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Solar PV and hybrid energy storage Virtual Power Plant for smart energy communities

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Introduction

The market for distributed Renewable Energy Systems (RES) has been increasing considerably in recent decades due to economic, commercial, and climate related factors. In the UK RES increased their share of power generation to 37% as of 2019, reducing the requirement for oil and coal power [1]. A method for balancing the non-dispatchable renewable resource will be required to ensure power system stability during the removal of traditional ramping generators.
One solution is to store excess energy for later use, however current battery technology cannot fill these requirements. Combining batteries with an energy dense hydrogen system would combine the benefits of both technologies whilst removing the shortcomings.


Figure 1: Roof-top PV solar panels

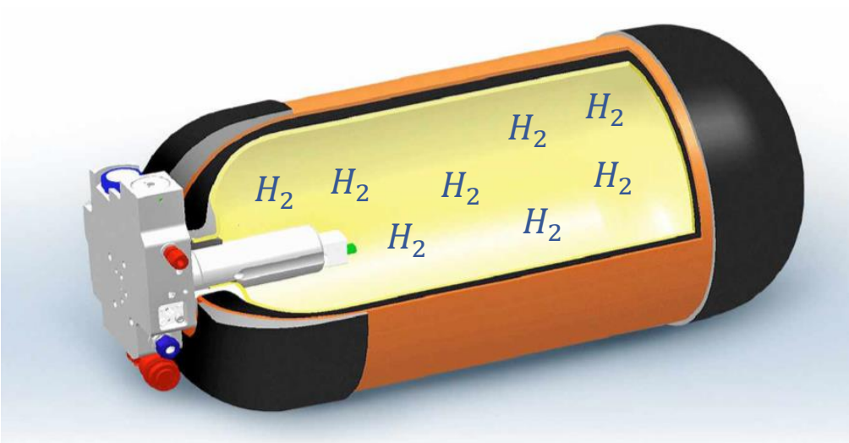


Figure 2: Pressurised Hydrogen storage tank (700bar)

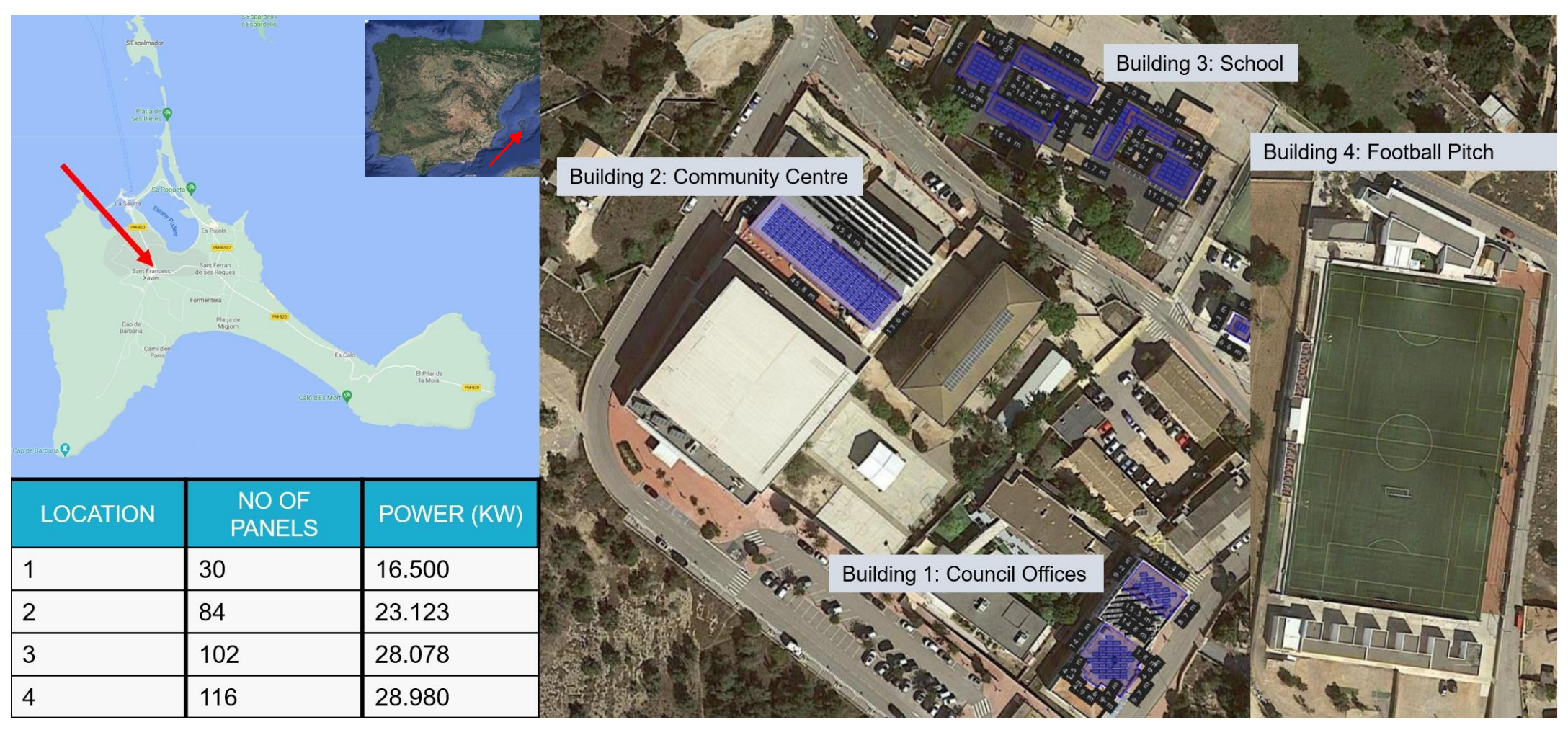
A Virtual Power Plant (VPP) combines the power outputs of several DES along with Energy Storage Systems (ESS) to function as a single energy source [2]. Renewable PV solar can form the base power generation, then an ESS can store the excess energy and release at a later stage. A VPP in theory would remove the congestion problems of increased RES , so is explored in this work.

The objectives for this are as follows:

- Design a small-scale VPP system based on real load and generation data
- Implement a hybrid battery and fuel cell ESS to store excess power produced, and to provide parallel energy services
- Optimise storage design for highest economic performance whilst taking into account the environmental impact

‘Smart’ Energy Community Design

The chosen system location is the urban centre on the Balearic Island of Formentera. The high solar resource and increased energy carbon impact [3] provides a good test field for the VPP.
Four community buildings have been identified with preexisting PV solar installations, and through analysis with Helioscope software, locations on the rooftops for expansion of these systems have been identified. The total PV energy potentially available at these sites is displayed in figure 3.



LOCATION	NO OF PANELS	POWER (KW)
1	30	16.500
2	84	23.123
3	102	28.078
4	116	28.980

Figure 3: (a) Island of Formentera with location of central town, (b) VPP building locations with PV solar installations, (c) PV solar capacities

Materials and Methods

The design of the VPP system was conducted in MATLAB/Simulink, with all required generation, load, and energy storage systems. Figure 4 shows the diagram of the small scale VPP, with the four community buildings connected to both the grid and the hybrid ESS.
Figure 5 displays a sample 1-week power demand and PV generation for each of the four buildings. Data was produced through analysis of real building power consumption and similar data from within the UK.

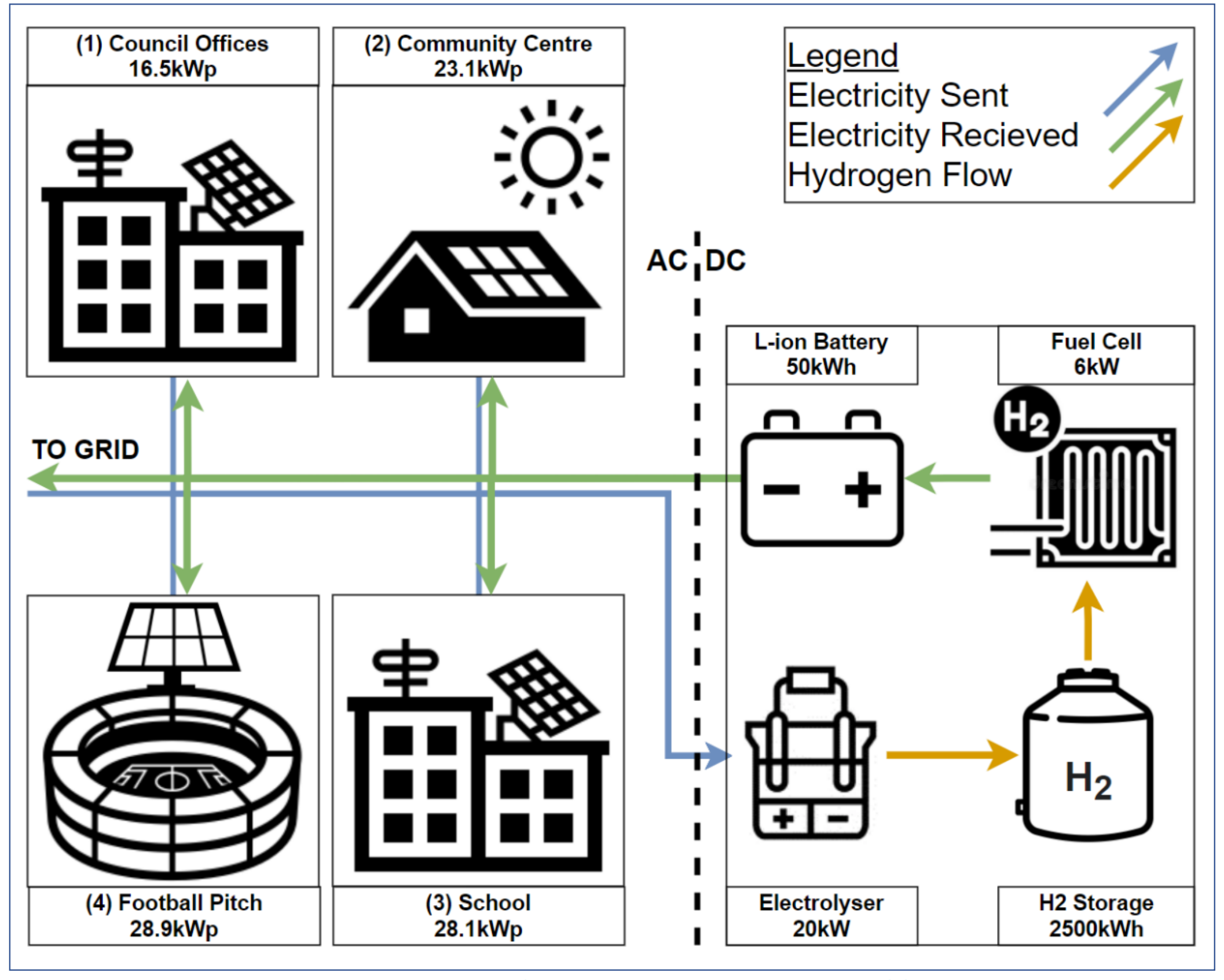


Figure 4: VPP system architecture Design with four connected loads and hybrid ESS

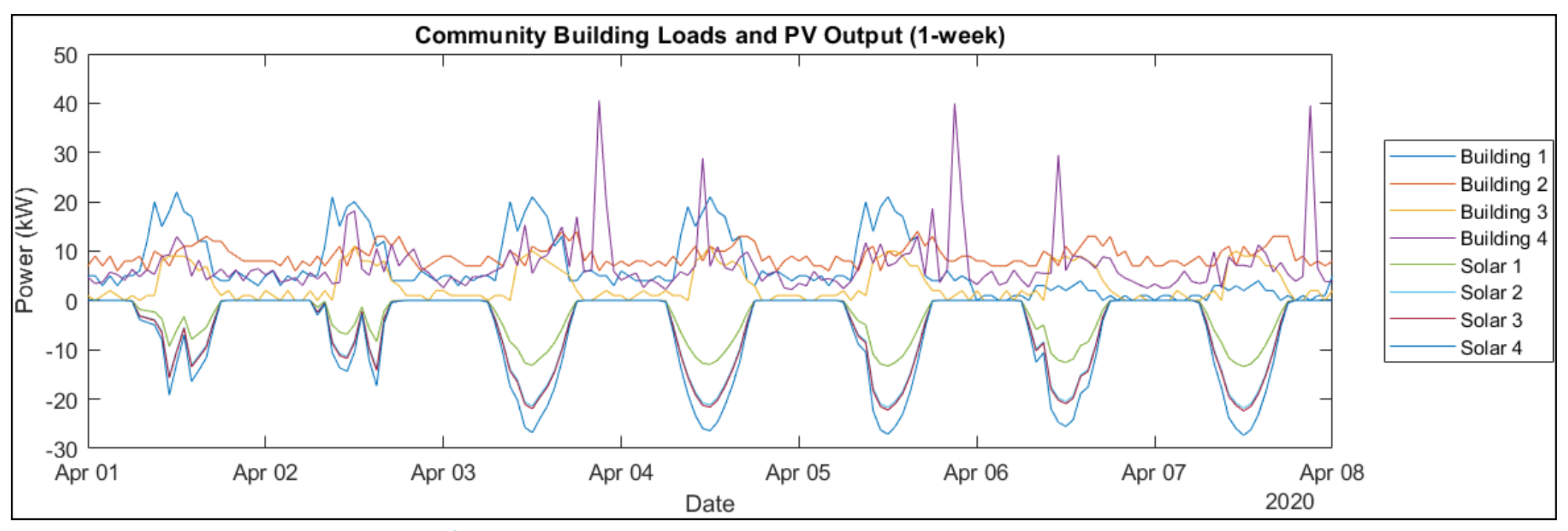


Figure 5: A one-week sample of the building loads and PV generation, April 2020

System Sizing Method and Control Logic

The optimisation of the ESS was performed by varying the Li-ion battery from 20-500kWh and finding the lowest Levelised Cost of Electricity (LCOE), and Internal Rate of Return (IRR) over the estimated lifespan. MATLAB was used to provide the optimisation procedure, with CAPEX and OPEX data gathered from [4,5].
The PEM fuel cell and electrolyser sizes were predetermined to ensure that the system could regenerate the required amount of hydrogen throughout one year, and thus provide a seasonal storage service.
The chart in figure 6 shows the control logic of the VPP system, and the state outcomes for each of the individual components.

Table 1: VPP system component sizes

Component	Power - Capacity
PV Solar (all buildings)	96.6Kwp
Fuel Cell	6kW
Electrolyser	20kW
Hydrogen Storage	2500kWh
Battery	20-250kWh

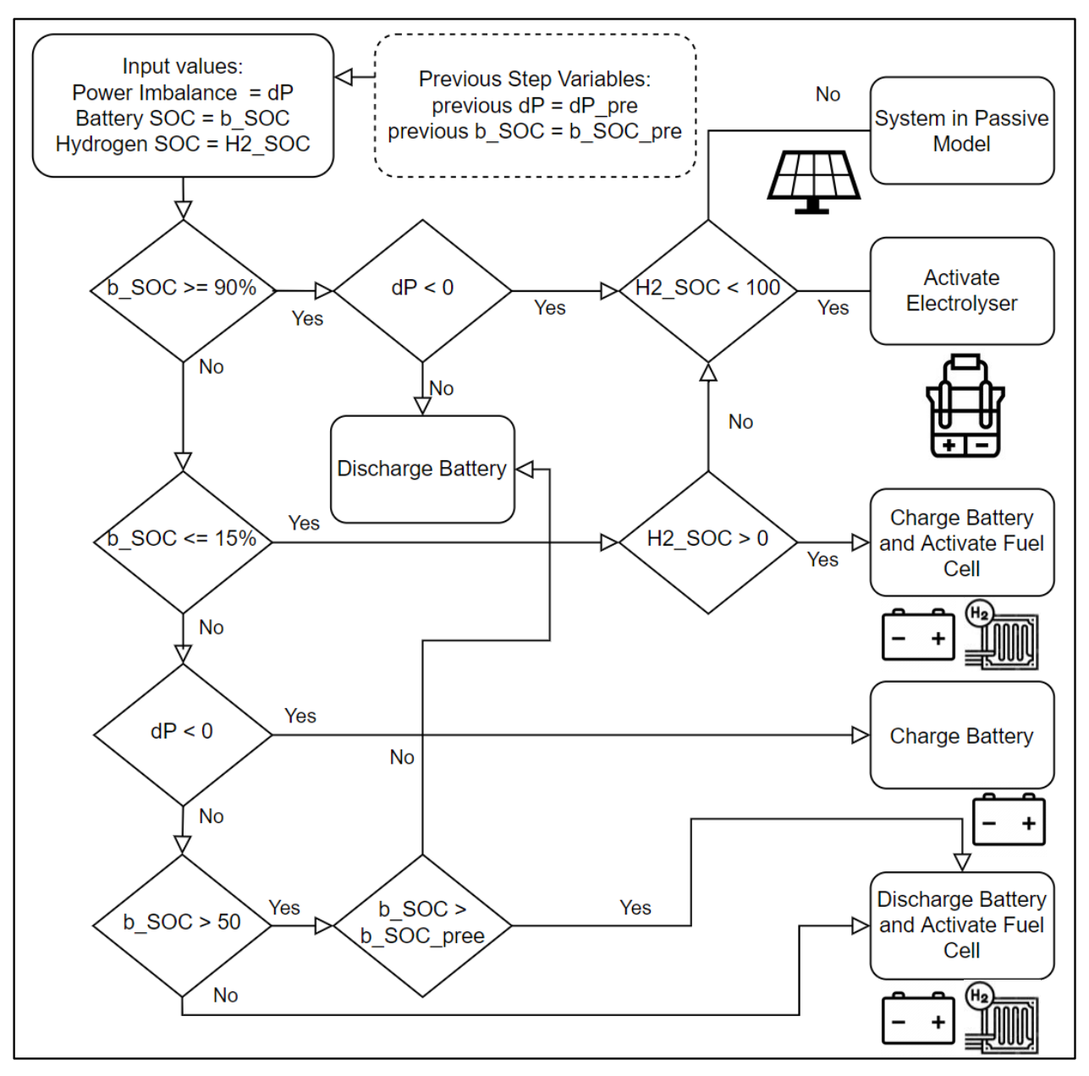


Figure 6: VPP state-based control logic

Results

Energy Storage Sizing and Economic Optimisation

Figure 7 displays the results for the economic optimisation. The model gave a battery size of 40kWh to be paired with the hydrogen system, and that increasing or decreasing the size gives a sub-optimal outcome. A cost of 30€c/kWh was used to represent the grid energy usage in Spain based on available data. The optimal result leads to a system LCOE and IRR of 10.68 €c/kWh and 10.78%, respectively. Table 2 below gives all numerical results of the simulation.

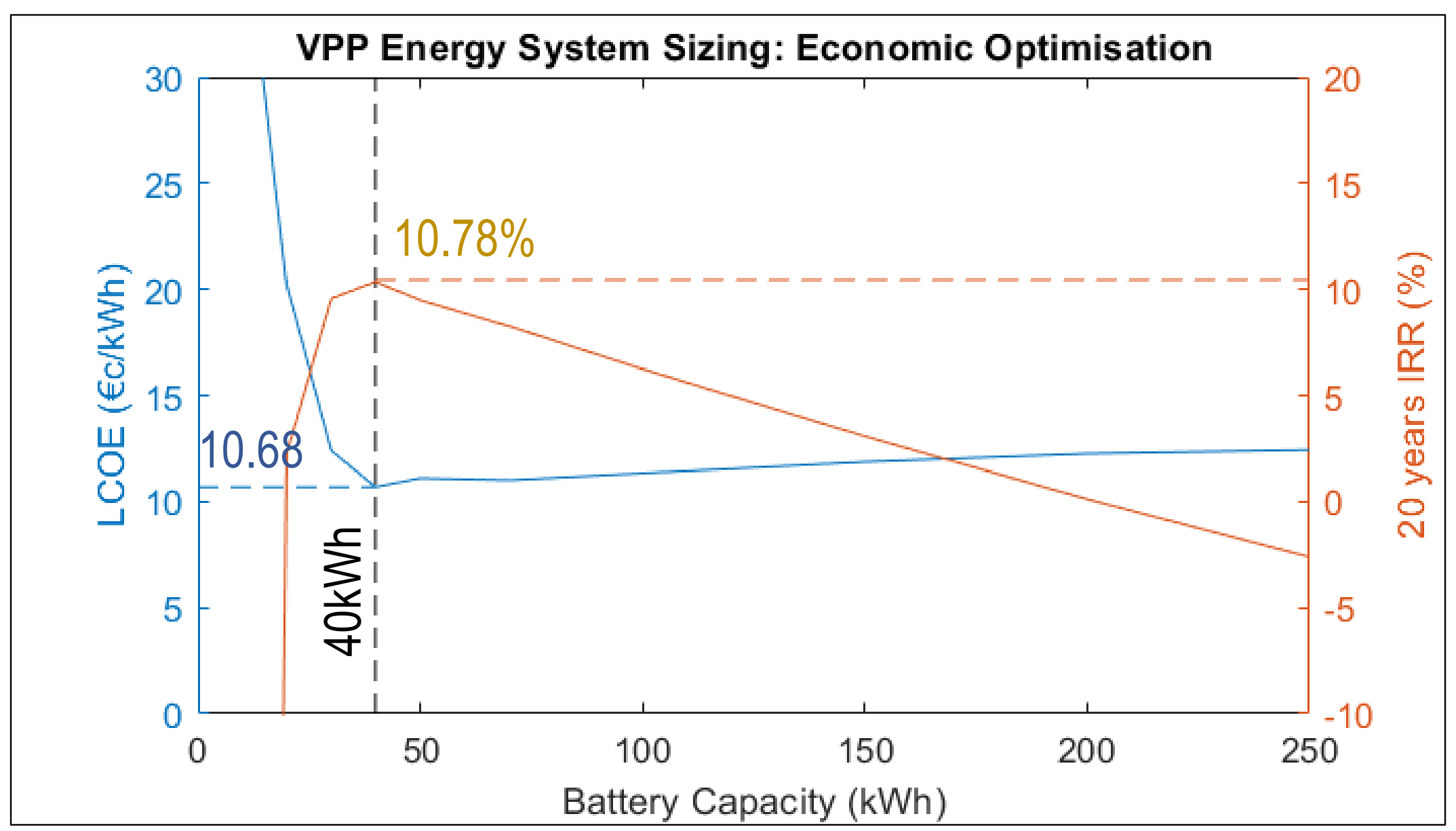


Figure 7: Economic optimisation of the PV/ESS with LCOE and IRR values (20-year lifespan)

Table 2: Economic and operational data of the VPP energy system

Component	CAPEX (€)	OPEX (€/yr)	Lifetime	Energy/Year (MWh/yr)	LCOE (€c/kWh)	Efficiency (%)
PV solar	80274.6	1339	20	164.7	4.7	16.5
Battery	19500	639	5	13.1	19.9	92.5
Hydrogen System	91000	925	20	46.3	11.6	33.7
ESS Total	110500	1564	20	59.4	13.5	-
VPP Total	190774.6	2903	20	224.1	7.0	24.5

System Model Dynamics and Load Balancing Ability

The final energy system design was simulated over a one-year period using loading and weather information based on 2020 data. The graph in figure 8 contains a sample 1-week period in early April 2020 displaying the dynamics of the energy system based on the state-based control logic.
When PV solar is available in excess, the battery charges to 100%, after which the electrolyser begins creating and storing hydrogen. Once excess PV solar is no longer available, the battery discharges whilst also begin charged by the hydrogen fuel cell during the night period. Figures 9 and 10 show the system component efficiencies and the composition of the energy production/consumption of the VPP, respectively.

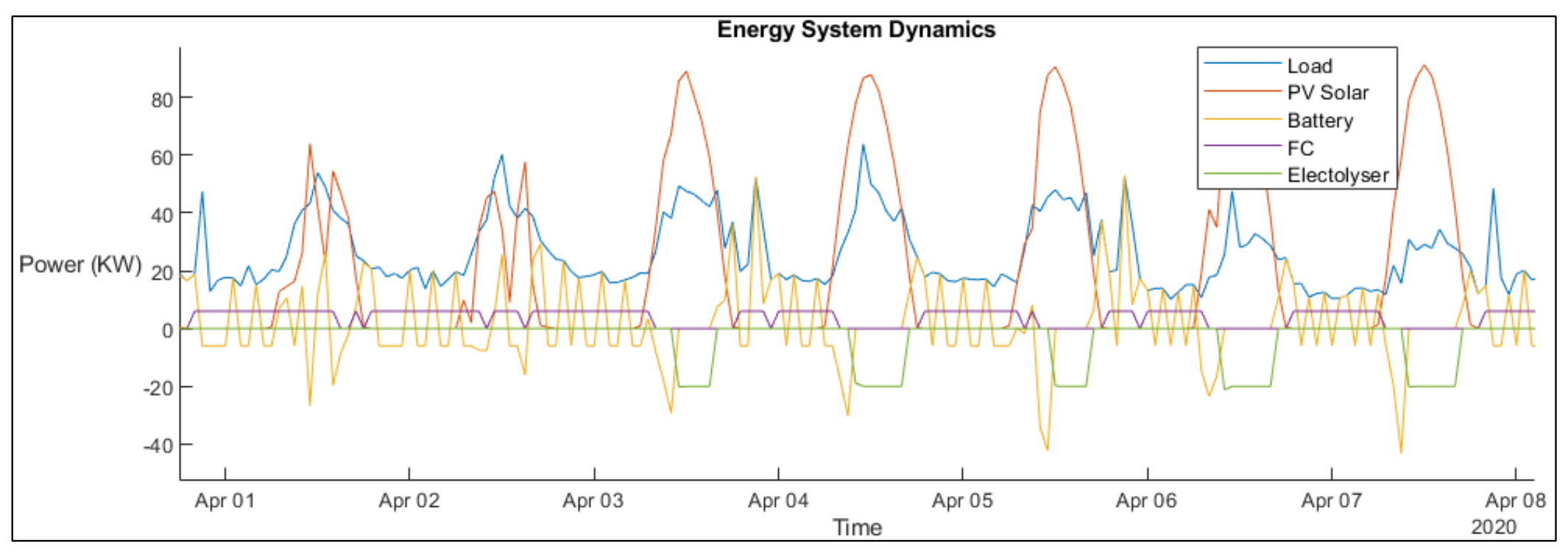


Figure 8: Economic optimisation of the ESS with LCOE and IRR values (20-year lifespan)

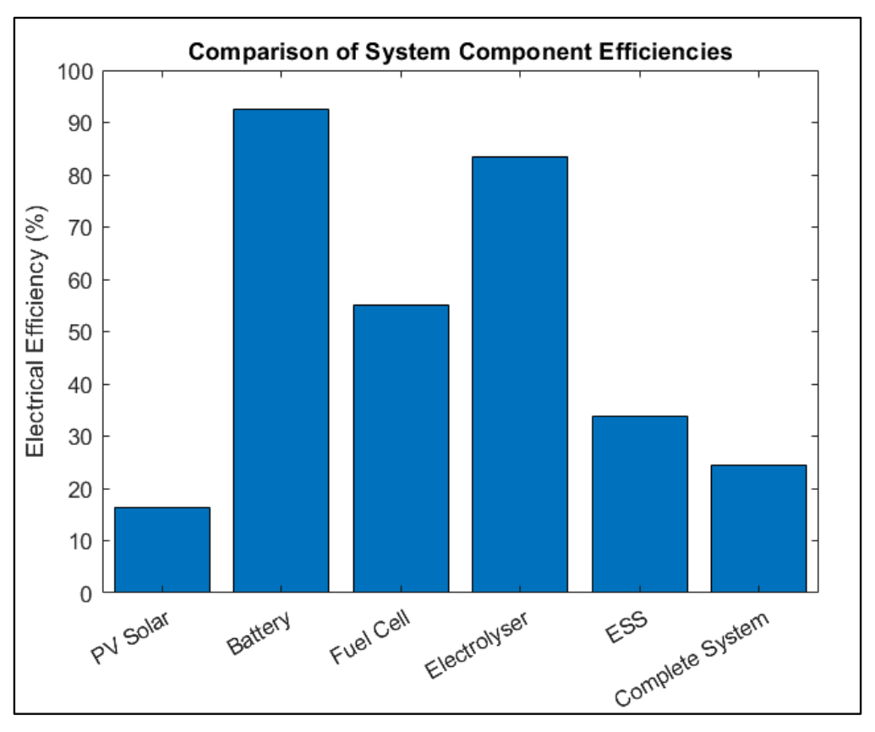


Figure 9: System Component Efficiencies

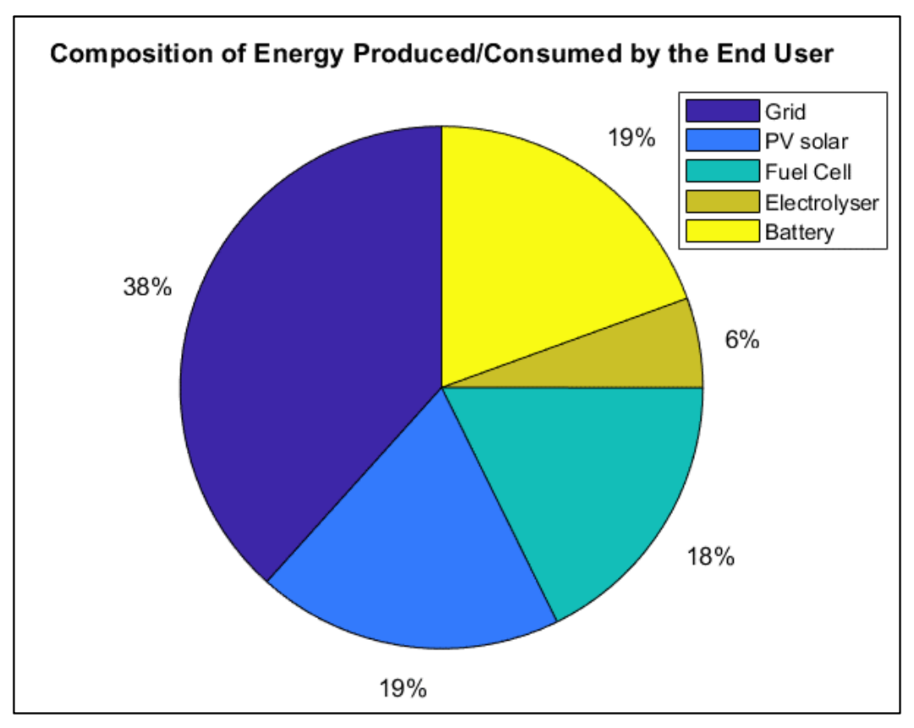


Figure 10: Total energy produced and consumed

Environmental Emissions and Sustainability

The graph in Figure 11 displays the change in the emissions intensity (kgCO2e/kWh) of the energy delivered throughout one year of VPP simulation. The data includes the emissions of the island grid as a reference (Source: RED Electrica), with an average yearly value of 0.290 kgCO2e/kWh. The impact of all four buildings included in the VPP are significantly lower, with building 4 averaging 0.121 kgCO2e/kWh. The is due to the ability of the hybrid energy system to take advantage of the excess PV solar energy available. The emissions intensity values used are given in table 3.

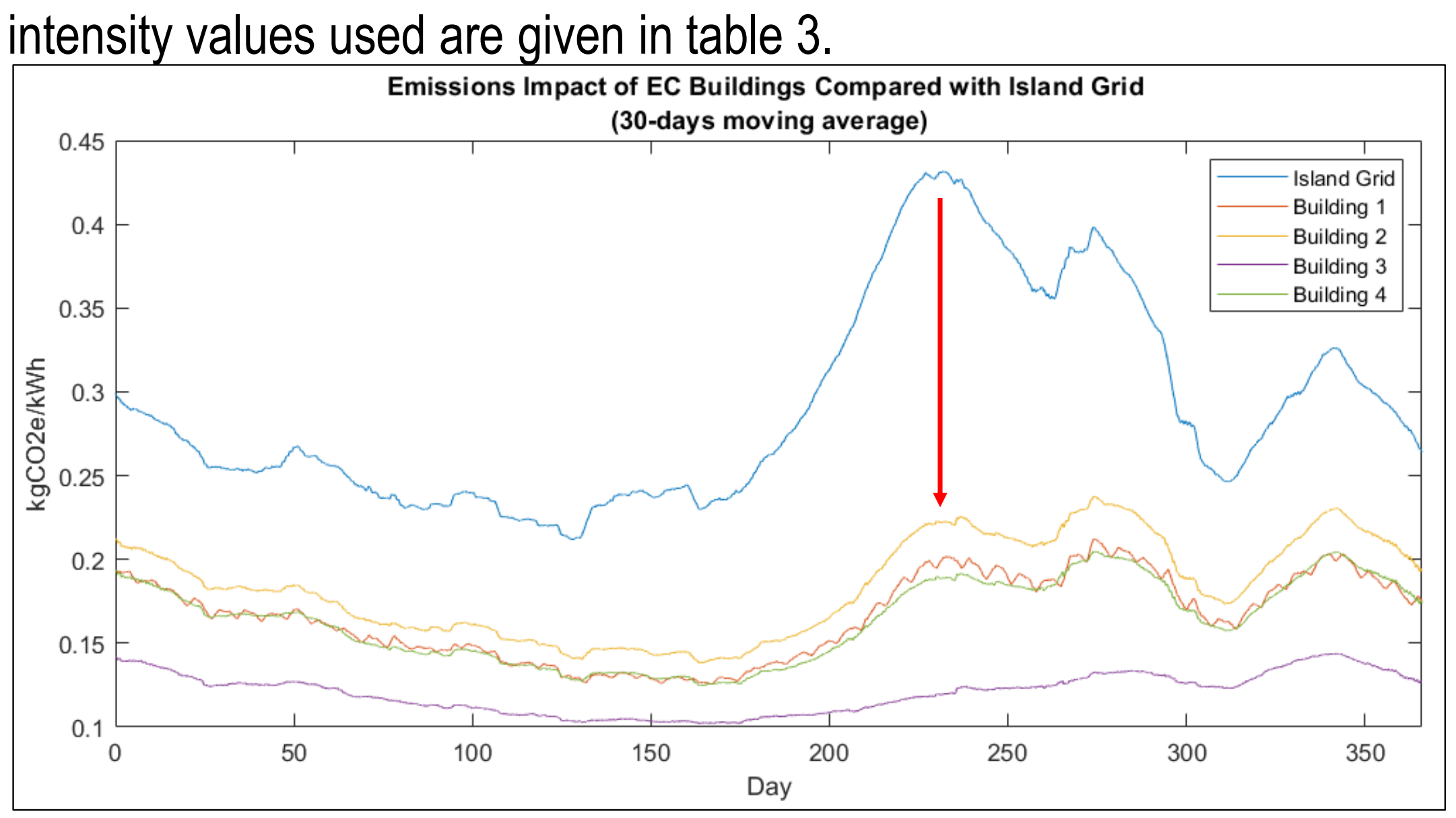


Figure 11: Emissions intensity of the island grid and building loads over 1-year period – 30-day moving average

Table 3: Emissions intensity values used for VPP components

EMISSIONS INTENSITY (KGCO2E/KWH) [4,6]	
PV Solar	0.045
Battery	0.125
Hydrogen System (Total)	0.100

The improvements in both environmental impact and energy cost provided by the trading of electricity within the VPP are shown in table 4, with a minimum 36.6% and 24.7% improvement in emissions and cost, respectively.

Table 4: VPP emissions and cost improvements over the reference energy grid

Site	Average Emissions (kgCO2e/kWh)	Improvement (%)	Average Cost (€c/kWh)	Improvement (%)
Building 1	0.166	42.8	22.6	24.7
Building 2	0.184	36.6	21.3	29.0
Building 3	0.121	58.3	15.1	49.7
Building 4	0.164	43.4	19.6	34.7

Conclusion

The aim of this work was to produce a small-scale VPP concept integrated into the urban centre of the island of Formentera. The results show considerable improvements in cost and carbon impact over relying on the local energy grid over the 20-year lifetime.
The design system was able to provide both load following capabilities as well as seasonal storage with hydrogen as a multi energy vector. Hydrogen could also be delivered to the island to increase capacity further and provide heating services for industrial loads.
While the ESS reduced overall carbon impact, there is a correlation between the amount of PV excess available from a building due to the low emissions intensity from PV solar technology.
The optimisation process was successfully able to produce the most cost-effective sizing of the hybrid hydrogen and battery energy storage system, with a combined LCOE of 10.68 €c/kWh including PV solar. Further work should be conducted to increase the IRR of the system, as 10.8% over 20-years is relatively low. With the targets in place to significantly reduce the cost of hydrogen power [7], it is likely the returns can be increased with future design optimisations.

Acknowledgements

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