

University of Wales Trinity Saint David Wales Institute of Science & Arts



Prifysgol Cymru
Y Drindod Dewi Sant
University of Wales
Trinity Saint David

A study on reducing demand on our national grid with local green energy networks.

By Craig Worsley - 2213643

Supervisors: D. Chidambaram, J. Prince Devaraj and I. Neaga

Project submitted as part of the requirements for the award of CerTHE Skills for Engineering, University of
Wales Trinity Saint David.

May 2023

Declaration

'I have read and understood the University Regulations concerning plagiarism and I undertake:

That all material presented for examination is my own work and has not been written for me, in whole or in part by any other person(s). That any quotation or paraphrase from the published or unpublished work of another person has been duly acknowledged in the project [Craig John Worsley]

FORM OF CONSENT

I Craig John Worsley hereby consent that my Project, submitted in candidature for the Certificate of Higher Education: CertHE Skills for Engineering degree, if successful, may be made available for inter-library loan or photocopying (subject to the law of copyright), and that the title and abstract may be made available to outside organizations.

Acknowledgements

I would like to thank my wonderful family for the support throughout my course,

I would also like to give a big thank you to the wonderful staff at UWTSD, especially the lecturers that have helped me on this journey, a big thank you is also needed to all my references for all their hard work that has made my research and work possible.

Abbreviations

H ₂	Hydrogen
CH ₄	Natural Gas
O ₂	Oxygen
MG	Micro Grid
AEM	Alkaline Anion Exchange Membrane
PEM	Proton Exchange Membrane
FC	Fuel Cell
EL	Electrolyser
LGEM	Local Green Energy Network
NG	National Grid
DC	Direct Current
AC	Alternating Current
HESS	Hydrogen Energy Storage System
PV	Photovoltaics
SWB	Saltwater Battery
HEMS	Home Energy Management System

Contents Page

ABSTRACT	6
INTRODUCTION	7
CURRENT ELECTRICITY TRANSPORT AND ENERGY INPUT CONSIDERATIONS	9
PHOTOVOLTAICS	10
PEROVSKITES	10
WIND TURBINE	11
FUEL CELLS	12
ELECTROLYSERS	13
HYDROGEN STORAGE VESSELS AND CONTROL SYSTEMS	14
MICRO-CONTROL UNIT – ARDUINO (SMALL SCALE OPERATION)	14
OPERATING TEMPERATURE	15
SALTWATER BATTERIES	16
CONCLUSION	17
LGEM BUILDING DESIGN	18
RENEWABLE HOME DESIGN	18
GANTT CHART SHOWING A STRUCTURE OF PREPARING THE INITIATION OF THE PROJECT.....	19
APPENDICES.....	20
AVERAGE ENERGY CONSUMPTION IN THE UK.....	20
DESIGN IMPLEMENTATION CALCULATIONS	20
HOUSING PV FIGURES.....	21
LGEM GENERATION	21
PEMFC AND ELECTROLYSER CALCULATIONS.....	21
SYSTEM OVERALL VALUE CALCULATIONS	22
LGEM USING SWB.....	23
<i>Hydrogen production supply by a national infrastructure</i>	<i>23</i>
<i>Giga Factories for large scale distribution of Hydrogen.....</i>	<i>24</i>
OTHER FORMS OF ENERGY GENERATION OR UPCOMING DEVELOPMENTS	25
CRYOBATTERY	25
KINETIC ENERGY.....	25
HYDROGEN AND FUEL CELLS.....	25
REFERENCES.....	26

Abstract

In the coming chapters it will be unveiled whether local green energy networks using Hydrogen as an energy storage solution is a viable option by creating a local green energy network to supply and store energy, the implementation would assist the national grid by reducing demand in local areas, thus reducing fluctuation and providing a stronger more stable energy network, that can cut out the use of fossil fuels at a faster pace than what is predicted at present, which would transition the United Kingdom to net zero at an improved pace.

The work will start by investigating systems and issues surrounding energy production, storage and transmission, moving into the products needed to produce this theoretical solution.

Moving forward into an in depth look at the technologies involved and suggested units to meet the derived parameters.

Once the system structure is decided, calculations will be made to validate if the system can produce, supply and store the necessary energy needed at cost for H₂ to be considered a viable option.

In the final chapters calculations will be made to assess the cost of implementing this technology and a final statement will be made on my findings.

Introduction

In the research material [1], [2] the broader energy system landscape, hydrogen is reviewed as a possible hybrid solution to the climate crisis, breaking down the information surrounding H₂ implementation to review its possibility as a solution and challenges surrounding implementation.

In [3] it is discussed that more green energy storage technologies are needed to move away from fossil fuels, a strategic plan is also put in place for implementing a H₂ piping network, other forms of green energy storage are discussed with the opportunity of funding. In the relatively big push on green electricity the national grids systems have had to shut down generation of energy at points, as the national grids capacity for renewable energy couldn't cope with the energy being generated, that being said the fluctuation of generation in renewables can be stunted by weather conditions thus not creating enough.

In the coming chapters information will be examined on producing and storing green energy, it will be analysed if H₂ technologies can be used to reduce the nations carbon footprint and get closer to net zero by creating a theoretical LGEN.

Commercial homes will be the solar farms and H₂ will be the storage medium for excess energy.

The design presented is a system that has multiple ways of being implemented, because of the customisability examples of products will provide information on the components needed, the parts required to bring this type of system together, as well as information to consider for the reader to create a personalised solution to suit their own energy needs.

The design will be for a network of homes as this is the most cost effective and productive way to implement the design.

Using renewable energy to supply electricity and H₂ to store excess energy, the system design is aimed at supporting a considerable number of homes, to reduce fluctuation for the NG and subsequently reduce the use of high polluting forms of energy generation, this solves two problems, the space used in solar farming, damaging agriculture and reduces cost. The design is aimed at councils, government, energy companies and housing associations.

The price of the system is dependent on advancements in technologies and market prices for Fuel Cells, Electrolysers, wind turbines and Photovoltaic panels.

The design starts by having PVs on commercial homes coupled with an inverter for converting direct current energy into alternating current.

Current Electricity Transport and energy input considerations

Electricity is transmitted through extensive networks and transmission lines over long distances, this creates energy losses. A major part of the energy losses comes from the Joule effect in transformers and power lines, The energy is lost as heat in the conductors [4].

Considering the main parts of a typical Transmission & Distribution network, here are the average values of power losses at the different steps: 1-2% Step-up transformer from generator to Transmission line, 2-4% Transmission line, 1-2% Step-down transformer from Transmission line to Distribution network, 4-6% Distribution network transformers and cables. The overall losses between the power source and consumers are roughly between 8 and 15%. An energy assessment [4] concluded that, 100 units of energy saved at the end consumer could save around 300 units from the energy source.

This emphasises why LGEN are more cost effective and efficient and with the use of Peer-to-peer energy trading [5] it will save a significant amount of energy.

Though a high Self consumption ratio PV's can be the ideal solution in reducing demand and to exchange electricity with the grid, however a high PV concentration in low voltage distribution grids can cause several challenges if the PV penetration is more than 20% [6].

A typical MG set up needs: Solar panels, cables/connecting wires, solar current controller, inverter, circuit breaker, isolation switches and a battery system (optional).

Photovoltaics

Most solar cells that are available today have an efficiency of around 17-22% [7], it's calculated that the silicon type of PV has a limitation of 31%, this is known as the Shockley-Queisser limit [8]. There are three spectrums of light, Ultraviolet, Visible, and Infrared.

Typically, only visible light is used when creating a charge in silicon solar cells, silicon is arranged into two different layers the P type, which can receive electrons and the N type, that can give electrons [9].

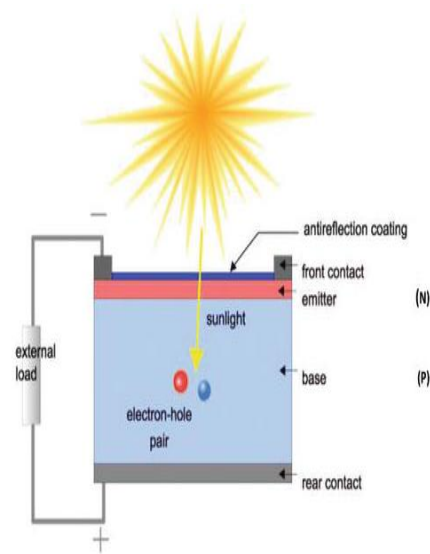


Figure 1: Incident light on a typical PN solar cell
Source: Adapted from [9]

Perovskites

A new crystalline structure from a mineral called perovskite has been in development [10], this crystalline structure of calcium titanium oxide (CaTiO_3), can be manipulated to generate more energy from the different spectrums of light by manipulating its crystalline structure, it can create energy from different spectrums of light in multi-junction PV cells, it is more efficient, cheaper to produce, can be created from relatively cheap materials in a lab, it's lighter so reduces cost in transport, the PV using Perovskite can be as small as 5 microns thick, can be built into a glass pane and even sprayed over the panel of a car.

Wind Turbine

The type of wind turbine that is most suited to this task is a design from Aeromine [11] the designs energy supply is stable enough to support energy supply during the night and add value during the day, the company Aeromine has discovered how to manipulate air flow through low pressures, taking advantage of a buildings structure to increase air flow producing energy, this design is an amazing discovery.

This F1 inspired design is capable of

producing around 10-15 MWh annually with a 5-kW turbine, it produces very low noise and can be mounted with multiple units, with only one moving part it makes maintenance minimal. Through the laws of aerodynamics this

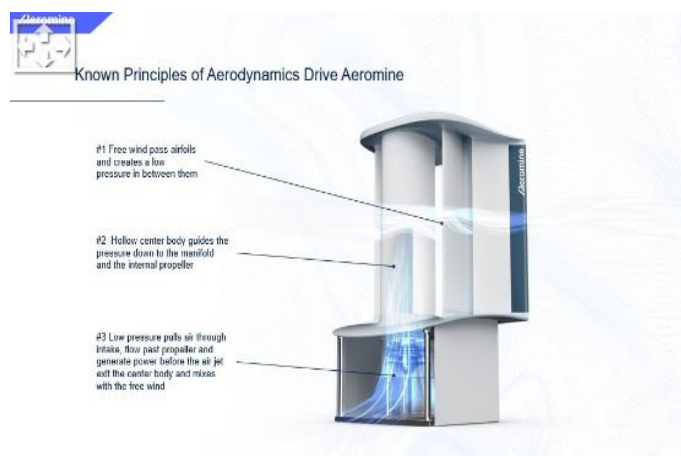


Figure 3: *Known principles of aerodynamics drive Aeromine*

Source: Adapted from [11]



Figure 2: *Known principles of aerodynamics drive Aeromine*

Source: Adapted from [11]

machine manipulates the air hitting the structure, with the channel of air above it creates a flow and a vacuum, which drives the low vibration blade to generate electricity. The unit does have some drawbacks, it needs to be mounted around 4.4 meters above ground and on the edge of a building, it weighs a whopping 410kg's.

Fuel Cells

Fuel cells convert stored energy (H_2) into electricity in peak demand, the FC in this design will be PEM however, the power capabilities are roughly the same as AEM, it's the price of the materials that make the AEMFC so appealing, the only differentiating factor for this design is time tested, in [12] an AEMFC was tested for 5000h continuously and it was still producing a steady current at an improved efficiency than PEMFC.

The performance of a FC is only limited by the availability of the fuel and oxidant supply not by the cell design, fuel cells are rated by their power output kW, rather than by their capacity kWh, they can be fuelled at higher pressures to produce more energy [13].

Converting hydrogen into electricity through fuel cells has an efficiency of around 60%, AEMFC are a semipermeable membrane that are an advancement to PEM's, the exchange membrane is the main difference between the two units [14].

There are six principal types of fuel cells [14]: Low temperature (50–150°C): alkaline electrolyte (AFC), proton-exchange membrane (PEMFC), direct methanol (DMFC) and other liquid-fed fuel cells.

Medium temperature (around 200°C): PAFC.

High temperature (600–1000°C): molten carbonate (MCFC) and SOFC.

New materials for fuel cells, together with improvements in the performance and lifetimes of stacks, are underpinning the emergence of the first truly commercial systems [12].

Electrolysers

Electrolysers are a low-cost solution for storage of H₂ with previous systems a compressor was needed however, the EL [15] is capable of direct compression of up to 35bar, by storing excess energy produced at a lower power consumption, the steady supply of energy in peak consumption periods means less demand would be required from the NG, EL figures on performance usage and size can be seen in the data sheet, by storing excess energy produced into H₂, the EL can help boost energy production at peak times to support the stabilization of energy flow and the NG during high energy consumption.

Specifications	
Production rate	Up to 500 NL/h, up to 1.0785 kg/24 h
Hydrogen output purity	35 barg: 99.9% (1,000 ppm H ₂ O) at 25 °C 8 barg: 98.8% (~ 12,000 ppm H ₂ O) at 25 °C
Output pressure	Up to 35 barg
Nominal power consumption per Nm³ of H₂ produced	4.8 kWh/Nm ³ , beginning of life
Operative power consumption	2.4 kW, beginning of life
Peak power consumption	3 kW
Heat dissipation	0.6 kW, beginning of life
Max heat dissipation	0.9 kW, end of life
Standby power consumption¹	0.5 kW
Power supply	220 – 230 V (AC), 50/60 Hz
Maximum water input conductivity	20 µS/cm at 25 °C
Water consumption	~ 420 mL/h at 25 °C
Water input pressure range	1 – 4 barg
Ambient operative temperature range	5 °C – 45 °C
Ambient operative humidity range	Up to 90% humidity, non-condensing
IP rating	IP 20
Dimensions	W: 482 mm x D: 635 mm x H: 266 mm
Weight	42 kg
Space inside cabinet	6 U
Control and monitoring	Fully automatic with Enapter's EMS via 2.4 GHz Wi-Fi and Bluetooth, Modbus TCP over Ethernet
Conformity	CE mark according to the machine directive 2006/42/EC UKCA mark according to Supply Machinery (Safety) Regulations 2008 ²

Figure 4: AEM Electrolyser EL 4.0

Source: Adapter from [15]

Enapter [16], has disclosed a 54.8kWh per 1Kg of h₂ running cost for its EL, a rough price for its 1MW AEM EL is around \$500 in 2025, Lifetime expectancy is guaranteed at 35,000h however testing has indicated it is capable of 70,000h. A unique idea from Enapter on mass production to bring H₂ energy to a broader audience, is mass producing smaller stackable units, a 2.4Kw EL stacks so 1MW and requires 420 stacks, [17] Filling up a 500 L tank with one EL running at 100% and at 35 bar takes $500 \text{ L} \times 35 / 500 \text{ NL/h} = 35\text{h}$ until it is full, the electrolyte working temperature in the EL is 55°C. AEM EL can tolerate a lower degree of water purity, works in a highly diluted alkaline environment, this makes it much safer to handle, uses cost efficient materials while still producing a high purity H₂ at a higher efficiency than current EL, the unit is scalable and cost effective for remote deployment which makes it ideal for linking up with a variety of renewable energy sources.

Hydrogen storage vessels and control systems

In the reviewing article [6] H_2 storage vessels are reviewed as a seasonal storage option as well as other energy storage solutions, it is also discussed if H_2 storage is a viable option to small scale MG or if other forms of storage or grid reliance is more fitting, information on other storage systems are also discussed.

The type [18] and estimated cost of H_2 storage vessels [19] start at \$28,806.54 = £23,231.08.

A control system needs to be in place to manage the operation, software needs to communicate with valves to control the flow of the system.

Data Acquisition hardware is needed to control and read all the instruments [18], it needs to be able to send commands while operating actuators and control modules.

Industrial control systems include Modbus, ethernet/ip and profibus, the system needs redundancy controls and an automatic purge system is a necessity in this system.

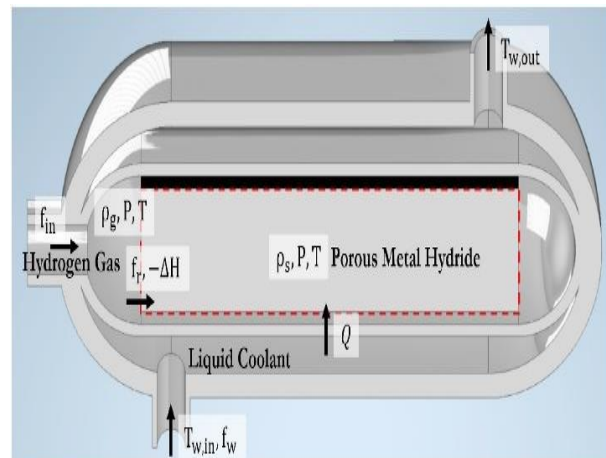


Figure 5: *Schematic of a metal hydride tank*

Source: Adapted from [18]

Micro-Control Unit – Arduino (small scale operation)

Arduino could be used as a HEMS to manage/monitor with a multi-meter reader, pressure sensor, voltage monitor and coding to direct how to utilise the systems in an efficient and stable manner, a small DC motor could be used on a tee valve for release of the H_2 in peak energy demand to supply the fuel cells, Arduino's are cheap and have been used in other MG networks [20].

Operating temperature

AEM Electrolyser
EL 4.0



Figure 6: *AEM Electrolyser EL 4.0*

Source: Adapted from [15]

The system will need to be temperature regulated for optimal use, this can be achieved using sensors at each individual component location and monitored for optimum working conditions, if using the Arduino system in a small-scale system, the disadvantages of cooling could be a positive parameter in the system, it can be turned into

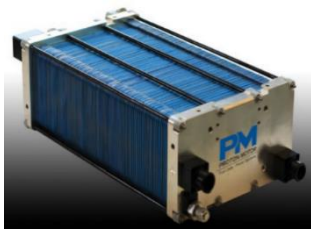


Figure 7: *A 96-cell, water-cooled PEMFC stack*

Source: Adapted from [12]

heat generation via a sand heat storage system [21], [22], by storing the heat generated in this way waste energy is reduced making the whole system more efficient. Pipework inside the sand storage design can transfer heat upon request via a heat exchanger in the commercial or industrial property.

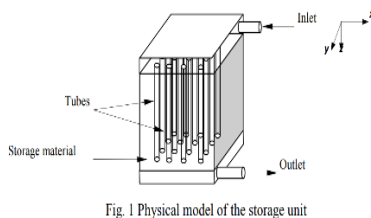


Fig. 1 Physical model of the storage unit

Figure 9: *Physical model of the storage unit*

Source: Adapted from [22]

Operating temperatures of fuel cells can reach [12] 150–180°C while in use.

The system for the LGEN building would work in the same way for cooling, supplying hot water to the building with a cooling system in the form of a floor heat exchanging system that doubles as a regulating system for the building.

Saltwater Batteries

SWB can last up to 20 years with an efficiency of 90% going down to around 60% at the end of its life, it can store up to 9kw, works exceptionally well with photovoltaics, can work with AC or DC, SWB are 100% recyclable, do not damage the environment and are easily interchangeable [23]. Molten salt batteries [24] have shown to have promising results in taking over from lithium-ion batteries, lithium-ion batteries need to be refined, have a lower life expectancy and with the demand from clean energy storage, electric vehicles and general consumer electronics a solution has emerged, renewable and environmentally friendly molten salt batteries are not a new concept but through advancements and understanding we have managed to change the capacity which was the issue holding the technology back.

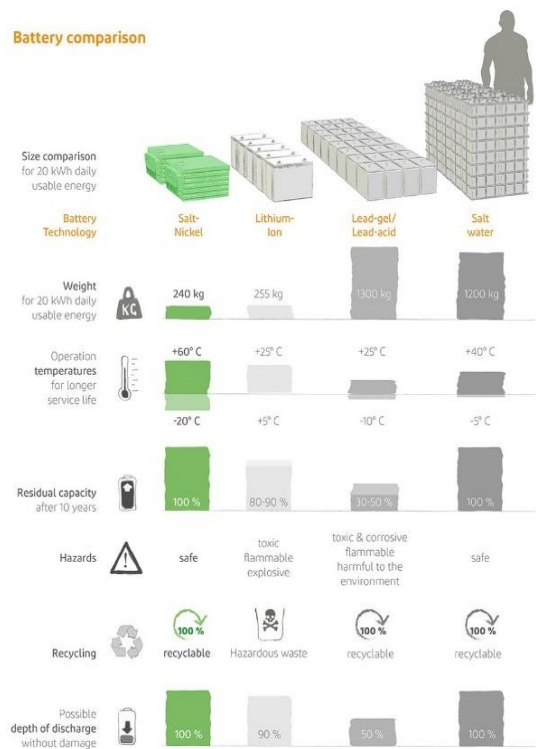


Figure 10: Battery Comparison

Source: Adapted from [23]

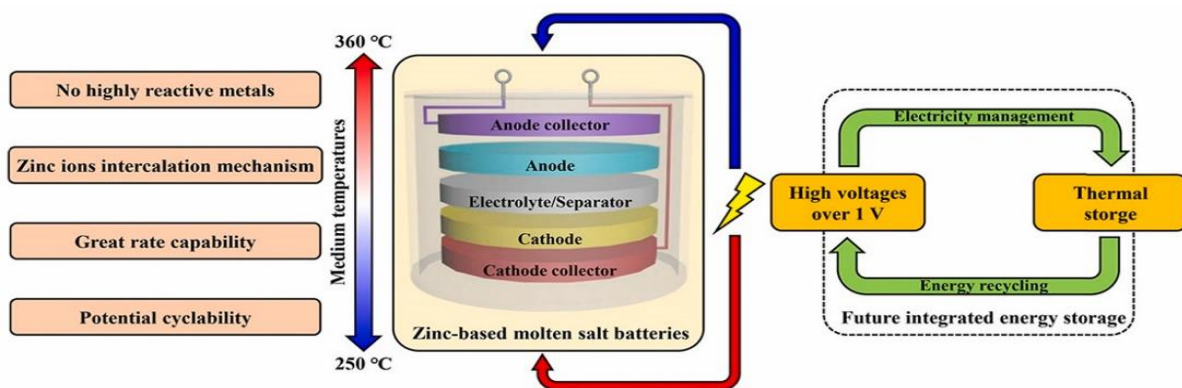


Figure 11: Graphical abstract

Source: Adapted from [24]

Conclusion

In conclusion reviewing the costs to profits below shows that Hydrogen is a cost-effective energy storage solution.

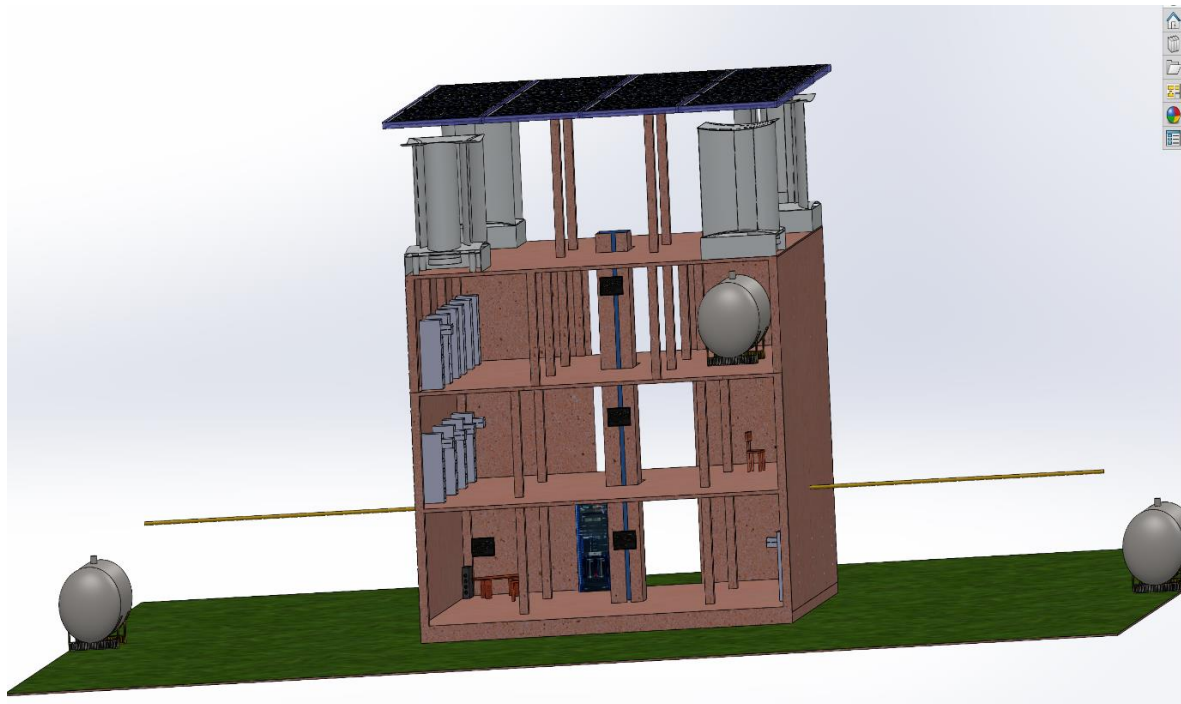
The full calculations are noted in the appendices.

Implementation	Profits for a 20-year system
LGEN using H ₂ and 8kwh PV 18,000 homes	£415,472,124.39
LGEN using SWB and 8kwh PV 18,000 homes	£371,915,733.34
individual resident using SWB and 4kwh PV 18,000 homes	£118,800,000.00
individual resident using SWB and 4kwh PV 128,430 homes	£847,638,000.00

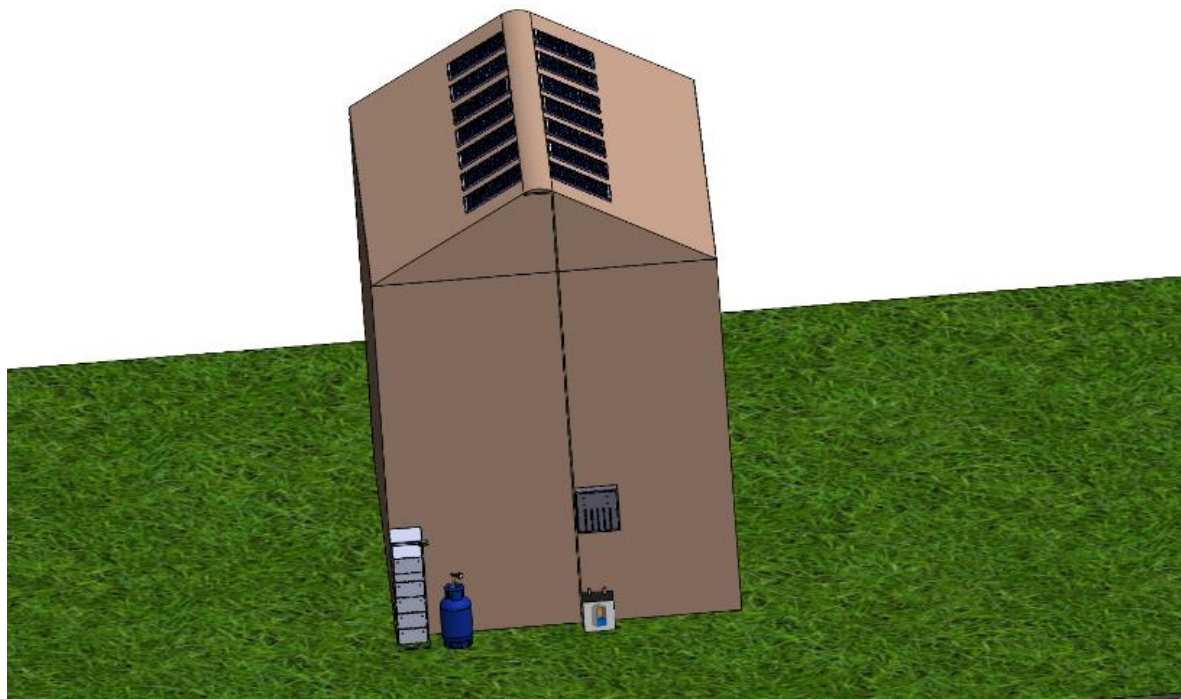
The red figure in the table is at a larger scale and thus is only there to demonstrate the sheer scale of individual systems needed to compete with what 18,000 homes and Hydrogen storage is accomplishing. The first three are the best guide as all missing factors are identified or missing from all, thus keeping a comparative view on a balance.

The only thing off balance is the LGEN building which is a one-off cost or an adapted building cost. This project validates a deeper review on H₂ with the possibility of implementation, because of the expansion capabilities i.e., no H₂ piping network in place, H₂ cars and H₂ boilers, this is not only a multi directional profitable expandable design, it can help to create a carbon neutral United Kingdom. A few points to add would be AEMFC are not commercially available yet but would be a considerable amount cheaper than PEMFC. Lithium-ion batteries are 2/5 of the price but last 10 years so the figure for the batteries is 1/5 less but because of this study being for an environmentally friendly approach I didn't include these. A review of other relevant information towards implications of other factors are in the appendices which adds value to future scope of the systems reviewed in this document.

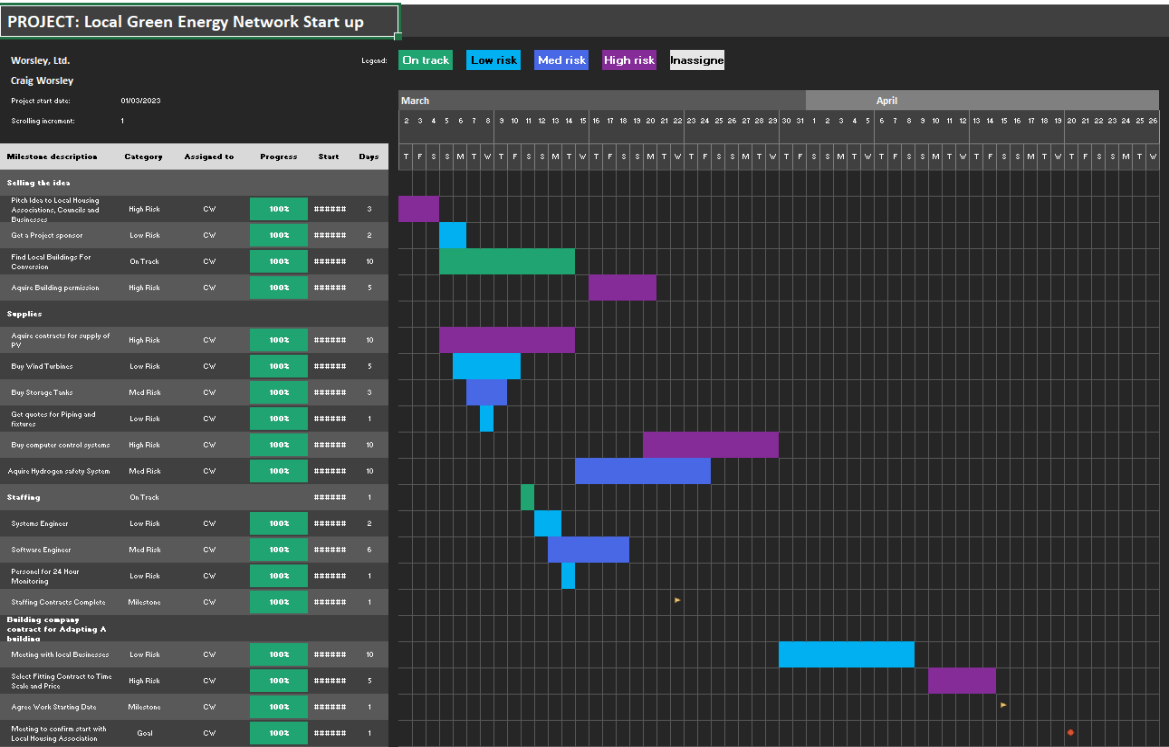
LGEM Building Design



Renewable Home Design



Gantt chart showing a structure of preparing the initiation of the project.



Appendices

Average Energy consumption in the UK

An 8Kwh PV system on each home feeding surplus energy into the networks storage regardless of occupants.

2,900kWh a year average is the working parameter of this system. Ofgem figures [25] show that the average usage in the UK is 2,900kWh electricity a year and 12,000kWh gas.

Typical values

The energy price cap is calculated using the values below.

Energy Use	Example – home type and number of residents	Typical annual gas use (kWh)	Typical annual electricity use (kWh)
Low	Flat or 1-bedroom house; 1-2 people	8,000	1,800
Medium	2-3 bedroom house; 2-3 people	12,000	2,900
High	4+ bedroom home; 4-5 people	17,000	4,300

Figure 12: *Typical Values*

Source: Adapted from [25]

Design Implementation Calculations

The system could supply around 45% of the towns needs with 16% of the homes.

The cost of electricity [26], 16.6p/kWh.

Electrical usage for Bolton = $285,000 \times 2,900\text{kWh} = 826,500,000\text{kwh} / 100 \times 45 = 371,925,000\text{kwh}$, to supply 45% of electricity 371,925,000kwh would be needed to be produced.

Housing PV Figures

In Bolton there are around 285,400 houses [27], Bolton at home [28] a housing association, manages and maintains 18,000 of these homes.

Using online calculation software PV energy production can be calculated for the area in which the panels are collecting, the pitch of roof and typical weather data, 8kw solar system on average is 10,000kWh, $18,000 \times 10,000 = 180,000,000\text{kWh}$ or divided by 1000 = 180,000 MWh annual figure.

18,000 homes fitted with 8kWh PV x collection 10,000kWh = 180,000,000kWh per year

180,000,000kWh x 16.6p = £29,880,000 per year x 20 = £597,600,000 production value

8kWh PV system around £10,000 = £180,000,000 cost

LGEN generation

Wind = 4 X 15MWh = 60,000kWh+PV = 10,000kWh = 70,000kWh total per year x 16.6p = £11,620.00 x 20 = 1,400,000kWh for 20 years x 16.6p = £232,400.00

PEMFC and Electrolyser Calculations

The usage for night-time would be less than 10% but cost will be calculated at this for the H₂ system.

LHV (lower heating value) = 33.3Kwh/Kg

HHV (higher heating value) = 39.4kWh/Kg

Efficiency = 50%-60% life expectancy = 30,000h

Cost [29] = 250kw=\$50,008.96/\$1.24=£40,329.81x2=£80,659.61

20-year design = 3.43 years = £80,659.61 x 6 = £483,957.66

10% = 82,650kWh/0.5 = 165,300kg of H₂ a year, 165.3MWh / 365 = 452.88kWh PEMFC

Fuel cell loss = 82,650kWh a year x 20 = 1,653,000kWh = £274,398.00

EL's needed = 453 x \$500 = \$226,500 or (£1.00 = \$1.24) = £182,661.29

EL's last four years so a 20-year system = £913,306.45

Enapters EL = 54.8kWh per 1Kg of H₂

9,058,440kWh would be used by the EL 9,058.44MWh

The loss of energy for using H₂ as a storage system is 9,058,440kWh x 16.6p = £545,689.16 a year.

System Overall Value Calculations

LGEM using H₂ production cost without including the building.

£182,360,275.61 for a 20-year system.

LGEM building Production profit £232,400.00 + £597,600,000 = £597,832,400.00

£597,832,400.00 - £182,360,275.61 = £415,472,124.39

Average Cost of 45% of Homes in Bolton using Batteries Independent Systems

SWB cost around £5000 for 9kWh system, PV system 4kWh = £5,000

45% 285,400 = 128,430 x £10,000 = £1,284,300,000.00 for a 20-year system for each individual resident.

£2,131,938,000.00 Production profit 20-year system.

£2,131,938,000.00 - £1,284,300,000.00 = £847,638,000.00

SWB cost around £5000 for 9kWh system, PV system 4kWh = £5,000

18,000 x £10,000 = £180,000,000 for a 20-year system for each individual resident.

£298,800,000.00 Production profit 20-year system but could only supply 18,000 homes.

£298,800,000.00 - £180,000,000 = £118,800,000.00

LGEN using SWB.

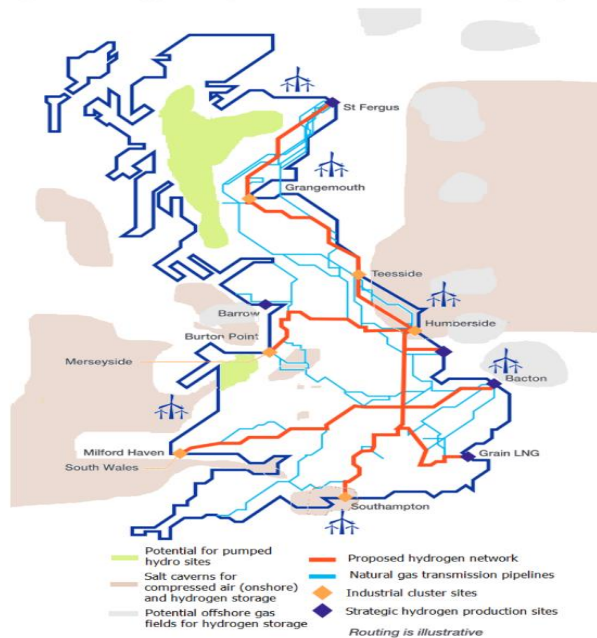
(10% out of production hours) £45,916,666.66 for SWB + 180,000,000 = £225,916,666.66 roughly for a 20-year system. LGEN building Production profit £232,400.00 + £597,600,000 = £597,832,400.00 - £225,916,666.66 = £371,915,733.34

Hydrogen production supply by a national infrastructure

Transportation of hydrogen [30]-[32] , “Steel pipelines cannot transport hydrogen because the metal becomes embrittled, all low-pressure UK pipelines will already be hydrogen-ready by 2030 under the Irons Mains Replacement Programme. The program mandates that these pipelines be upgraded with polyethylene, which is a material suitable for transporting hydrogen at low pressures”.

A predicted plan for H₂ storage locations and piping infrastructure system has been released by the UK parliament [3].

Figure 1 Energy Storage Locations and Planned Hydrogen Network in GB



Source: National Grid Gas Transmission – key, pumped hydro, salt caverns and gas fields overlaid, 113–116

Figure 13: Energy Storage Locations and Planned Hydrogen Network in GB

Source: Adapted from [3]

Giga Factories for large scale distribution of Hydrogen

The transition from CH₄ (natural gas) to H₂ will create green energy factories for large scale production of H₂, the distribution over national networks will create a secondary network of energy delivery, creating more stability and reducing demand on the national grid, Thyssenkrupp has already started on the construction in Rotterdam of a 200 MW facility [33],

they also have plans for giga factories [34].

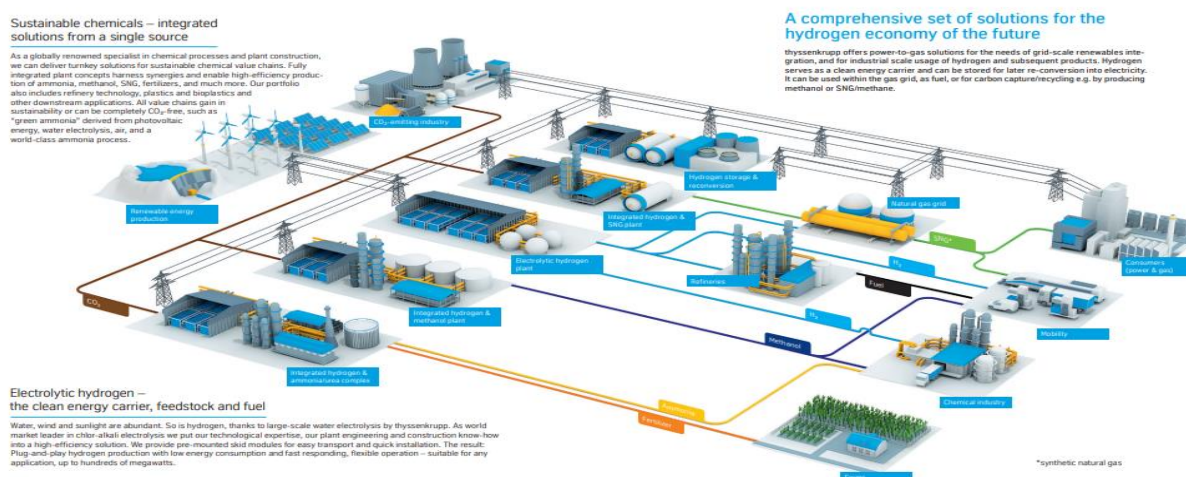


Figure 14: A comprehensive set of solutions for the hydrogen economy of the future

Source: Adapted from [34]

	10 MW module	20 MW module
Design capacity H ₂	2000 Nm ³ /h	4000 Nm ³ /h
Efficiency electrolyzer (DC)	> 82% _{HHV} *	> 82% _{HHV} *
Power consumption (DC)	max. 4.3 kWh/Nm ³ H ₂	max. 4.3 kWh/Nm ³ H ₂
Water consumption	<1l/Nm ³ H ₂	<1l/Nm ³ H ₂
Standard operation window	10% - 100%	10% - 100%
H ₂ product quality at electrolyzer outlet	> 99.95% purity (dry basis)	> 99.95% purity (dry basis)
H ₂ product quality after treatment (optional)	as required by customer, up to 99.999%	as required by customer, up to 99.999%
H ₂ product pressure at module outlet	~300 mbar	~300 mbar
Operating temperature	up to 90 °C	up to 90 °C

* HHV = calculated with reference to higher heating value of hydrogen.
All values may vary depending on operating conditions.

Figure 15: A comprehensive set of solutions for the hydrogen economy of the future

Source: Adapted from [34]

Other forms of Energy Generation or upcoming developments

CryoBattery

The CryoBattery development in Manchester [35] is an amazing innovation of energy storage, it can store enough energy to supply energy to 200,000 homes for five hours, the facilities can be designed to create “100 MWh to more than 200 MW (2 GWh) of energy and has a lifespan of over 30 years”.

Kinetic Energy

Through kinetic energy cars can generate electricity by compressing speed bumps, it can be used to generate energy much like kinetic tiles [36].

Hydrogen and Fuel Cells

New materials for fuel cells, together with improvements in the performance and lifetimes of stacks, are underpinning the emergence of the first truly commercial systems in applications that range from forklift trucks to power sources for mobile phone towers [12].

It is expected that a FC has a practical life of 40,000h, “Sure Power Corporation who put together the equipment has guaranteed 99.9999% reliability of the whole power system” [12].

To date, the PEMFC has proved to be the most successful commercially. The electrolyte is a solid polymer, in which protons are mobile [12].

References

- [1] W. McDowall, "Exploring possible transition pathways for hydrogen energy: A hybrid approach using socio-technical scenarios and energy system modelling," *Futures : The Journal of Policy, Planning and Futures Studies*, vol. 63, pp. 1-14, 2014. . DOI: 10.1016/j.futures.2014.07.004.
- [2] V. M. Maestre, A. Ortiz and I. Ortiz, "The role of hydrogen-based power systems in the energy transition of the residential sector," *Journal of Chemical Technology and Biotechnology (1986)*, vol. 97, (3), pp. 561-574, 2022. . DOI: 10.1002/jctb.6938.
- [3] 20/12/. 2022.
- [4] (25/03/). *How big are Power line losses?*. Available: <https://blog.se.com/energy-management-energy-efficiency/2013/03/25/how-big-are-power-line-losses/#:~:text=The%20transmission%20over%20long%20distances,as%20heat%20in%20the%20conductors.&text=The%20overall%20losses%20between%20the,range%20between%208%20and%2015%25>. [Accessed 18/04/ 2023].
- [5] C. Zhang *et al*, "Peer-to-Peer energy trading in a Microgrid," *Appl. Energy*, vol. 220, pp. 1-12, 2018. . DOI: 10.1016/j.apenergy.2018.03.010.
- [6] D. Keiner *et al*, "Seasonal hydrogen storage for residential on- and off-grid solar photovoltaics prosumer applications: Revolutionary solution or niche market for the energy transition until 2050?" *Appl. Energy*, vol. 340, pp. 121009, 2023. Available: <https://www.sciencedirect.com.ezproxy.uwtsd.ac.uk/science/article/pii/S0306261923003732>. DOI: 10.1016/j.apenergy.2023.121009.
- [7] L. Fara and M. Yamaguchi, *Advanced Solar Cell Materials, Technology, Modeling and Simulation*, Hershey, PA: Engineering Science Reference, 2013.
- [8] L. Fara and M. Yamaguchi, *Advanced Solar Cell Materials, Technology, Modeling and Simulation*, Hershey, PA: Engineering Science Reference, 2013.
- [9] D. Bigot, *Solar Collectors and Panels, Theory and Application*, .
- [10] P. Liu *et al*, "High-Quality Ruddlesden–Popper Perovskite Film Formation for High-Performance Perovskite Solar Cells," *Adv Mater*, vol. 33, (10), pp. e2002582-n/a, 2021. . DOI: 10.1002/adma.202002582.
- [11] (19/08/). *Formula One Design Inspired a Rooftop Wind Turbine With No External Moving Parts*. Available: <https://www.autoevolution.com/news/formula-one-design-inspired-a-rooftop-wind-turbine-with-no-external-moving-parts-201686.html> [Accessed 15/04/ 2023].

- [12] A. L. Dicks and D. A. J. (J. Rand, *Fuel Cell Systems Explained*, Hoboken, New Jersey :: Wiley, 2018.
- [13] Anonymous "Direct liquid fuel cells," in *Fuel Cell Systems Explained* Anonymous 2018, Available: <https://doi.org/10.1002/9781118706992.ch6>. DOI: 10.1002/9781118706992.ch6.
- [14] M. F. Lagadec and A. Grimaud, "Water electrolyzers with closed and open electrochemical systems," *Nature Materials*, vol. 19, (11), pp. 1140-1150, 2020.
- [15] (). *The AEM Electrolyser: Making Green Hydrogen Easy*. Available: <https://www.enapter.com/aem-electrolyser> [Accessed 16/04/ 2023].
- [16] (20/06/). 'Our unique AEM electrolyzers will produce cheaper green hydrogen than any rival tech'. Available: <https://www.rechargenews.com/energy-transition/-our-unique-aem-electrolyzers-will-produce-cheaper-green-hydrogen-than-any-rival-tech-/2-1-1042573> [Accessed 19/04/ 2023].
- [17] (). *AEM Technology*. Available: <https://handbook.enapter.com/knowledge-base/aem-technology.html> [Accessed 19/04/ 2023].
- [18] A. L. J. Keow *et al*, "Active disturbance rejection control of metal hydride hydrogen storage," *Int J Hydrogen Energy*, vol. 46, (1), pp. 837-851, 2021. Available: <https://www.sciencedirect.com.ezproxy.uwtsd.ac.uk/science/article/pii/S0360319920336090>. DOI: 10.1016/j.ijhydene.2020.09.169.
- [19] (01/05/). *Hydrogen Storage Cost Analysis*. Available: https://www.hydrogen.energy.gov/pdfs/review22/st235_houchins_2022_p.pdf [Accessed 21/04/ 2023].
- [20] A. O. Ali *et al*, "Closed-loop home energy management system with renewable energy sources in a smart grid: A comprehensive review," *Journal of Energy Storage*, vol. 50, pp. 104609, 2022.
- [21] S. Kiwan and Q. R. Soud, "Experimental investigation of the thermal performance of a sand-basalt heat storage system for beam-down solar concentrators," *Case Studies in Thermal Engineering*, vol. 19, pp. 100609, 2020. Available: <https://www.sciencedirect.com/science/article/pii/S2214157X1930187X>. DOI: 10.1016/j.csite.2020.100609.
- [22] N. Mahfoudi, A. Moummi and M. E. Ganaoui, "Sand as a Heat Storage Media for a Solar Application: Simulation Results," *Applied Mechanics and Materials*, vol. 621, pp. 214-220, 2014. Available: <https://www.proquest.com/scholarly-journals/sand-as-heat-storage-media-solar-application/docview/1555323792/se-2?accountid=130472>
https://librarysearch.uwtsd.ac.uk/openurl/44WHELF_UWTSD/44WHELF_UWTSD:44WHELF_UWTSD_VU1?rft.atitle=Sand+as+a+Heat+Storage+Media+for+a+Solar+Applicat+ion%253A+Simulation+Results&rft.au=Mahfoudi%252C+Nadjiba%253BMoummi%252

[C+Abdelhafid%253BGanaoui%252C+Mohammed+El&rft.jtitle=Applied+Mechanics+and+Materials&rft.date=2014-08-01&rft.volume=621&rft.issue=&rft.spage=214&rft.issn=16609336](https://doi.org/10.4028/www.scientific.net/AMM.621.214)
<https://doi.org/10.4028/www.scientific.net/AMM.621.214>. DOI:
10.4028/[www.scientific.net/AMM.621.214](https://doi.org/10.4028/www.scientific.net/AMM.621.214).

[23] (14/04/). *The heart of the salt battery*. Available:
<https://www.innov.energy/en/faqs/salt-battery/technique> [Accessed 14/04/ 2023].

[24] Q. Dong *et al*, "Novel zinc-based molten salt batteries with high voltages in medium temperature environment," *J. Power Sources*, vol. 550, pp. 232143, 2022. Available:
<https://www.sciencedirect.com.ezproxy.uwtsd.ac.uk/science/article/pii/S037877532201120X>. DOI:
10.1016/j.jpowsour.2022.232143.

[25] (14/04/). *Average gas and electricity use explained*. Available:
<https://www.ofgem.gov.uk/information-consumers/energy-advice-households/average-gas-and-electricity-use-explained> [Accessed 17/04/ 2023].

[26] (15/03/). *Energy Price Guarantee*. Available:
<https://www.gov.uk/government/publications/energy-bills-support/energy-bills-support-factsheet-8-september-2022#:~:text=The%20floor%20unit%20prices%20vary,through%20to%2030%20June%202023> [Accessed 20/04/ 2023].

[27] (July). *Population and household statistics*. Available:
<https://www.bolton.gov.uk/statistics-data/population-household-statistics> [Accessed 15/04/ 2023].

[28] (18/04/). *Read our story*. Available: <https://www.boltonathome.org.uk/about-us/#:~:text=We%20own%2C%20manage%2C%20and%20maintain,18%2C000%20homes%20across%20the%20borough>. [Accessed 18/04/ 2023].

[29] (01/01/). *Manufacturing Cost Analysis of 100 and 250 kW Fuel Cell Systems for Primary Power and Combined Heat and Power Applications*. Available:
<https://www.energy.gov/eere/fuelcells/articles/manufacturing-cost-analysis-100-and-250-kw-fuel-cell-systems-primary-0> [Accessed 21/04/ 2023].

[30] P. Agnolucci and W. McDowall, "Designing future hydrogen infrastructure: Insights from analysis at different spatial scales," *Int J Hydrogen Energy*, vol. 38, (13), pp. 5181-5191, 2013. Available: <https://www.sciencedirect.com.ezproxy.uwtsd.ac.uk/science/article/pii/S0360319913004084>. DOI:
10.1016/j.ijhydene.2013.02.042.

[31] P. E. Dodds, "Can we use hydrogen as a storage vector to reduce the cost of intermittent renewables?" in 2013, .

[32] C. Baldino *et al*, "Hydrogen for heating? Decarbonization options for households in the United Kingdom in 2050," *International Council of Clean Transportation*, 2020.

[33] (10/01/). *Thyssenkrupp to install 200 MW green hydrogen facility for Shell in port of Rotterdam*. Available: <https://www.thyssenkrupp.com/en/newsroom/press-releases/pressdetailpage/thyssenkrupp-to-install-200-mw-green-hydrogen-facility-for-shell-in-port-of-rotterdam-125812> [Accessed 16/04/ 2023].

[34] (unknown). *Hydrogen from large-scale electrolysis*. Available: [https://ucpcdn.thyssenkrupp.com/binary/UCPthyssenkruppBAISUhdeChlorineEnginers/en/products/water-electrolysis-hydrogen-production/alkaline-water-electrolysis/link-thyssenkrupp Hydrogen Water Electrolysis and green chemicals.pdf](https://ucpcdn.thyssenkrupp.com/binary/UCPthyssenkruppBAISUhdeChlorineEnginers/en/products/water-electrolysis-hydrogen-production/alkaline-water-electrolysis/link-thyssenkrupp%20Hydrogen%20Water%20Electrolysis%20and%20green%20chemicals.pdf) [Accessed 16/04/ 2023].

[35] (18/6/). *Greater Manchester to house world's largest liquid air battery*. Available: <https://www.gov.uk/government/news/greater-manchester-to-house-to-worlds-largest-liquid-air-battery#:~:text=The%20world's%20largest%20and%20first,of%20the%20latest%20green%20technologies>. [Accessed 17/04/ 2023].

[36] M. Gholikhani *et al*, "Harvesting kinetic energy from roadway pavement through an electromagnetic speed bump," *Appl. Energy*, vol. 250, pp. 503-511, 2019. Available: <https://www.sciencedirect.com/science/article/pii/S0306261919309158>. DOI: 10.1016/j.apenergy.2019.05.060.