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REWIRE

Domestic Archetype Development - Report

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Domestic Archetype Development

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Introduction

OVERVIEW

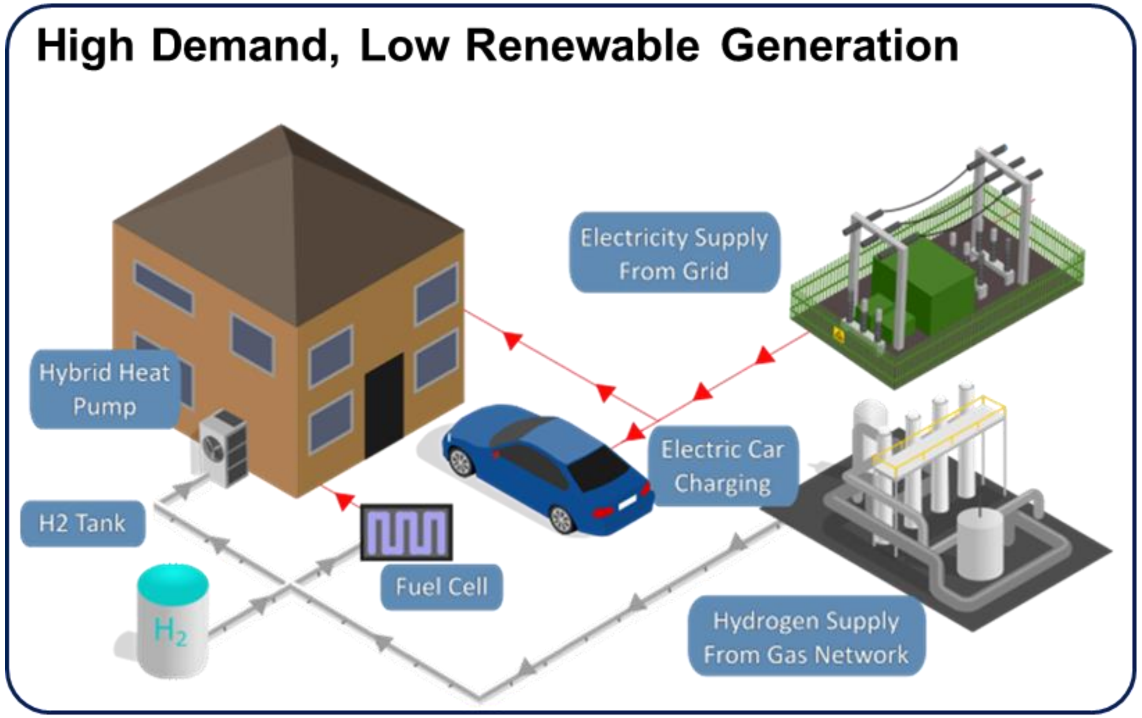
The energy system's ability to recover from disruptive events will be significantly improved with the integration of localised storage, which could be provided by REWIRE's exploration of multi-energy systems. The challenge of whole system energy balancing will grow with increasing penetration of intermittent renewables, 50GW of offshore wind predicted by 2030, alongside embedded distributed generation, 40 GW of domestic solar predicted by 2050.

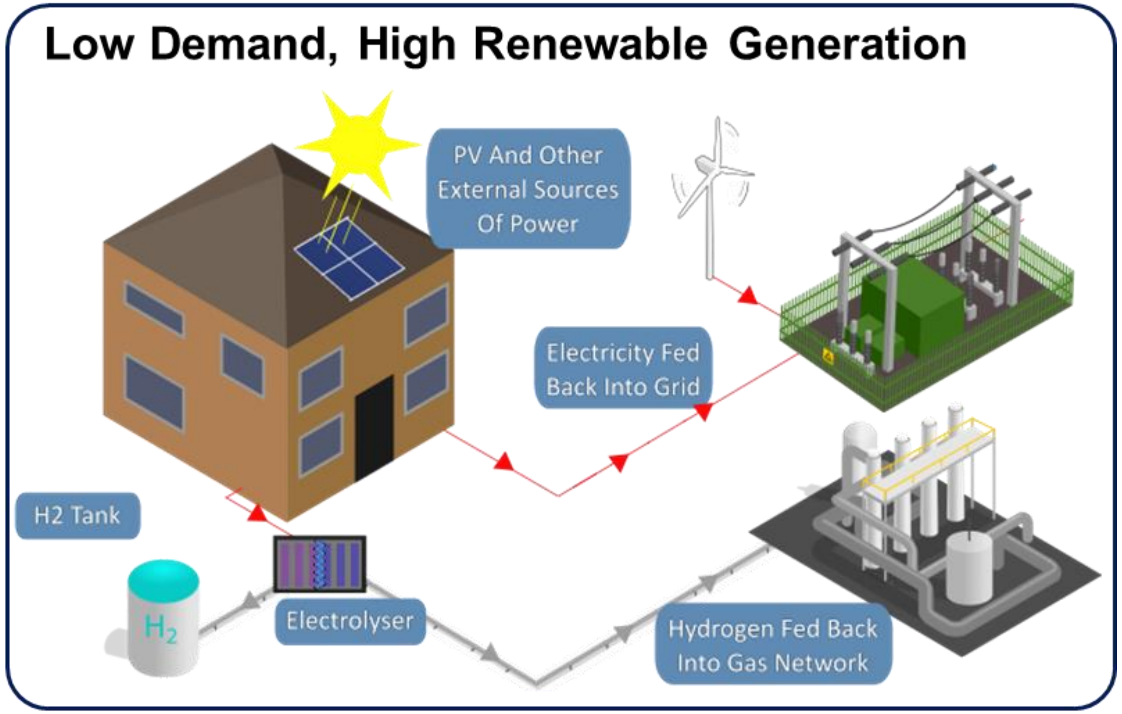
Growing electrification of residential transport and heat increases the likelihood of system imbalances. The future role of hydrogen for heat remains uncertain, with domestic demand forecasts ranging from 0 to 145 TWh, possibly leaving infrastructure redundant. Climate change and geopolitical instability are increasing the likelihood of extreme weather and infrastructure attacks, respectively, impacting future system resilience.

CHALLENGE STATEMENT

The low wind, low solar at peak demand scenario on a decarbonised national grid would cause resilience issues. The low demand, high renewable generation scenario can cause resilience issues and costs for generation reduction. REWIRE is a domestic cross-vector storage system, exploiting power-to-gas and gas-to-power technology with integrated local hydrogen storage.

Identify if it is technically and economically viable and beneficial to integrate vector conversion technology and energy storage at a domestic level to support national and local system resilience.





Domestic Archetype Development

The key objectives of the report are to present findings from the following:

- **Literature Review**: contextualise previous work to understand the current landscape.
- **Define residential scalability requirements** for different property types (e.g. Multi-occupancy buildings (MOBs), terrace, semi-detached, detached), including PV generation, energy demand and storage requirements.
- **Technology viability assessments** for behind the meter applications, based on the scales identified in previous task:
  - Vector conversion: Power-to-gas (P2G), Gas-to-power (G2P)
  - Hydrogen Storage
- **Develop property archetypes** by mapping technologies to property types based on current technological viability, future potential, or not viable.
- **Define additional technical factors** for consideration impacting potential viability.
- **Financial viability assessment** of technology cost vs counterfactuals, including potential returns on investment.

Feasibility Threshold

This project aims to explore the challenge statement and define the Alpha phase problem statement, whilst not necessarily answering the exam question in full during the Discovery Phase.

The following feasibility threshold claims will be used to define whether the project is worth progressing to Alpha Phase:

- It is technically feasible to integrate P2G, G2P and hydrogen storage technologies at domestic scale.
- There are combinations of property types, network characteristics and geographies where this could be deployed.
- The locally deployed solution can be implemented to improve resilience at national scale.
- There is at least one legitimate consumer use case for installation of the systems.
- The technology provides comparable consumer and network benefits with counterfactual systems, such as battery storage.

Literature Review: Current Landscape

1. Domestic Energy Storage
2. Domestic Hydrogen Storage
3. Network Resilience Approaches
4. Uninterruptable Supply

Domestic Energy Storage Technologies

Storage technologies have two primary use cases at domestic scale:

- Integrating with domestic PV systems to store surplus generation for meeting demand when PV generation is reduced – typical use for UK.
- Arbitrage to reduce energy bills through Time-of-Use tariffs from energy.

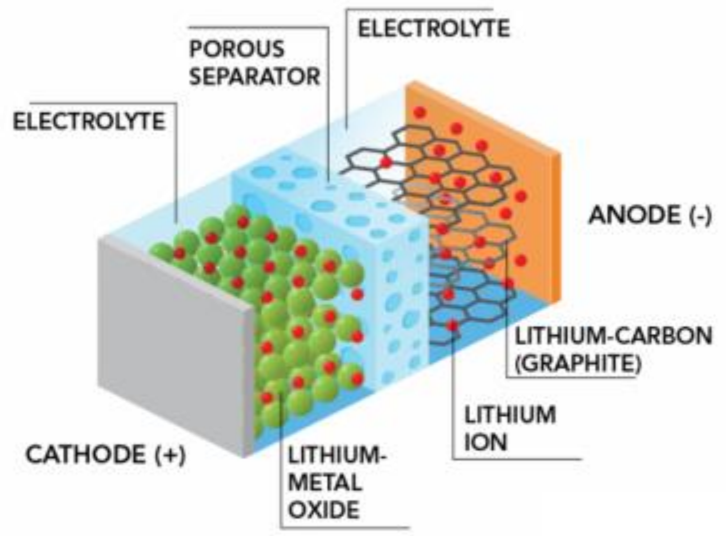
Energy is generally stored to help with meeting:

- Power demand
- Heat demand

Domestic Energy Storage Technologies - Power

Battery Energy Storage Systems (BESS)

- Batteries are electrochemical systems that use power to move ions in a reversible process during charging (surplus energy generation) and discharging (surplus energy demand).
- Two main technologies on the market for domestic use:
  - **Lead-acid battery** – Mature and cost effective technology, however, they have limited lifetime when charged/deep discharged, low energy density, high maintenance requirements and contain hazardous materials [1].
  - **Lithium ion battery** – this dominates new BESS designs, with high energy and power density, good cycle life and energy efficiency, however they are relatively high cost with potential safety considerations [1].
  - Other batteries are in development such as salt water batteries.
- Typical BESS sizes are 2.5-25.2kWh useable energy, with a 10 year warranty [1,2]. Batteries are modular and it is relatively easy to build up different size systems.
- V2X (Vehicle to X, where X could be G - Grid, H - Home, B - Building etc) uses Electric Vehicles (EVs) rather than a separate BESS. This is a cost-efficient form of storage system assuming an EV is required, as no additional hardware investment is required. In this case, typical maximum power is 10kW [3]

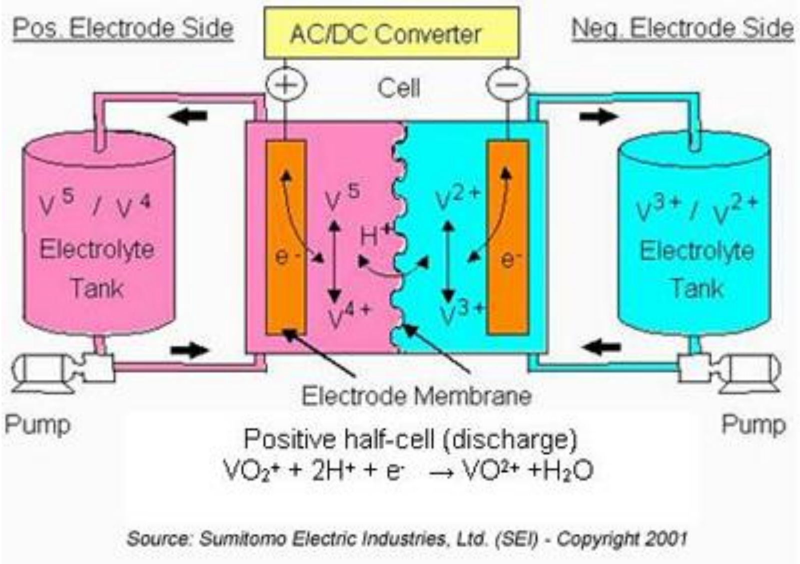


Source: https://www.ucl.ac.uk/chemical-engineering/lithium-ion-batteries

Domestic Energy Storage Technologies - Power

Redox Flow Battery (RFB)

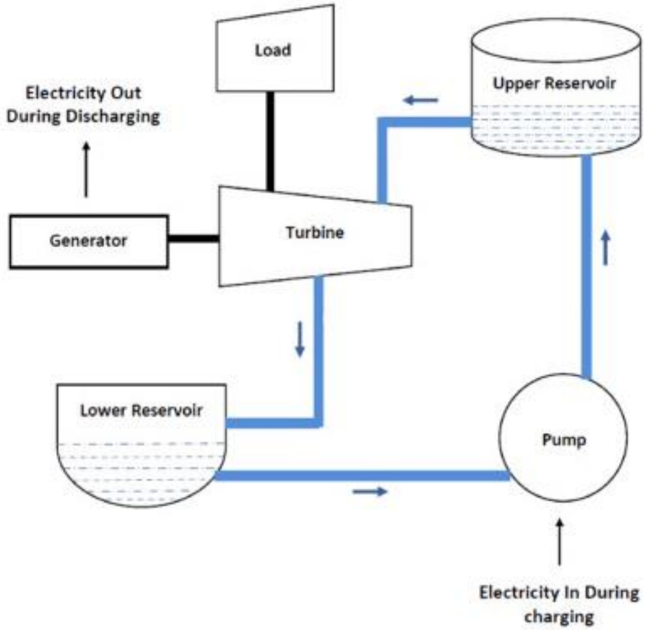
- RFBs are electrochemical systems that use power to charge ions in a reversible process during charging (surplus energy generation) and discharging (surplus energy demand).
- The main difference to typical BESS is that they require a flow of electrolyte through the cell where they are charged/discharged. The electrolyte is where the energy is stored, which is contained in separate tanks in the charged or discharged state. Increasing the electrolyte (and hence tank) volume increases the size without significantly increasing the cost.
- The main flow battery is based on vanadium ion electrolytes. They claim to address some of the disadvantages of Li-ion batteries such as increased lifespan (20 years), 10,000+ cycles, cost-effective, improved safety, able to fully discharge without degradation of capacity [4,5]. However, their main disadvantage is low energy and power density [6].
- VoltStorage offer a system for residential use at 1.5kW, 6.2kWh nominal energy, 10 year warranty [4].
- Others are in development with their own unique advantages, such as higher power and energy densities, more freely available electrolyte materials, but typically have lower stabilities [4, 6].
  Examples of this include the hydrogen bromine flow battery being developed by Elestor in the Netherlands and the iron-salt battery (based on RFB technology) developed by VoltStorage.



Domestic Energy Storage Technologies - Power

Pumped Hydro Energy Storage (PHES)

- Two reservoirs at different heights are used.
- Water is pumped from the lower reservoir to a higher altitude reservoir during periods of surplus energy supply – energy is stored as potential energy;
- The is then passed from the upper to the lower altitude reservoir via turbines, to produce electricity, during periods of surplus energy demand.
- Typically used on a large scale for load balancing;
- System size will strongly impact levelised cost of energy (LCOE)s, with larger systems offering higher efficiencies (70-85% [7]) and lower LCOE;
- Mature technology and so the cost is unlikely to significantly change.
- Demonstration PHES installation in France of use on the domestic small-scale [8]:
    - Goudemande 3-building apartment complex: 240 apartments ~700 people;
    - PHES 50m^3 water reservoir capacity with a 30m height separation, 1.5kW pump, 450W turbine => 3.5kWh useful energy;
    - Used in combination with local PV & wind energy and BESS.
- [8] concludes this is an "*ill-suited solution for energy storage in buildings*", due to strict water standards, dimensional differences between PHES and typical building water systems and high LCOE.

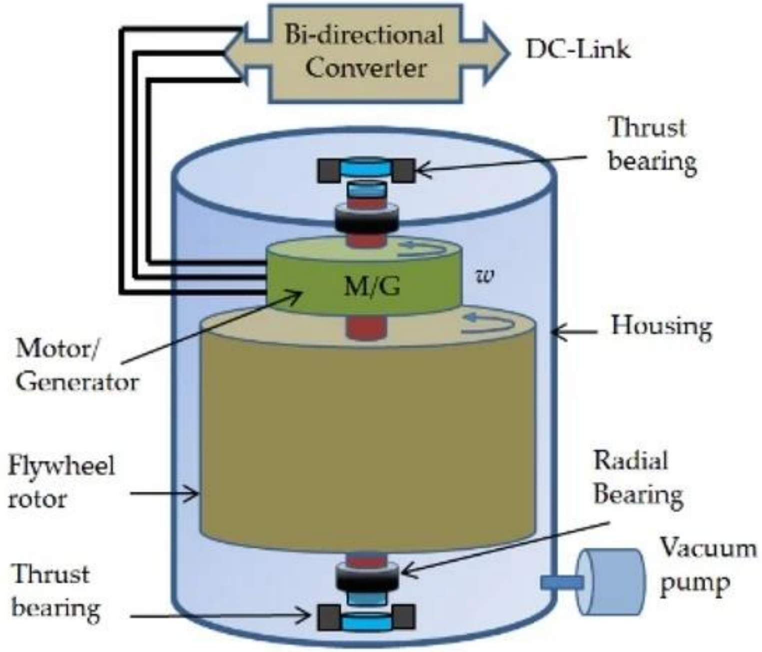


Source: Renewable and Sustainable Energy Reviews, 44, 2015, 586-598

Domestic Energy Storage Technologies - Power

Flywheel Energy Storage System (FESS) [9]

- A rotating mass (up to 100,000 rpm for advanced systems) with very low frictional losses is used;
- The speed of rotating mass is increased by an integrated motor-generator during periods of surplus energy supply – energy is stored as kinetic energy;
- Energy stored is related to the mass' moment of inertia and angular velocity;
- The motor-generator is then used to produce electricity during periods of surplus energy demand, slowing the mass' rotational speed;
- Best used for high power, low energy applications where a high number of cycles is required. Efficiencies of ~85%.
- Some small scale applications exist:
  - Energiestro [10] has developed a 10kW (1m diameter, 3 tonne) pre-stressed concrete FESS with a charge discharge time of 1 hour (10kWh) that can fit in a residential garden, currently offered in France's overseas territories and Africa. The design is guaranteed for 30 years, whilst the inverter is anticipated to require replacement after 15 years. They aim to increase capacity to 20kWh and then 50kWh to ultimately reach 24 hours storage.
  - Amber Kinetics produce an 8kW, 32kWh (4 hour discharge), 85% DC efficiency steel FESS [11]. Response time is claimed to be <1s, and a 30 year life [12]. They aim to group these systems together in a modular system for grid-connection.

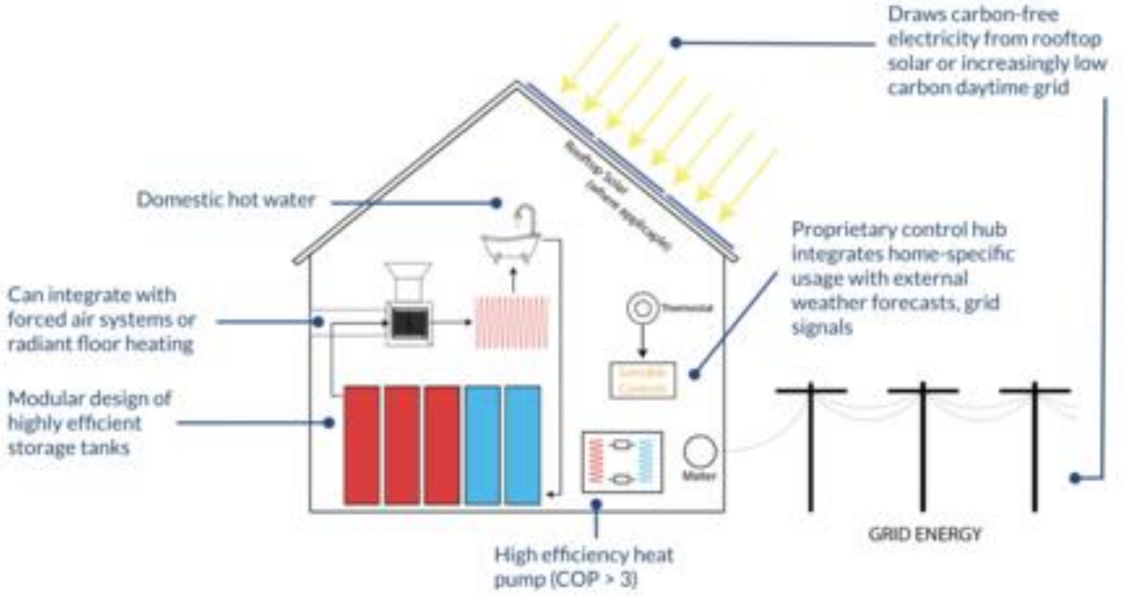


Source: Appl Sci, 7(3), 2017, 286-, 44, 2015, 586

Domestic Energy Storage Technologies – Heat/Power

Sensible Heat Storage (SHS) [13]

- A medium is heated to a high temperature by electric heater elements, or from thermophotovoltaic (TPV) cells during periods of surplus energy.
- The medium is typically stored underground, in a well insulated storage tank, bore hole and aquifer are alternatives.
- The stored energy could be used directly as heat (from the medium directly or from passing air), or it could be converted back to electricity by TPV during periods of high demand [14].
- Various different mediums exist:
  - Water – simplest and most common. Water has a high specific heat capacity, and an efficiently insulated tank can store heat for days;
  - Ceramic blocks, heated up to 600°C
  - Molten salt. Typical temperatures are cold tank ~290°C & hot tank ~500°C.);
  - Other mediums for heat storage are under development. For example, molten silicon (temperature range of ~1925°C cold tank to 2370°C hot tank) has the ability to store significant energy in small volumes [14] is being developed by a number of start-ups (eg Silbat in Spain).



Source: https://www.otherlab.com/sensible-heat

Domestic Energy Storage Technologies – Heat/Power

Latent Heat Storage (LHS) [13]

- The basic principle of this technology takes advantage of the fact that at the point of material's phase change (solid to liquid) a large amount of heat energy can be stored with only a small change in temperature.
- Typically storage capacities are higher than that of SHS systems. See for example Thermino thermal storage [15] which uses sodium acetate as the medium and claims 4 times better energy density than water, 40,000 charge cycles (50 years use), with 1.75x less heat loss compared to a comparable energy standard, top quality hot water storage cylinder.

Thermal Energy Storage (TES) Summary

The following table summarises the two key technologies for domestic intra-day storage [16]:

TES	SHS/LHS	Description	Efficiency	TRL	Cost
Tank Thermal Energy Storage (TTES)	SHS	All conventional and renewable heating systems	50-90%	9	25 -180 £/kWh
Phase Change Material (PCM)	LHS	All conventional and renewable heating systems	75-90%	5-8	250-400 £/kWh

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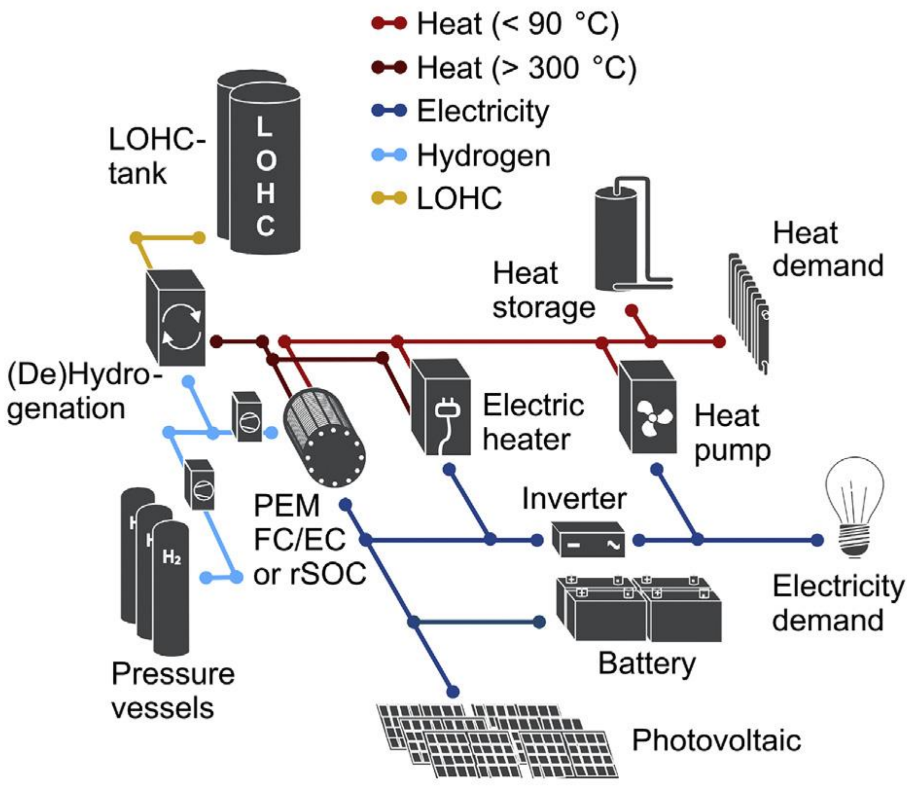
Domestic Hydrogen Storage

The purpose of this study is to consider whether hydrogen can be used as a domestic energy store, with this subsection introducing some fundamentals about the use of hydrogen as a vector for energy storage.

- Hydrogen can be produced via electrolysis during surplus energy generation, such as domestic PV generation.
- Hydrogen is used to create electric and/or heat energy during surplus energy demand:
  - Hydrogen can be used by fuel cell systems in Combined Heat and Power (CHP)
  - Hydrogen can be burned in hydrogen ready boilers. Current UK government proposals are that all new natural gas boilers installed from 2026 will be hydrogen ready [1]
- Likely to be combined with other technologies [2]
  - Battery and heat storage is optimal for short-term (intra-day rather than inter-seasonal) uses.
- Systems for domestic use in demonstration now
  - LAVO system [3]
  - GKN Hydrogen HY2Mini system [4]

The technology viability assessment that focuses on key components is included later in the report.



Source: Int J Hydrog Energy, 46(42), 2021, 21748-21763

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Network Resilience Current Approaches UK

There are multiple approaches that operators can take to improve network resilience and mitigate against the risk of outages, with increased penetration of storage technologies creating economic value by offering fundamental services, including:

- **Voltage control**
  - Maintain the voltage level on system within acceptable limits
- **Reactive Power Compensation**
  - Process of adding or injecting positive and/or negative VAr's to a power system to essentially attain voltage control
- **Frequency Response**
  - Used for second by second grid balancing. Fast response time required.
- **Demand Side Response**
  - Energy users are provided with a financial incentive to turn down or turn off non-essential process at times of peak demand which in turn keeps the grid balanced

Network Resilience Current Approaches UK

Need for Energy Storage in the Network [1]

- In 2021, low carbon electricity storage was just 0.01% (28GWh) of total energy demand. Current requirement estimates are (noting that substantial electrification of the heat sector, currently met by natural gas would create increased electric storage capacity):
    - 3-4TWh capacity by medium duration storage technologies for inter-day applications;
    - 10s of TWh capacity by long duration storage for seasonal applications;
    - ~100TWh for multi-year applications.
- Medium duration storage are typically high efficiency technologies with short discharge times (e.g. BESS):
- Long duration storage, high capacity for secure storage is important and efficiencies are less important, (e.g. hydrogen).
- There is a significant gap in the availability of short and long duration storage capacity in the UK.

Network Resilience Current Approaches UK

Current use of domestic energy storage, network resilience and demand side response

- Some utilities already administer time of use tariffs, that encourage customers to reduce power consumption during peak demand periods [2]
- BESS are currently installed in 10,000 (~0.8%) of UK homes [3].
- BESS in the form of electric vehicles (EVs) are a large growth market in the UK. In March 2023, the estimated number of EVs were 735,000 and an additional 480,000 plug in hybrids (PHEVs) [4].
- Thermal storage systems are currently installed in 1.8 million homes (~6.2%) as electric storage heaters, and 11 million homes (37.9%) as hot water tanks [5].
- Electric storage heaters are commonly operated on economy 7, aiding balancing of the grid. BESS could be used in the same manner, or linked to PV within the home.
- The proportion of hot water tanks that are used in this manner is less clear, as it is dependent on how the water within the tank is heated (electricity or gas), but could also be used in this manner.
- At least 7% of UK homes currently contribute in some capacity to network resilience as medium duration storage (inter-day), to charge energy storage systems during off-peak (high supply) and use during peak (high demand) times.

Network Resilience Pilot Schemes

- Linking residential batteries together could deliver grid support services further to how they already do, at potentially low cost relative to alternative options [2].
- Residential energy-storage network operators will need to ensure customers have "bought in" to using their batteries to support the grid and demonstrate to the local utility that these behind-the-meter systems are reliable and dispatchable at a moment's notice when the utility grid network needs the support [2].
- Within the US, some states have launched pilot programmes that let utilities pay battery-equipped households for using some of their stored power at times when the system is under strain [2].
  - Within New England, provision of BESS within homes has lead to many successes, in particular the successful reduction in peak demand. Challenges noted were interconnection barriers, out-of-date regulations and immature markets [6].
  - Within New Hampshire, Liberty Utilities pilot concerning BESS within homes successfully provided power into the grid during periods of peak demands. Liberty Utilities retains the right to control batteries in periods of peak demand, and paid a monthly fee to the residential property owners for this service [7].
- A further case study, but on a larger scale of microgrid in South Africa [8] was also a success providing resilience to the PV/BESS owner reducing costs during times of peak demand to the grid (demand side response), and increasing resilience during grid outages. Services to the grid were proposed to be (with advance notice):
  - Peak-shaving / load capping to avoid grid updates or prevent overloads;
  - Load shifting intra-day for periods of grid stress / peak consumption
  - Fast frequency response to help stabilize the grid
  - Power export to support the grid when needed
  - Expansion of EV fleets without requiring infrastructure upgrades
  - Allowing higher penetration of renewables at total grid level by providing flexibility etc.

Network Resilience Recommendations

- A number of studies have been carried out examining the use of microgrids to aid network resilience. For example:
  - [9] reviews various approaches to address resilience issues including but not limited to Networked Micro-Grids (NMG), control schemes, communication resilience requirements, hybrid Microgrids (MG), Demand Response (DR) programs and EVs, multi-energy MGs, dynamic optimization schemes, and Mobile Energy Resources (MER).
  - [10] reviews existing NWGs, noting they can be very effective to improve grid resilience, robustness and efficiency.
- Industry guidance to resilience [11] notes "leveraging technologies such as microgrids, renewables and battery energy storage, smarter switchgear, advanced distribution management systems, autonomous drone usage, real-time analytics, augmented by machine learning and artificial intelligence" as an opportunity to improve asset resilience.
- A step-by-step methodology for increasing grid resilience for the uncertainty brought on by climate change through targeted investments is given in [12] and should be borne in mind when considering use of domestic storage for grid resilience.

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Uninterruptable Supply

Uninterruptable Power Supply (UPS) is important where it is important that a consumer, or building, does not lose supply, for example a hospital. UPS is typically achieved by battery, supercapacitor or fly wheel energy storage systems and is available in a large range of capacities. It is often coupled with back-up generators.

- BESS can currently be used as UPS systems for residential applications.
  - Average electricity usage per day in the UK 8.5-10kWh, and 33-38kWh gas [1].
  - As, the load should not exceed 75-80% of the UPS system capacity [2], a typical house would need a UPS capable of providing up to 13.3kWh to provide back up for 1 day assuming heating was still provided by gas, or 64kWh if all energy needs were met by electricity.

- Alternatives to BESS for residential use do exist. For example GenCell G5 Long-Duration UPS:
  - 5kW alkaline fuel cell,
  - Can absorb dynamic peak loads of up to 100kVA.
  - Run time of 15 hours at 5kW – with 6 fuel (hydrogen gas) cylinders.

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Domestic Archetype Development

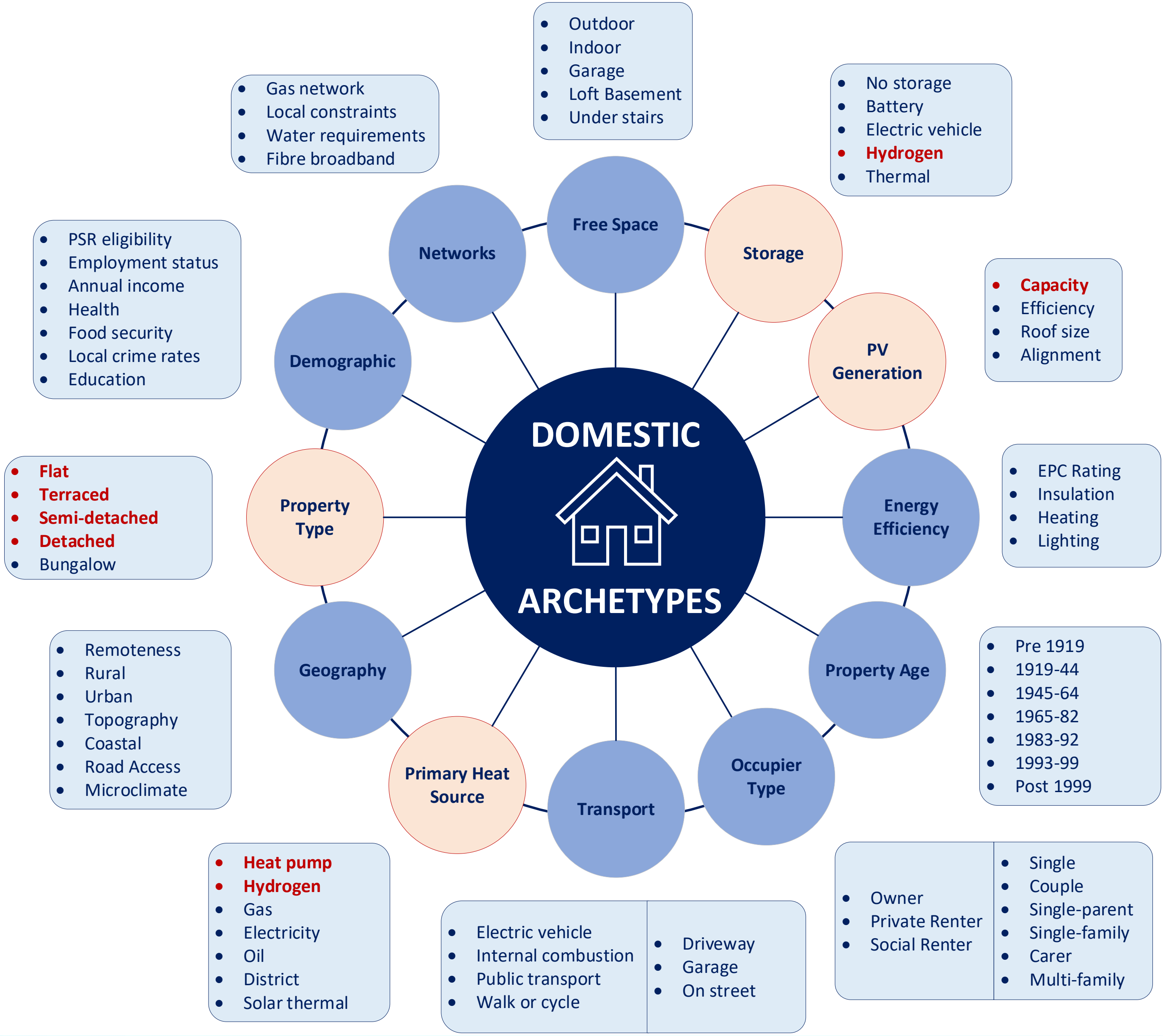
The range of potential domestic archetypes have been developed by combining different configurations of vector conversion technologies, hydrogen storage and network connection. These have been evaluated to define two principle deployment options for the REWIRE solution.

Domestic Archetypes

There are multiple characteristics associated with domestic properties, meaning that there is significant complexity involved with trying to categorise based on each possible combination.

For the purpose of this short Discovery Phase project, the characteristics that have been focussed on are (highlighted in the figure):

- Property types
- PV generation
- Primary heat source
- Storage



Domestic Deployment Options

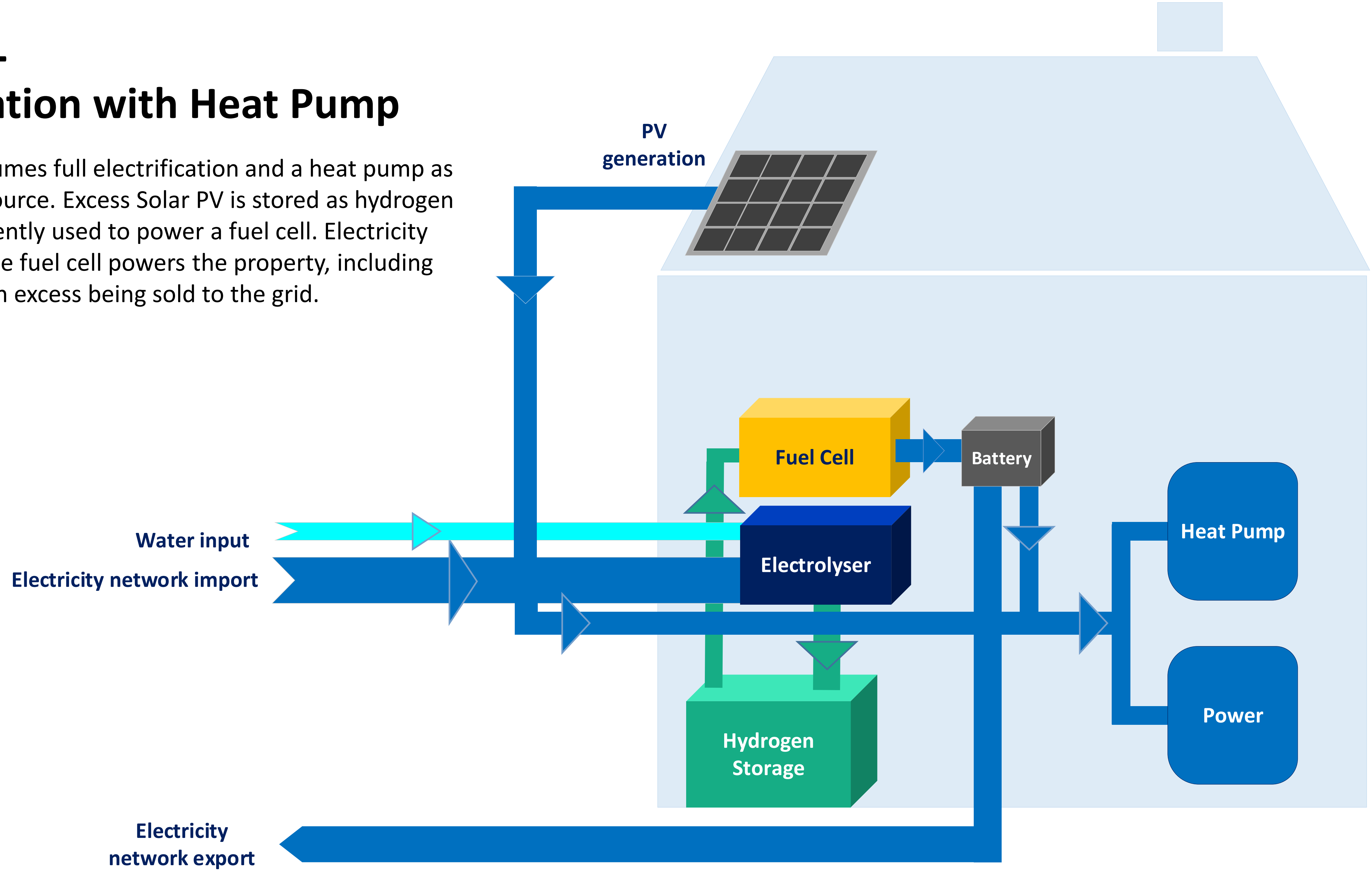
There are several potential configurations whereby the domestic vector conversion technology could be deployed at domestic scale, with two being considered for the purpose of this phase of the project:

- **Option 1** - Electrification with heap pump
- **Option 2** - Hydrogen network with CHP and hydrogen boiler

Characteristic	Feature	Option 1	Option 2
Deployable	Technology exists	✓	
Generation	PV	✓	✓
Network Connection	Electricity network	✓	✓
	Hydrogen network		✓
Vector Conversion	P2G	✓	✓
	G2P	✓	✓
Storage	Hydrogen	✓	✓
	Small Battery	✓	✓
	Thermal		✓

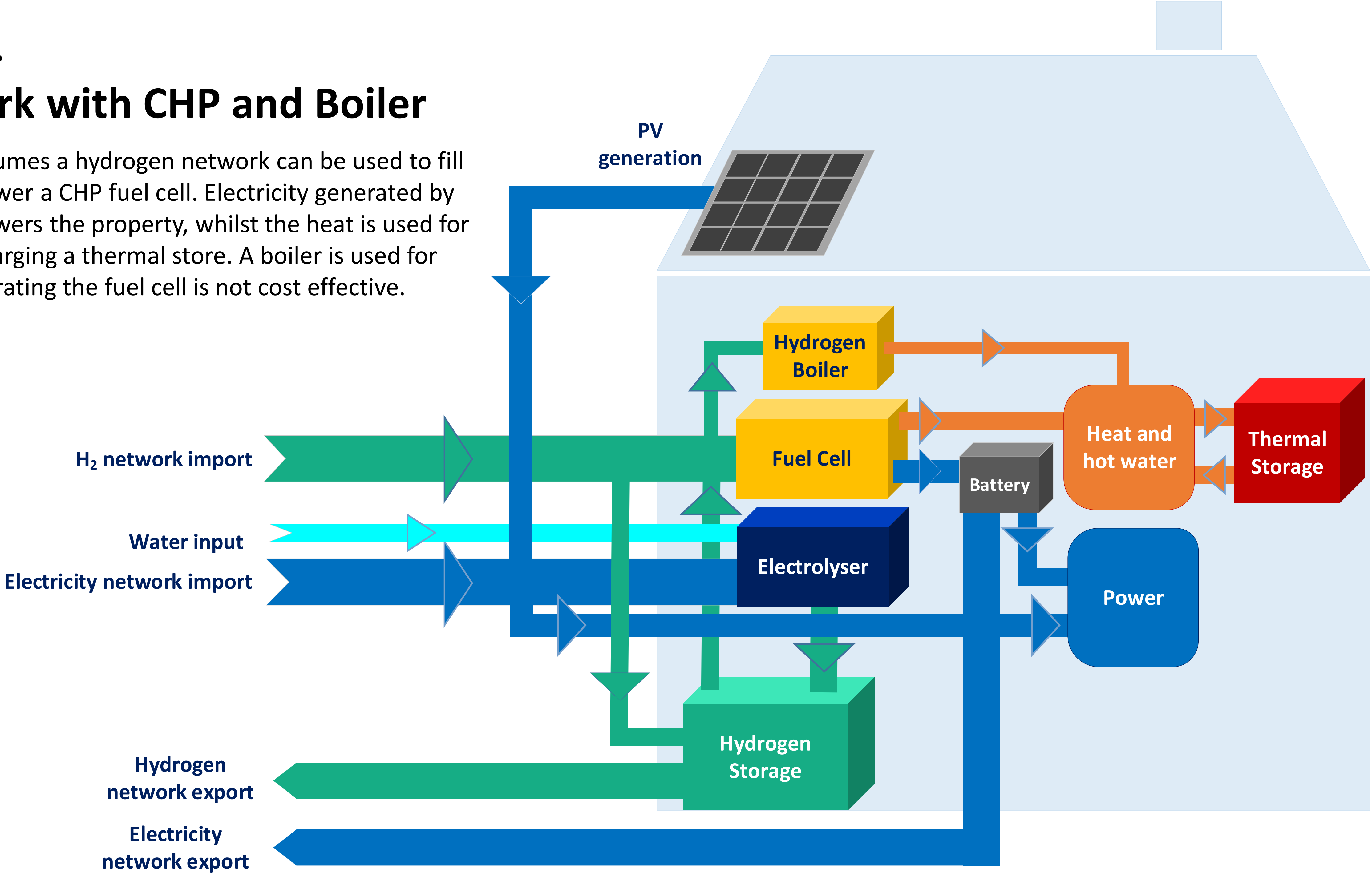
Option 1
Electrification with Heat Pump

This option assumes full electrification and a heat pump as the only heat source. Excess Solar PV is stored as hydrogen that is subsequently used to power a fuel cell. Electricity generated by the fuel cell powers the property, including heat pump, with excess being sold to the grid.



Option 2
H_2 Network with CHP and Boiler

This option assumes a hydrogen network can be used to fill storage and power a CHP fuel cell. Electricity generated by the fuel cell powers the property, whilst the heat is used for heating and charging a thermal store. A boiler is used for heat when operating the fuel cell is not cost effective.



Additional Technical Considerations - GDN Perspective

A workshop with an engineer from Northern Gas Networks raised the following technical considerations:

- Currently meter capacity is 6 scm/hr for domestic meters, equating to 19.5 scm/hr for hydrogen, assuming the CV of natural gas is 39MJ/m^3 and hydrogen is 12.11MJ/m^3. This would mean that service pipe diameter would need to be 32 mm diameter if current velocity limits of 15m/s were to apply, meaning most properties would need a new service.
- A method would need to be developed to allow gas networks to measure gas fed back into the low pressure (LP) network. Currently, the increase in pressure would slam shut the upstream district governor and the local area would lose supply.
- Ability to increase maximum pressure on the network is limited until 100% PE transition. Once hydrogen is in the low pressure network, it is very difficult to move it up the pressure tiers without energy intensive compression. Currently, there are no LP network compressors installed for natural gas.
- A mechanism to deal with over pressurisation would need to be in place to deal with pipe integrity issues. Pressure release valves may be needed, meaning possible venting of hydrogen to atmosphere. This would limit the maximum discharge rate of the storage system to the LP network. With hydrogen moving from the home to network, or vice versa, from system pressure of 60 bar to network pressure of 25 mbar, will cause significant temperature increase/decrease.
- Future variations in the cost of hydrogen and electricity may lead to unfair arbitrage. Consumers will prefer to use the cheapest option, which will complicate the markets and domestic properties could begin influencing national prices, especially if domestic properties begin operating as mini power generation plants. No tariff for hydrogen exists, with the closest equivalent being biomethane injection.

Summary

- There is a wide range of archetypes that can exist, with relation to the categorisation of residential properties.
- For the purpose of Discovery Phase exploration the key features that will be considered are the type of property, PV generation, primary heat source and storage.
- Multiple deployment options for REWIRE exists, but the two that will be focussed on for Discovery Phase are electrification with heat pump and hydrogen network connection with CHP and hydrogen boiler.
- There is a notable challenge with exporting gas (including hydrogen) from a property back to the low pressure network, and then being able to utilise it once it has been exported.

Technology Viability Assessments

This section involves a detailed assessment of different vector conversion and hydrogen storage technologies. Preferred components for the REWIRE system are then down-selected, based on their viability for deployment at domestic scale.

The feasibility of deploying the different components at different property types is then considered to understand if there are any properties where this solution becomes unviable.

Fuel Cells

Phosphoric Acid Fuel Cell (PAFC)

- Electrodes typically made from gold, tantalum, titanium and carbon
- Catalyst must be made from platinum group metals due to corrosion issues
- Transport of protons

Feature/Parameter	PAFC
Electrolyte	Phosphoric acid solutions
Oxidant	Air to enriched air
Internal Reforming	No
Operating Temperature	150°C - 200°C
Contaminate Sensitivities	CO, Sulphur
Typical Stack Size	5kW – 400kW,
Anode Reaction	$H_2 \rightarrow 2H^+ + 2e^-$
Cathode Reaction	$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$
Overall Reaction	$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$

Advantages	Disadvantages
Most widely tested fuel cell in building applications	Relatively low electrical efficiency
Fuel flexibility – natural gas, hydrogen, methanol	Expensive catalysts
Suitable for CHP	Long start-up times
Increased tolerance to fuel impurities – CO_2 tolerance allows use of normal air	Less powerful than other fuel cells for the same weight and volume
Maturity	

Fuel Cells

Proton Exchange Membrane Fuel Cell (PEMFC)/Polymer Electrolyte Membrane (PEM)

- Uses a solid polymer membrane as the electrolyte
- Electrodes are platinum group-based metals
- Transport of protons

Feature/Parameter	PEMFC/PEM
Electrolyte	Polymer membrane
Oxidant	Air to O_2
Internal Reforming	No
Operating Temperature	<120°C
Contaminate Sensitivities	CO, Sulphur and NH_3
Typical Stack Size	<1kW – 100kW
Anode Reaction	$H_2 \rightarrow 2H^+ + 2e^-$
Cathode Reaction	$½O_2 + 2H^+ + 2e^- \rightarrow H_2O$
Overall Reaction	$H_2 + ½O_2 \rightarrow H_2O$

Advantages	Disadvantages
Lightweight and portable	At around 40% they have relatively low electrical efficiency
Fast start-up time	Fuel type restriction – must be high purity hydrogen
Fasting growing in the market	Expensive catalysts
Reduced corrosion due to solid electrolyte	Sensitivity to humidity and salinity
Quick output variation for shifting power demands	

Fuel Cells

Solid Oxide Fuel Cell (SOFC)

- Consist of thin layer ceramics
- Common materials include nickel/yttria-stabilised zirconia cermet for the anode and perovskite lanthanum manganate for the cathode
- Transport of oxide ions

Feature/Parameter	SOFC
Electrolyte	Yttria stabilised zirconia
Oxidant	Air
Internal Reforming	Yes
Operating Temperature	500°C - 1000°C
Contaminate Sensitivities	Sulphur
Typical Stack Size	1kW – 2MW
Anode Reaction	$H_2 + O_2- \rightarrow H_2O + 2e-$
Cathode Reaction	$O_2 + 4e- \rightarrow 2O_2-$
Overall Reaction	$O_2 + 2H_2 \rightarrow 2H_2O$

Advantages	Disadvantages
High reliability	Long start-up time
Fuel flexibility – natural gas, methanol, ethanol, biogas, coal gas, hydrogen	Limited number of shutdowns
Ceramic construction makes them more expensive than other fuels cells	High temperature corrosion
Relatively high electrical efficiency	Inexpensive catalyst compared to low temperature fuel cells
Suitable for CHP	Low maturity
	Slow response to changing electricity demand

Fuel Cells

Alkaline Fuel Cell (AFC)

- Non-precious metal electrodes if operating at high-temperatures
- Cathodes usually made from platinum for low temperature operation
- Transport of hydroxide ions

Feature/Parameter	AFC
Electrolyte	Potassium hydroxide solution
Oxidant	Purified air to O_2
Internal Reforming	No
Operating Temperature	<100°C
Contaminate Sensitivities	CO, CO_2 and Sulphur
Typical Stack Size	1kW – 100kW
Anode Reaction	$H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$
Cathode Reaction	$\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^-$
Overall Reaction	$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$

Advantages	Disadvantages
Wide range of stable materials resulting in lower cost components	Sensitivity to CO_2 in fuel and air
Quick start-up	Large size and weight due to liquid electrolyte
Resistance to humidity and salinity	Declined interest since PEM technology
Pre-heating minimal – almost instant operation	

Fuel Cells

Molten Carbonate Fuel Cell (MCFC)

- Nickel is a common catalyst material
- Transport of carbonate ions from the cathode to the anode

Feature/Parameter	MCFC
Electrolyte	Molten lithium, sodium and/or potassium carbonates
Oxidant	Air
Internal Reforming	Yes
Operating Temperature	600°C - 700°C
Contaminate Sensitivities	Sulphur
Typical Stack Size	300kW – 3MW
Anode Reaction	$H_2 + CO_3^{2-} \rightarrow CO_2 + H_2O + 2e^-$
Cathode Reaction	$\frac{1}{2}O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$
Overall Reaction	$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$

Advantages	Disadvantages
Fuel Flexibility – natural gas, methanol, ethanol, biogas, coal gas and hydrogen	High temperature corrosion due to electrolyte
High efficiency	Long start-up time/slow response
Inexpensive catalyst makes it cost competitive	Low power density
Suitable for CHP	Slow response to changing electricity demand

Fuel Cells

Other Fuel Cells/Solutions

Regenerative/Reversible Fuel Cells

- Can act as an electrolyser to also produce hydrogen and oxygen.
- PEM-RFC and SOFC-RFC
- PEM-RFC and SOFC-RFC
  - Fuel Cell Mode: $H_2 + ½O_2 \rightarrow H_2O$
  - Electrolysis Mode: $H_2O \rightarrow H_2 + ½O_2$

- Another example of this is Elestor's self-contained hydrogen and bromine cell [29]
- No hydrogen compressor required
- It operates as an electrolyser during charge and a fuel cell during discharge
  - $H_2 + Br_2 \rightleftharpoons 2HBr$ + electrical energy

Direct Methanol Fuel Cell (DMFC)

- Solid polymer fuel cell
- Uses methanol directly as a fuel
- Anode reaction: $CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^-$
- Cathode reaction: $3(½O_2) + 6H^+ + 6e^- \rightarrow 3H_2O$
- Overall reaction: $CH_3OH + H_2O + 3(½O_2) \rightarrow CO_2 + 3H_2O$

IPG Flameless Generator

- Clean replacement for diesel generators – flameless combustion to lower emissions
- Can use a variety of fuels including hydrogen
- Seems to be on the industrial scale at the moment [30]

Fuel Cells

To consider

Potential consideration for future projects

Technology not ready/infeasible for application

Summary

Fuel Cells

- Polymer Electrolyte Membrane (PEM)
- Solid Oxide Fuel Cell (SOFC)
- Phosphoric Acid Fuel Cell (PAFC)
- Molten Carbonate Fuel Cell (MCFC)
- Regenerative/ Reversible Fuel Cell
- Alkaline Fuel Cell (AFC)
- Direct Methanol Fuel Cell (DMF)

PEMFC/PEM

- Low temperature PEMFC has gained most attraction for use in buildings/domestic settings [15, 16, 17, 20]
- Low temperature operation and high efficiency – suitable for CHP applications [20]
- Quick response therefore ideal for grid balancing

Solid Oxide Fuel Cell (SOFC)

- High temperature SOFC has gained most attraction for use in buildings/domestic settings [15, 16, 17, 20]
- High operating temperatures results in high-quality heat but less suitable for home applications [20]
- Not as suited to intermittent use.

Phosphoric Acid Fuel Cell (PAFC)

- Indication that PAFC are used in domestic sector but this seems to be for larger applications such as hospitals, hotels or urban/residential areas rather than single households [17, 18, 19, 4]
- Unsuitable for domestic application but widely used in large scale powerplants [20]

Molten Carbonate Fuel Cell (MCFC)

- Unsuitable for domestic application but widely used in large scale powerplants [20, 18]

Alkaline Fuel Cell (AFC)

- Development stalled as was overtaken by PEMFC/PEM [1]
- However, start-up company has recently developed a prototype [21]

Regenerative/Reversible Fuel Cell

- Seem to still be undergoing research phase as to whether economically feasible.
- Potential to save on capital costs but development is required in terms of performance and life-time goals. [8, 9, 10]
- Indication that SOFC-RFC are on the market but rarely get used for reverse application. [11]
- Cost effectiveness is still an issue [11, 12]

Direct Methanol Fuel Cell (DMF)

- Still undergoing research and development is at an early stage due to low efficiencies due to lower electrochemical activity of methanol than hydrogen [3, 13]
- Indication that small solutions exist for travelling with maximum power up to 125W [14]

Fuel Cell Comparison

**Defined as average time between failures where the system is inoperable. Also an assumed value due to limited data availability. Also note that source 27 does not distinguish between PEMFC and SOFC for some values.*
*** Time in operation*

	PEMFC/PEM	SOFC
Reliability	30,000 Mean Time Between Failures (MTBF) (hours) [27]* Availability: 97% [27]**	30,000 MTBF (hours) [27] Availability: 97% [27]**
Operational Life	Stack lifetime: 80,000h [16] ≥40,000h [27] 40,000 – 80,000h[25]	Stack lifetime: 40,000 - 60,000h [16] *** 40,000h [27] 40,000 – 90, 000h - [25]
Installation and Maintenance Downtime	Maintenance downtime – every 6 years with replacement parts [23]	Stack replacement every 5 years [25]
Efficiency	Electrical Efficiency: 38% [16] Overall Efficiency: 92% [16] Electrical Output 0.75kW [16] Thermal output: 1.1kW [16] Electrical efficiency (%LHV): 25 - 40% [27] Thermal efficiency (%LHV): 50 - 75% [27]	Electrical Efficiency: 38% - 60% [16] Overall Efficiency: 88% - 90% [16] Electrical output: 0.75 [16] Thermal output: 1.25 [16] Electrical efficiency (%LHV): 30 - 60% [27] Thermal efficiency (%LHV): 30 - 60% [27]
Ramp up/Down Times	Ramp up: <1 minute [5]	Ramp up: 60 minutes [5] (However, tend to be kept at constant temperature after ramp up)
Safety	High purity hydrogen requirement – management/safety considerations	High temperature operation
Technical Maturity	Developed in the 1960s for NASA manned spacecraft and has significant investment since from the auto industry. The modularity and ease of manufacture has led to uptake in residential distributed generation applications [5]	Commercially available since 2010. Applications include: auxiliary power, electric utility and distributed generation, and residential [5]

Fuel Cell Comparison

	PEMFC/PEM	SOFC
CAPEX	0.35kW – 0.7 kW 7802 – 31,208 £/kW [25] 0.5 – 5 kW 8800 - 11,270 £/kW [27]*	0.5 – 5 kW 11,270 £/kW [27]*
OPEX	< 3p/kWh [27]**	< 3p/kWh [27]**
Hurdle Rate	10% (assumed similar value as FCEV) [28]	10% (assumed similar value as FCEV) [28]
Frequency Response/ Operating Reserves	Quick output variation for shifting power demands.	Slow response time to changing electricity demand
Typical Planned and Maximum Size	Width x Depth x Height 622 X 600 x 1271mm [22] 240 l/kW [27]	1200 x 550 x 1014 mm [24] 240 l/kW [27]

** Cost of manufacturing including labour, materials and utilities. Note, report indicates that range of values for PEM is much broader than SOFC.*
***Defined as operation and maintenance costs per kWh of electricity produced (including stack replacement) but excluding cost of fuel, insurance and taxes*

Note: potential bias sources for CAPEX and OPEX but limited data available.

	Micro-CHP (PEMFC,SOFC)	Mini-CHP (SOFC)
OPEX [k€]	0.5	0.85
CAPEX [k€/kW]	34	18.4
Installation, Control, Auxiliary [k€]	6.15	12.7
Added system [k€]	13.5	48.5
Stack [k€]	11.5	43.9
Maintenance [k€]	0.5	0.8
Stack Replacement [k€]	6.7	24

Source 25. Note micro-CHP is ~1kW_{el} and 1.45 kW_{th}. Mini-CHP is 5kW_{el} and 4 kW_{th}. Source data is from 2015. Maintenance/replacement assumes 10 years with 2 replacements.

Fuel Cell References

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Electrolysers

Alkaline

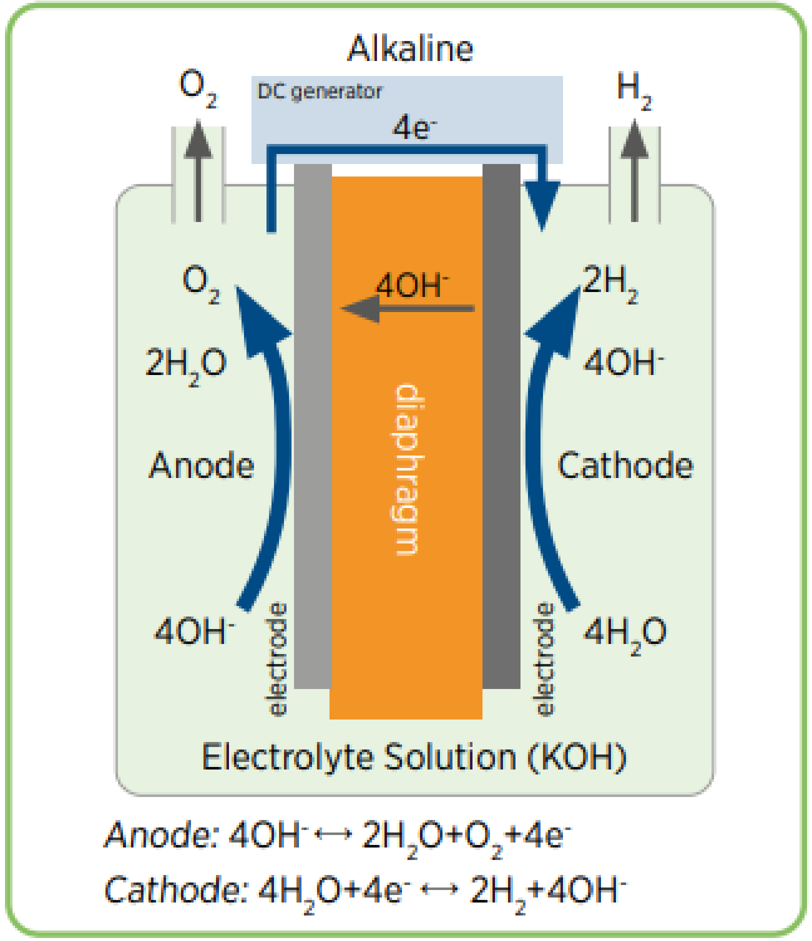


Figure 1: Alkaline electrolyser [1]

Feature/Parameter	Alkaline
Operating Temperature (°C)	70 - 90
Operating Pressure (bar)	1 – 30
Electrolyte	Potassium hydroxide
Anode PTL material	Nickel mesh (not always present)
Cathode PTL material	Nickel mesh
Anode Catalyst material	Nickel coated perforated stainless steel*
Cathode Catalyst material	Nickel coated perforated stainless steel*

**variation dependent on supplier*

Advantages	Disadvantages
Simple design and easy manufacture	Low current densities and some energy loss as constrained by operating limits to prevent gas mixing
Easy to maintain as no noble metals	Prone to electrode corrosion
Low capital cost	High response time compared to PEM – not ideal for storing renewable energy
	Low H_2 purity

Electrolysers

Alkaline

System Level Considerations:

- Pumping to recirculate electrolyte
- Gas-water separators to remove alkaline solution from gases produced
- Water management system regulates filling of gas separators
- Mixing pipe to balance charges between anode and cathode water/gas separator
- Possible to operate at high pressure but more resistance cell frames and balance of plant are needed resulting in higher CAPEX

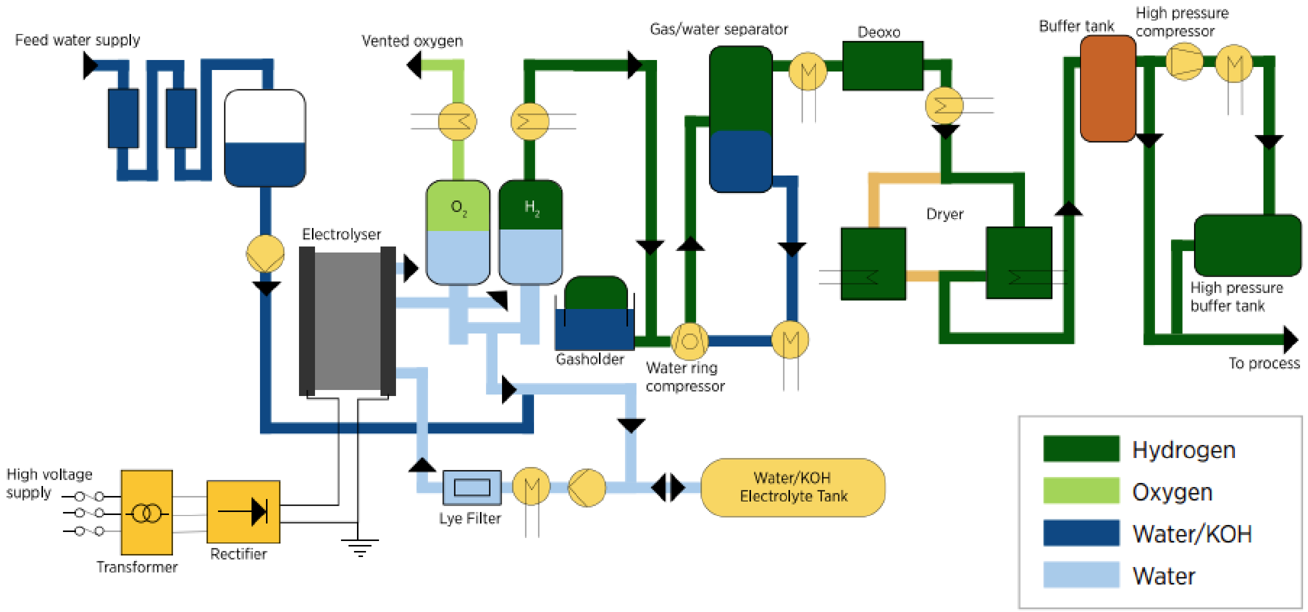


Figure 2: Typical system for alkaline electrolyser [1]

Electrolysers

Proton Exchange Membrane (PEM)

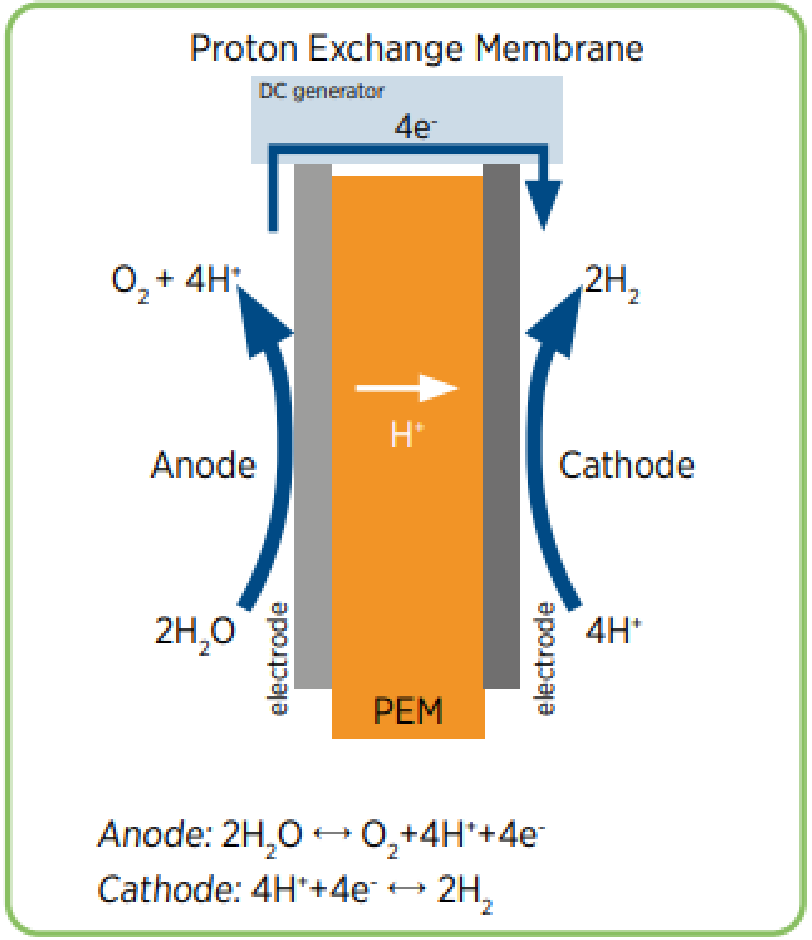


Figure 3: PEM electrolyser [1]

Feature/Parameter	PEM
Operating Temperature (°C)	50 - 80
Operating Pressure (bar)	< 70*
Electrolyte	PFSA membranes
Anode PTL material	Platinum coated sintered porous titanium
Cathode PTL material	Sintered porous titanium or carbon cloth
Anode Catalyst material	Iridium Oxide
Cathode Catalyst material	Platinum nanoparticles on carbon black

**variation dependent on supplier*

Advantages	Disadvantages
Highest current densities	Uses noble metals – expensive and supply problems
Fast and dynamic response – suitable for load fluctuation	High membrane cost
Ideal to store excess renewable energy	Low durability
High hydrogen purity	Acidic environment

Electrolysers

Proton Exchange Membrane (PEM)

<u>System Level Considerations:</u>

- Simpler than alkaline
- Usually require circulation pumps, heat exchangers, anode side pressure control and monitoring
- At the cathode side: gas-separator, de-oxygenation component (may not be required when operating with a high differential pressure), gas dryer, and compressor.
- Variety in system design choices which can reduce cost, complexity and maintenance.
  - Atmospheric – constant pressure operation > 1atm
  - Differential - 10 – 70 bar but may require thicker membrane and additional catalyst for stability and re-conversion of hydrogen.
  - Balanced pressure – anode and cathode are at the same pressure level (atmospheric represents a case of balanced pressure)

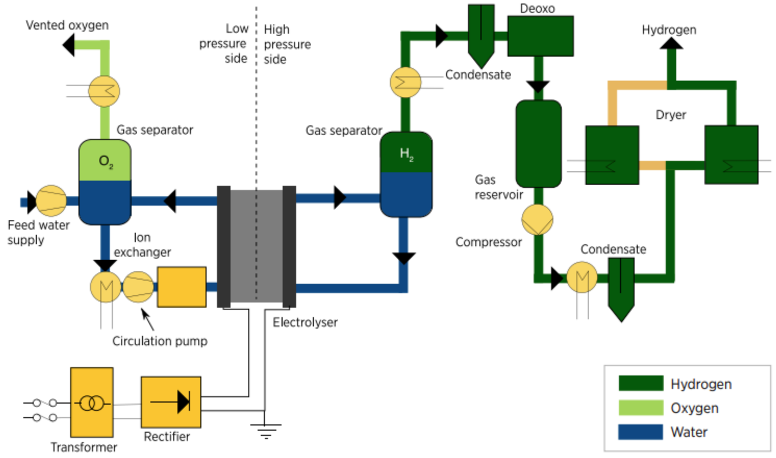


Figure 4: Typical system for proton exchange membrane [1].

Electrolysers

Solid Oxide

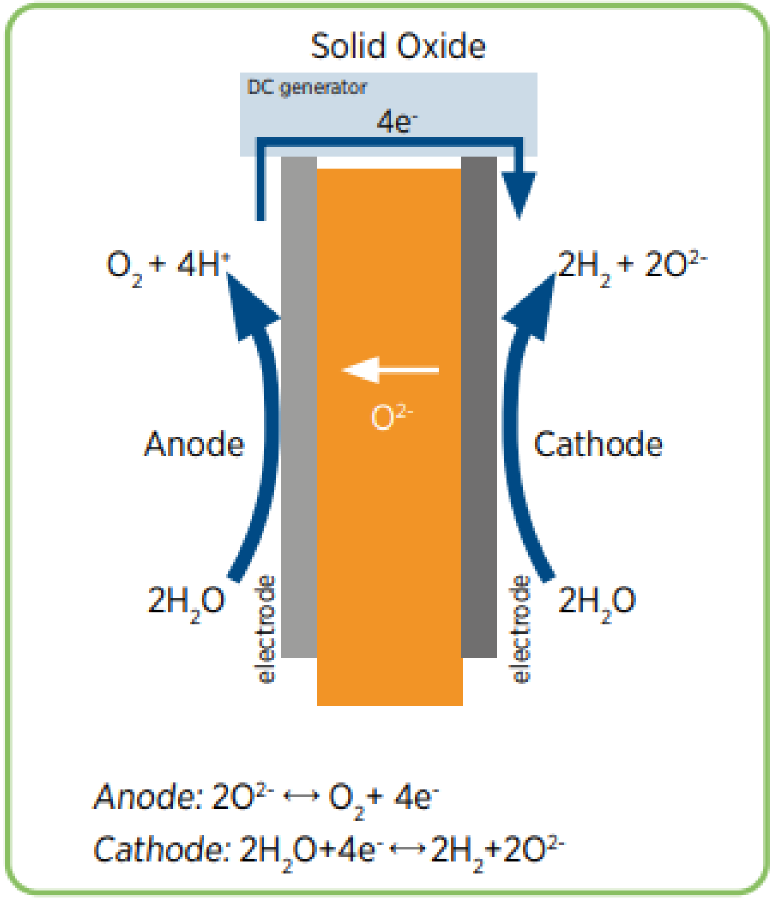


Figure 5: Solid oxide electrolyser [1]

Feature/Parameter	Solid Oxide
Operating Temperature (°C)	700 – 850*
Operating Pressure (bar)	1*
Electrolyte	Yttria-stabilised Zirconia
Anode PTL material	Coarse Nickel-mesh or foam
Cathode PTL material	None
Anode Catalyst material	Perovskite-type (e.g. LSCF, LSM)*
Cathode Catalyst material	Ni/YSZ

**variation dependent on supplier*

Advantages	Disadvantages
Does not require noble metals	High temperatures cause durability problems
Can be reversed to a fuel cell	Unstable electrodes
High efficiency	Safety and sealing problems
Low capital cost	Bulky design
	Uses brittle materials

Electrolysers

Solid Oxide

System Level Considerations:

- Common components as with other systems: water purification, dryers, compressors and electrical systems [6]
- Higher system efficiency can be gained by coupling with heat-producing technologies to supply heat for high temperature operation.

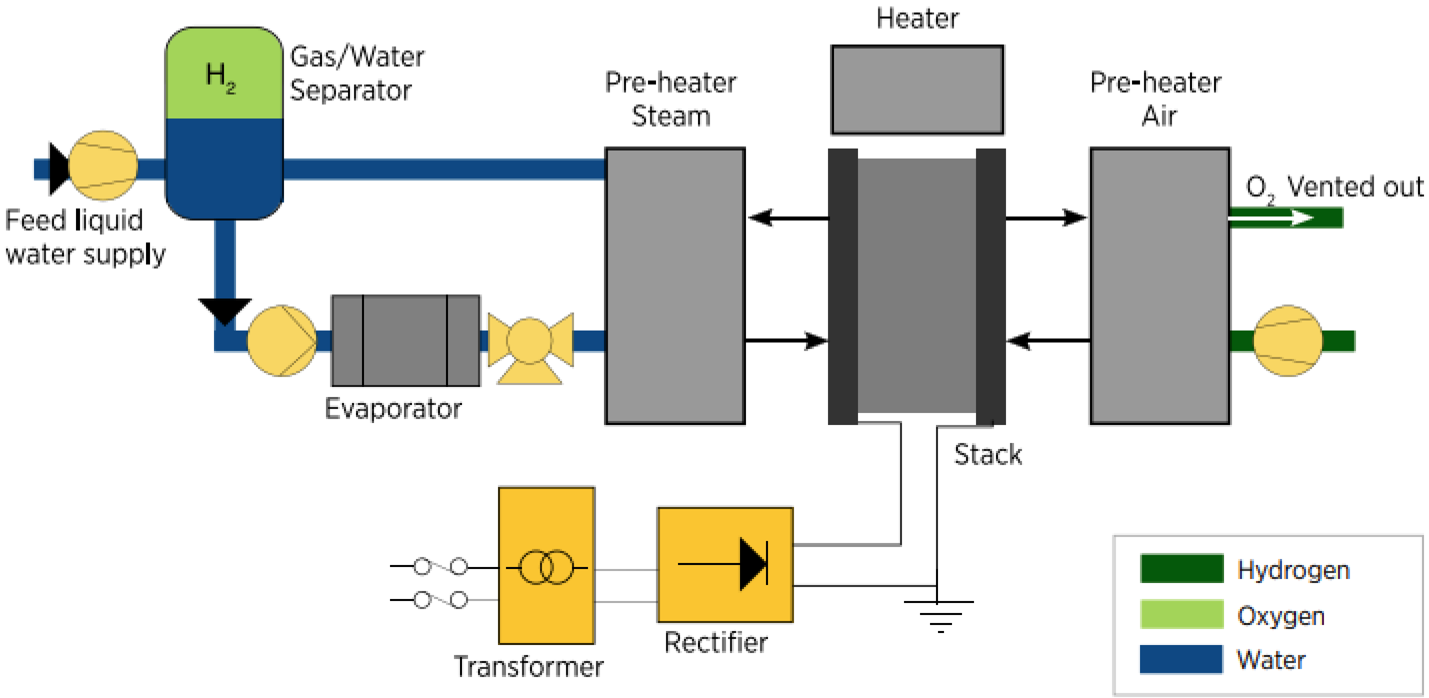


Figure 6: Typical system for Solid Oxide electrolyser [1].

Electrolysers

Anion Exchange Membrane (AEM)

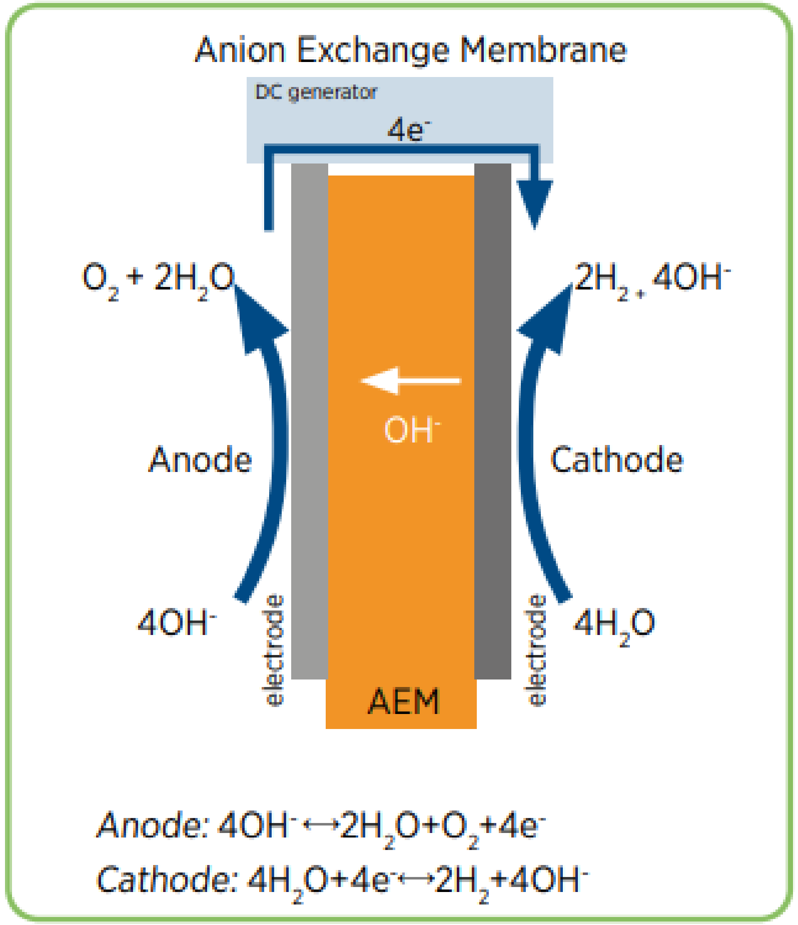


Figure 7: AEM electrolyser [1]

Feature/Parameter	AEM
Operating Temperature (°C)	40 – 60*
Operating Pressure (bar)	< 35*
Electrolyte	DVB polymer support with KOH or $NaHCO_3$*
Anode PTL material	Nickel foam*
Cathode PTL material	Nickel foam or carbon cloth*
Anode Catalyst material	High surface area Nickel or NiFeCo alloys*
Cathode Catalyst material	High surface area nickel*

**variation dependent on supplier*

Advantages	Disadvantages
Mix of PEM and Alkaline advantages – less harsh environment than alkaline and simplicity and efficiency of PEM	Low lifetime
Suitable for load fluctuation	Low membrane stability
Cheap components	Poor performance due to slow catalyst
	Low ionic conductivity

Electrolysers

Anion Exchange Membrane (AEM)

System Level Considerations:

- Similar design to PEM
- Low maturity therefore there are some challenges with differential pressure design
- It is expected that AEM will offer advantages of higher membrane stability, gas purity and higher power range that alkaline.

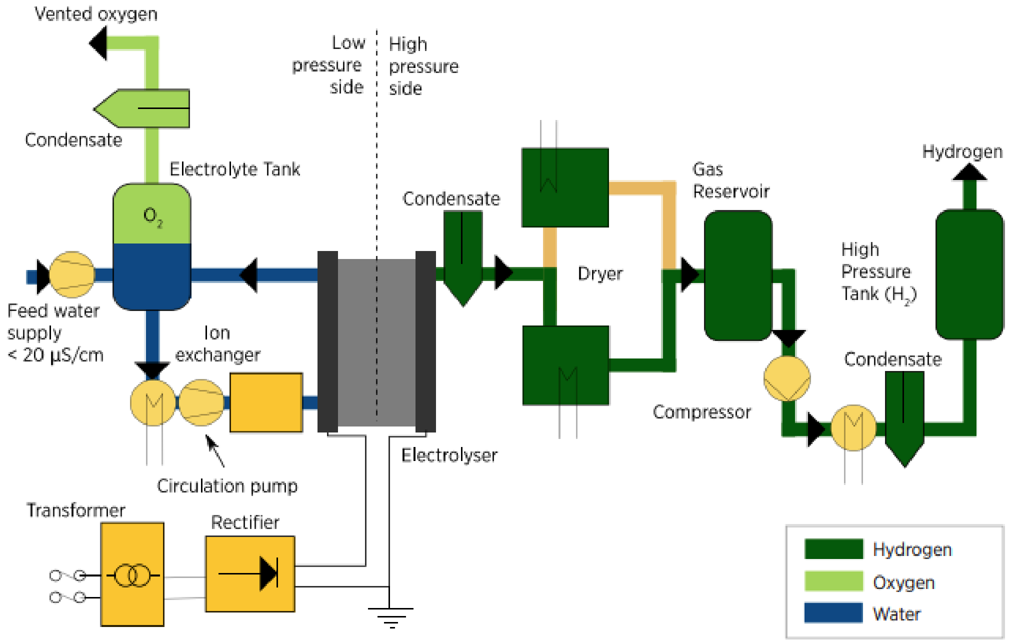


Figure 8: Typical system for Anion Exchange Membrane electrolyser [1].

Electrolysers

Other Technologies

Membrane-Free

- Overcomes the performance drop associated with membrane technologies. [7]
- Cryogenic system is used to cool the mixed gas and separate hydrogen and oxygen. [7]
- In demonstration phase with an estimated TRL 6. [7]
- No precious metals needed [8]
- Development company, CPH2, states it has lowest OPEX and LCOH of water electrolysis technologies for hydrogen production [8]

Microbial Electrolysis Cells (MECs)

- Can offer reduced operating costs as biomass is used to for some electrical energy. [6]
- Can have various outputs, including hydrogen [6]
- Water splitting can occur at temperatures as low as 30°C [6]
- Main disadvantage is the need for precious metals. [6]
- Development phase needs to improve hydrogen purity and production capacity to make it a feasible option compared to other technologies [6]

Photoelectrochemical (PEC)

- Requires solar energy [6]
- Semiconductor materials are in a water-based electrolyte and sunlight provides the energy to split the water [6]
- Reduced size and capital costs over other technologies due to combination of photovoltaic and electrolyser system [6]
- Further improvements needed to increase efficiency, durability and lifetime to be feasible on the market [6]

Electrolysers

Other Technologies

Sylfen Reversible Electrolyser

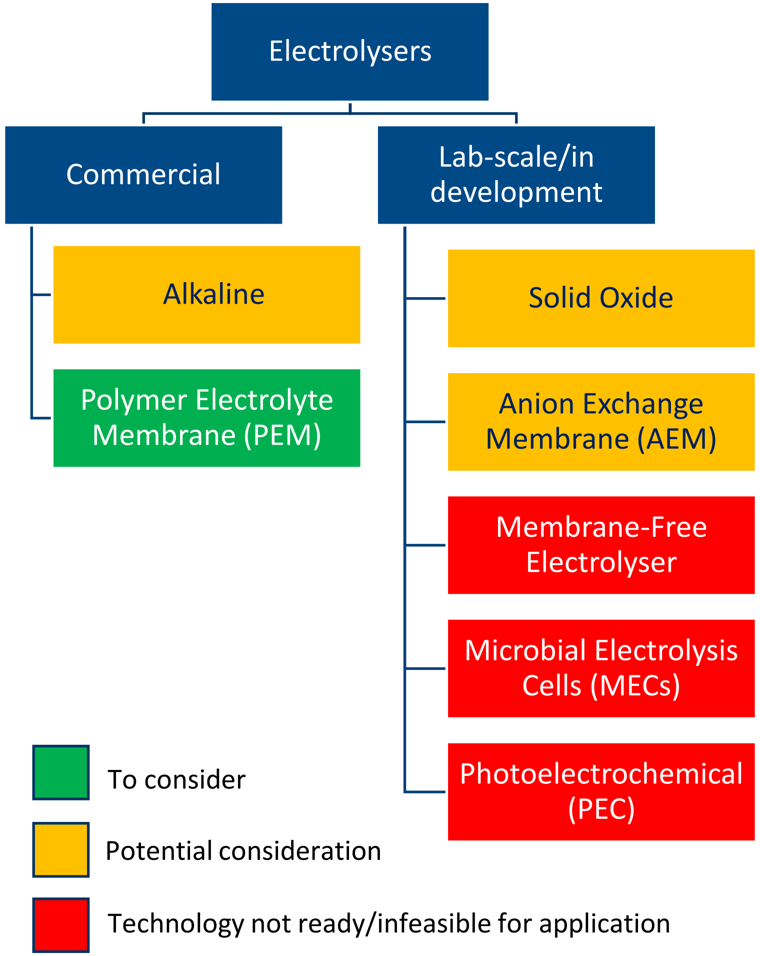
- Stores excess electricity as hydrogen by working as an electrolyser and acts as a fuel cell when electricity is needed.
- Single point of installations and maintenance is more efficient in terms of space and cost.
- Also can working cogeneration by using methane if hydrogen supply is depleted
- Allows flexibility in pursuing the cheapest option – refilling hydrogen when electricity is cheap or using methane instead when electricity is high [9]

Atawey Hydrogen Refuelling Station

- Compact XS model can include an electrolyser for onsite production
- Footprint $6m^2$ (2.9 x 1.8m)
- Production capacity 0.5kg/day
- An all-in-one station with storage, compression and distribution. [10]

Electrolysers

Summary



Alkaline
- Most advanced and already commercial along with PEM [1]
- Lowest installed cost [1]
- Simple stack and design, relatively easy manufacture [1]
- Not as suited to intermittent use and load following which may be required

PEM
- Most advanced and already commercial along with alkaline [1]
- Smaller footprint then alkaline and higher current density and output pressure [1]

Solid Oxide
- Highest electrical efficiency [1]
- Less mature technology – only a few companies and OEMs involved in development [1]
- Potential for reversibility to also operate as a fuel cell [1]
- Typically deployed at kW scale currently [1]
- May be less suitable for pairing with intermittent renewables due to high temperature operation requiring longer start-up times [6]

AEM
- Less mature technology – only a few companies and OEMs involved in development [1]
- Limited deployment [1]

Membrane-Free Electrolyser
- Low maturity and in development phase [6]

Microbial Electrolysis Cells (MECs)
- Low maturity and in development phase [6]

Photoelectrochemical (PEC)
- Low maturity and in development phase [6]

Electrolyser Comparison

	Alkaline	PEM	Solid Oxide	AEM
Operational Life (h)	Stack lifetime: 60000 hours [1]	Stack lifetime: 50 000-80 000 hours [1]	< 20000 hours [1]	Stack lifetime: > 5000 hours [1]
Installation and Maintenance Downtime	Stack replacement every 9 years over 30 year life-time [2]	Stack replacement every 11 years over 30 year life-time [2]	Stack replacement every 7 years over 30 year life-time [2]	
Efficiency	Voltage efficiency (LHV): 50% - 68% [1] Electrical efficiency (stack): 47 -66 kWh/kgH_2 [1] Electrical efficiency (system): 50-78 kWh/kgH_2 [1]	Voltage efficiency (LHV): 50%-68% [1] Electrical efficiency (stack): 47-66 kWh/kgH_2 [1] Electrical efficiency (system): 50-83 kWh/kgH_2 [1]	Voltage efficiency (LHV): 75% - 85% [1] Electrical efficiency (stack): 35 -50 kWh/kgH_2 [1] Electrical efficiency (system): 40 - 50 kWh/kgH_2 [1]	Voltage efficiency (LHV): 52% - 67% [1] Electrical efficiency (stack): 51.5 - 66 kWh/kgH_2 [1] Electrical efficiency (system): 57 – 69 kWh/kgH_2 [1]
Ramp up/Down Times	< 50 minutes [1]	< 20minutes [1]	> 600 minutes [1]	< 20 minutes [1]
Safety	70 – 90 °C [1] < 30 bar cell pressure [1]	50 – 80 °C [1] <30 bar cell pressure [1]	700 - 850°C [1] 1 bar cell pressure [1]	40 -60 °C [1] < 35 bar cell pressure [1]
Technical Maturity	Commercial but usually on MW scale [1]	Commercial but usually on MW scale [1]	Less mature technology – only a few companies and OEMs involved in development. Deployed at kW scale currently but market is rapidly changing [1]	Less mature technology – only a few companies and OEMs involved in development. Limited deployment [1]
Water Consumption	Demineralised water is 9kg H_2O for 1kg H_2 Typical value for mains water is 17kg H_2O for 1kg H_2[3] [4] Dependent on impurity level of water [3] [4]	Demineralised water is 9kg H_2O for 1kg H_2 Typical value for mains water is 17kg H_2O for 1kg H_2[3] [4] Dependent on impurity level of water [3] [4]	Demineralised water is 9kg H_2O for 1kg H_2 Typical value for mains water is 17kg H_2O for 1kg H_2[3] [4] Dependent on impurity level of water [3] [4]	Demineralised water is 9kg H_2O for 1kg H_2 Typical value for mains water is 17kg H_2O for 1kg H_2[3] [4] Dependent on impurity level of water [3] [4]

Electrolyser Comparison

	Alkaline	PEM	Solid Oxide	AEM
CAPEX	Stack minimum 1MW: 229 £/kW [1]* System minimum 10MW: 423 – 847 £/kW [1] 750 – 1200 £/kW H_2 (HHV) [2]** 10 -15 £/MWh H_2 (HHV) [2]	Stack minimum 1MW: 339 £/kW [1]* System minimum 10MW: 593 – 1185 £/kW [1] 1000 – 1900 £/kW H_2 (HHV) [2]** 15 -20 £/MWh H_2 (HHV) [2]	Stack minimum 1MW: > 1693 £/kW[1]* System minimum 10MW: Unknown [1] 25 -30 £/MWh H_2 (HHV) [2]	Unknown [1]*
OPEX	Fixed OPEX: 5 £/MWh H2[2]*** Variable OPEX: 7. £/MWh H2 [2]****	Fixed OPEX: 5 £/MWh H2[2]*** Variable OPEX: 5 £/MWh H2 [2]****	Fixed OPEX: 10 £/MWh H2[2]*** Variable OPEX: 20 £/MWh H2 [2]****	Fixed OPEX: [2]*** Variable OPEX: [2]****
Hurdle Rate	Assume 10% hurdle rate to discount costs and output across time [2]	Assume 10% hurdle rate to discount costs and output across time [2]	Assume 10% hurdle rate to discount costs and output across time [2]	Assume 10% hurdle rate to discount costs and output across time [2]
Frequency Response/ Operating Reserves	Slower response to fluctuating power supply than PEM [2]	Rapid dispatchability and turndown to match energy output [2]	Less suitable for cycling due to high temperatures required [5]	
Typical Planned and Maximum Size	Electrode area: 10000 – 30000 cm^2 [1] 0.136 m^2/kW H2 HHV output (inc. balance of plant) [5] 10 hectares for 1GW facility [1]	Electrode area: 1500cm^2 [1] 0.0737 m^2/kW H_2 HHV output (inc. balance of plant) [5] 8 hectares for 1GW facility [1]	Electrode area: 200cm^2 [1] 0.136 m^2/kW H2 HHV output (inc. balance of plant) no data currently so assumed same as alkaline [5]	Electrode area: < 300cm^2 [1]

*Includes: ▪ Single cell unit – catalyst, membrane and electrodes etc
▪ Stack – PTLs, bipolar plates, spacers, seals, frames etc. Usually 40%-50% of total
▪ System costs – rectifier, water purification unit, hydrogen gas compressing, and cooling components etc. Usually 50%-60% of total [1]

** Covers electrolyser system (stack), all balance of plant, civil works and electricity grid connection
***Fixed OPEX includes direct labour, administration/general overheads, insurance/local taxes and maintenance
****Variable OPEX includes stack replacement costs

Electrolyser References

[1] Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5C climate goal (irena.org)
[2] Hydrogen production costs 2021 (publishing.service.gov.uk)
[3] https://www.paconsulting.com/newsroom/the-water-report-the-water-industry-in-a-hydrogen-economy-12-july-2021
[4] https://itm-power-assets.s3.eu-west-2.amazonaws.com/Green_Hydrogen_Water_Use_56b96f577d.pdf
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[6] https://www.oxfordenergy.org/wpcms/wp-content/uploads/2022/01/Cost-competitive-green-hydrogen-how-to-lower-the-cost-of-electrolysers-EL47.pdf
[7] https://www.gov.scot/binaries/content/documents/govscot/publications/research-and-analysis/2022/10/assessment-electrolysers-report/documents/assessment-electrolysers-final-report/assessment-electrolysers-final-report/govscot%3Adocument/assessment-electrolysers-final-report.pdf
[8] Hydrogen as energy | CPH2
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[10] Compact hydrogen station for H2 cars & hydrogen bikes | Atawey

Hydrogen Storage

Compressed Gas

- There are currently four types of high-pressure tank storage as seen in Table 1 [10]

	Type I	Type II	Type III	Type IV
Structure	Metal material	Carbon fibre or glass material which wraps around a thick metal ring liner	Composites which wrap around an internal metal liner	High-density polymer liner surrounded by carbon fibre compound.
Pressure	150 – 300 bar	Up to 1000 bar	350 – 700 bar	Up to 700 bar
Advantages	Widely used and least expensive	High hydrogen tank pressure and relatively thin liner	Internal liner prevents hydrogen leakage and composites means the tank can withstand mechanical stress. Also lighter than Type I due to composite use instead of thick metal walls	Polymer-liner prevents leakage by diffusion. Valves for refuelling and supply of hydrogen.
Disadvantages	Not suitable for portable/vehicle applications due to heavy mass	Not suitable for portable/vehicle applications due to heavy mass	Expensive	Expensive
Application	Industrial gas storage	Hydro generators	Portable applications	Portable applications

Hydrogen Storage

Liquid Hydrogen

- Liquid hydrogen also results in an increase in density and is twice as much as compressed gas at 700 bar
- The process of liquefication requires compressors, heat exchangers and expansion valves
- The Linde cycle or Joule-Thompson expansion cycle is used
- Most suitable for large amounts of hydrogen storage due to long loading and unloading times
- Requires high energy input
- Spherical vessels are use to minimise the boil-off rate by minimising surface-to-volume ratio
- Vessels have a gap between the double wall to minimise conduction and convection effects [10]

Figure 9: Example of Liquid hydrogen storage vessel [10]

Cryo-compresses Hydrogen Storage

- Vessel can store liquid hydrogen, supercritical cryogenic hydrogen or two-phase state
- Cryogenic temperatures are used in a pressurised vessel
- Higher pressures utilised reduces the boil-off seen in liquid hydrogen storage [10]

Adsorption

- Hydrogen can be in molecular or atomic
- A porous solid is required for storage
- Due to weak van der Waal's forces, low temperatures and high pressure (10 - 100 bar) is needed to achieve good hydrogen storage density
- Liquid nitrogen is a common refrigerant to regulate heat [10]

Hydrogen Storage

Chemical Hydrides

- Uses covalent bonding between a non-metallic element and the hydrogen
- Liquid form resulting in more simple transport and storage than metal hydrides as they are lighter
- Storage of hydrogen can be eliminated as some can produce hydrogen on demand such as ammonia cracking and methanol cracking [10, 11]

Liquid Organic Carriers

- Organic compounds which utilise reversible hydrogenation and dehydrogenation process
- Atmospheric pressure and temperature storage
- Hydrogen is relatively pure after dehydrogenation
- The process is addition of hydrogen to the organic carrier whilst it is cooled and slightly pressurised.
- This can then be transported/stored. To release the hydrogen, the temperature would be increased and pressure decreased slightly [10]

Metal Hydride

- Heat is used to alter the pressure as above the balance pressure, the hydrogen absorbs to the metal hydride and below the balance pressure it is released
- Metal hydride have high volumetric storage density as the hydrogen is distributed throughout the matrix
- Various metals and alloys can be used such as magnesium, titanium, manganese, nickel and chromium [10]
- Ideal for stationary applications as it is best to be left in situ due to heavy metal storage

Hydrogen Storage

Complex Hydride

- Consist of alanates, borohydrides and amides
- High gravimetric hydrogen storage due to light elements resulting in raised interest for FCV applications
- Hydrogen is part of a complex anion which bonds to a metal cation which can lead to difficult separation
- Similar to above, a temperature increase results in the release of hydrogen [10]

Other Solutions

Hysilabs – Hydrosil

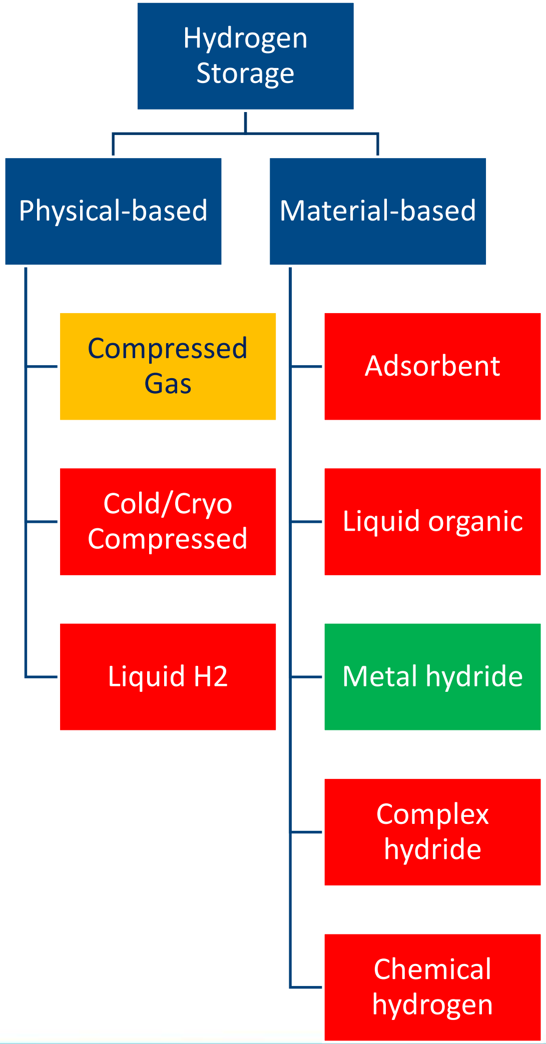
- Inorganic liquid hydrogen carrier that can use existing infrastructure due to ambient temperature and pressure
- The liquid is charged with hydrogen and can be release by a chemical reaction in a small carburettor
- Extremely high purity of hydrogen
- Seems to be being developed at industrial scale where mass amounts of hydrogen would be charged and transported and is also still in development phase
- Based on a silicon hybride molecule so it not toxic to humans or the environment [14]

Hydrogen Storage

To consider

Potential consideration

Technology not ready/infeasible for application



Compressed Gas

- Simplest, most widespread use and efficient [11]
- Perceived safety concerns due to high pressures

Cold/Cryo Compressed

- Still under development [10]

Liquid H2

- High energy requirements
- Strict temperature control needed to avoid overpressure
- Smaller vessels suffer more from evaporated hydrogen losses [11]

Adsorbent

- Limited advancement and most vessels have only been developed to bench-top scale [10]

Liquid Organic

- Still under development to address challenged such as economic viability, safety, and hydrogen storage capacity [10]

Metal Hydride

- High volume storage and safety compared to compressed gas or liquid storage [10][11]

Complex Hydride

- High temperature thermolysis to release hydrogen
- Catalyst or additive is usually required to release the hydrogen [10]

Chemical Hydrogen

- Would require another feedstock such as ammonia, formic acid or methanol which have concerns around toxicity in domestic applications [10]

Hydrogen Storage Comparison

*dependent on pressure and temperature.

	Compressed Gas	Metal Hydride
Hydrogen Stored	4.2kg at 60 bar and 15°C [1] 17 – 33 kgH2/m^3 [4]	56 -106 kgH_2/M^3 [6] [4] 3-4x storage density of compressed hydrogen [5]
Operational Life	20 years [9] / 10 000 cycles[1]	3000 cycles [6] Storage life expectancy 30 years [8] <20000 hydride cycles with 30 year life expectancy [13]
Efficiency	~90% for compression (at 350 bar) and 85 – 88% (at 700 bar) [4]	80 – 98 % (including auxiliary systems and hydrogen losses) [4]
Ramp Up/Down Times	N/A to storage	N/A to Storage
Safety	Wide range of flammable concentration in air – easy ignition. Tanks must be free of air [2] High pressure storage due to low ambient temperature density [2] Invisible flames – need special flame detectors [2] Suitable storage and piping to prevent hydrogen leaks and adequate ventilation [2]	Safer – no need to further compress or liquefy hydrogen [4] Low pressure operation (up to 12 bar) [5] Invisible flames – need special flame detectors [2] Suitable piping to prevent hydrogen leaks and adequate ventilation [2]
Technical Maturity	Widely used and most common from of storage at the moment	Seems to be up and coming – a few companies are developing hydride storage solutions
Discharge Time	Seconds [4]	~2kg/min [4]
Water Consumption	N/A to storage	N/A to storage

Hydrogen Storage Comparison

	Compressed Gas	Metal Hydride
CAPEX	11.45 £/kWh (HHV) based on a 95m^3 at 50-80 bar [3] 0.8 – 2.4 £/MW (compressor) and 5080 – 8467£/MWh storage tank in 2014 [4] CAPEX – power related 1541 £/kW [9] CAPEX energy related 0.21£/kWh	Unknown [4] ~1/2 capital cost of compresses hydrogen storage (£/kg H_2) [5]
OPEX	Fixed OPEX: 0.34 £/kWh [3] Variable OPEX: 0 [3] OPEX power related 62 £/kw [9] OPEX energy related 0 £/kWh [9]	Limited literature data
Hurdle Rate	Limited literature data	Limited literature data
Frequency Response/Operating Reserves	N/A to storage	N/A to storage
Typical Planned and Maximum Size	Inner volume: 850L [1] Mass of empty tank 215kg and mass of hydrogen 4.2kg at 60bar (15°C) [1] External dimensions (cm) without support: Ø 84 x 187 [1]	10 – 25 kg of hydrogen in 3m x 2.5m x 2.6m (note this is an integrated solution with fuel cell, electrolyser and storage) [8]

Hydrogen Storage References

[1] CL-DS10-Data-sheet-60bar-850L-EN.pdf (mahytec.com)
[2] Common compressed hydrogen safety concerns - Atlas Copco UK
[3] Hydrogen supply chain evidence base (publishing.service.gov.uk)
[4] ab80d85b-faa3-9c7b-b12f-27d8bad0353e (energy-transition-institute.com)
[5] "Hydrexia provides hydrogen Storage equipment, Metal hydride, Mg-based solid-state hydrogen storage trailer"
[6] Hydrogen storage breakthrough is here with Hydrexia's Metal Hydride Technology ----safe, reliable, and ready for the future. (linkedin.com)
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[8] GKN_HY2MINI_ProductSheet.pdf (gknhydrogen.com)
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[10] Hydrogen storage methods | SynerHy
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[14] Technology | HySiLabs

LAVO

The LAVO system appears to be the only commercially available integrated solution, with P2G, G2P storage, developed by an innovative Australian company. The system can power an average Australian home for 2 days.

Key Parts [1]:

- PEM Fuel cell – converts stored hydrogen energy to electrical power
- DC-DC converter – Regulates power output from fuel cell
- Battery – traditional Lithium-ion battery to enable fast response time
- Hybrid inverter (not included [2]) – Manages electrical flow between solar, house and LAVO.
- Electrolyser – Converts excess solar energy to hydrogen
- Water purifier – De-mineralises tap water for electrolyser use
- LAVO Hydride – patented metal hydride hydrogen storage solution
- CAPEX: £18,800 [2]
- Potential price reduction in 2022 resulting in ~£16,000 [2]
- Outdoor installation required [2]
- Annual professional maintenance probable [2]

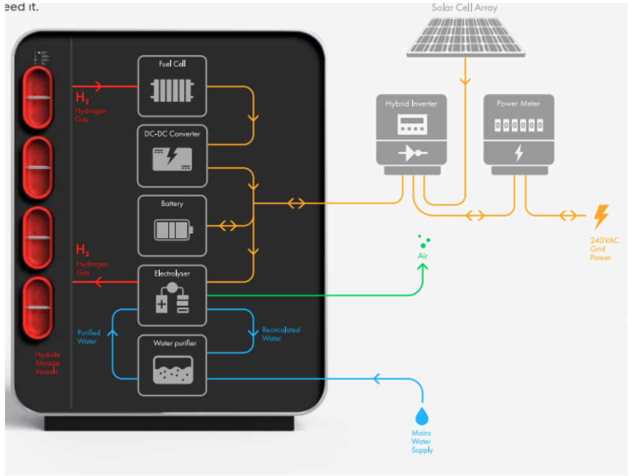


Figure 1: LAVO set-up [1]

Mechanical

Dimensions (HxWxD)	1680 x 1240 x 400 mm
Weight	196 kg
Hydride Vessels	4 vessels
Max System Pressure	35 bar_g
Vessel Weight	32 kg
Total Installed Weight	324 kg
Mounting	Floor Mount / Outdoors

Environmental

Operational Temperature Range	-10° to +50° C
Recommended Temperature Range	5° to 45° C
Environmental Humidity Range	3 to 100% RH
Maximum Elevation	2000 m
Noise Level	< 45 dB
Enclosure Protection Rating	IP54

Performance

Usable Capacity	40 kWh
Real Power, max continuous	5 kW (charge and discharge)
Nominal Voltage	48 V DC
Output Voltage Range	45 – 53 V DC
Hydride Cycles	< 20,000
Warranty	10 years
Lifetime	30 years

Connections

Water Supply	Portable Mains Water / LAVO™ water purification unit
Communication	Local WiFi / Ethernet / 4G / 5G

Figure 2: LAVO specifications [2]

LAVO References

[1] https://www.h2networks.com.au/pdf/Small-Scale-LAVO-Residential-Unit-Brochure.pdf
[2] LAVO's Hydrogen Battery: Incredible Engineering. Tough Sell. (solarquotes.com.au)

Mapping Technology to Property Types

Based on the technology viability assessments, it was decided that the following technologies would be explored as potential components in the proposed system, as they were ranked as green based on their system parameters:

- PEM Fuel Cell
- PEM Electrolyser
- Metal Hydride Storage

Each of these technologies has been mapped against the different property types, based on the size of the LAVO components, and given a RAG status based on the following criteria:

Green	Feasible during SIF
Amber	Potential future feasibility
Red	Not feasible

Mapping Technology to Property Types

	Feasible during SIF project
	Potential future feasibility
	Not feasible

The following table demonstrates the feasibility of the entire system characteristics and the fuel cell component with respect to installation at different property types.

Property Characteristics	System Characteristics	Fuel Cell (PEM) Characteristics								
Type	**Size**	**Reliability**	**Operational Life**	**Cost**	**Maintenance**	**Efficiency**	**Ramp Up Time**	**Safety**	**Technical Maturity**	**Frequency Response**
Overview		*97% availability*	*40,000 – 80,000 hours*	*Most expensive component*	*Every 6 years*	*Overall 92%*	*< 1minute*	*Requires highly reformed hydrogen**	*Uptake in residential distributed generation applications*	
Flat										
Semi and Terrace										
Detached										

- Feasibility for most characteristics is not unique to specific property types, except for space requirements and outdoor installations. Flats can be ruled out as feasible property types, due to the relatively large space requirements for the system and preferred outdoor installation.
- As replacement of the fuel cell is the most costly component to be replaced, current operational life and cost of component replacement could mean that it is not a feasible option within the project timescales.

Mapping Technology to Property Types

Green	Feasible during SIF
Amber	Potential future feasibility
Red	Not feasible

The following table demonstrates the feasibility of the electrolyser component with respect to installation at different property types.

Property Characteristics	Electrolyser (PEM)								
Type	**Operational Life**	**Cost**	**Maintenance**	**Efficiency**	**Ramp Up Time**	**Safety**	**Technical Maturity**	**Water Consumption**	**Frequency Response**
Overview	*50,000 – 80,000 hours*		*Stack replacement every 11 years*	*47 - 66 kWh/kgH$_2$*	*< 20 minutes*	*Outdoor storage preferable*	*Commercial but usually on the MW scale*	*9-14 kg per kg H$_2$ produced*	*Rapid response*
Flat	[Potential future feasibility]	[Potential future feasibility]	[Feasible during SIF]	[Feasible during SIF]	[Feasible during SIF]	[Not feasible]	[Feasible during SIF]	[Feasible during SIF]	[Feasible during SIF]
Semi and Terrace	[Potential future feasibility]	[Potential future feasibility]	[Feasible during SIF]	[Feasible during SIF]	[Feasible during SIF]	[Feasible during SIF]	[Feasible during SIF]	[Feasible during SIF]	[Feasible during SIF]
Detached	[Potential future feasibility]	[Potential future feasibility]	[Feasible during SIF]	[Feasible during SIF]	[Feasible during SIF]	[Feasible during SIF]	[Feasible during SIF]	[Feasible during SIF]	[Feasible during SIF]

- Feasibility for most characteristics is not unique to specific property types, except for safety, which is the result of preferred outdoor storage. Flats can be ruled out as feasible property types, due to the relatively large space requirements for the large system and preferred outdoor installation.
- Similar to the fuel cell, current operational life and cost of component cost could mean that replacement of the component makes the electrolyser less feasible within the project timescales.

Mapping Technology to Property Types

	Feasible during SIF
	Potential future feasibility
	Not feasible

The following table demonstrates the feasibility of the storage component with respect to installation at different property types.

Property Characteristics	Metal Hydride Storage				
Type	**Storage Capacity**	**Operational Life**	**Safety**	**Technical Maturity**	**Charge/Discharge Time**
Overview	*3 - 4 x storage density of compressed hydrogen*	*30 years*	*Low pressure - up to 10 bar*	*Seems to be under development*	*Few hours 0.5g H_2/min*
Flat					
Semi and Terrace					
Detached					

- Feasibility for all characteristics is not unique to specific property types. This is assuming that the storage capacity isn't large enough for significant space requirements.
- It may be that this technology is not mature enough for the SIF project timescales, although limited commercially available options do exist.
- Existing charge/discharge times are slower than for compressed hydrogen storage, meaning real-time load following could be more difficult.

Summary

- It is technically feasible to integrate these technologies at domestic scale, with a commercially available system already on the market.
- Specific technologies for the subsystems have been down-selected based on their performance characteristics being most appropriate at this scale, for intermittent use and their maturity allowing for procurement in project timescales. These technologies are PEM Fuel Cell, PEM Electrolyser and Metal Hydride Storage.
- Other technologies may become preferable in the future, such as reversible fuel cells, but their technology readiness does not allow for demonstration within the SIF timescales.
- It does not appear that the technology is viable at for individual flats, due to preferred installation outside of the property for safety reasons.

Residential Scalability Requirements

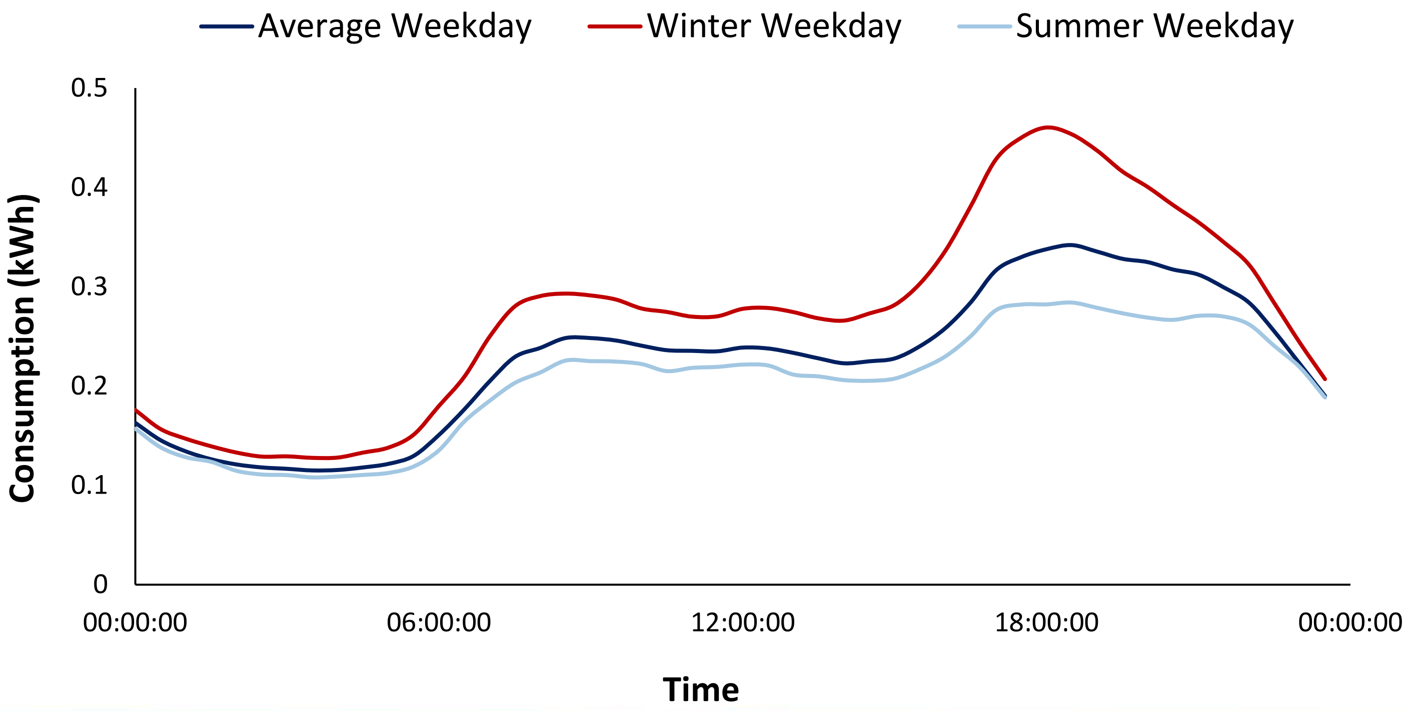
Power and heat demand profiles have been analysed for the two deployment options discussed in the domestic archetype development section.

Domestic specific PV generation profiles and storage requirements have also been investigated.

Domestic Electricity Consumption Profiles

Representative daily average load profiles, from Elexon Balancing and Settlement Code (BSC), were used to obtain time dependent electricity consumption for domestic properties [1].

The figure below shows half-hourly settlement unrestricted domestic electricity demand (excluding heating) for an average summer and winter weekday, converted to kWh.

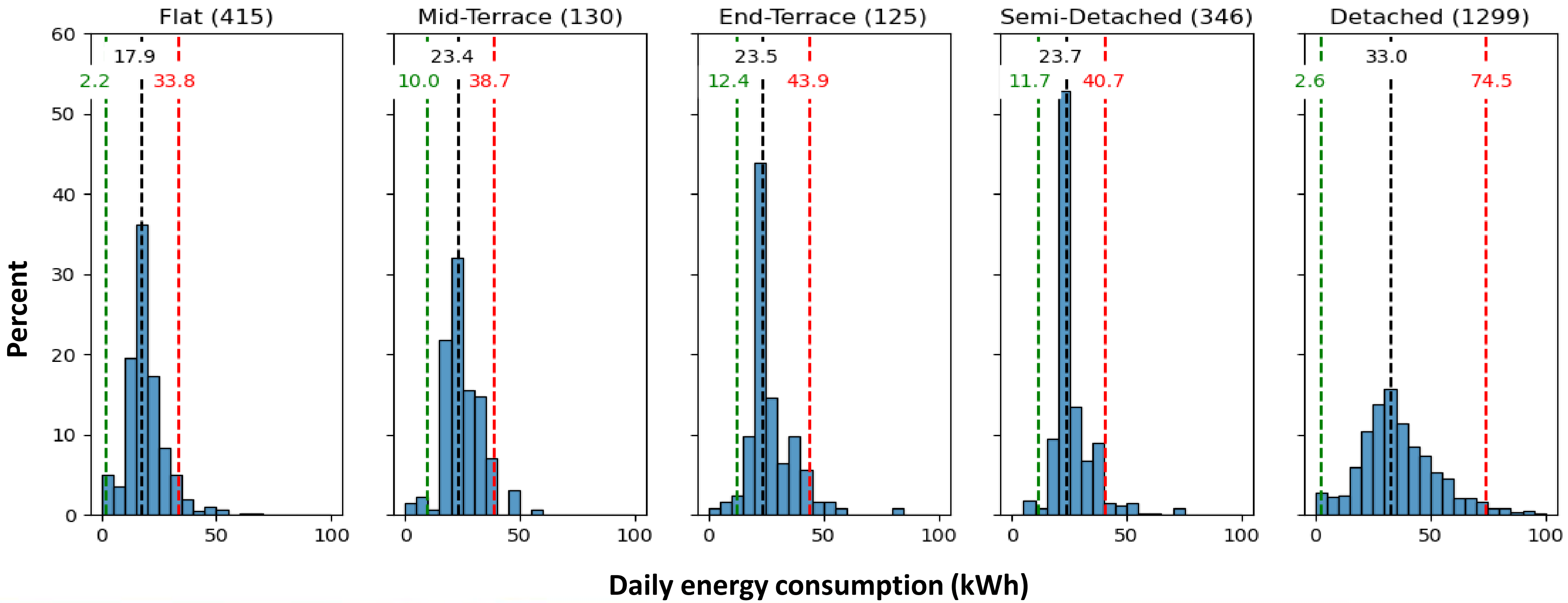


Seasonal Electricity Demand	
Average Weekday	10.88 kWh
Summer Weekday	9.73 kWh
Winter Weekday	12.98 kWh

Demand by Property Types

Government Energy Performance of buildings data [2] was explored to understand domestic energy demand for different property types. The Energy Performance Certificate (EPC) data is updated for each house every 10-20 years, so the initial focus was on EPC rated properties with heat pumps, as there would be no discontinuity for unit conversion for gas, and the number of heat pumps has grown rapidly in the last decade, so records can be assumed to be relatively up to date.

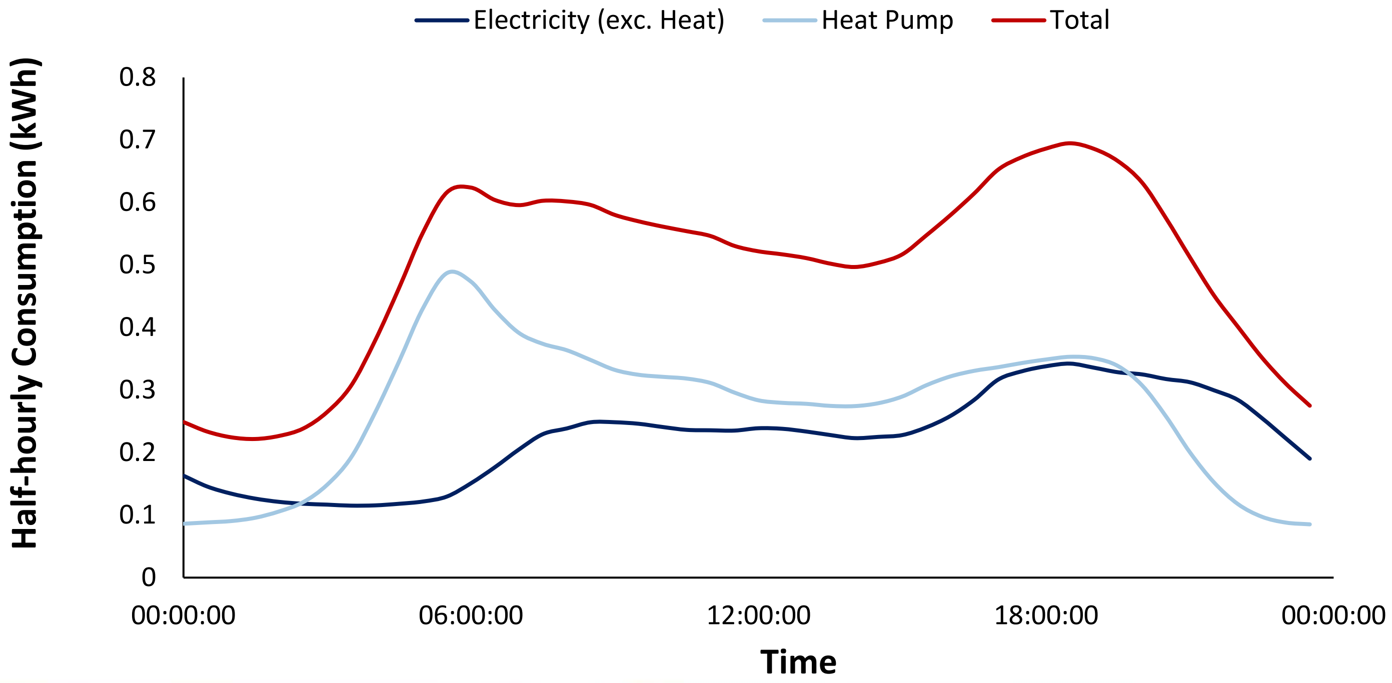
The following distributions shows the variability in energy demand for different property types that have EPC ratings A & B and a heat pump installed:



Daily Heat Demand – Heat Pump

For a median daily energy demand of 23.5 kWh (inline with EPC A&B terrace and semi detached homes with heat pumps) and daily average electricity demand of 10.88 kWh, excluding heat, the difference can be used to estimate the average daily heat pump demand.

When2Heat Data is heat pump demand time series data for space and water heating, computed by combining gas standard load profiles with spatial temperature and wind speed reanalysis data as well as population geodata [3,4,5]. This data was used to determine a half-hourly daily consumption profile for a heat pump of 12.62 kWh. The figure shows the average daily demand profile for a terraced/semi-detached property.

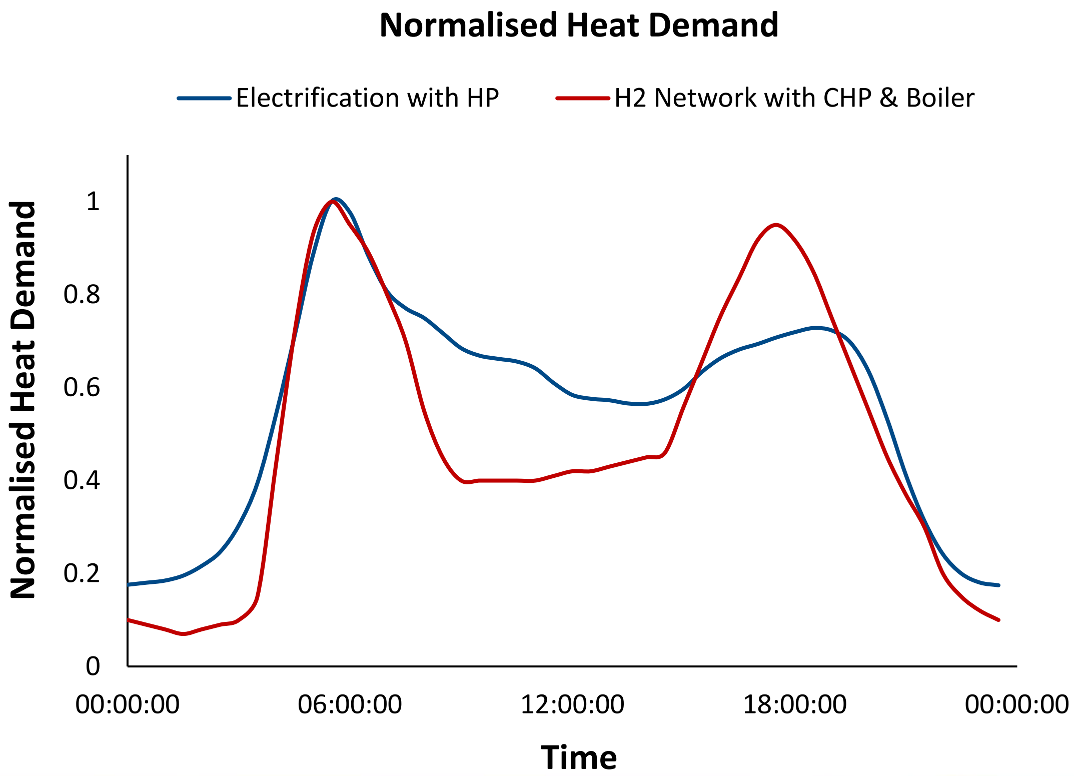


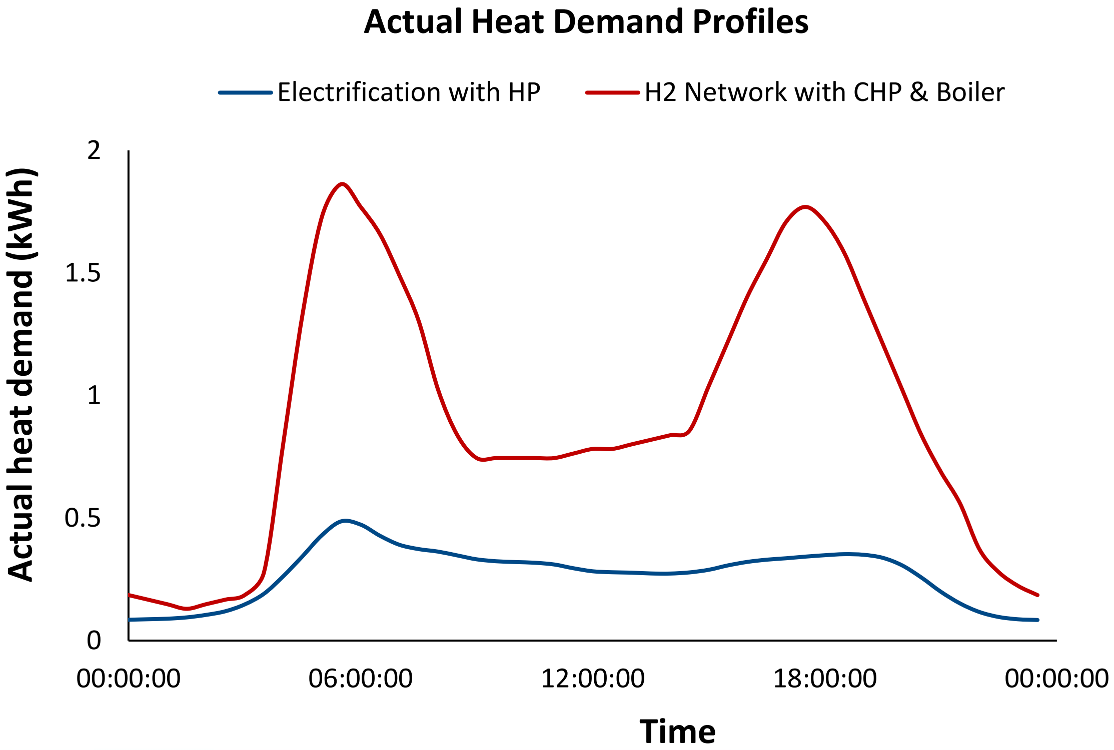
Daily Demand	
Heat Pump	12.62 kWh
Electricity (exc. heat)	10.88 kWh
Total	23.50 kWh

Daily Heat Demand – Boiler

A daily energy consumption profile was generated for a property heated with a boiler, using the heat pump demand profile, a normalised boiler demand profile [6] and the assumption that boilers and heat pumps have efficiencies of 90% and 300%, respectively.

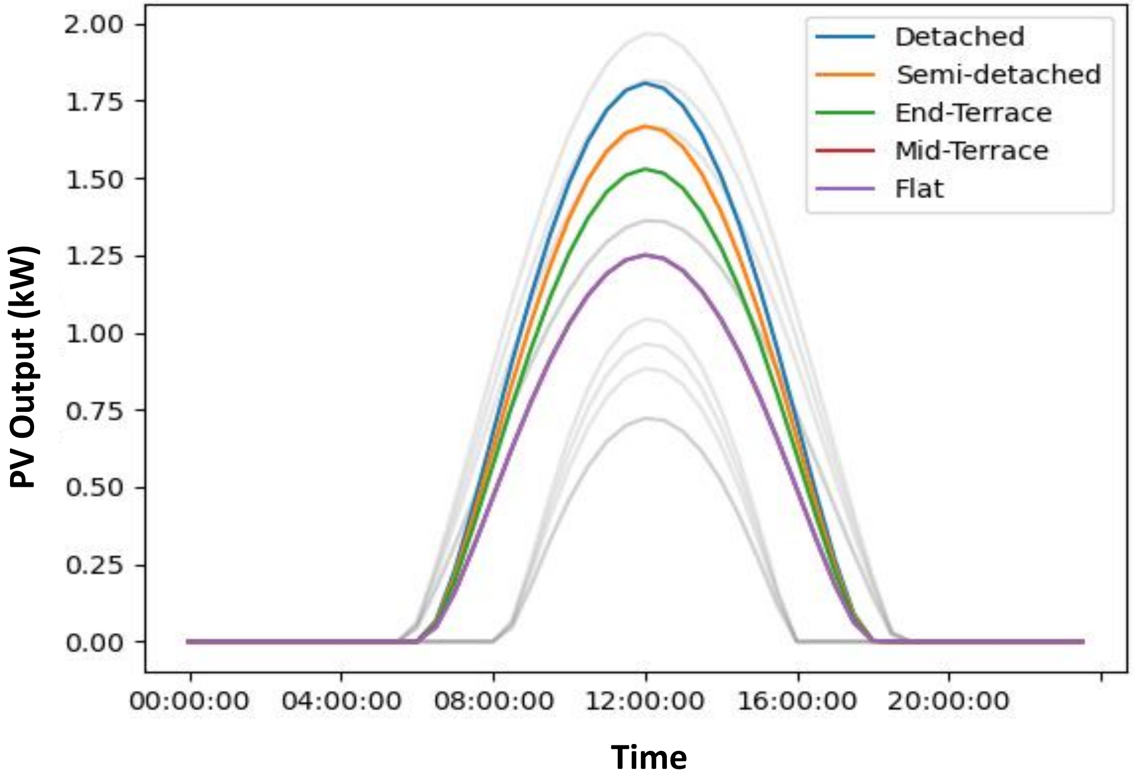
Daily Energy Consumption	
Heat	42.067 kWh
Electricity (exc. heat)	10.88 kWh
Total	52.95 kWh





PV Generation

PV profiles were generated using a python package called solarenergy 0.1.7 [7]. Profiles were generated for different property types based on the table on the right.



House Type	Total Output of Solar PV System (W)
Detached	4,160
Semi-detached	3,840
End Terrace	3,520
Mid-terrace	2,880
Flat	2,880

The profiles show the power PV output for different property types. For the purpose of the Discovery Phase project, it has been assumed that there was no cloud cover and that approximately 1kW installed capacity generates 1,000kWh/year [8]. Colour represents an average day, with low and high outputs grey lines representing winter and summer, respectively.

Storage Requirements

Ofgem have a Quality of Service Guaranteed Standards, which determine the level on compensation the electricity network must pay in recognition of the inconvenience caused by an outage. The length of these outages varies depending on whether there is a severe weather event or normal conditions, but generally the consumers electricity supply is 12, 24 and 48 hours. This corresponds to the following outage lengths:

This corresponds to median electricity storage requirements for homes with heat pumps and EPC ratings A&B:

Property Type	12-hour Outage	24-hour Outage	48-hour Outage
Flat	9.0 kWh	17.9 kWh	35.8 kWh
End-Terrace	11.7 kWh	23.4 kWh	46.8 kWh
Mid-Terrace	11.8 kWh	23.5 kWh	47.0 kWh
Semi-Detached	11.9 kWh	23.7 kWh	47.4 kWh
Detached	16.6 kWh	33.0kWh	66.0 kWh

For context, the average Customer Minutes Lost (CML) in 2019-2020 for GB electricity networks ranged between 30 and 50 minutes for the different networks [9].

Summary

- Due to having such similar energy consumption distributions, for the purpose of Discovery Phase, terraced and semi-detached houses have been combined to be a single property type, which will form the baseline for further analysis.
- Having a heat pump significantly reduces your overall energy consumption, due to the efficiencies associated with water and space heating.
- PV generation is typically at its greatest during the day whilst energy consumption is low, indicating that domestic storage system can contribute towards reducing curtailments, and therefore consumer energy bills.
- Loss of electricity supply is massively inconvenient for consumers, however the average number of minutes lost per customer is generally between 30 and 50 minutes. Storage systems are likely to be able to deal with these outages, however more severe outages that contribute towards reduced network resilience may be more difficult to withstand using conventional domestic storage.

Scalability Requirements References

[1] https://assets.elexon.co.uk/wp-content/uploads/2012/01/28163748/Average_Profiling_data_201314_evaluated%4010yearNET_v1.0.xlsx

[2] https://epc.opendatacommunities.org/

[3] Ruhnau, O., Hirth, L., and Praktiknjo, A. (2019). Time series of heat demand and heat pump efficiency for energy system modeling. Scientific Data, 6, 189. https://doi.org/10.1038/s41597-019-0199-y

[4] Ruhnau, O., Muessel, J. (2022). Update and extension of the When2Heat dataset. Econstor Working Paper. http://hdl.handle.net/10419/249997

[5] Ruhnau, O., Muessel, J. (2022). When2Heat Heating Profiles. Open Power System Data. https://doi.org/10.25832/when2heat/2022-02-22

[6] Love, Jenny, et al. "The addition of heat pump electricity load profiles to GB electricity demand: Evidence from a heat pump field trial." *Applied Energy* 204 (2017): 332-342.

[7] https://pypi.org/project/solarenergy/

[8] https://cat.org.uk/info-resources/free-information-service/energy/solar-photovoltaic/

[9] RIIO-ED1 Network Performance Summary 2019-20 (2020) Ofgem

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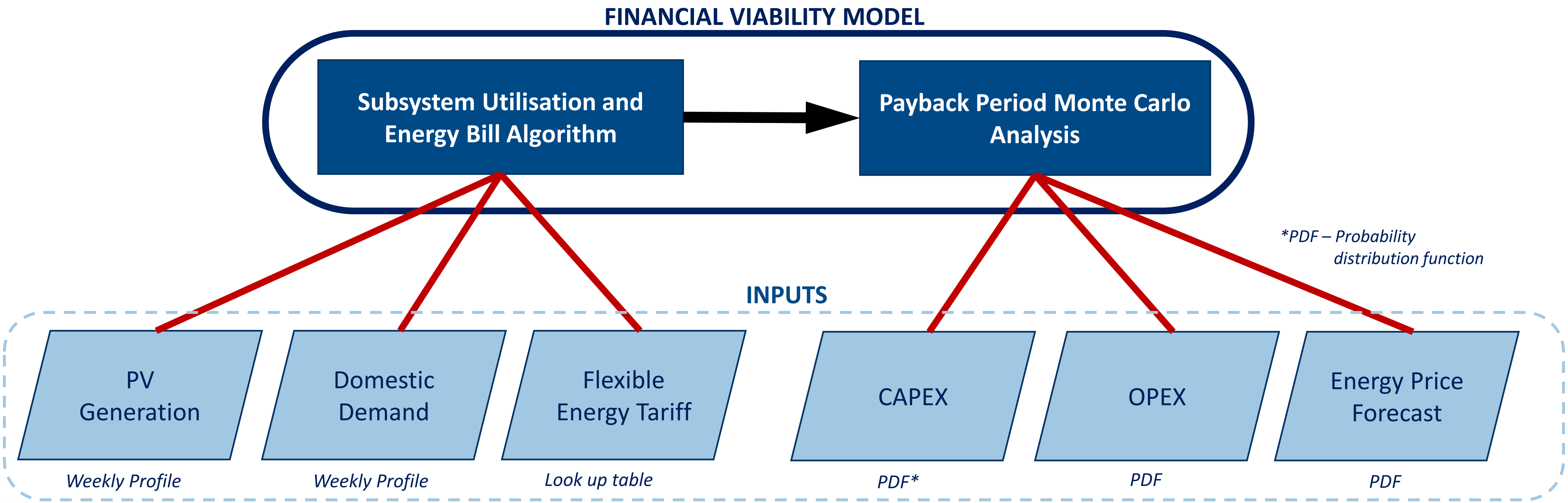
Financial Viability Assessment

It is important to understand whether the technology is economically viable from a consumer perspective. A financial viability model has been developed to generate a payback period for different technology configurations, based on the property energy demand and PV generation profiles.

This has been compared to a property with a Tesla Powerwall storage, to understand the relative payback period compared to market leading counterfactual storage technologies.

Financial Viability Model - Overview

A model was developed to determine how the system would operate during an average week and therefore the energy bills (net income or expenditure) a consumer may expect from having to buy and sell energy. Monte Carlo analysis was used to calculate the payback period for the system, to allow for the inherent uncertainty in CAPEX, OPEX and future energy costs. An overview of the model has been presented here:



Financial Viability Model - Inputs

Technology Parameters – Technology parameters such as efficiencies (η) have been obtained from the Literature Review and Technology Viability Assessments.

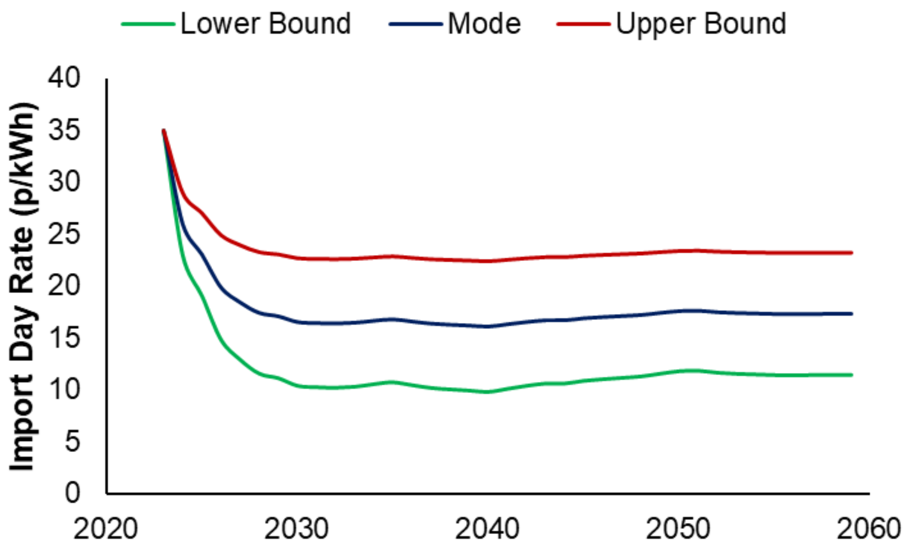
CAPEX - CAPEX costs for individual components were scaled (based on the Technology Viability Assessments) to equal the £20,000 associated with a commercially available LAVO.

OPEX – The costs of an annual service was estimated to be between £360 - £500.

Discount Rates – Discount rates obtained for the vector conversion technologies were generally around 10%, so this was assumed for the entire system.

Current Electricity Costs – The Octopus Flux tariff was used for current import and export costs. With export costs higher during peak demand (4pm – 7pm) and import costs being lower during low demand (2am – 5am).

Forecasted Electricity Costs – The forecasted cost of retail energy is highly uncertain. For the future electricity costs it was assumed that existing Octopus Flux tariff costs followed the forecasted EU baseload trend to 2060 [1]. The figure on the right shows the time-resolved triangular distribution parameters for the standard day rate, which starts at 34.76p/kWh in 2023.



Forecasted Hydrogen Costs – To remove the influence of arbitrage, import hydrogen costs were estimated based on dividing electricity costs by electrolyser efficiency (η_{FC}) and export were based on dividing by fuel cell efficiency (η_E).

Financial Viability Model

Subsystem Utilisation and Energy Bill Algorithm

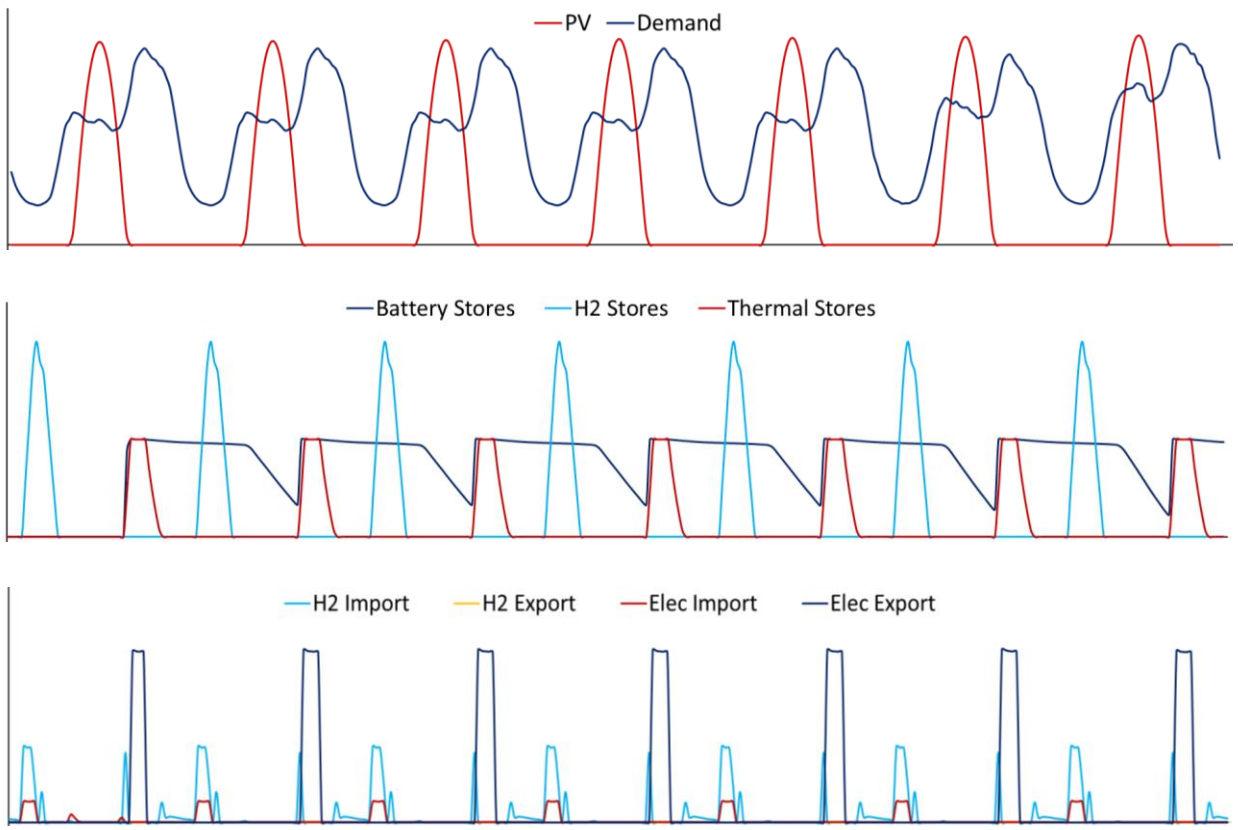
The Subsystem Utilisation and Energy Bill Algorithm was developed to do the following:

1. Ingest the average weekly domestic energy (electricity and heat demand) profiles and PV generation,
2. Calculate the half-hourly utilisation of different subsystems (vector conversion technologies and storage charging/discharging),
3. Compute the energy import required to meet demand when stores are empty,
4. Compute the energy export potential when stores are full,
5. Calculate the expected energy bill associated with the import/export of energy,
6. Determine the expected annual income/expenditure.

Financial Viability Model

Subsystem Utilisation and Energy Bill

An example with arbitrary data has been included below:



Algorithm

As a result of this analysis an average weekly energy bill can be calculated and an annual value can be estimated. This is fed into the Payback Period Monte Carlo Analysis.

The key assumptions by the model include:

- Electrolyser utilises excess PV to generate hydrogen, which is stored.
- Electrolyser also uses electricity during period of low cost electricity, based on Octopus Flux tariff (2am-5am).
- Fuel cell generates electricity to sell during period of high electricity costs, based on Octopus Flux tariff (4pm-7pm).
- Surplus electricity from fuel cell is sold back to the grid.

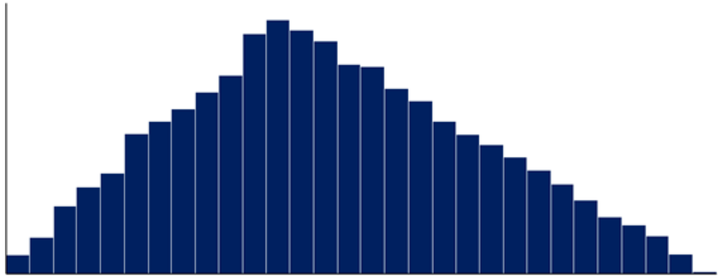
Financial Viability Model

Payback Period Monte Carlo Analysis

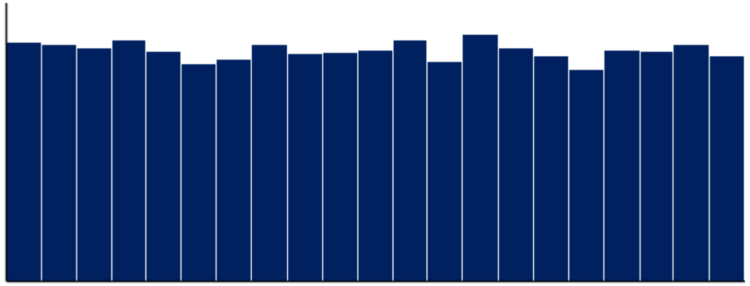
The Payback Period Monte Carlo Analysis was developed to do the following:

1) Define a probability distribution function (PDF) for each of the input parameters, CAPEX, life expectancy, OPEX and energy price. For this study uniform and triangular distributions were used to represent random variables, based on:
    - **Uniform** distribution if there is range of possible probabilities, without a single most likely outcome.
    - **Triangular** distribution if there is range of possible probabilities, yet a single most likely outcome can be identified.
2) Implement a Monte Carlo simulation to randomly sample the potential CAPEX, life expectancy, OPEX and energy price, based on 10,000 simulations.
3) For each simulation calculate the return on investment (ROI), and subsequently the payback period, compared to the counterfactual of having no storage and PV.

Example triangular distribution



Example uniform distribution

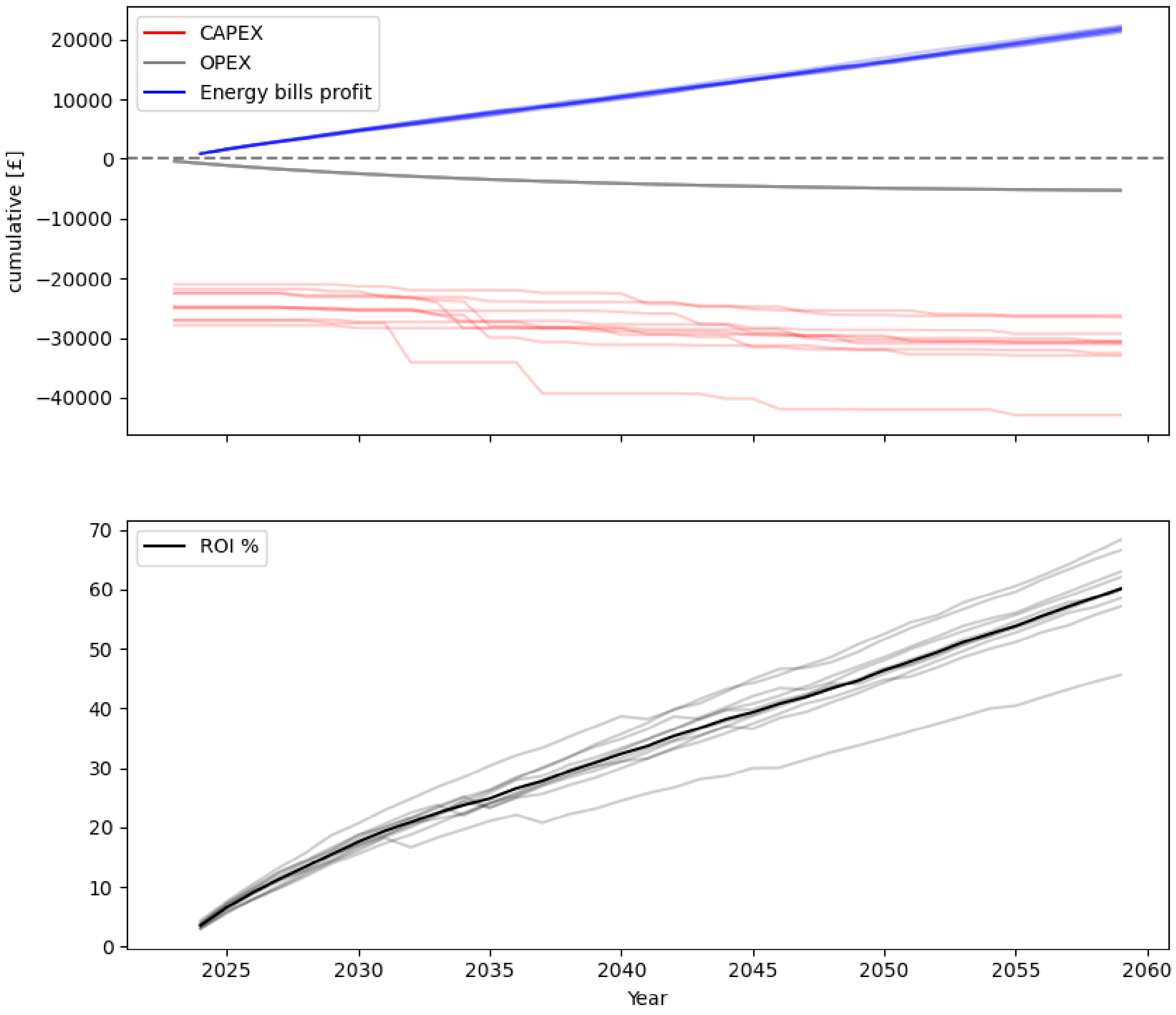


Financial Viability Model

Payback Period Monte Carlo Analysis

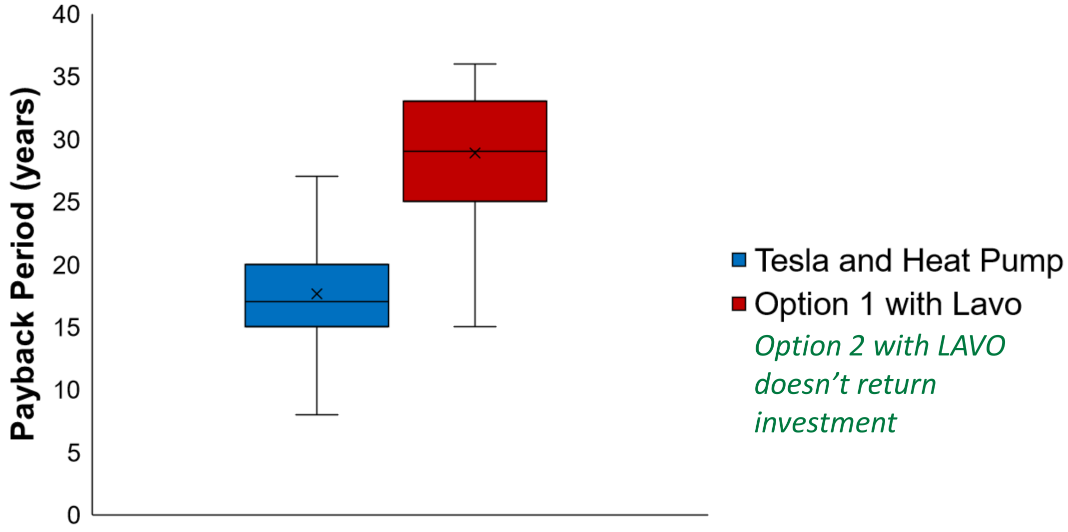
The graphs show how ROI period was calculated in a probabilistic way, using 10 sample examples. The input values for ROI: CAPEX, OPEX, and Profit were sampled randomly 10,000 times. CAPEX and Profit were randomly inputted based on a triangular distribution, whilst OPEX values were randomly simulated using a uniform distribution.

This allows us to understand both the expected ROI over time, as well as the range of uncertainty in its value. Note the graphs are to demonstrate the method for calculating ROI, and is not representative of final ROI or Payback Period estimates. It's clear in the above figure that CAPEX is the main driving factor of uncertainty in the ROI period.



Payback Period

Initially, hydrogen storage deployment Options 1 (with heat pump) and 2 (with CHP and boiler) were modelled, using the specifications associated with the LAVO. These were compared to installation of a Tesla power wall and heat pump, to represent the relative payback period of current commercially available options.



Specifications	Tesla	LAVO
H2 Storage Capacity	0 kWh	40 kWh
Battery Storage	13.5 kWh	5 kWh
Electrolyser Capacity	5 kW	5 kW
Fuel Cell Capacity	5 kW	5 kW

Preliminary results showed that the use of hydrogen storage for a fully electrified property, with a heat pump (Option 1), is not competitive with Tesla, with an average payback period of 29 years, compared to 17 for a Tesla. In the presence of a hydrogen network with a CHP and boiler (Option 2) and LAVO component sizes, the system never pays itself off as the fuel cell never generates enough energy to charge the thermal stores.

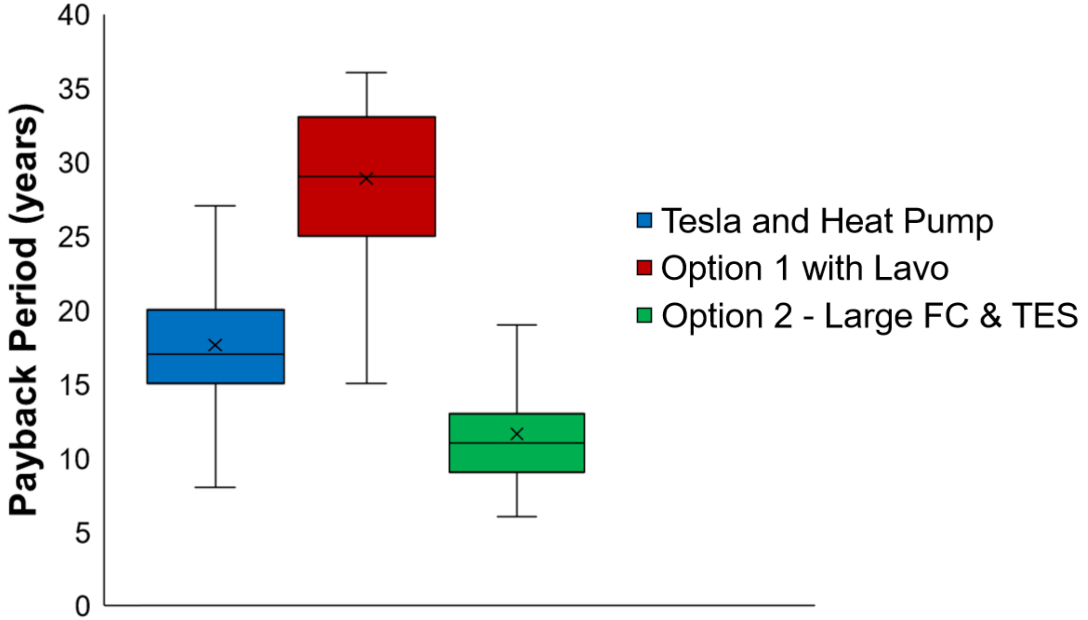
Technology Configurations	CAPEX		
	P5	P50	P95
Tesla and Heat Pump	£21.6k	£25.5k	£30.4k
Option1 with LAVO	£28.7k	£32.8k	£37.7k
Option 2 with LAVO	£20.5k	£23.4k	£26.7k

Payback Period – Option 2 Resizing

A preliminary investigation into different component sizing options to understand whether there were any combinations that made the hydrogen storage device competitive with the Tesla, found that increasing fuel cell capacity and thermal energy storage (TES) capacity gave a notably improved payback period, as discussed on the following slide.

Specifications	Option 1 with Tesla	Option 1 with LAVO	Option 2 - Large FC & TES
H2 Storage Capacity	0 kWh	40 kWh	10 kWh
Battery Storage	13.5 kWh	5 kWh	5 kWh
Thermal Storage	0 kWh	0 kWh	35 kWh
Electrolyser Capacity	5 kW	5 kW	5 kW
Fuel Cell Capacity	5 kW	5 kW	15 kW

Technology Configurations	CAPEX		
	P5	P50	P95
Tesla and Heat Pump	£21.6k	£25.5k	£30.4k
Option1 with LAVO	£28.7k	£32.8k	£37.7k
Option 2 - Large FC & TES	£39.4k	£47.8k	£57.3k



Summary

Option 1 – Electrification with heat pump

- Analysis indicates that the hydrogen storage with vector conversion is unlikely to compete directly with a battery energy storage system for fully electrified properties without connection to the hydrogen network, likely due to lower roundtrip efficiencies.

Option 2 – Hydrogen network with CHP and boiler

- Results suggest that Option 2 isn't feasible with LAVO sized subsystems.
- Energy consumption for heating is more than 3 times higher than using a heat pump. As a result, the 5 kW fuel cell CHP never produces enough surplus thermal energy to match heat demand and charge the TES, making it redundant. Therefore, the property is primarily heated by the boiler.
- Increasing the size of the fuel cell to 15 kW and TES capacity to 35 kWh means that when the fuel cell is generating electricity during the peak export price period, it matches the property's power demand, exports surplus to the grid, and generates sufficient thermal energy to heat the property whilst simultaneously charging the thermal energy store. It should be noted that the CAPEX costs are extremely high for this system configuration.
- The hydrogen storage is difficult to fill with the limited PV surplus and by running the electrolyser during the period of low electricity cost. Also, hydrogen stores are depleted rapidly with the 15 kW fuel cell operating at full capacity, meaning fuel cell operation resorts to depending on supply from the hydrogen network. This suggest that filling the hydrogen storage vessel and using it for long term storage rather than intraday fuel cell operation could be a more effective strategy.

Financial Viability References

[1] https://energypost.eu/eu-energy-outlook-to-2060-how-will-power-prices-and-revenues-develop-for-wind-solar-gas-hydrogen-more/

Conclusions

Conclusions have been drawn based on the Feasibility Threshold statements, outlined at the beginning of the report.

Conclusions

Based on work completed during Work Package 1, the following feasibility threshold responses can be concluded:

- It is technically feasible to integrate P2G, G2P and hydrogen storage technologies at domestic scale.
  - *The Technology viability assessment suggests it is technically feasible to install these systems at property level, with space and cost being the greatest barrier.*
- There are combinations of property types, network characteristics and geographies where this could be deployed.
  - *It appears that most property types, with exception of a flat, could deploy this technology, due to preferentially being installed outside. Network characteristics and geographies will be explored in WP2.*
- The locally deployed solution can be implemented to improve resilience at national scale.
  - *This is being investigated in WP3 by Imperial College London.*
- There is at least one legitimate consumer use case for installation of the systems.
  - *Preliminary results suggest that the legitimate consumer use case would require connection to a hydrogen network, with optimal sizing of the fuel cell and TES being critical. Currently, upfront costs are likely too high for most consumers, so rollout could dependent on appropriate subsidisation or carbon taxing.*
- The technology provides comparable consumer and network benefits with counterfactual systems, such as battery storage.
  - *Once upfront costs have been covered the consumer can have their energy bills covered whilst making a profit. The novel network resilience is offered through utilisation of a parallel hydrogen network.*