed to the electrolyser is set equal to the difference between the hourly PV output power and the hourly building load demand when the hourly PV excess is less than or equal to the capacity of hydrogen electrolyser. When the hourly PV excess is exceeding the rated capacity of hydrogen electrolyser, then the hourly power fed to the electrolyser is set equal to its rated capacity. The hourly mass of the hydrogen generated by electrolyser, and the molar flow rate of the generated hydrogen gas are calculated using equations (5) and (6) [16].

$$\boldsymbol{P_{ele}(t)} = \begin{cases} \boldsymbol{\Delta P(t)}, & \boldsymbol{\Delta P(t) \le P_{ele}} \\ \boldsymbol{P_{ele}}, & \boldsymbol{\Delta P(t) > P_{ele}} \end{cases} \tag{3}$$

$$\boldsymbol{\Delta P(t) = P_{PV}(t) - P_l(t)} \tag{4}$$

$$\boldsymbol{m_g\,(t) = P_{ele}(t) \times \dot{m}_{gH2}} \tag{5}$$

$$\boldsymbol{n_g\,(t) = \frac{m_g\,(t)}{M}} \tag{6}$$

Where; $\boldsymbol{P_{ele}(t)}$ is the electrolyser hourly input power, $\boldsymbol{\Delta P(t)}$ is the hourly PV excess, $\boldsymbol{P_{PV}(t)}$ is the hourly PV output power, $\boldsymbol{P_l(t)}$ is the hourly load demand, $\boldsymbol{m_g\,(t)}$ is the hourly mass of hydrogen generated by electrolyser, $\boldsymbol{n_g\,(t)}$ is the molar flow rate of hydrogen gas generated, $\boldsymbol{\dot{m}_{gH2}}$ is the mass flow rate of generated hydrogen, and $\boldsymbol{M}$ is the molar mass of hydrogen gas (2.016 x 10^{-3} Kg/mol).

4.2 Sizing the Fuel cell and Modelling its Output Power Generation and its Input H2 Fuel Consumption

The fuel cell is considered as the secondary clean energy source used in feeding the building load demand after the PV arrays. Thus, the fuel cell is sized to cover the maximum deficit in meeting the load by PV which can occur during the hours of low or no PV production. Based on the proposed PV system capacity, the PVsyst simulation shows that the day of highest deficit in meeting the load demand by the sized PV capacity is the 30th of December, as illustrated in Figure 3.

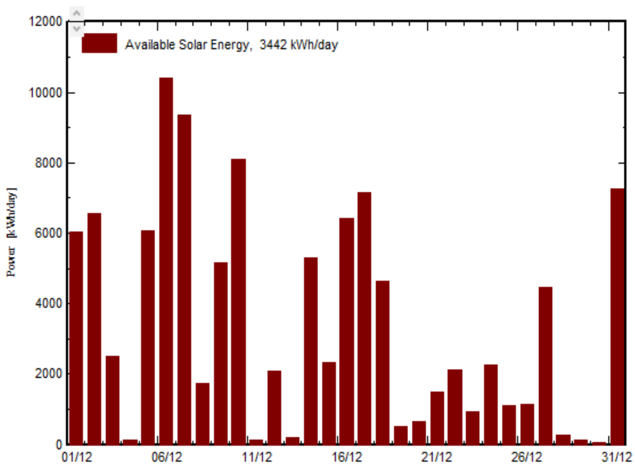

Figure 3 PVsyst Simulation for December (Month of Minimum PV Production)

The size of the proposed fuel cell was then identified as given by equation (7).

$$\boldsymbol{P_{FC}} = \mathbf{max}\,[\boldsymbol{P_l(t)^{PV\,min}} - \boldsymbol{P_{PV}(t)^{PV\,min}}] \qquad (7)$$

Where; $\boldsymbol{P_{FC}}$ is the rated capacity of fuel cell, $\boldsymbol{P_l(t)^{PV\,min}}$and $\boldsymbol{P_{PV}(t)^{PV\,min}}$ are the hourly load demand and hourly PV output power at the day of minimum PV production, respectively, and max is the maximum value of hourly deficit in meeting demand on the day of minimum PV production.

The hourly output power from the fuel cell has been modelled using equations (8) and (9). During the hours of deficit of PV production in meeting demand, the fuel cell hourly output power is set equal to the mismatch between the hourly load demand and the hourly PV output power when the hourly deficit is less than or equal the proposed capacity of fuel cell. When the hourly deficit is exceeding the rated capacity of fuel cell, then the hourly output power of fuel cell is set equal to its rated capacity. The hourly mass of hydrogen consumed by fuel cell to generate this power, and the molar flow rate of hydrogen gas consumed are given by equations (10) and (11) [16].

$$\boldsymbol{P_{fc}(t)} = \begin{cases} \boldsymbol{P_{def}(t)}, & \boldsymbol{P_{def}(t) \le P_{FC}} \\ \boldsymbol{P_{FC}}, & \boldsymbol{P_{def}(t) > P_{FC}} \end{cases} \qquad (8)$$

$$\boldsymbol{P_{def}(t) = P_l(t) - P_{PV}(t)} \qquad (9)$$

$$\boldsymbol{m_c\,(t) = \alpha_1 P_{FC} + \alpha_2 P_{fc}(t)} \qquad (10)$$

$$\boldsymbol{n_c\,(t) = \frac{m_c\,(t)}{M}} \qquad (11)$$

Where; $P_{fc}(t)$ is the hourly output power of fuel cell, $P_{def}(t)$ is the hourly deficit of PV output power in meeting the building load demand, $m_c\,(t)$ is the hourly mass of hydrogen consumed by fuel cell, $n_c\,(t)$ is the molar flow rate of hydrogen gas consumed, α_1 and α_2 are the fuel cell intercept coefficient and fuel cell slope curve, respectively (α_1 = 0.0003 kg/h/kW; α_2= 0.058 kg/h/kW) [16].

4.3 Sizing the Hydrogen Storage Tank and Modelling its Filling and Discharging with Green H2 Gas

The storage tank is used to store the hydrogen generated by electrolyser during the hours of excess PV production, to be used by the fuel cell to generate electricity during the hours of deficit in PV production. The produced green hydrogen gas is compressed to minimize the volume of hydrogen storage tank. Based on the specifications of the sized electrolyser, the H2 storage tank is selected. The maximum permissible working pressure of the selected electrolyser corresponds to 200 bar, thus a Manifold 15-Cylinder Pallet (MCP) of the same pressure is selected to store the surplus PV electricity as green hydrogen. The selected tank has a maximum storage capacity of 1331 kg, as per the specifications of the proposed HESS listed in Table 2.

Table 2 Sizing and Specifications of the Proposed HESS

Component	Parameter	Value
Electrolyser	Rated Capacity: ($\boldsymbol{P_{ele}}$)	2.28 MW
	Mass flow rate: ($\boldsymbol{m^{\bullet}_{gH2}}$)	0.0237 kg/h/kW
	Target pressure	1-200 bars
Storage Tank	Storage Capacity	1331 kg
	Tank Volume	132 m^3
	Target Pressure	200 bars
Fuel Cell	Rated Capacity: ($\boldsymbol{P_{FC}}$)	500 kW

The storage tank will accumulate the hydrogen generated by the electrolyser during the hours of daylight excess PV production and will feed the fuel cell during the hours of deficit. To ensure that the maximum accumulation of hydrogen inside the proposed tank is maintained below the maximum storage capacity throughout the year, the filling and discharging of the tank are modelled on an hourly-basis as part of the energy management model developed in Section 5. In the developed filling/discharge model, the process of hydrogen filling terminates when the storage tank pressure build-up reaches the maximum permissible working pressure. The hourly operating pressure of the hydrogen tank is calculated using the ideal gas law considering an isothermal compression process. With the operating pressure maintained below the target pressure, the hourly number of hydrogen moles present in the storage tank and the hourly mass status of hydrogen tank are modelled using equations (12) and (13), respectively.

$$\boldsymbol{n_{tank}\,(t) = n_{tank}(t-1) + n_g(t)} \qquad (12)$$

$$\boldsymbol{m_{tank}(t) = m_{tank}(t-1) + m_g(t)} \qquad (13)$$

Where; $n_{tank}\,(t)$ is the hourly number of hydrogen moles present in the tank, and $m_{tank}(t)$ is the hourly mass status of hydrogen tank.

The process of hydrogen discharging is modelled by the hourly drop in the operating pressure of storage tank as the number of hydrogen moles present in the tank and the mass status of hydrogen tank decrease based on the mass of hydrogen consumed by fuel cell as given by equations (14) and (15).

$$\boldsymbol{n_{tank}(t) = n_{tank}(t-1) - n_c(t)} \quad (14)$$

$$\boldsymbol{m_{tank}(t) = m_{tank}(t-1) - m_c(t)} \quad (15)$$

5 Developing Energy Management Model

To ensure the balance of energy flow between the proposed HESS components and the grid, an effective energy management model is developed within a MATLAB environment to schedule their operation on an hourly-basis throughout the year. Figure 4 illustrates the flowchart of the developed energy management model. In the developed model the hourly mismatch between the solar output power from the sized PV system and the load demand is evaluated based on PVsyst hourly simulation results. When there is a surplus in the PV electricity production, the electrolyser is powered generating green H2 and the storage tank is allowed to fill up with green hydrogen as long as the operating pressure is below the target pressure. If the operating pressure reaches the threshold of target pressure, then the storage tank stops filling the hydrogen gas. If the PV surplus electricity exceeds the rated capacity of the electrolyser, then the electrolyser is set to operate at its rated capacity and the extra PV power excess is quantified using equation (16):

$$\boldsymbol{P_{ex}(t) = \Delta P(t) - P_{ele}}, \qquad \boldsymbol{\Delta P(t) > P_{ele}} \quad (16)$$

Where; $\boldsymbol{P_{ex}(t)}$ is the value of PV power surplus that exceeds the electrolyser rated capacity at time step (t).

On the other hand, when the proposed PV system output is not enough to meet the load demand, the output power of fuel cell is set to cover this deficit as long as this deficit is below or equal to the fuel cell rated capacity and the mass of hydrogen required to be consumed by fuel cell is available in tank. If the hydrogen available in the tank is insufficient, then the fuel cell delivers an output power corresponding to the mass of hydrogen available in the tank as per equation (10) and the remaining of load is met by the utility grid as per equation (17):

$$\boldsymbol{P_{grid}(t) = P_{def}(t) - P_{fc}(t)} \quad (17)$$

Where; $\boldsymbol{P_{grid}(t)}$ is the power imported from the utility grid at time step (t).

If the deficit in meeting the building load demands is exceeding the rated capacity of the fuel cell, then the fuel cell is set to operate at its rated capacity and the remaining of load is met from the utility grid, as given by equation (18):

$$\boldsymbol{P_{grid}(t) = P_{def}(t) - P_{FC}} \quad (18)$$

Within the developed energy management model, the annual GHG emissions eliminated upon integrating the proposed hybrid PV-H2 energy system compared to that eliminated if the PV capacity is used alone without energy storage is estimated using equations (19) and (20).

$$\boldsymbol{E_{grid} = \sum_{t=1}^{8760} P_{grid}(t)} \quad (19)$$

$$\boldsymbol{GHG = E_{grid} \times f_e} \quad (20)$$

Where, $\boldsymbol{E_{grid}}$ is the annual energy imported from the utility grid, $\boldsymbol{GHG}$ is the annual GHG emissions equivalent to the amount of grid energy import, and $\boldsymbol{f_e}$ (0.23112 $kgCO_2e/kWh$) is the latest UK conversion factor of direct GHG emissions including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions [17].

The annual amount of green energy supplied by both the sized PV system and fuel cell to the building load demands is also quantified in the developed model using equations (21) and (22). Equation (23) estimates the annual reduction in the building GHG emissions upon integrating the sized hybrid PV-H2 system based on the system annual green energy provided that would have otherwise been imported from the utility grid.

$$\boldsymbol{E_{green} = \sum_{t=1}^{8760} [P_{PV}^{l}(t) + P_{fc}(t)]} \quad (21)$$

$$\boldsymbol{P_{PV}^{l}(t) = \begin{cases} P_{PV}(t), & P_{PV}(t) < P_l(t) \\ P_l(t), & P_{PV}(t) \geq P_l(t) \end{cases}} \quad (22)$$

$$\boldsymbol{GHG_{el} = E_{green} \times f_e} \quad (23)$$

Where; $\boldsymbol{E_{green}}$ is the annual green energy supplied to the building load demands, $\boldsymbol{P_{PV}^{l}(t)}$ is the hourly PV output power supplied to load demands, $\boldsymbol{P_{fc}(t)}$ is the hourly fuel cell power supplied to load demands and $\boldsymbol{GHG_{el}}$ is the annual GHG emissions eliminated upon integrating the sized PV-H2 energy system.

The improvement in the utilization of the proposed PV system total energy production throughout the year when adding the HESS is also assessed within the developed model. The annual PV energy excess fed to the hydrogen electrolyser and the annual PV energy excess that is non-utilized, are calculated using equations (24) and (25), respectively. Finally, the model also estimates the turn-around efficiency of the sized HESS using equation (26).

$$\boldsymbol{E_{PV}^{ele} = \sum_{t=1}^{8760} P_{ele}(t)} \quad (24)$$

$$\boldsymbol{E_{PV}^{ex} = \sum_{t=1}^{8760} P_{ex}(t)} \quad (25)$$

$$\boldsymbol{\eta_{HESS} = \frac{\sum_{t=1}^{8760} P_{fc}(t)}{\sum_{t=1}^{8760} P_{ele}(t)}} \quad (26)$$

Where; $\boldsymbol{E_{PV}^{ele}}$ is the annual PV energy excess fed to electrolyser, $\boldsymbol{E_{PV}^{ex}}$ is the annual PV energy excess that is non-utilized, and $\boldsymbol{\eta_{HESS}}$ is the turn-around efficiency of the sized HESS.

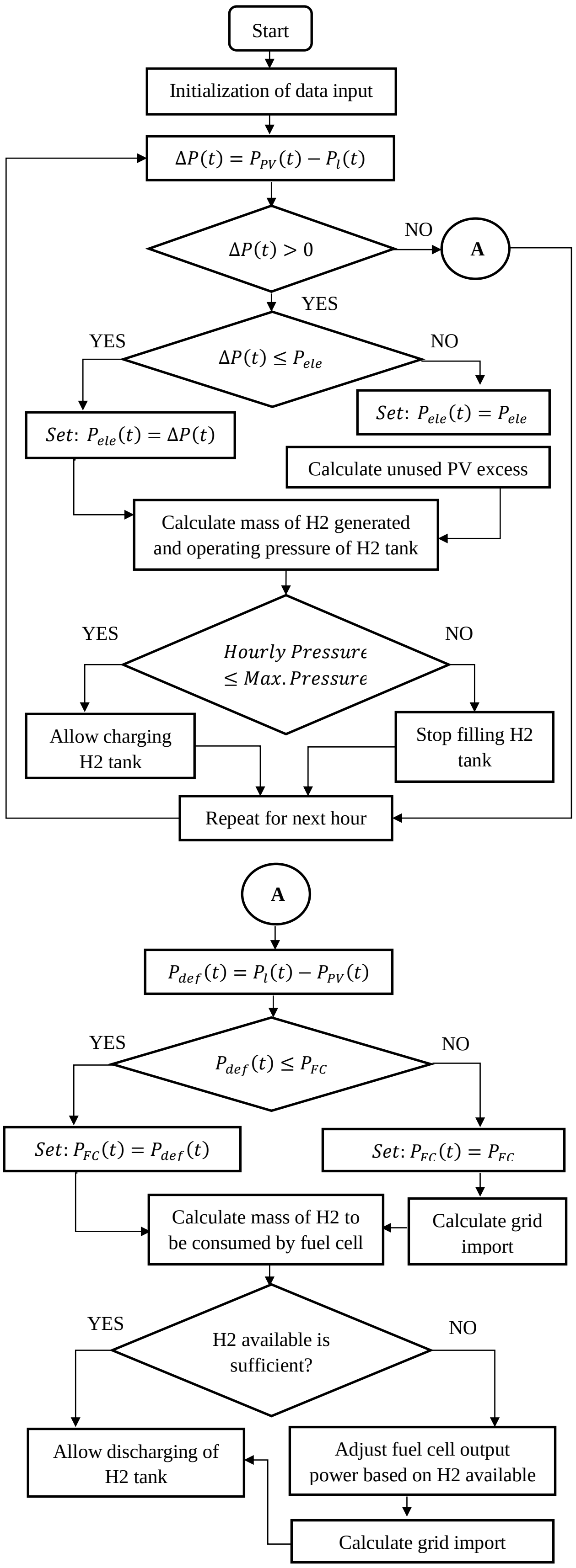

Figure 4 Flowchart of the Developed Energy Management Model

6 Results and Discussion

Figure 5 shows the PVsyst simulation results for the monthly solar energy production from the previously sized PV system capacity, showing a total annual energy production of 4235 MWh at the output of PV arrays and 4173 MWh useful energy production at the output of PV inverters. Figure 6 illustrates the performance of this PV system capacity in supplying the building load demands prior to integrating the proposed HESS. It has been found that around 1697 MWh from the total useful PV production has been used in feeding the building load demands, thus the contribution of the sized PV system alone (without energy storage) in supplying the annual building energy demands is estimated as 38%. Approximately 2475 MWh, representing around 59.3% of total annual PV production, accounts for non-utilized PV energy excess due to the time shift between the periods of high PV production and load demands. When the proposed PV system capacity is utilized with no energy storage, about 2821 MWh have to be imported from the utility grid to compensate for the 62% shortage of PV system in feeding the load demand. The carbon footprint associated with this grid import is found to be 651,989.52 kgCO2e.

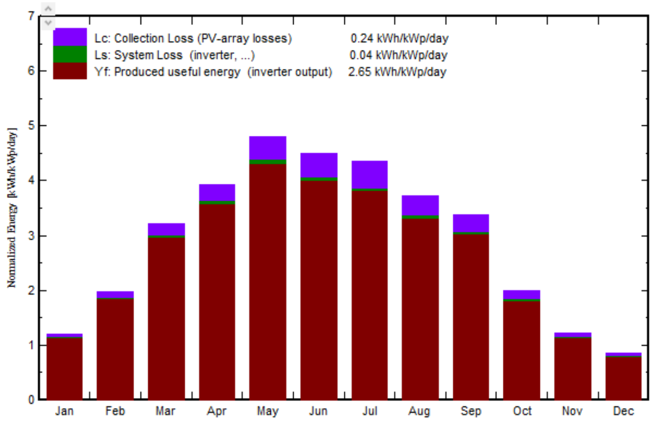

Figure 5 PVsyst Simulation Results of Monthly PV System Energy Production

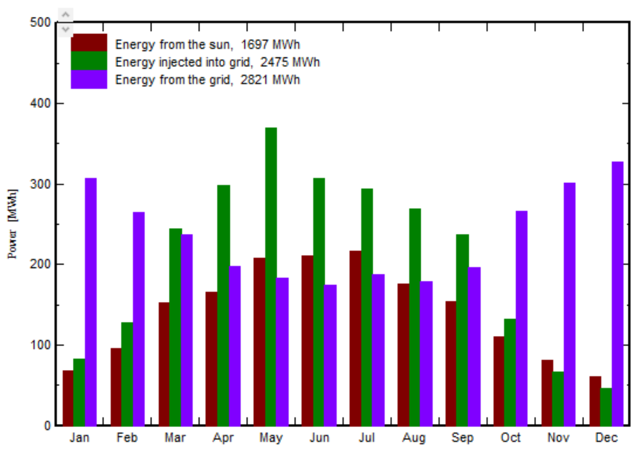

Figure 6 The Monthly PV Energy Fed to the Building Load Demand, the PV Energy Excess and the Grid Import for the Proposed PV Capacity without Energy Storage

Figure 7 illustrates the hourly energy management operation of the proposed grid-connected PV-H2 system components while feeding the building load demand throughout the year. It can be seen from the obtained results that the proposed HESS has increased the level of utilization of the PV surplus electricity, while allowing a partial operation of the fuel cell with the utility grid to compensate for the intermittency of solar energy production. To allow a better observation of the developed energy management process, Figure 8 shows the hourly energy management of the proposed system scenario over one summer week and Figure 9 shows this for one winter week. It can be seen from Figure 8 that during the time interval (8-18), the PV production is high and thus the electrolyser is operating, without exceeding its rated capacity, to store the PV surplus electricity in the form of green hydrogen. Simultaneously, the mass status of hydrogen in the tank is seen increasing from around 22.66 kg to 443 kg of hydrogen and the operating pressure building-up to approximately 40 bar, indicating that the storage vessel is filling up with the green hydrogen generated. Conversely, during the time interval (19-31), there is a shortage in the PV production and thus the status of hydrogen in the storage tank is seen decreasing from 423.7 kg to 102.6 kg of hydrogen and the operating pressure dropping down to around 9 bars indicating that the storage vessel is discharging its stored green hydrogen for operating the fuel cell to contribute in feeding the load demand, thus lowering the contribution from utility grid. Similarly, Figure 9 illustrates the hourly energy management operation for the proposed PV-H2 within the grid-connected building over one winter week, indicating more utility grid contribution to cover the load demand during the lack of winter PV energy production and the lack of stored hydrogen availability inside the storage tank.

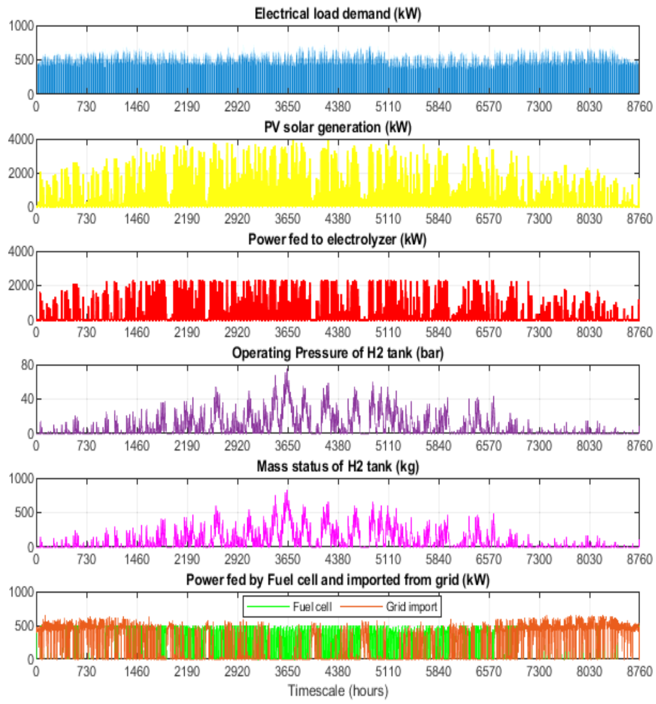

Figure 7 Hourly Energy Management Operation of PV-H2 Grid-connected Building Scenario throughout the year

To ensure that the maximum accumulation of hydrogen mass inside the tank throughout the year doesn't exceed the proposed tank capacity, the operation of the hydrogen storage tank is simulated over the months of highest PV production. It can be seen in Figure 10, that the maximum accumulation of hydrogen mass inside the storage tank, which occurs during the month of June, reached 823 kg at hour (18) in the beginning of the month, thus confirming that the accumulated H2 mass never exceeded the maximum storage capacity of the proposed hydrogen storage tank. The corresponding operating pressure attained at this hour is found around 74 bar, thus confirming that pressure was maintained below the maximum permissible working pressure allowed for the proposed hydrogen tank.

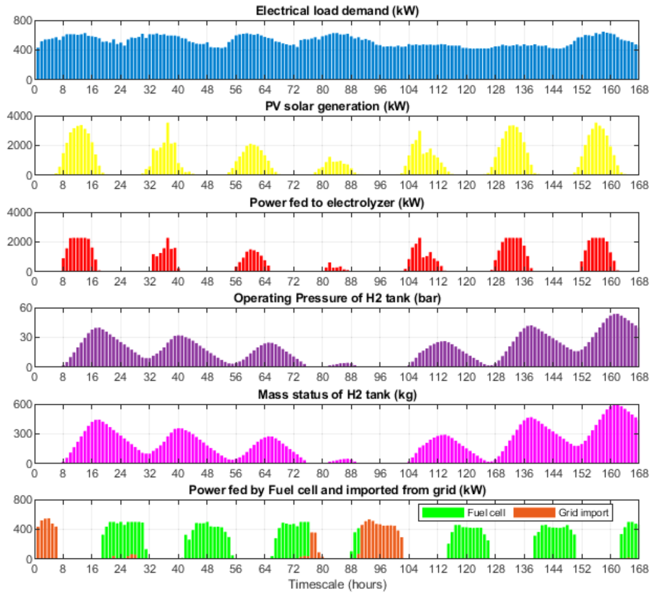

Figure 8 Hourly Energy Management Operation of PV-H2 Grid-connected Building Scenario over one summer week

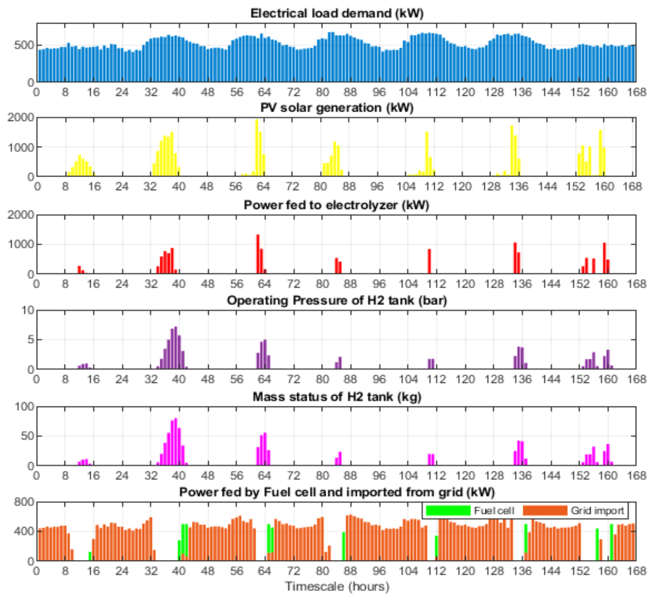

Figure 9 Hourly Energy Management Operation of PV-H2 Grid-connected Building Scenario over one winter week

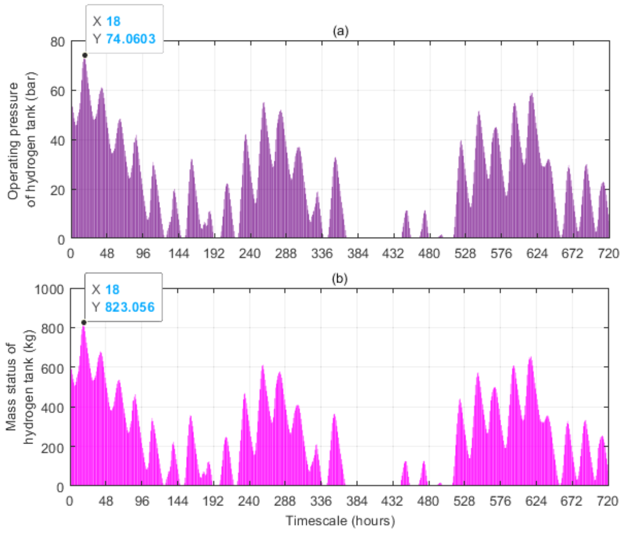

Figure 10 (a) Hourly Operating Pressure of Hydrogen Storage tank during the month of June, (b) Hourly Status of Hydrogen Storage Tank During the Month of June

Figure 11 illustrates the monthly power exchange between the proposed system components and the grid based on the developed energy management model. It can be indicated from Figure 11 that the annual green energy supplied to the building load demand from both the proposed PV system and fuel cell has accounted for approximately 2648 MWh, equivalent to around 59% clean energy contribution of which the share of the hydrogen fuel cell is 21%. The overall GHG emissions eliminated upon integrating the sized PV-H2 energy system are then calculated as 612,005.76 kgCO2e throughout the year. The annual grid contribution is reduced to around 1871 MWh eliminating about 219,564kgCO2e, which corresponds to 34% reduction in the building carbon footprint compared to the case of the proposed PV capacity without energy storage. With the integration of the proposed HESS, around 2366 MWh of the PV excess production is utilized in the hydrogen electrolyser for energy storage and only 111.2 MWh accounted for non-utilized PV energy excess throughout the year. This accordingly has significantly improved the utilization of the proposed PV system capacity by around 57%. Figure 12 shows the simulated monthly hydrogen production and consumption while assuming the storage tank is initially empty. Increased rate of hydrogen production by the electrolyser can be seen during the summer months where higher availability of solar energy excess exists during the long daylight hours, and simultaneously increased rate of hydrogen consumption by fuel cell for feeding the building load demands can be seen during the night hours. Finally, the overall turn-around efficiency of the proposed HESS is found to be around 40.17%. Future work needs to address the improvement in turn-around efficiency of HESS, while minimizing the levelized cost of energy from the optimally sized hybrid renewable-hydrogen energy systems.

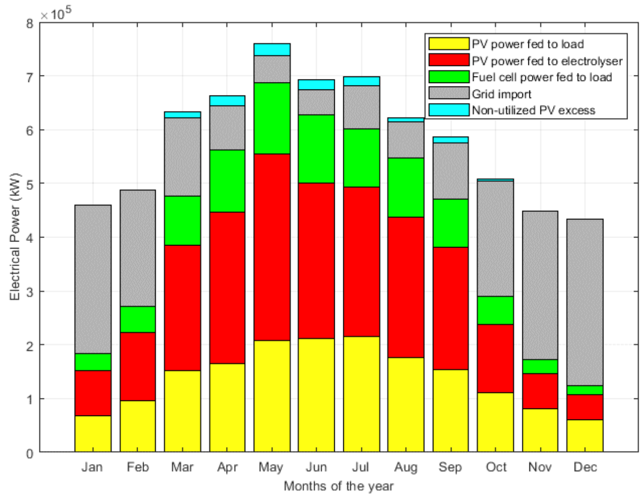

Figure 11 Monthly Power Exchange between the Proposed System Components throughout the year

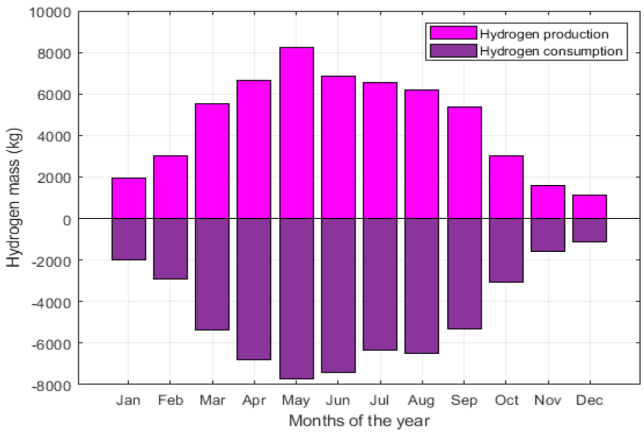

Figure 12 Monthly Balance of Hydrogen Production and Consumption throughout the year

7 Conclusion

This paper develops a capacity sizing and energy management modelling for a Hybrid Photovoltaic-Hydrogen energy system to accelerate the decarbonization of grid-connected buildings while ensuring reliable system operation. The developed system sizing and energy management model results have demonstrated a maintained energy balanced operation throughout the year between the PV renewable generation, the electrolyser operation for green hydrogen production and storage, and the utilization of hydrogen by fuel cell to feed the building demands together with the lowered power import from the utility grid. The integration of the proposed Hybrid PV-H2 system within the grid-connected building has allowed a 59% green energy contribution in feeding the building load demand, while eliminating 612,005.76 kgCO2e throughout the year. Adding the HESS has improved the utilization of the proposed PV system capacity by 57%. Further research is required to enhance the turn-around efficiency of the state-of-the-art HESS to allow more renewables integration towards a net zero-carbon future and full sustainable development.

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