Department of Mechanical and Aerospace Engineering

Enhancing the utilisation of non-dispatchable Renewable power

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A thesis submitted in partial fulfilment for the requirement of the degree

Master of Science

Sustainable Engineering: Renewable Energy Systems and the Environment

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Copyright Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: Date: 4th September 2015

Abstract

The purpose of this thesis is to investigate opportunities of **enhancing the utilisation of non-dispatchable on-site Renewable power**, when in excess to site demand. To investigate this, an energy intensive factory that has deployed several on site renewable energy technologies was studied. After analysis and modelling of the energy supply and demand requirements of the factory, the project reviewed all possible electrical energy storage technologies and progressed to differentiate the technologies that were most applicable to the site under review.

One technology reviewed that does technically achieve the site requirements, is liquid air energy storage, (LAES), which has the potential to deliver various benefits to the factory, including almost 3,000 tonnes per year of CO_2 reductions and £1m of energy cost benefits, in addition to enhanced security of supply.

A detailed review of the background to LAES was completed before carrying out a cost benefit analysis. This highlighted that the capital costs requirements of a LAES plant currently prove prohibitively high, for this application, due to the development status of the technology package. A sensitivity analysis indicates that individually, capital costs or grid electricity price would need to move substantially to change the commercial viability of the technology, but a more realistic combined impact is possible.

The project concludes that there are selected emerging technologies, (LAES, Power to gas, and batteries), that meet the site requirements, but future analysis is required to assess the commercial viability of each, particularly with ongoing development, improving efficiency and reducing equipment capital costs.

Acknowledgements

This thesis concludes my studies with the University of Strathclyde as a part time student. I would therefore like to thank all of the staff on the Renewable Energy Systems and the Environment course for their help and in particular Dr. Paul Strachan, from whom I have received valuable support throughout the last 2 years of study. My family and work colleagues also need thanks for their patience and support in helping me complete this thesis.

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1. Introduction

1.1. Objectives

The purpose of this thesis is to investigate opportunities of **enhancing the utilisation of non-dispatchable on-site Renewable power**, when in excess to site demand. To investigate this, an energy intensive factory that has deployed several on site renewable energy technologies was studied, although the technologies and strategies investigated are also applicable on a regional and national level.

Many organizations today have clear strategies on environmental sustainability, GlaxoSmithKline (GSK) has corporate responsibility commitments that are aligned to delivering our products, to our customers within a global market that are affordable and have minimal impact on the environment.

GSK values use engagement with a range of external stakeholders as an effective tool for gaining deeper insight into societal trends and expectations, as well as offering us the opportunity to challenge our own assumptions about the way we work.

We are willing to fundamentally change the way we do things to better meet stakeholder expectations. As well as ongoing stakeholder engagement, we carry out additional research to determine current and emerging issues to help shape our approach to responsible business.

For example, in 2013, GSK undertook a formal materiality analysis, gathering internal and external perspectives on the key areas that have considerable financial, operational, and/or reputational impacts on the company (see chart below). While this identified all the issues relevant to our business, we focus our efforts on those of high or medium importance to GSK and our stakeholders (1)[1].

[1] http://www.gsk.com/media/618264/gsk-responsible-business-supplement-2014.pdf

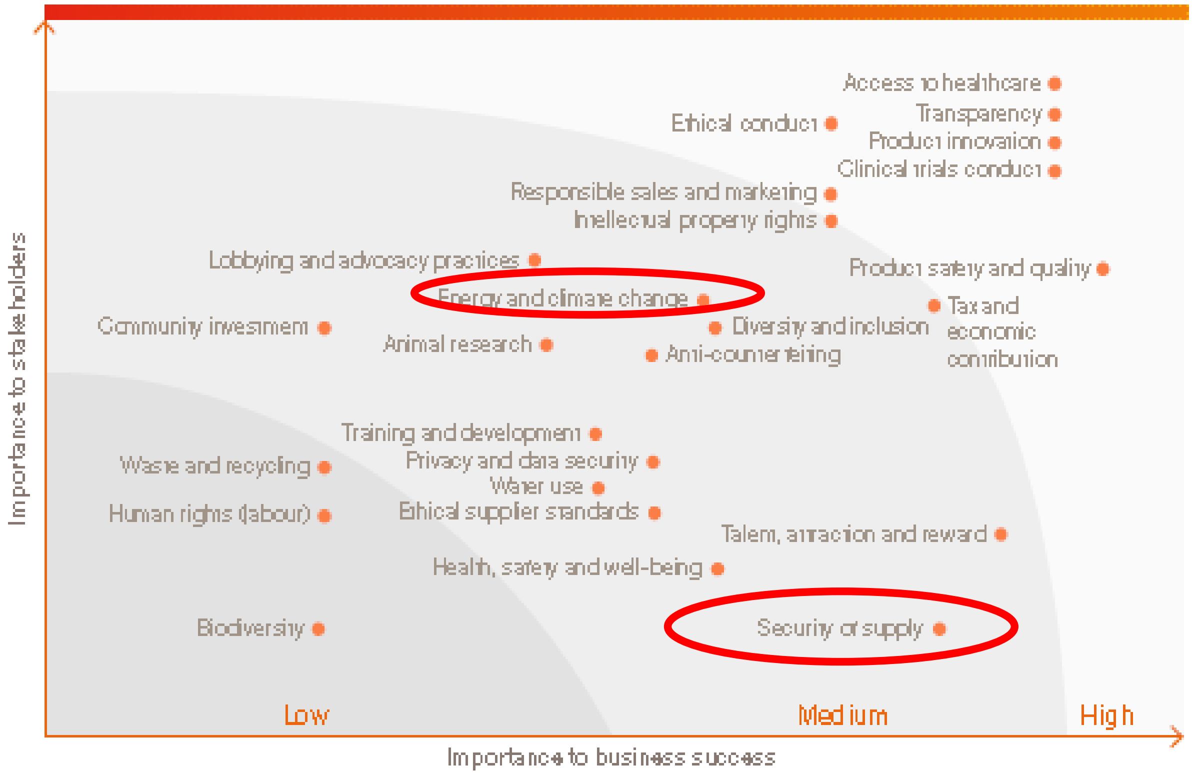

Figure 1 : Prioritising our most material issues, Sourced from GSK website. (2)

From an environmental and product cost perspective "Energy and Climate change" and "Security of supply" are relevant to this thesis.

"Energy & Climate Change" is one of the world's most pressing issues and a major threat to people's health and global economic development. Impacts like extreme weather and heat waves affect food production and availability of clean water and sanitation, and threaten hard-won global health improvements.

By using resources more efficiently, and collaborating with others to tackle these challenges, we can reduce costs and enhance competitiveness. GSK have set ambitious goals to reduce carbon, water and waste across our value chain – from the sourcing of raw materials and the impacts of our own labs and factories, to the use and disposal of our products by patients and consumers.

GSK would like to be the most sustainable healthcare company and has set a target to reduce its carbon footprint by 25% by 2020 and have a carbon-neutral value chain by 2050. The GSK Irvine Sustainability programme is a key element in achieving these targets.

Therefore, with the considerable investment that has been placed into the Irvine site GSK continues to investigate the most cost efficient and environmentally favourable technologies to maximize the benefits of this investment. There are several elements of the site demand, related to the size/scale of the onsite generation that are key in developing the need for this.

The GlaxoSmithKline (GSK) manufacturing facility, located in Irvine, Ayrshire, 30 miles South West of Glasgow, Scotland is the single largest energy consumer within GSKs global network of 80 manufacturing facilities. The site is a key asset in the manufacture of Antibiotics, converting primary raw materials, through fermentation, enzymatic and extraction technologies, into Active Pharmaceutical Ingredients (APIs), for GSKs global Augmentin franchise. Due to the large-scale fermentation, enzymatic and extraction technologies required to manufacture these products, the quantity of energy required is considerable. The facility runs 24/7 with infrequent downtime as maintenance and cleaning activities are carried out within production cycles. On average the facility has a 20 MWe power demand and an 18MWth heat demand that results in a £15m annual energy cost. The subsequent Carbon footprint of the site is considerable with a peak of 102,000 tonnes of CO_2 from scope 1&2 emissions[2] in 2014.

Despite increasing production volumes, over the last 6 years GSK Irvine has been extremely successful in delivering year on year carbon footprint reductions, which have been achieved through the installation of energy efficiency improvement projects including, (electric motor upgrades, chiller, compressor, and motor control improvements, transformer upgrades, lighting and HVAC control upgrades, 4MW natural gas CHP with absorption chilling, and small scale solar PV for individual buildings).

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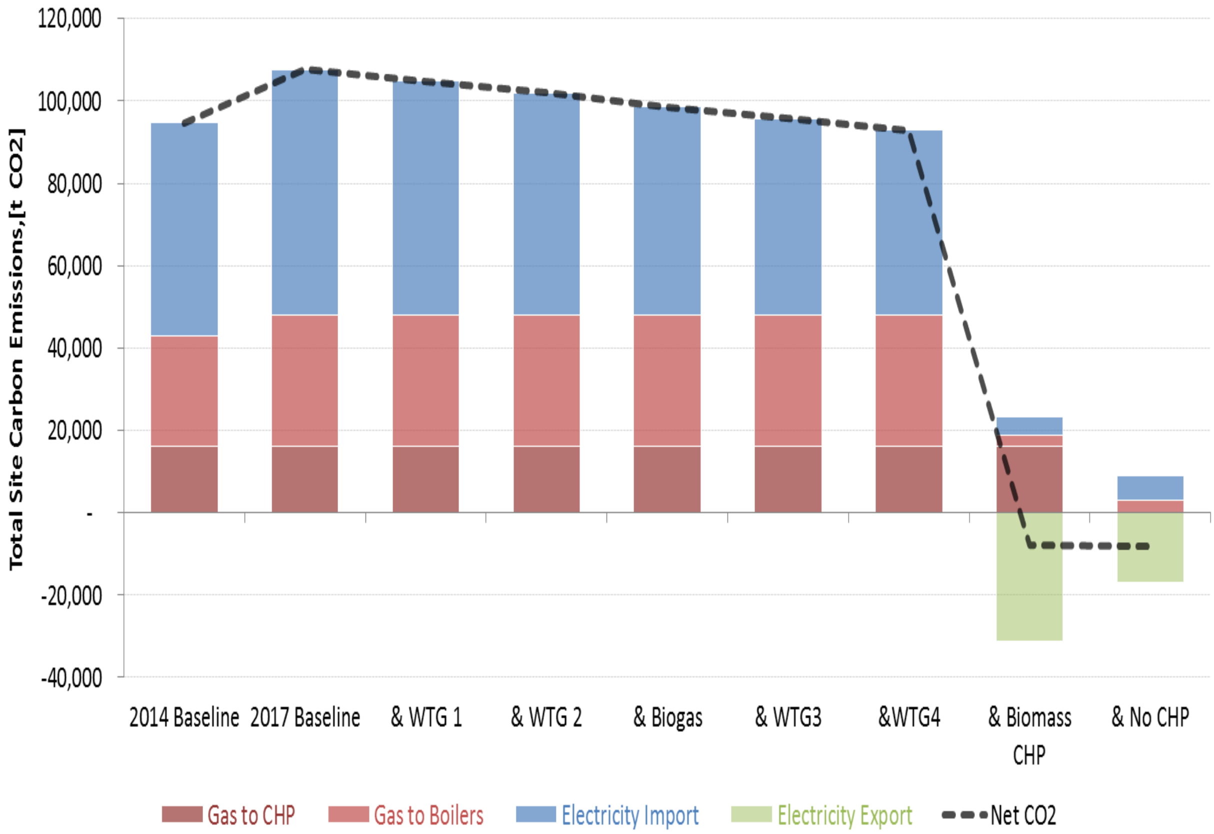
[2] Scope 1 (Direct emissions): Emissions from activities owned or controlled by your organisation. Examples of Scope 1 emissions include emissions from combustion in owned or controlled boilers, furnaces, vehicles; emissions from chemical production in owned or controlled process equipment.

Scope 2 (Energy indirect): Emissions released into the atmosphere associated with your consumption of purchased electricity, heat, steam and cooling. These are indirect emissions that are a consequence of your organisation's energy use but which occur at sources you do not own or control.

Alongside these efficiency improvements monitoring and targeting of key energy users within the site, with real time performance management, that is aligned to GSKs lean management system (GPS) was also developed.

Following the ongoing efficiency improvement activity, GSK has invested in large-scale renewable technologies

- Anaerobic digestion of site effluent to produce Biogas – 2x500 KW CHP.
- Wind Turbine Generators – 2 x 2.5 MW installed, 2 x 2.5 MW planned.
- Biomass –20 MWe / 18 MWth Recycled & Residue woodchip CHP.



Graph 1 : Route to Carbon Neutral (from GSK Biomass Concept Report – 2014)

1.2. Report Structure/ Project Methodology

Section 2 - **Error! Reference source not found.**, will establish an overview of energy storage technologies and develop a selection process designed to identify the most likely commercial or emerging technology that will enable the enhancement of the use of excess non-dispatchable renewable power.

Section 3 - Error! Reference source not found.**,** models the site power demands, their variable profile in relation to the size of each on-site renewable technology. This also needs to be considered in relation to the current 9MWe export capacity for spill of surplus power into the distribution and transmission networks and a proposed increased export capacity that is required for financial investment in a planned 20MWe Biomass CHP. Also within this section is a review of the financial impacts of the import / export power prices and how this influences the need for onsite energy storage.

Section 4 -Assessment of Applicable Storage Technologies, covers the comparison of the reviewed energy storage technologies and investigates which technology or group of technologies are most appropriate towards implementing electrical energy storage within the Irvine site.

Section 5 - Assessment of Liquid Air Energy Storage (LAES), covers an assessment of an emerging technology that has the potential to maximize the use of excess non dispatchable renewable power and provides an overview of LAES. This includes a detailed review of the technology constraints and details on its application within the GSK Irvine site by modelling the site energy profile after implementation. Finally completing a cost benefit analysis to identify if the technology is feasible for use within the Irvine site and its sensitivity the capital cost and grid electricity price movements.

Finally, **section 6** - Conclusion completes the thesis by summarising the content and identifying the recommendations required to facilitate the development and implementation of this technology.

2. Review of Energy Storage Technologies

2.1. Introduction:

Renewable energy sources, such as wind power and solar PV and Biomass/Biogas CHP, as stated above have vast potential in minimising the reliance on fossil fuels and subsequent unsustainable emissions of greenhouse gas. Within the GSK Irvine site the size and scale of these technologies have been developed to provide the most economical use of base load technologies, with Biomass CHP being scaled to the site heat demand and Biogas CHP maximising the use of available waste streams. The installation of wind energy achieves the sites energy demand requirements, enabling the site to achieve full autonomy of net annual energy demand, although as seen in the previous section the demand profile coupled with a variable and uncertain wind power output results in the export “spill” of renewable power onto the grid and undesired import of grid power at various times. This is also exacerbated by the reliance on combined heat and power as the demand for heat sometimes occurs during, windy periods, when electricity demand is low and wind generation is high. This combination sometimes results in an oversupply of generation and has led to investigation of the deployment of energy storage as a component of the site energy system.

Energy storage provides a solution to avoiding this situation by absorbing unusable generation and moving it to times of high demand. To establish the feasibility of integrating energy storage a technical and economic assessment of a variety of competing technologies was required. This included demand response, capacity, efficiency, cost, flexibility, impact on system stability and the maturity of each technology. (2)[3]

Before assessing storage technologies it is important to note that there is a range of alternative options available to mitigate this issue, for the Irvine site these include, demand management and flexible generation, which have been described in section 1, in addition to storage technologies.

[3] **The Role of Energy Storage with Renewable Electricity Generation,** Paul Denholm, Erik Ela, Brendan Kirby, and Michael Milligan ***Technical Report,*** **NREL/TP-6A2-47187 January 2010**

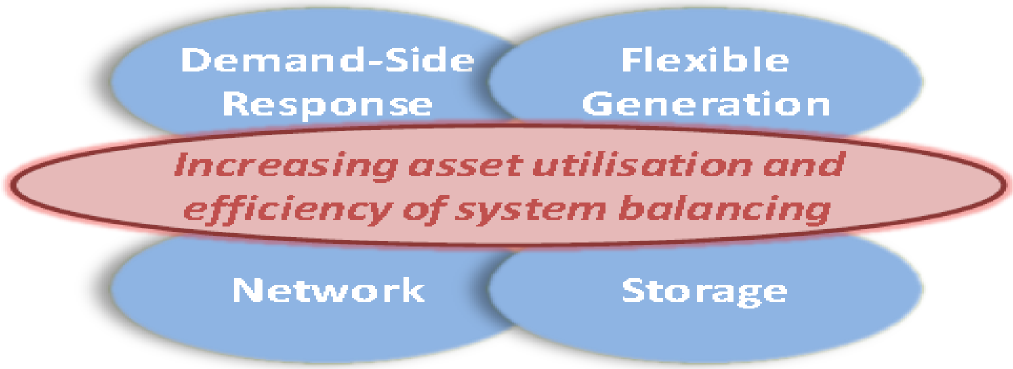


***Figure** 2 : Technology options for mitigating system integration cost in low carbon systems (3)* [4]

2.2. Overview of Energy Storage Technology

Energy storage systems are normally classified by the form in which the energy is stored (see Figure 3) and their key characteristics include the amount of power that they can deliver, how much energy they can store, their round trip efficiency, and the extent to which increasing numbers of charging / discharging cycles impacts their performance.

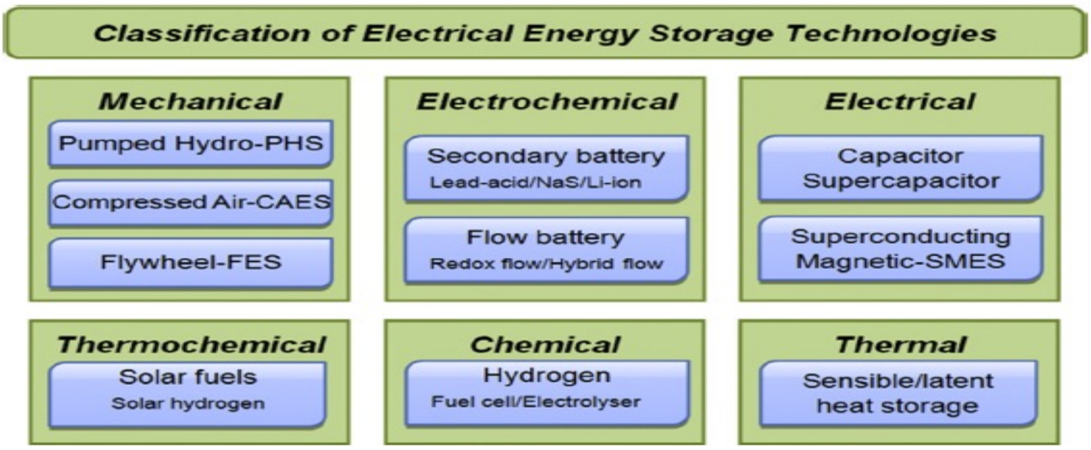


Figure 3 : Examples of energy storage technologies classified by the form of stored energy (3).

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[4] **Strategic Assessment of the Role and Value of Energy Storage Systems in the UK Low Carbon Energy Future Energy Futures Lab, Imperial College London, Report for The Carbon Trust, June 2012, Goran Strbac, Marko Aunedi, Danny Pudjianto, Predrag Djapic, Fei Teng, Alexander Sturt, Dejvises Jackravut, Robert Sansom, Vladimir Yufit, Nigel Brandon**

Considering these various types of storage technology, the following diagram illustrates typical system, power and storage sizes. An overview of typical characteristics of some energy storage technologies is then provided in table 2.

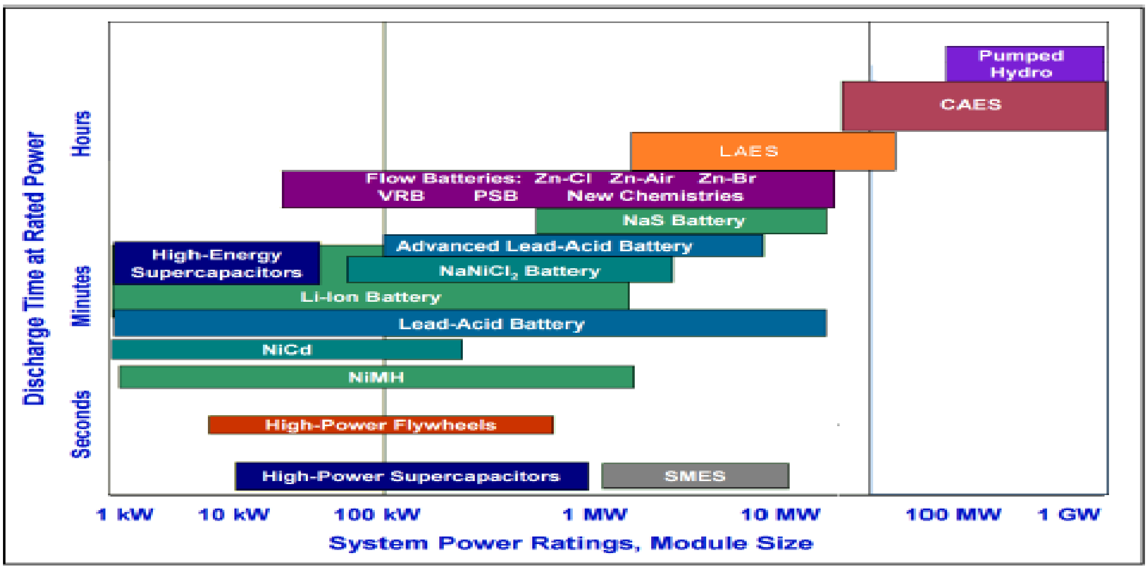

Figure 4 : Energy storage classified by typical power ratings and discharge times (adapted from EPRI).N.B. CAES: Compressed Air Energy Storage; LAES: Liquid Air Energy Storage; VRB: Vanadium Redox Battery; PSB: Polysulfide bromide battery; SMES: Superconducting (4)

2.3. Overview of Main Storage Technologies:

2.3.1. Pumped Hydro

Pumped hydropower is at the present time the most widely utilised storage technology in the world at around 99% of the current worldwide energy storage capacity, representing around 127,000 MW (5)[5]. The technology developed can be scaled up to several Giga watts (GW) and has a typical efficiency of 70% to 80%. Pumped storage hydroelectric technology is well developed and well-suited for applications requiring large power levels and long discharge times. The general configuration and operational sequencing includes water being pumped into a storage reservoir during times of low load when surplus electricity is available. This water is then released through turbines to generate power supplying the peak demand.

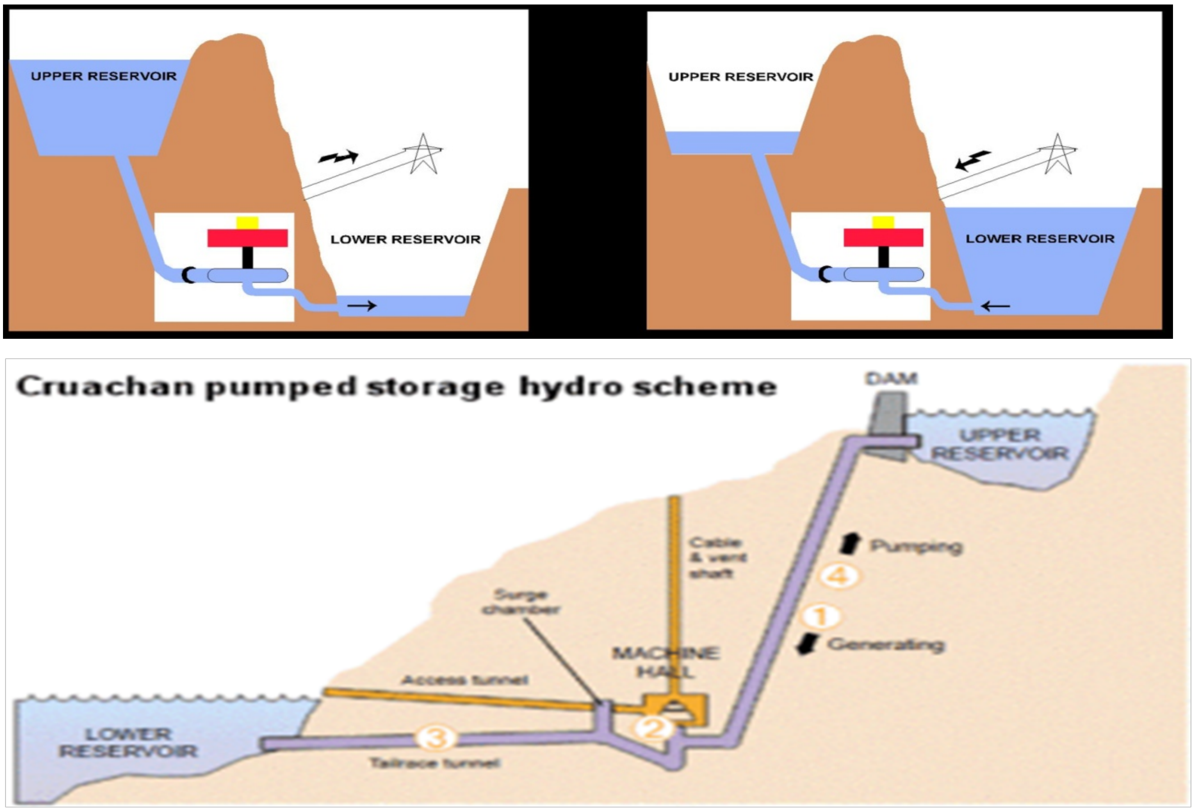

Figure 5 : Schematic of the Cruchan pumped storage hydro scheme. (7)

[5] "Energy storage - Packing some power". *The Economist*. 2011-03-03. Retrieved 17 July 2015.

Pumped hydro schemes (PHS) are utilised in situations where an immediate supply of power is needed, (spinning reserve) to cover demand peaks, frequency regulation and voltage control.

By using variable speed turbines and pumps these facilities can either use available electricity to transfer water between reservoirs to store potential energy, then during peak-load periods, control the generation of electricity in response to the required demand, (Power output can be changed in times of 10-30 ms). PHS has a low energy density and therefore requires either very large reservoirs or a large height difference between the upper and lower reservoirs which is a key aspect in limiting the deployment of this technology. There are also concerns over the substantial environmental impact and considerable initial capital cost although as an established mature technology with high reliability and a lengthy lifecycle, PHS delivers a cost effective means of large scale energy storage.

Characteristic	**Value**
Typical production capacity (MW)	5,000
Maturity	Commercial
Deployment time	minutes
Efficiency	70-80%
Cycle lifetime (cycles)	20,000-50,000
Life time (yr)	> 30
Self-discharge (%/month)	0

Table 1 : Characteristics of Pumped Hydro Storage systems (7)[6]

2.3.2. Compressed Air

Compressed air energy storage, (CAES) can be used to store excess renewable electricity mechanically and is a commercialised technology at a scale that can provide a power output in excess of 100MW from an individual installation.
The system utilised excess renewable power to compress air, this is done by injecting it into large underground caverns or within surface tanks. During the compression process the air heats up, this heat is utilised in the next stage when power is required.

[6] Systems analyses Power to Gas: A technology review, Part of TKI project TKIG01038 – Systems analyses Power-to-Gas pathways Deliverable 1: Technology Review

During this second stage compressed air is released to drive turbines. This expansion cools down the air cools down and must be re-heated to improve efficiency. The way the cooling and reheating is utilised, characterises the CAES. If the heat produced on compression is lost, the air needs to be reheated prior to expansion in the turbine, The process is called diabatic CAES which has a low round-trip efficiencies typically <50%. In an adiabatic CAES process, the generated heat is retained in thermal storage prior to being used in the second stage during expansion in the turbine where typical efficiencies of up to 70 % can be achieved. (8)[7]

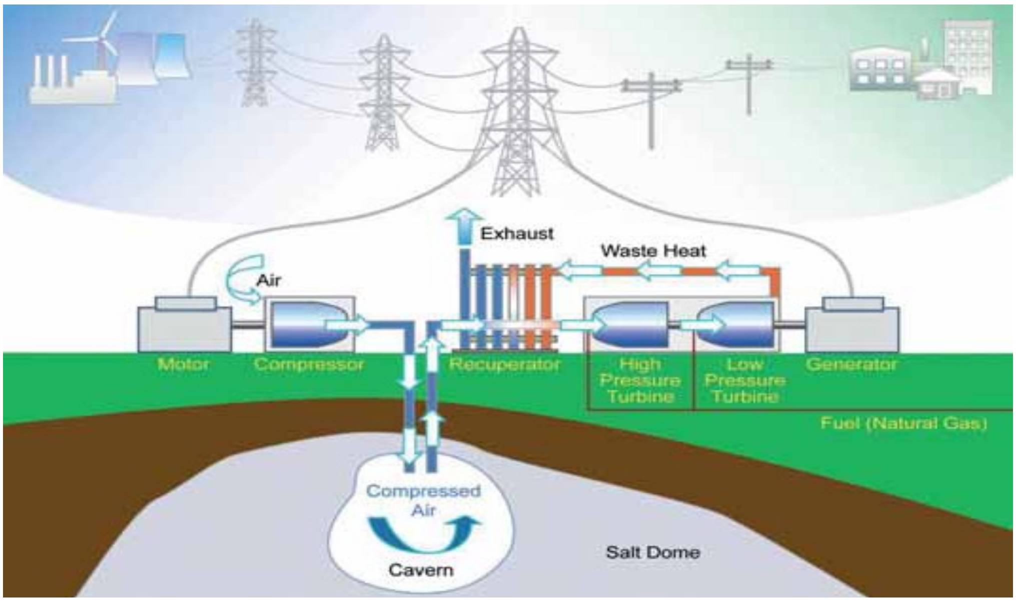

Figure 6 : Ridge Energy Storage & Grid Services L.P: (6)

http://www.ridgeenergystorage.com, Accessed 14th August 2015

2.3.3. <u>Thermal Energy Storage</u>

Thermal energy storage covers a range of technologies that utilise heat energy which can be stored in insulated environments. These technologies generally utilise a solid, gas or liquid material and a package of equipment including the insulated thermal store, chiller or refrigeration equipment, pumps and piping. One example of this type

[7] Overview of current development in electrical energy storage technologies and the application potential in power system operation, Xing Luo, Jihong Wang, Mark Dooner, Jonathan Clarke School of Engineering, The University of Warwick, Coventry CV4 7AL, UK

of technology is Cryogenic energy storage where liquid nitrogen or liquid air is used to achieve the electrical and thermal energy conversion. For example, Liquid Air Energy Storage (LAES) is an attractive option due to the high expansion ratio from the liquid state to the gaseous state and the high power densities of liquid air compared to that of gaseous state of air. The technology as demonstrated by is modular, which means that each of the charging, storage and discharging components of the system can be sized independently. Charging the system works by using electricity to cool air down to -196° (Stage 1 in Figure 3-1 below) at which point it is in a liquid state, and every 700 litres of ambient air have been compressed to form 1 litre of liquid air. During Stage 2, liquid air is stored in an insulated tank at low pressure. This equipment is already globally deployed for bulk storage of liquid nitrogen, oxygen and LNG. These storage units also represent a small amount of the total capital cost of the system. Finally, power is produced in Stage 3 by pumping the liquid air to a high pressure. On heating, using stored heat from the air liquefier or waste heat from other processes, a high pressure gas is produced which is then used to drive a turbine. During Stage 3, the waste cold produced is stored and used at a later time to enhance the efficiency of Stage 1. (10)[8]

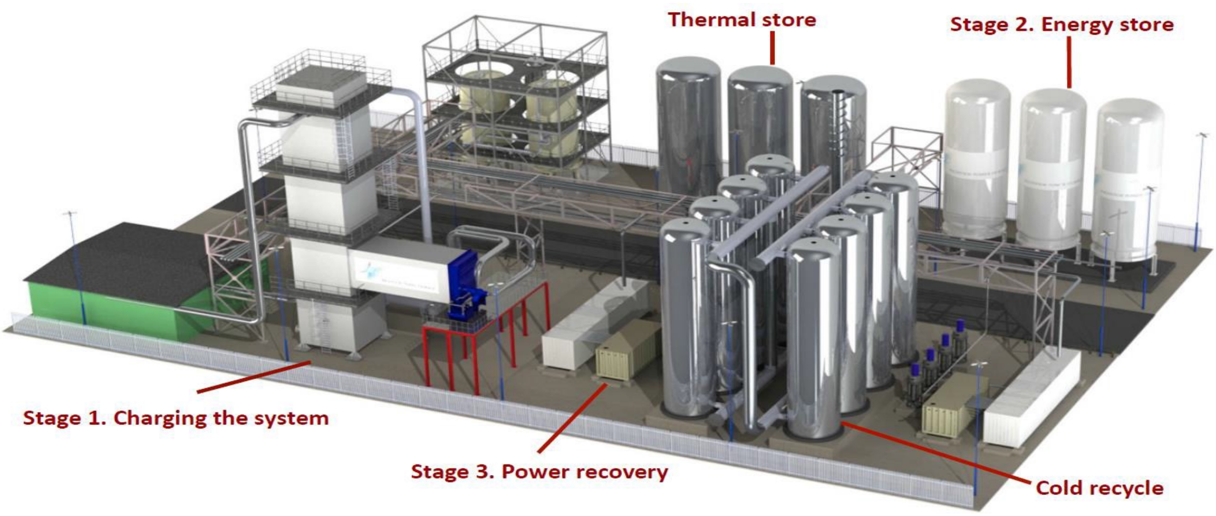

Figure 7 : Visualisation of an LAES plant. Source: Highview Power brochure.

8 Liquid air energy storage – Analysis and first results from a pilot scale demonstration plant, Robert Morgan, Stuart Nelmes, Emma Gibson, Gareth Brett, School of Computing, Engineering and Mathematics, University of Brighton, Brighton BN2 4GJ, United Kingdom, Highview Power Storage, 1 Northumberland Avenue, London WC2N 5BW, United Kingdom

2.3.4. Molten salt (Sodium sulphur battery (NaS))

The Sodium–sulfur battery (or NaS battery), along with the related lithium sulfur battery, is one of the more advanced molten salt battery systems. The NaS battery is attractive since it employs cheap and abundant electrode materials.
Sodium sulphur batteries as displayed in Figure 8, consist of liquid sulphur at the +ve electrode and liquid sodium at the -ve electrode; both liquids are separated by a solid ceramic electrolyte. The temperature is kept between 300 °C and 350 °C to ensure that the electrodes remain molten. Sodium-sulfur batteries are a commercially available with existing applications in distribution grid support, wind power integration, and high-value service applications on islands. The round-trip ac-to-ac efficiency of sodium-sulfur systems is approximately 80% with a life cycle of approximately 15 years at 4500 cycles. The main disadvantage is the need to keep the battery at a optimum temperature, therefore a separate or parasitic heat source is required, which impacts its efficiency partially reducing the battery performance. The technology is most suited to applications with daily cycling with a response time in milliseconds making the application ideal for grid stabilisation[9].

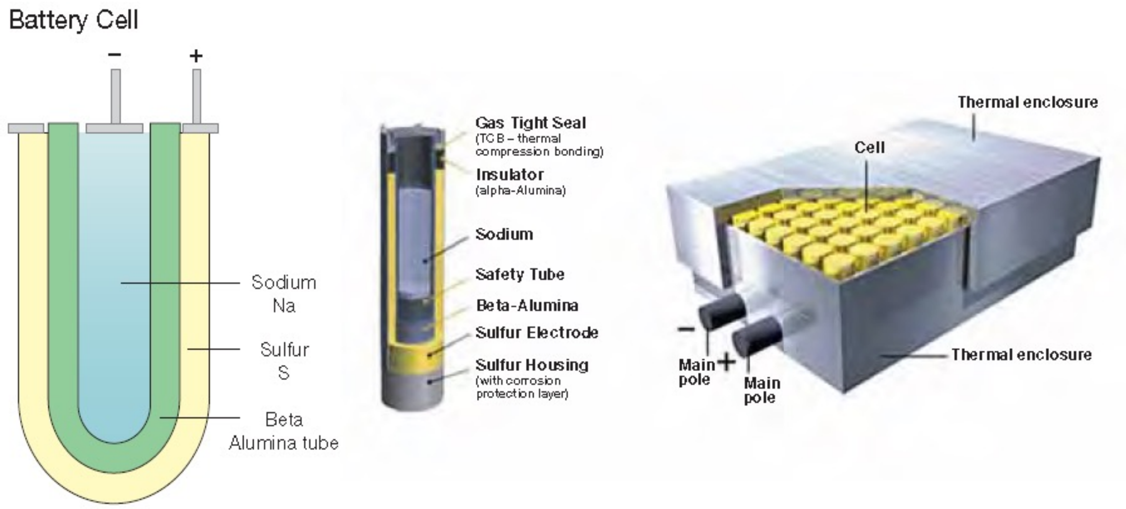

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Figure 8 : NaS Battery: Cell design and 50 kW module (11)

[9] International Electrotechnical Commission (IEC) - Electrical Energy Storage white paper 2011.

2.3.5. Flow batteries

Flow batteries store energy in two external liquid electrolyte tanks. The operation of a flow battery is based on the reduction-oxidation reactions of the electrolyte solutions and occurs when electrolytes are pumped from the tanks to the cells which are separated by ion selective membranes.

- When charging, one electrolyte is oxidized at the anode and another electrolyte is reduced at the cathode.
- Electrical energy is converted to the electrolyte chemical energy.
- On discharging the above process is reversed.

Flow batteries can be classified into the categories of redox flow batteries and hybrid flow batteries, depending on whether all electroactive components can be dissolved in the electrolyte. Figure 9 : Schematic diagram of a vanadium redox flow battery system. shows a schematic diagram of a vanadium redox flow battery system.

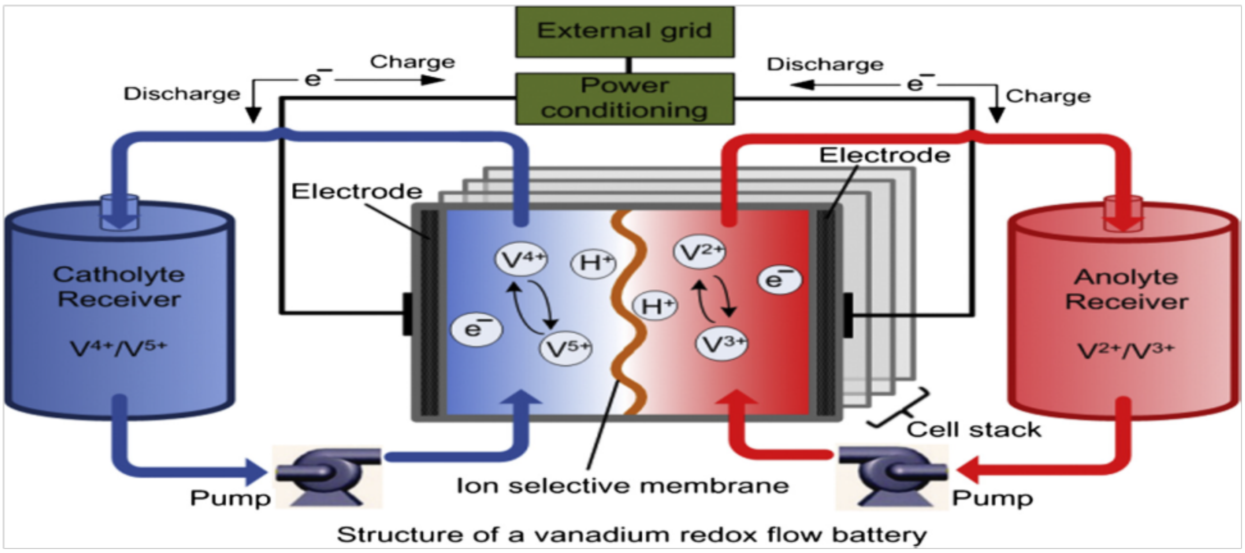

Figure 9 : Schematic diagram of a vanadium redox flow battery system (8).[10]

Redox flow batteries (RFB) have a catholyte (positive electrode) and anolyte (negative electrode) which are stored in two different storage tanks and circulation

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[10] Overview of current development in electrical energy storage technologies and the application potential in power system operation Xing Luo, Jihong Wang, Mark Dooner, Jonathan Clarke School of Engineering, The University of Warwick, Coventry CV4 7AL, UK

loops, but are passed into a common electrochemical cell. The electrolytes react via a redox reaction in the porous electrodes producing an exchange of charge. An ion selective membrane which is permeable only to specific ions is in place to separate each side of the electrode cell to equilibrate the redox reaction completing the circuit. The Vanadium Redox Flow Battery VRB is one of the most mature flow battery systems (12)[11].

Hybrid flow batteries include the features of established secondary batteries and redox flow batteries. Typical examples of a HFB are the ZnCe and the ZnBr systems. In a ZnBr battery there are two aqueous electrolyte solutions which contain the reactive components; these are based on zinc and bromine elements. These two electrolyte solutions flow through the electrolytic cells during the charging/discharging phases, where the reversible electrochemical reactions occur.

Electrical energy storage applications using ZnBr batteries are in their early stage of development and not fully commercialised, but they have some clear benefits with relatively high energy density and cell voltage with deep discharge capability and good reversibility.

The disadvantages of flow batteries:

1. low performance resulting from:

    a. non-uniform pressure drops and the reactant mass transfer limitation,

2. compared to traditional batteries flow batteries have high manufacturing costs due to complicated system requirements

An advantage of flow batteries are:

1. Discharge duration can be increased by adding more electrolyte or regenerated by replacing the depleted electrolyte.
2. They have a long life,
3. short response time,
4. low maintenance costs

[11] Battery energy storage technology for power systems , An overview K.C. Divya, Jacob Østergaard Electr Power Syst Res 2009

5. Efficiency near 75%.

2.3.6. Lead acid batteries

Lead acid batteries (LAB) are the most widely used rechargeable battery and have been commercially deployed for more than 100 years (13)[12].
The cathode is made of Lead dioxide, PbO_2 the anode is made Lead, Pb and the electrolyte is sulphuric acid, H_2SO_4.
$Pb + PbO_2 + 2\ HSO_4^- + 2\ H^+ \rightarrow 2\ PbSO_4 + 2\ H_2O$, E = +2.05 V

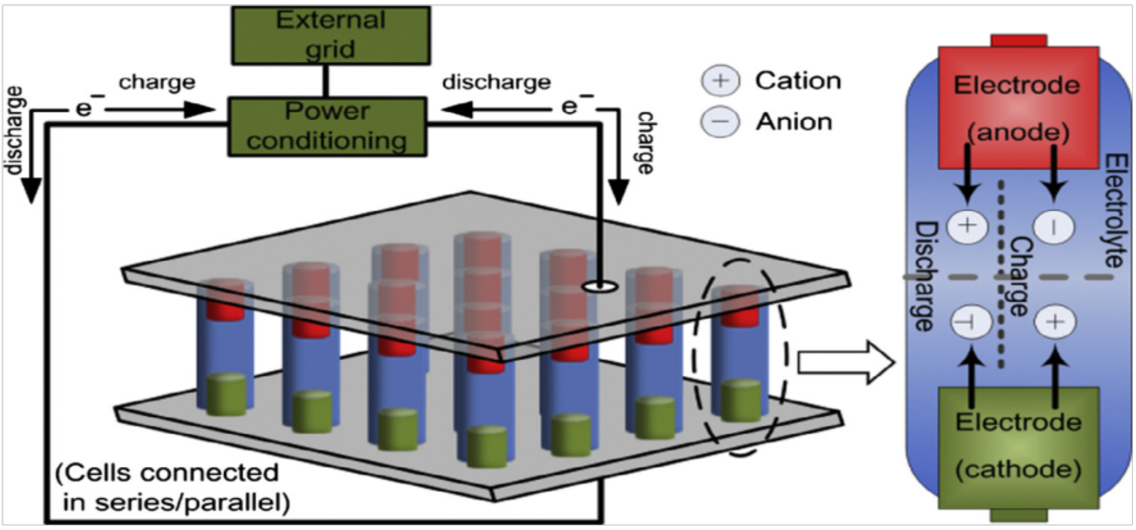

Figure 10 : Schematic diagram of a battery energy storage system operation (14)[14]

LABs have an efficiency of approximately 75 – 90%, their response times are relatively fast, a low power leakage rate of <0.3% per day with relatively low capital costs. One disadvantage is that they perform poorly at low temperatures and require a temperature management system increasing the overall cost. This along with their relatively low cycling times and energy density is limiting their application in commercial Electrical Energy storage application s (14)[14].

[12] Handbook of batteries / David Linden, Thomas B. Reddy.—3d ed. 2002

2.3.7. Lithium-ion battery (Li-ion) (15)[13]

The main development of rechargeable Li-ion batteries is associated with its use in small consumer electronic products. Li-ion is also now one of the leading technologies for hybrid and full electric vehicles, with battery packs sized up to 50 KWh. The operation of this technology is achieved via the electrochemical reactions between +ve and Li ions and anolytic and catholytic active materials. These developments have been derived from research into the active materials used for electrodes and the electrolyte,[14] (4) and have provided systems with higher energy density and specific energy, resulting in improvements in the speed of charging, with relatively high round trip efficiencies (78%) and a lifecycle up to 4000 cycles.
On the downside the Li-ion battery technology may not be appropriate for long term storage as they have a high leakage rate at between 1-5% per day. The life of the materials is dependent on cycle depth of discharge and it is therefore unsuitable for applications where they will become fully discharged.

2.3.8. Flywheels

These devices were developed and are in the main now used for mitigation against power quality issues and for bridging the switchover between different power sources. (8)[15] As this is not in line with the project objectives, no further details are required.

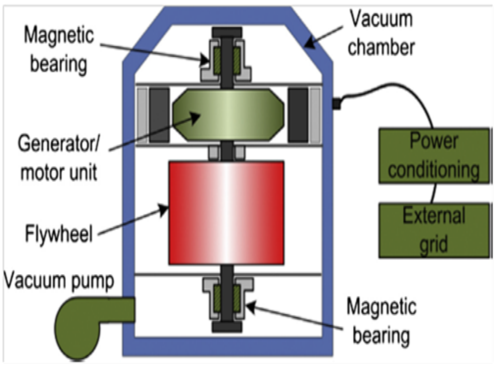

Figure 11 : System description of a flywheel energy storage facility[15].

[13] Electricity Energy Storage Technology Options, A White Paper Primer on Applications, Costs, and Benefits 1020676 Technical Update, December 2010

[14] Review of energy storage technologies for wind power applications Francisco Díaz-Gonzáleza, Andreas Sumpera, Oriol Gomis-Bellmunta, Roberto Villafáfila-Roblesb 2012.

[15] X. Luo et al. / Applied Energy 137 (2015) 511–536

2.3.9. Capacitors & Supercapacitors

A capacitor is constructed from two electrical conductors, (metal foils) separated by an insulating layer made from plastic or ceramic. When a capacitor is charged, energy is stored in the dielectric material in an electrostatic field. Supercapacitors, contain electrodes, an electrolyte and a porous membrane separator (*Figure 12*).

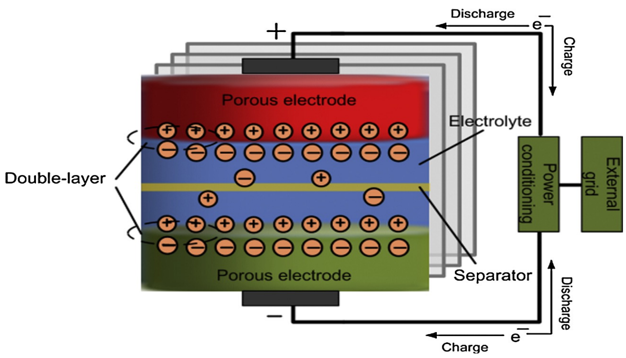

Figure 12 : Schematic diagram of a supercapacitor system.

The technology has a high power density and low charging times with a high round trip efficiency of up to 97%, although energy density is low and power leakage rate is extremely high at up to 40%. Capital cost is also relatively high. As such they are more applicable to short term storage and power quality applications, including HV power correction and UPS devices rather than large scale electrical energy storage.

Superconducting Magnetic Energy Storage (SMES)

An SMES can store electrical energy in a magnetic field created by the flow of electric current in a superconducting inductor that is cooled to its superconducting critical temperature. Electrical energy storage occurs when the current is increased within the inductor, stored indefinitely as there is no degradation. Removal of this energy is achieved by reducing the current within the inductor. At present the technology delivers a high cycle life and a rapid response, but currently has a relatively low energy density and high cost, and requires energy to constantly cool the magnet (4)[16].

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2.3.10. Electrolysis, Fuel Cell & Synthetic Natural Gas

The use of electrolysis within electrical energy storage involves two technologies, the production of Hydrogen by water electrolysis and the conversion of Hydrogen back to electricity by reaction with Oxygen, (from air) within a fuel cell. This technology system is shown below in Figure13.

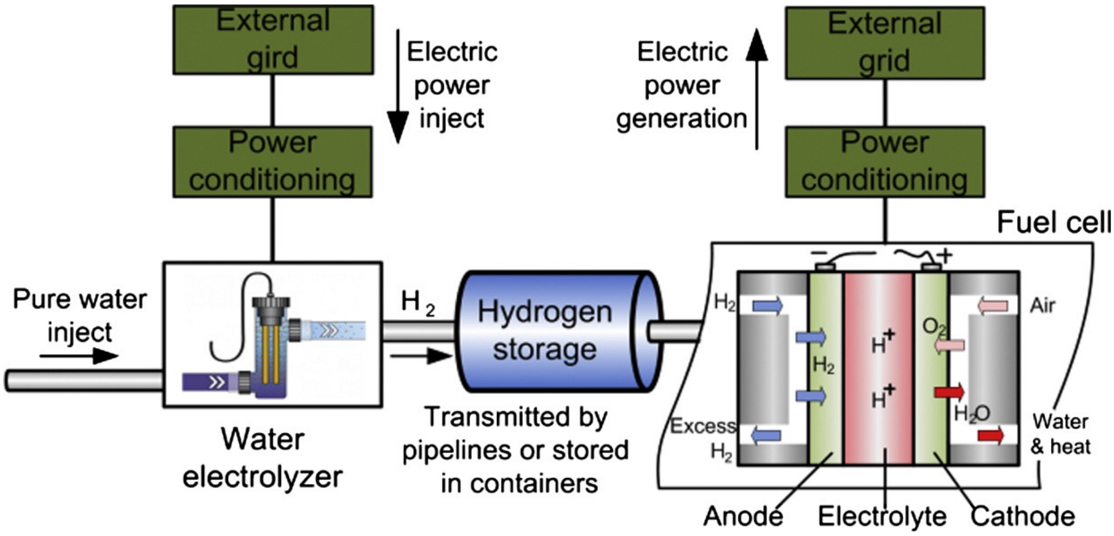


Figure13: Topology of hydrogen storage and fuel cell (8).[17]

There are a number of major fuel cell groups which include (8):

- Alkaline Fuel Cell,
- Phosphoric Acid Fuel Cell,
- Solid Oxide Fuel Cell,
- Molten Carbonate Fuel Cell,
- Proton Exchange Membrane Fuel Cell,
- Direct Methanol Fuel Cell,

This technology is in a development and demonstration phase and currently only has an overall efficiency around 30% for the combined fuel cell and electrolyser system.

Energy Futures Lab, Imperial College London, Report for The Carbon Trust, June 2012, Goran Strbac, Marko Aunedi, Danny Pudjianto, Predrag Djapic, Fei Teng, Alexander Sturt, Dejvises Jackravut, Robert Sansom, Vladimir Yufit, Nigel Brandon

[17] X. Luo et al. / Applied Energy 137 (2015) 511–536

Another related technology which is of interest is the development of a power to gas system as shown in Figure 14 below.

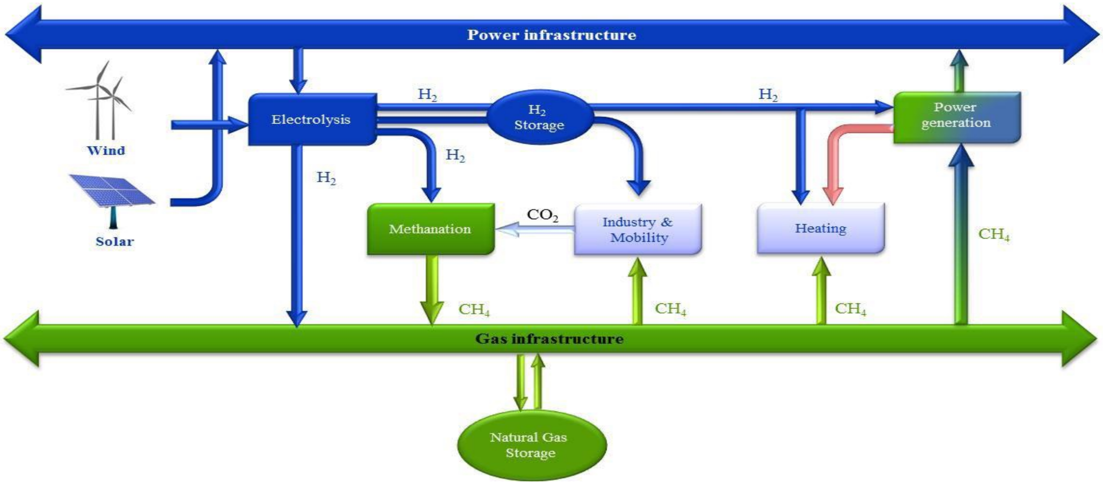


Figure 14 : Schematic description of the power-to-gas concept. (8)

The initial step, as above is the conversion of electricity into hydrogen via water electrolysis. This hydrogen produced can be utilised in several ways, either direct power production through a fuel cell, in direct heating or via Methanation in the production of renewable Methane for use /storage within the gas supply system.

A further adaptation is the concept of surplus renewable power to methane, which can be stored in the natural gas grid and converted back to power through combined heat and power when required (9).

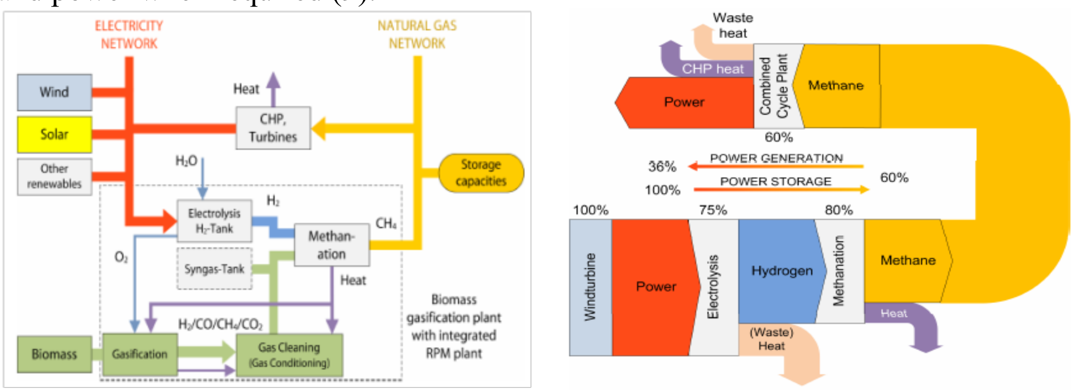


Figure 15 :Concept of a renewable power methane plant integrated into a biogas-SNG-plant and associated Sankey diagram of the renewable power methane concept (9).

This is an interesting concept particularly with the high heat demand within the Irvine production facility, although the overall efficiency could be as low as 22% for a power-to-methane-to-power plant (9). Therefore the Methane produced may be more valuable as a heat source used on site rather converting back into electricity.

The following table (Table 2 :Characteristics of various energy storage technologies. Note: technology status is on a scale of 1 – 5, 5 being most mature.) provides an overview of all key electrical energy storage technologies listed above. This is used in section 4 of the report, after an assessment of the onsite generation and energy demand profile which is covered in the next section of the report, (section 3). This is done to establish which of the various technologies is most applicable to implementation within the Irvine site.

Storage type	Description	Power (typical)	Capacity (typical)	Discharge time	Efficiency	Response time	Technology status	Lifetime	Lifetime
		MW	*MWh*	*hours*	*%*		*1 - 5*	*years*	*cycles*
Pumped Hydro	Water is pumped uphill to store energy and released downhill through turbines to generate electricity	5 2,000	50 - 14,000	7 - 24	50-85	seconds	5	>50	>15,000
Compressed Air	Air is compressed (store) and then released to a combustor in a gas turbine	10 - 2,500	15 - 5,000	1 - 20	40-75	minutes	4	>25	>10,000
Flywheels	Store electricity as rotational energy in a device spinning at high speed	0 - 10	0 - 5	< 0.5	80-90	seconds	3	15-20	10^4 - 10^7
Flow batteries	Two chemical components are dissolved and separated by a membrane, through which ion exchange occurs	0.01 - 20	0.1 - 500	1 - 6	60-75	seconds	2	5 - 20	1,000 - >10,000
Lead acid batteries	An electrochemical battery with lead / lead sulfate / lead oxide plates and a water / sulfuric acid electrolyte	0 - 10	0 - 100	1 - 12	75-90	seconds	4	3 - 15	250 - 1,500
Li-ion batteries	A battery in which lithium ions flow from negative to positive electrode during discharge.	0 - 25	0 - 100	0.1 - 6	85-98	seconds	3	5 - 15	500 - 104
Electrolysis	Water is separated into hydrogen and oxygen. Hydrogen later used to generate electricity	1 -	1 -	5 - 1000	34-44	sec - min	1	10 - 30	10^3 - 10^4
Synthetic natural gas	Following hydrolysis, hydrogen is reacted with CO2 to form methane	1 -	1 -	5 - 1000	30-38	minutes	1	10 - 30	103 - 104
Capacitors	Large electrostatic fields between two conductive plates separated by a small distance	0 - 1	0 0.005	seconds	85-98	seconds	2	4 - 12	10^4 - 10^5
Electromagnetic storage	Energy stored in a magnetic field created by the flow of DC electricity in a super-cooled coil	0.1 - 1	0 - 0.01	seconds	75-80	seconds	2	>20	104
Liquid Air Energy Storage	Air is cooled to ~-196°C and stored as a liquid. Expansion through a turbine delivers power	5 - 500	5 - 10s	hours	50-80	minutes	3	25	>10,000
Molten salt	Salt is heated then stored in an insulated container. Heat is extracted to boil water and drive a steam turbine	10 - 300	50 - 2000	hours	60-80	minutes	3	25-30	>10,000

Table 2 :Characteristics of various energy storage technologies. Note: technology status is on a scale of 1 – 5, 5 being most mature.

3. Site Demand & On-site Generation

3.1. Background

The GSK Irvine site has for several years implemented a programme of activity focused at improving the energy efficiency of its processes and utilities. This activity ranges from ways of working to improve demand management, replacement of lighting with LEDs, motor replacement, monitoring and targeting and developing of performance indicators to sustain improvements and promptly identify inefficiencies, through to the installation of a 4MWe Natural gas Combined Heat and Power plant (CHP) with absorption chilling and finally installation of on-site renewable energy technologies such as the anaerobic digestion of waste effluent with 2x 500KW Biogas CHP, 2x2.5MW wind turbine generators and a 20MW Biomass CHP. Management of our manufacturing processes and utilities has also been reviewed over this time to optimise resource requirements and minimise demand variability, through fixed repeating schedules and management of batch operations.

	Wind Turbines	Biogas CHP	Biomass CHP
Number of Units	4	2	1
Current Capacity (Planned Capacity)	5 MW (10 MW)	1MW (N/A)	N/A (20MW)
Heat Output	None	2 MW	18 MW
Incentive Scheme	ROC	FIT	ROC/RHI
Ouput	Non dispatchable	Fixed	Variable (heat leading)

Table 3 : Site Renewable Technology Installations GSK

3.2. Data Analysis

With committed capacity increases, the manufacturing site now has a total annual electrical demand of 182GWh, with an average demand of 20MWe and peak demand of up to 30MWe and a 162GWh heat demand with an average demand of 18MWth.

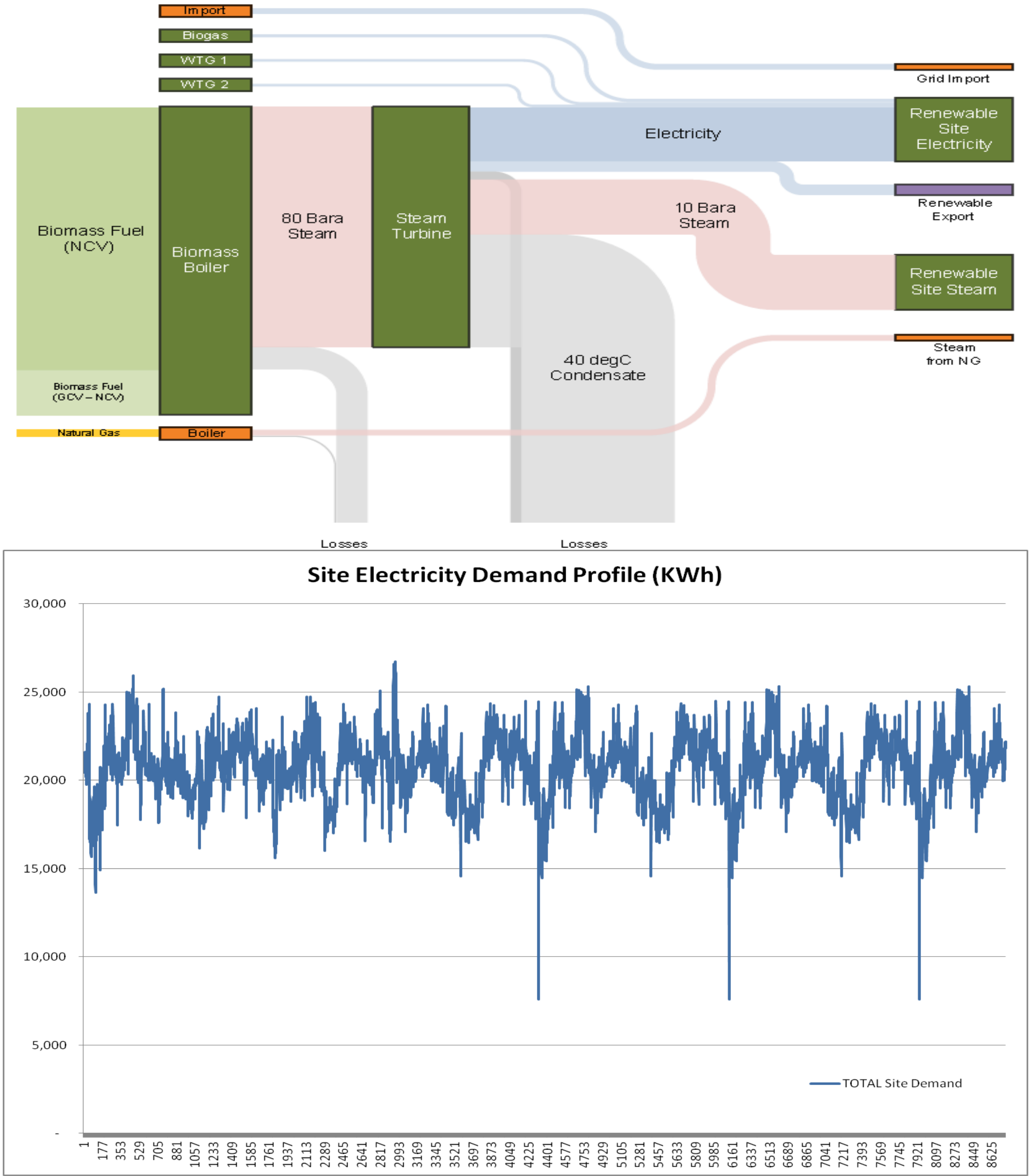


Figure 16: GSK Site Sankey diagram and Forecast Electricity Demand.

The strategy for utilisation of on-site generation is to maximise use of the waste to energy and wind resources. This is followed by the Biomass CHP which is sized and designed around delivering the heat demand from the site. As a result, in maximising the Biomass CHP efficiency there remains an element of import and export.

Source	KWh/Yr	%
TOTAL Site Demand	181,967,874	n/a
On Site Wind Turbine Generation	23,404,608	10%
On Site Biogas CHP Power Generation	8,409,600	4%
On Site Natural Gas CHP Power Generation	28,776,600	12%
Site Import	11,254,262	5%
Net Biomass Generation	160,965,523	69%
Total Generation	232,810,593	100%
Available to Export	50,842,719	22%

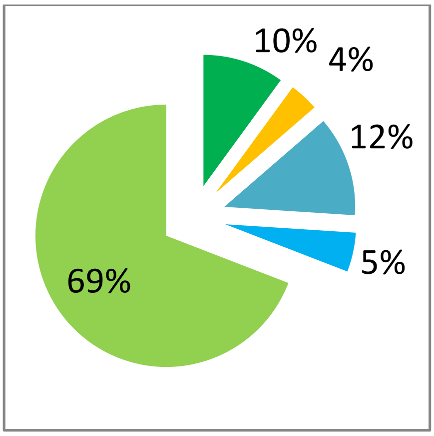
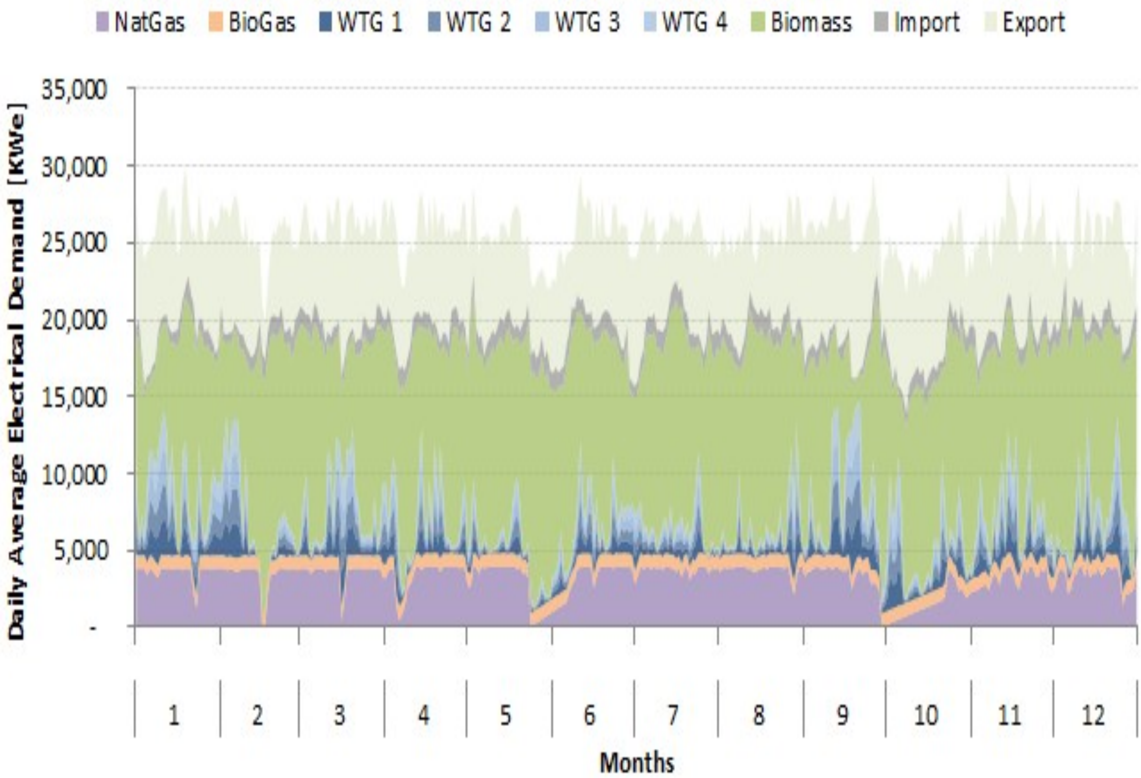
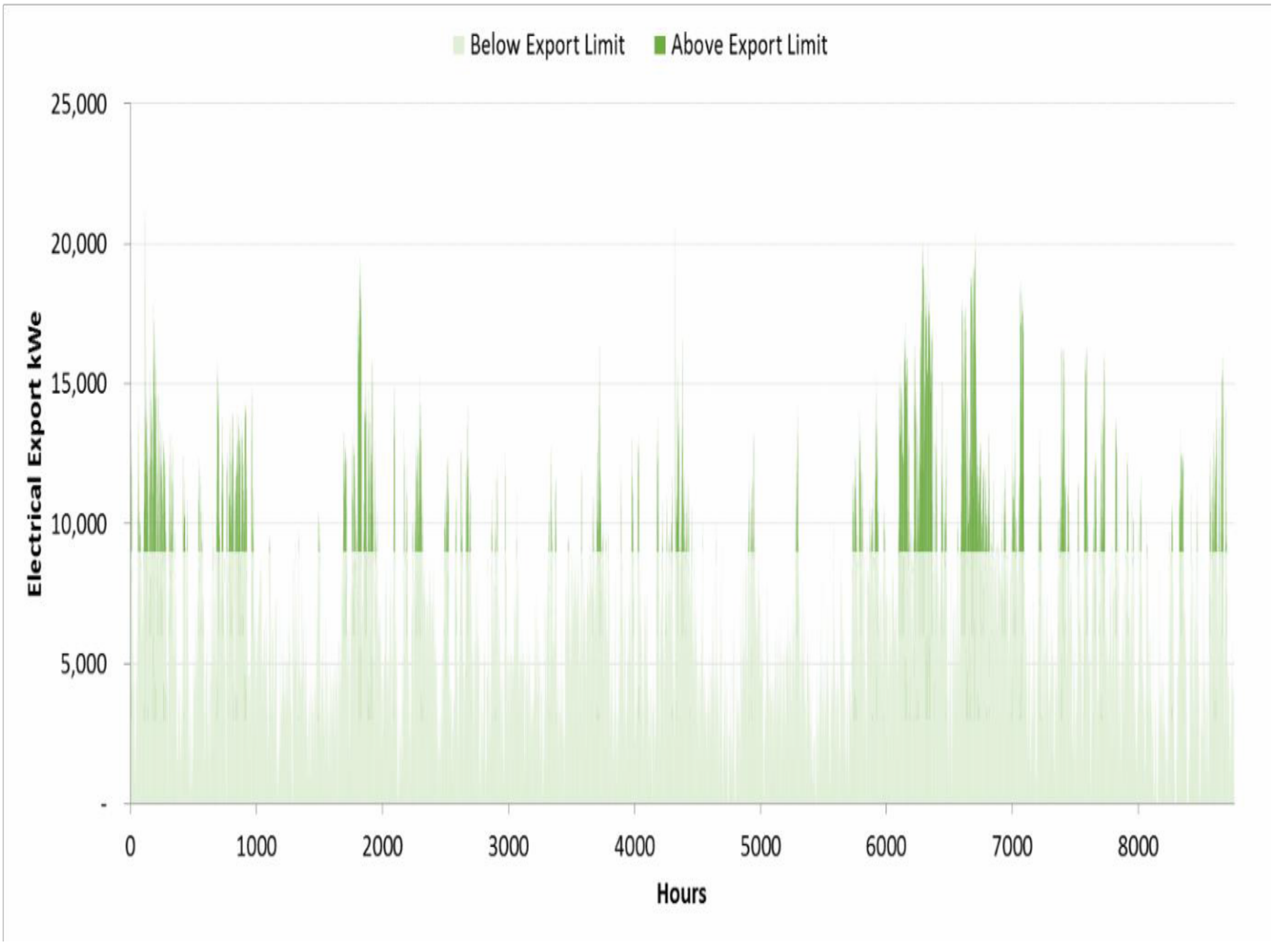


Table 4 : Site Electricity demand, breakdown of onsite generation and export



Graph 2: Site electricity generation and export profile.

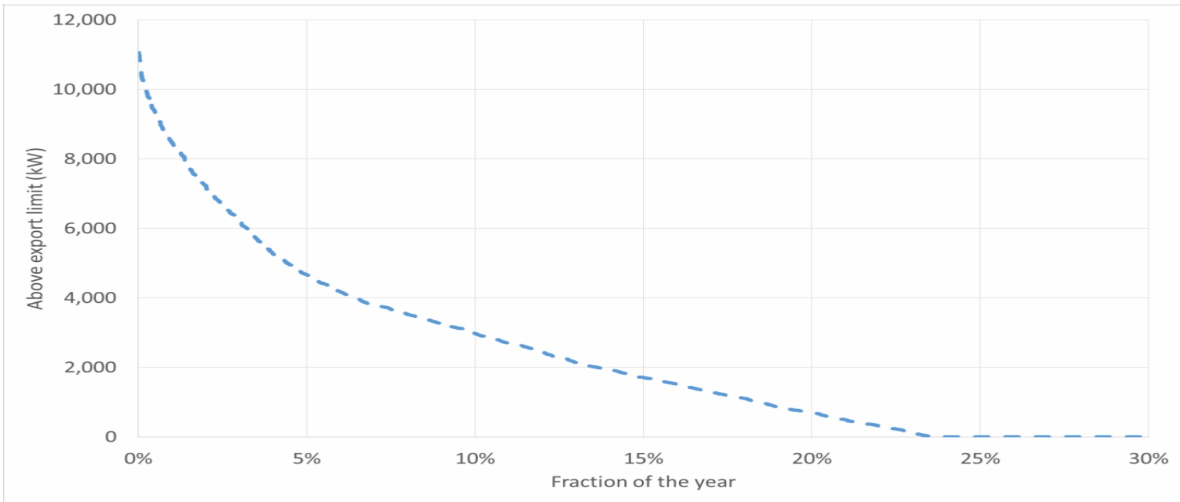
A specific problem that the site will encounter after the installation of the biomass CHP is the 9MWe export limit that is currently in place for the site. Whilst a revision to this is underway requesting a larger export limit, this is not likely to be granted until at least 2023. Analysis of the site electricity demand data and current/planned on site generation data has determined the forecast export, shown in Graph 3: at half hourly resolution.



Graph 3: Forecast export profile over the 9 MW export capacity.

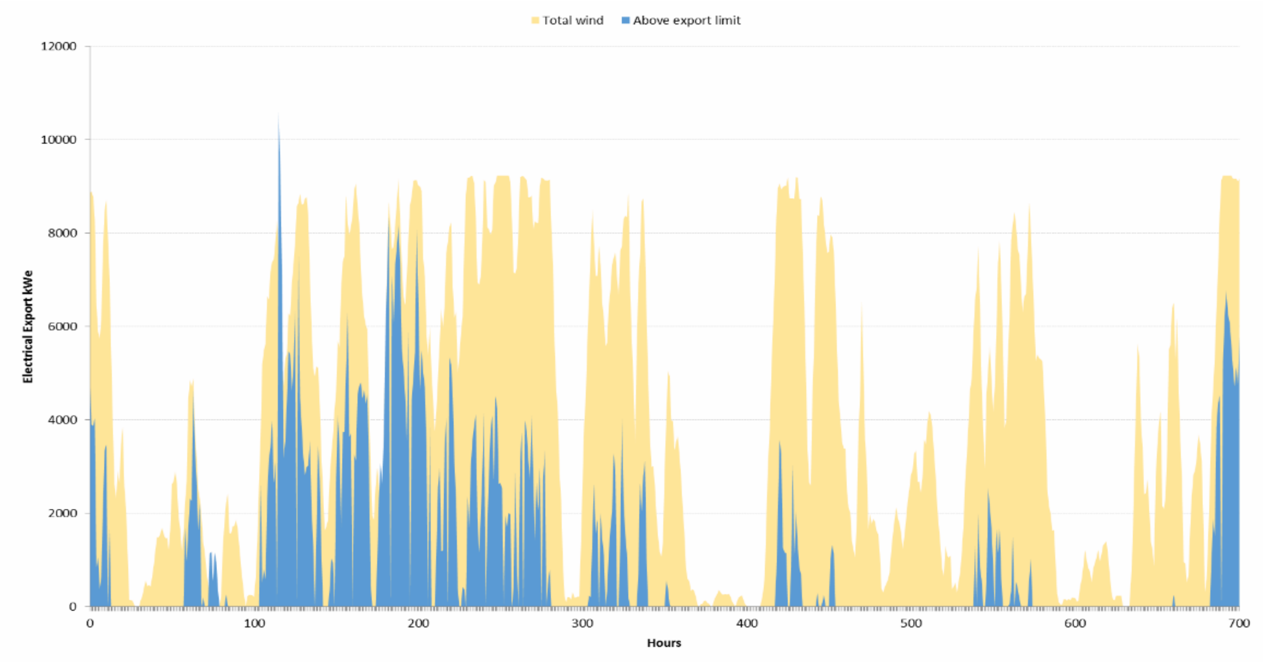
Graph 3 Shows that, in the case where WTGs 3 and 4 are built, and all other generators are present (natural gas CHP, biogas, WTGs 1&2 and the biomass CHP), the export limit would be exceeded 24% of the time as seen in Graph 4.

A load duration curve for this export limit breaching is shown in Graph 4: .



Graph 4: chart of site electricity Export load duration curve

This export limit breach is primarily driven by the on-site wind generation. Graph 5 : shows the correlation between the on-site wind generation and by how much the export limit is breached.

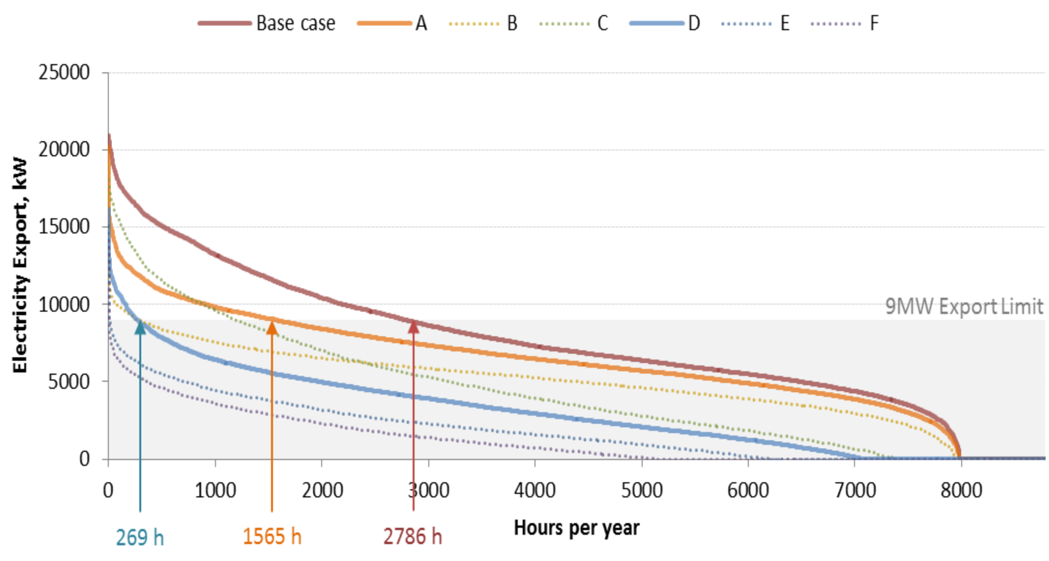


Graph 5 : Influence of Wind turbines of export capacity.

This illustrates one of the drivers for an energy storage plant. With the natural gas and Biogas CHP was running and all 4 wind turbines on line, the ramping down of on-site generation to avoid breaching the 9MWe export limit would cost between £0.8 and £1.5 million per annum, depending on the electrical strategy employed. The possible scenarios that are required to curtail the on-site generation are shown in Table 5, underutilisation of assets leading to an effective "loss" of renewable incentives (ROC & RHI) and export income that could otherwise have been realised. The only option that may be considered is case C, where the running strategy of the natural gas CHP is changed to a back-up/ peak load and security of supply duty.

Cases	WTG 1&2	WTG 3&4	Nat Gas CHP	Biogas CHP	Biomass CHP
Base Case	🟢	🟢	🟢	🟢	🟢
Case A	🟢	🔴	🟢	🟢	🟢
Case B	🔴	🔴	🟢	🟢	🟢
Case C	🟢	🟢	🔴	🟢	🟢
Case D	🟢	🔴	🔴	🟢	🟢
Case E	🔴	🔴	🔴	🟢	🟢
Case F	🔴	🔴	🔴	🔴	🟢

Table 5 : Options for future strategy of on-site generation (🟢 technology running, 🔴 technology off-line).



Graph 6: Load duration curves for each on-site generation strategy.

However, another option could be utilising an energy storage solution, which would store any electricity generated from the wind turbines that is in excess of 9MWe, in order that it could be used on site at a later time, or exported when the total electricity being exported is less than the limit. Results show that a considerable amount of Electricity is available for storage and use at times when it can mitigate against import and fill unused export capacity at other times.

3.3. Energy Management Opportunities with Storage

There are a variety of different ways in which an energy storage plant could bring value to the site.

3.3.1. The following section summarises the technical options available and provides an approximate value that each revenue stream could bring.

Black start for biomass CHP

This allows the biomass CHP to be restarted if grid power is lost and biomass plant trips and would require approximately 2.5MWe of power to be discharged over 2 hours. There would be no response time requirements. It also provides a potential capex avoidance of £2 million as there would be no need to install black start capability for the biomass CHP. However, recent analysis for the biomass CHP project has determined a limited economic case for black start capability for the biomass CHP due to infrequent utilisation.

Off-grid power for critical users

If power supply from both the grid and the Biomass CHP are lost, an energy storage plant could continue electricity supply to critical users to ensure that no batches of product were lost. Approximately 5MWe of power required (to power air compressors and critical control systems), with a potentially indefinite discharge time and a response time requirement of less than 30 minutes (the length of time it takes for a batch to be lost after a power interruption). A complete loss of connection to the grid is anticipated approximately once per year and the Biomass CHP is expected to be able to ride through approximately 75% of such events. The cost of a lost batch has been estimated at approximately £1 – 1.5 million per batch.

Continue full biomass generation in island mode

If the plant is operating in island mode, it is anticipated that the biomass CHP will modulate its output in order to match the on-site power requirements. If an energy storage plant was present, instead the biomass could continue to operate at as high a load as possible, while the storage regulated the total supply to site by modulating the power it is charging with. Due to the low frequency of occurrence, and low value of this issue, this will not be explored further at this stage.

Wind Turbine Generation in island mode

If the plant is operating in island mode the wind turbines will have to stop generating. An energy storage plant could in theory directly store any electricity being generated by the wind turbines. Due to the low frequency of occurrence, and low value of this issue, this will not be explored further at this stage.

Allow capacity for future Renewables

If any further on site generation is added, for example further wind turbines, they may cause breaches even of an increased export limit. An energy storage plant could mitigate this. This could contribute to GSK's overall sustainability strategy as adding renewable capacity at Irvine may be more straightforward than at other sites, and could offset emissions at other sites. This "sleeving" of energy could also provide cheaper electricity to other GSK sites.

3.3.2. The following section summarises the economic value of electrical energy storage to the site.

Reduce need for imported electricity

During periods when the biomass plant is shutdown (e.g. annual shutdown and unplanned outages), relatively expensive imported electricity is required. Instead, the energy storage plant could be used to import low cost electricity and off peak times for use at high cost times, reducing the site's total energy bill.

Improve EES performance

Waste heat from the biomass CHP, or steam extracted from the turbine, could be used to increase the efficiency of the EES plant and therefore improve its overall performance. For example in the Highview pilot plant trial results it is said that approximately 47% of this waste heat used is converted back into electricity (13).

Internal arbitrage

This would involve storing energy when the export income is lower, and discharging it selectively when the export income is higher (i.e. peak times, triad periods, red DUoS periods etc). However, the price differential is currently not strong enough for this to be economically viable. The price differential between the lower and higher tariffs would have to be at least 1.43, while it is currently approximately 1.13.

Export limit breach avoidance

Avoid exceeding the 9MWe export limit (currently predicted to be exceeded 24% of the year) by storing the energy instead. Previous recommendation was to turn off two WTGs and the nat. gas CHP to avoid this.

Economic value to grid (i.e. revenue opportunities for the LAES plant)

The following table details the revenue opportunities available for the LAES plant from grid services.

Option	Storage technology requirements: Description	Discharge time	Response time	LAES ?	Annual value per MW per	Notes / comments
Frequency control (instantaneous)	Instantaneous frequency response (must be generating continuously during available periods)	Unlimited?	Instant	X	>£60k	Incompatible with LAES response time
Frequency response (primary)	Discharge the storage unit to increase export to the grid when frequency is too low (too much demand compared to supply)	30s	<10s	X	>40k	Incompatible with LAES response time
Frequency response (secondary)	As above, this response comes online after the primary response but can be required for longer	30 mins	<30s	X	£34 - £37	Incompatible with LAES response time
High frequency response	Charge the storage unit to increase demand on the grid when frequency is too high (not enough demand compared to supply)	Unlimited, usually <30 mins	<30s	X	£24 - £27	Incompatible with LAES response time
Capacity market	The grid has recently started providing availability payments for providing capacity at required times.	Unlimited	4 hours	✓	£19.4k	Incompatible with 9MW limit – if 9MW is already being exported the capacity cannot be offered. High availability also required.
Grid arbitrage	Import during off peak times (and negative energy prices), export during peak times.	2 hours	Months	✓	Variable	Price differential currently not strong enough – see section 5.2
Red DUoS	Supplier will pay extra to supply more during Red DUoS periods	3 hours (16:30 – 19:30)	Months	✓	Variable	Possibly an option however low value due to relatively small volumes – for further work.
TRIAD	Triad charges are part of Transmission Network Use of System (TNUoS) charges.Avoidance of import during these times and supplier will pay extra to supply more	30-90 mins	4 – 6 hours	✓	£198K	Option to gain from eliminating import and maximizing export.
STOR	Capacity procured by national grid in order to meet demand when generation is not sufficient	< 4 hours	<20 mins	✓	£54K	Option to gain with contract for standby capacity.

Table 6: Grid side revenue opportunities for an energy storage plant.

4. Assessment of Applicable Storage Technologies

The ideal characteristics of an energy storage plant that would suit the Irvine site vary according to what the plant is trying to achieve. The main objective of the storage facility is in support of minimise the amount of curtailed power generation from the site wind turbines, to use this stored energy to avoid importing electricity from the grid at peak demand times, including Triad periods and facilitate the potential for standby generator payments such as the short term operating reserve (STOR).

The plant should therefore be able to store energy and supply power for significant periods of time, ideally on a weeks/months timescale for the storage of energy, and in hours for duration of supply. A quick response rate will also help support the site in terms of ability to ride through power outages and other power quality impacts from the grid connection. Capital costs are an important factor and along with operation and maintenance costs, should all be minimised in order to keep the business case as strong as possible. Assessment of the data in Table 6 comparing each technology against the site objectives has enabled a clear focus on the most appropriate technologies. This data highlights that there are only a couple of technologies assessed to be applicable to the site's electrical energy storage requirements. This is Liquid Air Energy Storage (LAES) which will be investigated in more detail in the following sections. The second technology electrolysis combined with production of synthetic natural gas, will not be investigated in detail but due to the potential synergies with the site power and heat requirements this will be proposed for further assessment.

Storage type	Comment	Storage Volume	Discharge duration	Response Time	Lifecycle	Technology development	Site Location	Suitable for the site
Pumped Hydro	Requires specific geologic features	✓	✓	✓	✓	✓	✗	**No**
Compressed Air	Response time of minutes, not seconds Requires specific geologic features at scale	✓	✓	✗	✓	✓	✗	**No**
Flywheels	Suitable for grid support. Not for site	✗	✗	✓	✓	✓	✓	**No**
Flow batteries	Quick response time, long discharge time, but low technology readiness and	✓	✓	✓	✓	✗	✓	**Maybe**
Lead acid batteries	Quick response time, long discharge time, high efficiency but low charge/discharge	✓	✓	✓	✗	✓	✓	**No**
Li-ion batteries	Quick response time, long discharge time, high efficiency, average charge/discharge cycle lifetime	✗	✓	✓	?	✓	✓	**Maybe**
Electrolysis	Very low efficiency. Slow response time. However, long term storage possible	✓	✓	✗	✓	✓	✓	**Yes**
Synthetic natural gas (Power to Gas)	Could be used to provide gas to the natural gas CHP	✓	✓	✓	✓	?	✓	**Yes**
Capacitors	Very short discharge time	✗	✗	✓	✗	✗	✓	**No**
Electromagnetic	Very short discharge time	✗	✗	✓	✓	✗	✓	**No**
Liquid Air Energy Storage	Assessed in rest of report	✓	✓	✓	✓	?	✓	**Yes**
Molten salt	Slow response time. More suited to solar installations	✓	✓	✗	✗	✗	✗	**No**

Table 7: Suitability of various energy storage solutions to the Irvine site.

5. Assessment of Liquid Air Energy Storage

Liquid Air Energy Storage, (LAES) (19)[18]

As discussed in the earlier sections of this project there are many different technologies and forms of energy storage that were historically and are currently deployed throughout the world. These range from large scale pumped-hydro storage through mechanical devices to a variety of batteries technologies applied at various scales and on many different applications. These are more commonly used technologies but there are several emerging technologies that are not currently widely utilised for electrical energy storage applications and may provide a better fit on specific applications.

LAES is currently an emerging technology that indicates considerable potential in either local or grid scale electricity storage when considering storage technologies required for enhancing the use of non dispatchable renewable electrical energy.

This section covers a more detailed overview of the status of this technology in general and its potential application to the Irvine site.

Electrical energy storage can deliver the benefit of improved energy management through the removal of barriers to generation of renewable electricity, by acting as a buffer between generation, demand and grid restrictions. This enhanced use of renewable energy has the potential to deliver improved efficiency of renewable installations without major behavioural changes from the customer. LAES storage has the potential to achieve these benefits over a wide range of application scales from localised industrial to grid scale applications. Figure 17 below outlines the key steps within a LAES system from the use of non peak of excess renewable energy through the required charging, storage and discharging steps required to supply electricity back to the user when it is required. This includes the thermal recovery steps from within the system and externally that are used to improve the overall round trip efficiency.

[18] Liquid Air in the energy and transport systems Opportunities for industry and innovation in the UK Summary Report and Recommendations, David Strachan, The Centre for Low Carbon Futures 2013.

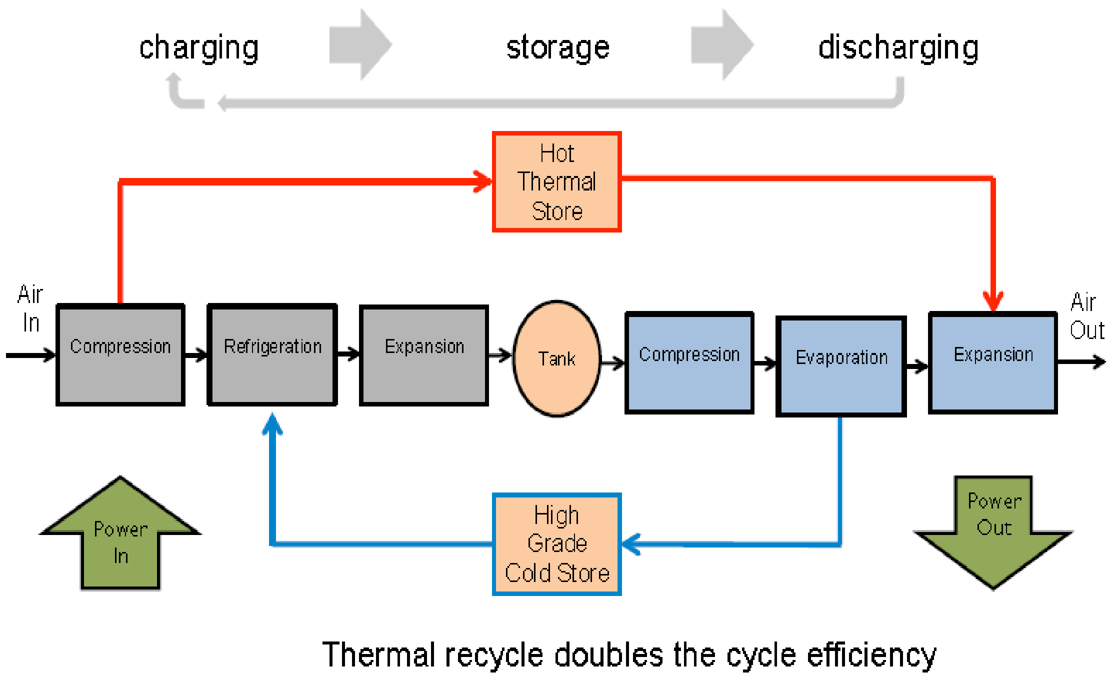


Figure 17 : Key steps in Liquid Air Energy Storage (20)[19]

Technology background

Gaseous air is converted to a liquid by cooling it to a temperature of -196 °C and is an established technology currently employed commercially with developed industrial scale equipment as used within the industrial gases industry. The volume of gas to liquid is 700:1, with the liquid being stored at atmospheric pressure in insulated vessels. To convert this liquid back to a gas, heat is applied to change the phase, thus increasing the volume by 700. This expansion can be used to power an engine or turbine and if connected to a generator thus produce electricity. Ambient temperature conditions can be used to achieve this but if a local source of low grade waste heat, with a temperature up to 150°C is available, the efficiency of this step of the process can be enhanced.

LAES system technology has been successfully tested and demonstrated via a fully operational LAES pilot plant over the last two years, (350kW/2.5MWh) and current developers are planning a 5MW/15MWh LAES system, funded by the Department of

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Energy and Climate Change with a grant worth over £8 million This system is due to enter operation by the end of 2015.

The technology is modular, which means that each of the charging, storage and discharging components of the system can be sized independently. Charging the system works by using electricity to cool air down to -196°C (Stage 1 in *Figure 18* below) at which point it is in a liquid state, with every 700 litres of ambient air being compressed to form 1 litre of liquid air.

During Stage 2, liquid air is stored in an insulated tank at low pressure. This equipment is already globally deployed for bulk storage of liquid nitrogen, oxygen and liquid natural gas (LNG). These storage units also represent a small amount of the total capital cost of the system.

Finally when required, power is produced in Stage 3 by pumping the liquid air to a high pressure. On heating, using stored heat from the air liquefier or waste heat from an adjacent process, a high pressure gas is produced which is then used to drive a turbine. During Stage 3, the waste cold produced is stored and used at a later time to enhance the efficiency of Stage 1 (20)[19].

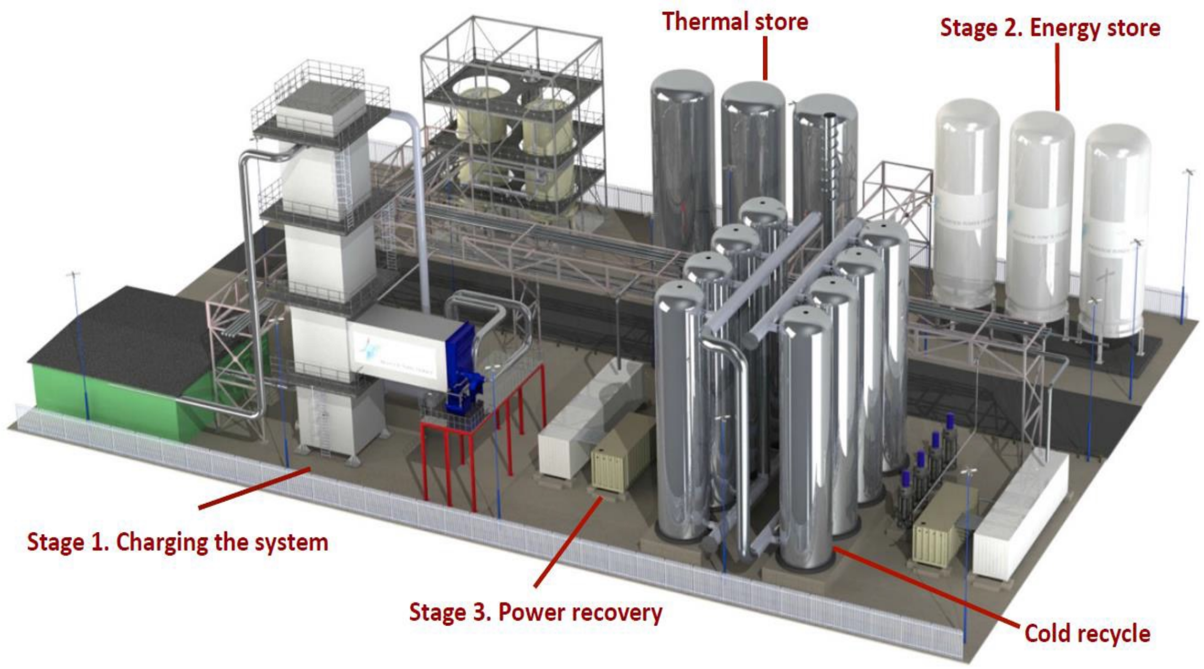


Figure 18 : Visualisation of an LAES plant. Source: Highview Power brochure.

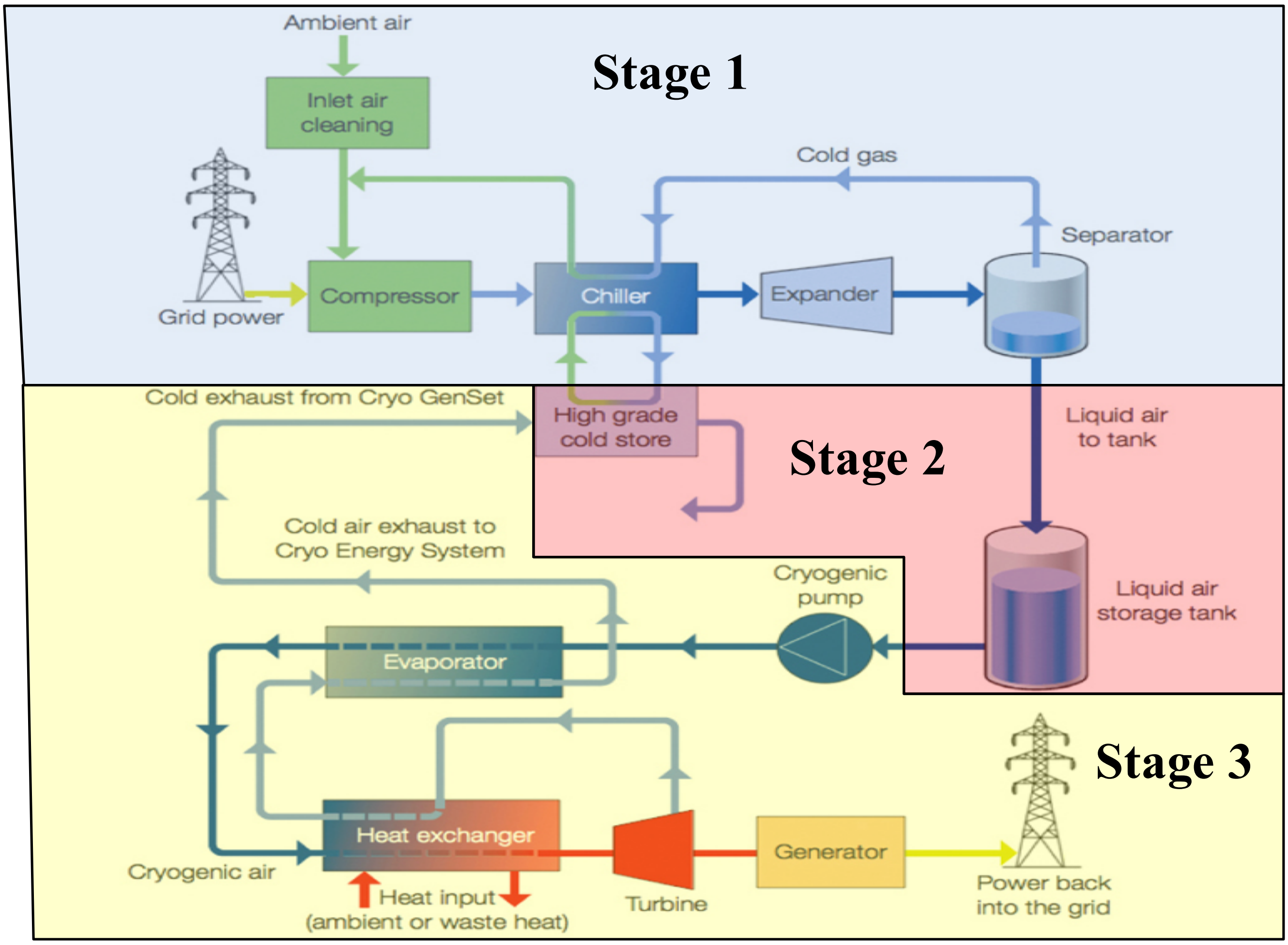


Figure 19 : Process flow for the Highview Liquid Air Energy Storage System adapted from Source: Highview Power brochure.

Thermodynamics

Liquefied air is a cryogen and the high grade cold energy that it contains, is a better thermal energy storage medium compared to heat (21)[20]. The figure below shows that at a given temperature difference, the stored cold is more valuable than the stored heat particularly at large temperature differences (20)[21]. They are able to store energy in the form of sensible and latent heat and have a higher exergy density than many thermal energy storage media. This enables them to be utilised as a more efficient thermal energy storage medium.

[20] YVONNE LIM1, MUSHTAK AL-ATABI1, RICHARD A. WILLIAMS LIQUID AIR AS AN ENERGY STORAGE: A REVIEW Journal of Engineering Science & Technology.

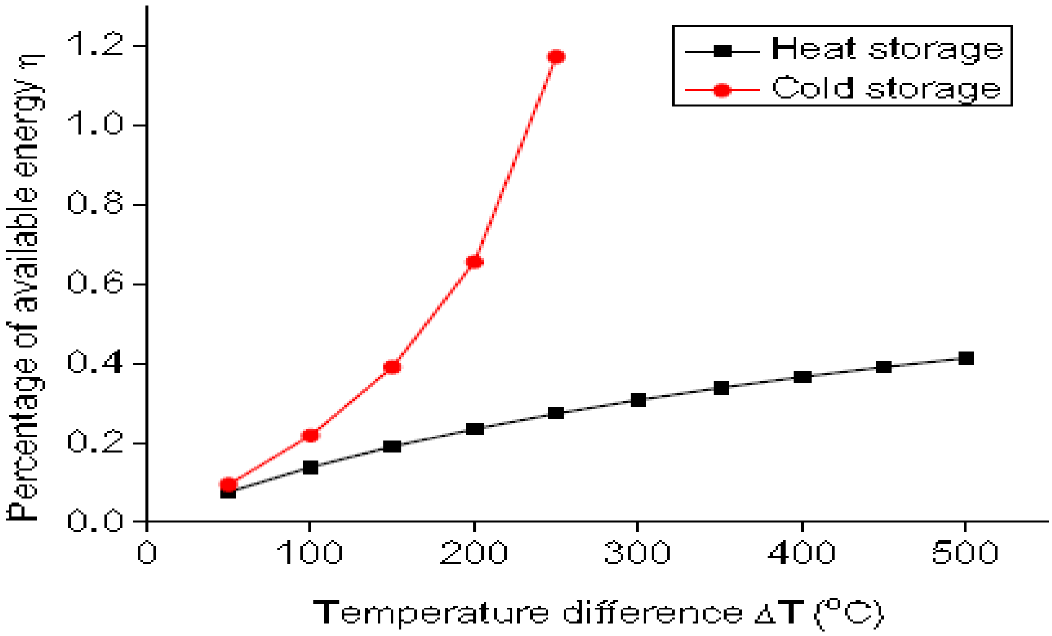


Figure 20 : Exergy percentage as a function of temperature difference for heat and cold (20)[21].

Cryogenic liquids, (liquids at temperatures below - 150°C or 123K) are used in many engineering processes. They are produced by the Liquefaction of gases to increase their density thus reducing the volume / mass for more efficient storage and transport. Many liquefaction cycles have been developed for specific gasses and have been modified to enable them to be applied to efficiently liquefy air. A thermodynamically ideal liquefaction system can be represented by the Carnot cycle. This theoretical system is represented by a reversible isothermal compression followed by a reversible isentropic expansion.

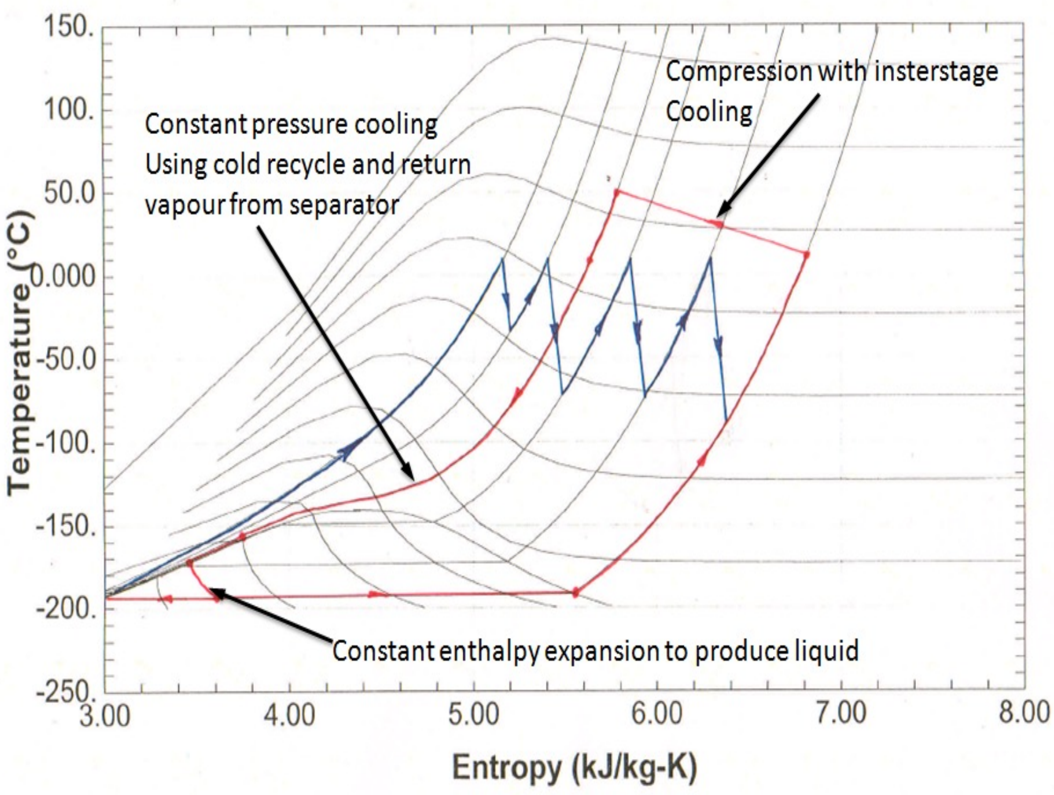
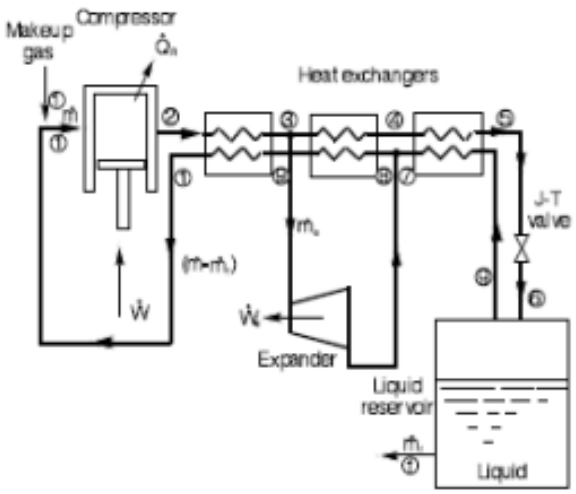


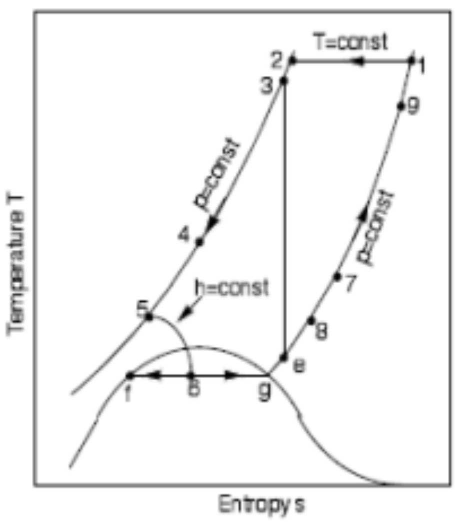
Figure 21: Liquid Air Energy Storage for Power Grids Liquid Air Conference Royal Academy of Engineers (20)[21]

- An isothermal process occurs when compression takes place at a constant temperature (ΔT = 0). With the ideal gas law the isothermal process can be expressed as: ***p / ρ = constant*** (where *p= absolute pressure and ρ=density).*
- Isentropic (or adiabatic) expansion of a gas takes place with no flow of heat energy either into or out of the gas. With the ideal gas law the isentropic (adiabatic) process can be expressed as: ***pV = constant*** *(where p= absolute pressure V = gas volume).*

[21] Liquid Air Conference Royal Academy of Engineers 9th May 2013 Dr Robert Morgan Principle Research Fellow.

Claude Cycle: Isentropic expansion (22)[22]



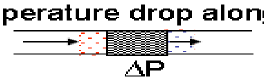


Isentropic expansion characterised by $\mu_s = dT/dP_s$ (always >0) results in a larger temperature drop for a given pressure drop than with isenthalpic expansion (22)[22].

The performance of this system can be optimised by varying P_2, T_3 and x
When the process stream is at an appropriate high pressure and sufficiently low temperature, the process stream is expanded via a Joule Thompson valve to produce liquid.

Joule-Thomson Coefficient

- 1885 - Joule & Thomson (Lord Kelvin) confirm that a gas flow through a restriction experiences a temperature drop along with the pressure drop.

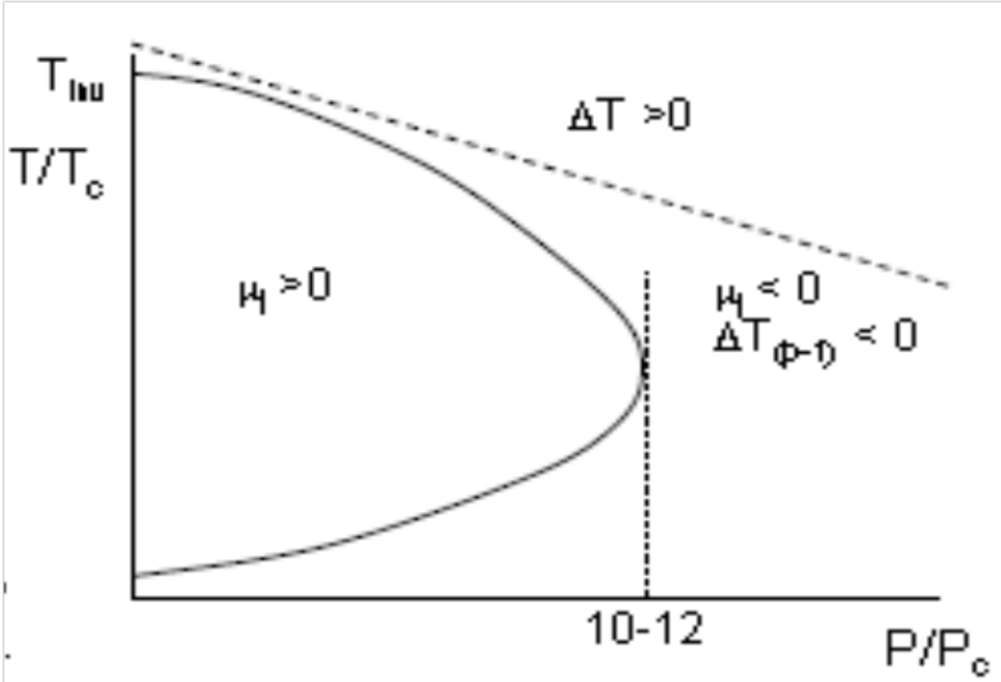


- The Joule-Thomson coefficient: $\mu_j = \left.\frac{dT}{dP}\right|_h$ characterizes the phenomenon.
- When μ_j>0, cooling accompanies a pressure drop.

The Joule-Thomson effect can be characterised by means of its coefficient, which at constant enthalpy is the partial derivative of the pressure wrt temperature. The fluid will cool on expansion if the coefficient is +ve and will increase in temperature if the

[22] Cryogenic Systems Randall F. Barron Oxford University Press, 1985

coefficient is –ve and will vary for any given fluid and as a function of pressure and temperature.



For a material, plotting a zero coefficient against pressure and temperature will give the inversion curve. Below this curve on expansion the fluid is cooled. The maximum inversion temperature can be derived showing that the fluid must be lower than this temperature to cool on expansion. The process stream then passes through a separator to isolate the liquid which is store in insulated low pressure vessels.

5.1. Process Details

Highviews development of this system has used a hybrid approach that utilises elements of the adiabatic and isothermal compressed air energy storage systems. This improves the efficiency by removing the requirement of heat from a fuel source (23)[23].

The process flow for a liquid air energy storage system, as shown in Figure 22 : System PFD of Highview's Pilot Plant. describes the stages and individual equipment requirements of this thermodynamic system and is used as an input to modelling on

[23] Thermodynamic modelling in MEI's Liquid Air Energy Storage System Study: *Emma Edwards1, Dr. Roger Dargaville, Professor Paul Webley April 2014*

process simulation systems such as Aspen HYSYS (21)[20]. Such tools are used to simulate a process under industrial conditions and in line with the systems material properties and thermodynamic laws.

The flow sheet indicates the individual equipment, unit operations and process streams used to complete liquefaction of the air. This involves the following items, with each component being identified as a block within the modelling system (24)[24].

1. **Feed Compressor** - With an acceptable isentropic efficiency
2. **Mixers** - The main purpose of the inline mixers is to ensure the input stream and recirculation stream are processed into one homogenous output stream.
3. **Recirculation compressors** - With an acceptable isentropic efficiency
4. **After Coolers** –The pressurised process flow post compressors is cooled to an acceptable temperature to enter the heat exchanger.
5. **Splitter / Heat exchanger** – Are used to separate fluid from the main process stream and achieve an optimal temperature for the following stage.
6. **Joule -Thompson Valve** – This is an isentropic JT valve that enables the Claude cycle to work at a constant enthalpy. This results in a decrease in pressure from which an appropriate drop in temperature is achieved, enabling the phase change to liquid.
7. **Expander** – the second separated process stream is expanded through this equipment before flowing into the separator.
8. **Phase separator** – this is used for separation/flashing the vapor liquid mixture that is fed from the JT valve.
9. **High Grade Cold Store** – is charged from the waste heat from the next stage during expansion and power generation and is used in the liquefaction s

[24] STUDY OF CRYOGENIC CYCLES WITH ASPEN - HYSYS SIMULATIONS, SUNIL MANOHAR DASH, Department of Mechanical Engineering National Institute of Technology, Rourkela 2009.

10. **Liquid Storage -** The liquid air is stored in an insulated tank at low pressure. Most cryogenic tanks are typically held at <10 bar (100 MT scale) or at atmospheric pressure at the >1,000 MT scale

11. **Cryogenic Pump** – used to pump the liquid to a high pressure.

12. **Heat Exchangers** – waste heat or ambient heat is applied to the liquid via these heat exchangers. This changes the liquid into a gas.

13. **Turbines** – The gas is utilised to power a series of turbines and generators when electricity is required.

To initiate the liquefaction process ambient air is taken through two compression stages with air cooling after each stage. The heat produced during this compression stage is stored within a thermal store, (hot water or oil) for use within the power generation stage of the process.

Post compression refrigeration is carried out with the air being expanded in a Claude cycle refrigerator. The efficiency of this operation is improved by utilising cold recovered from evaporation that takes place during power generation stage.

Within the power generation step of the process, initially the pressure of the liquid air is increased by pumping. An evaporation step then occurs to vapourise the air. The gaseous air is then heated from the thermal store heat that was collected during the liquefaction compression step. The gas is reheated during this multistage evaporation and used to drive a series of turbine generators.

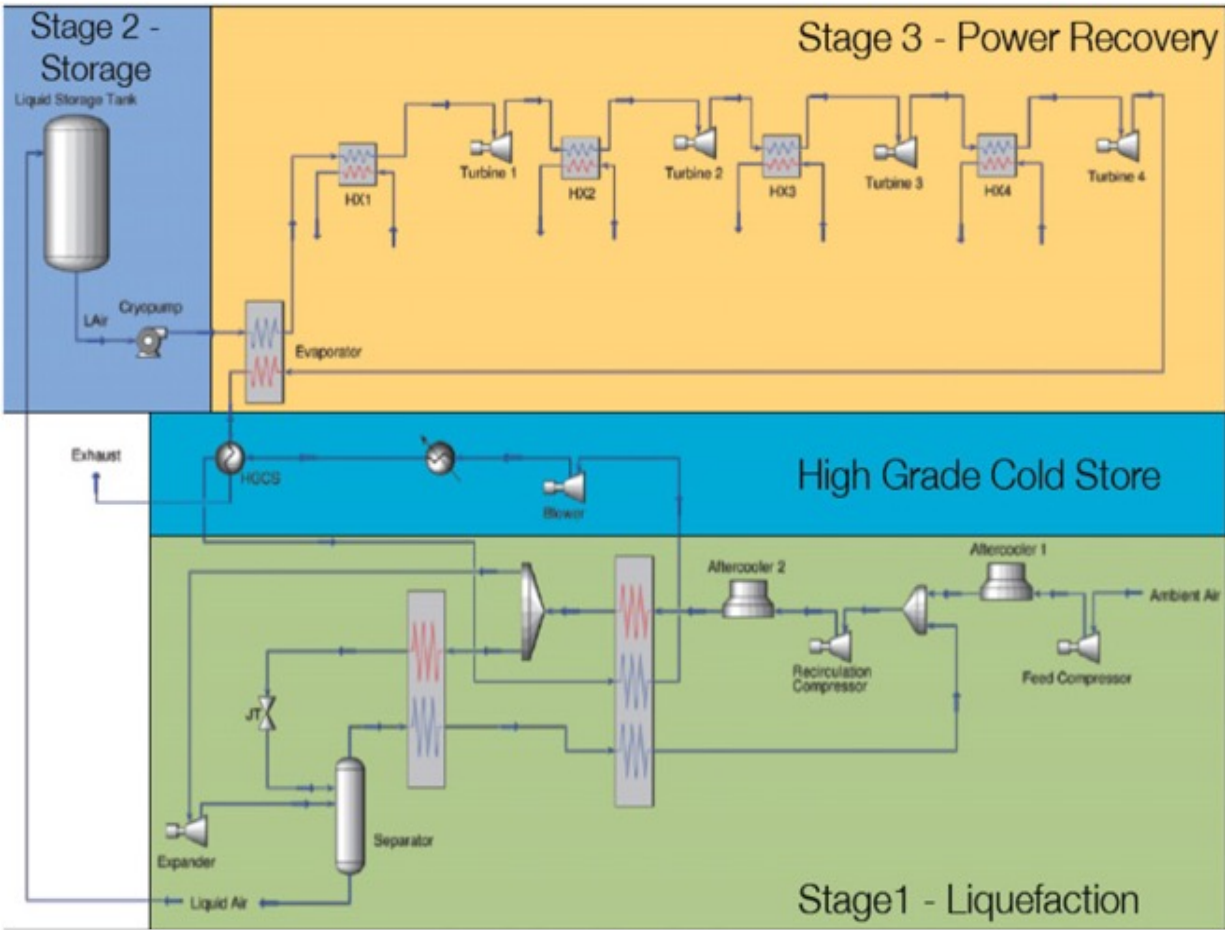


Figure 22 : System PFD of Highview's Pilot Plant (13).[25]

I addition to the basic scheme there are additional elements installed that are designed to increase the systems round trip efficiency. These include two expansion cycles during liquefaction to help run the compressors and waste heat recovery and storage.

With the installation of heat and high grade cold storage, the integration of the system with other processes that have waste heat or cold has been enabled. The reheating stage includes the use of waste heat form out with the LAES plant. The facility can also utilise cold from out with the plant, the main objective of this is to optimise the system and further increase the round trip efficiency and maximise the power output for any given amount of input power.

[25] The application of liquid air energy storage for large scale long duration solutions to grid balancing Gareth Brett and Matthew Barnett Highview Power Storage, London, UK. 2014. EPJ Web of Conferences 79, 03002 (2014)

5.2. Key Benefits from analysis of the LAES

The main parameters associated with the performance of any electricity energy storage system are indicated through the following:

1. **Storage system energy density**

Energy density is the volume of liquid air (kg) that are needed to deliver one MWh of electricity back into the production site after the parasitic losses have been taken into account. The developers of this technology (Highview) have noted that 10,000 kg per MWh is normal although with the introduction of available waste heat recovery (up to 400 °C), from available external processes there is an expectation that 7,000kg/MWh is achievable (18)[26]. (1 MWh = 3600MJ therefore liquid air at 7,000Kg/MWh = 0.514 MJ/Kg).

2. **Electricity round trip efficiency**

As with all electrical energy storage systems the round trip efficiency is one of the most important factors. Optimising this along with minimising capital cost of plant and equipment will have the greatest influence on whither the technology is successful adopted.

The advantages stated about the round trip efficiency of Highviews LAES are based on the utilisation of the use of waste cooling and waste heat from external sources to the storage system. In the case of waste heat from an external source, the power output of the generation step can be seen to improve from the use of low grade and high grade waste heat. The following figure Figure 23: Pilot Plant heat to power

[26] The application of liquid air energy storage for large scale long duration solutions to grid balancing Gareth Brett and Matthew Barnett Highview Power Storage, London, UK. 2014. EPJ Web of Conferences 79, 03002 (2014)

relationship : highlights the impact of low grade waste heat temperature showing a related increase in the on the Highview pilot plant power output.

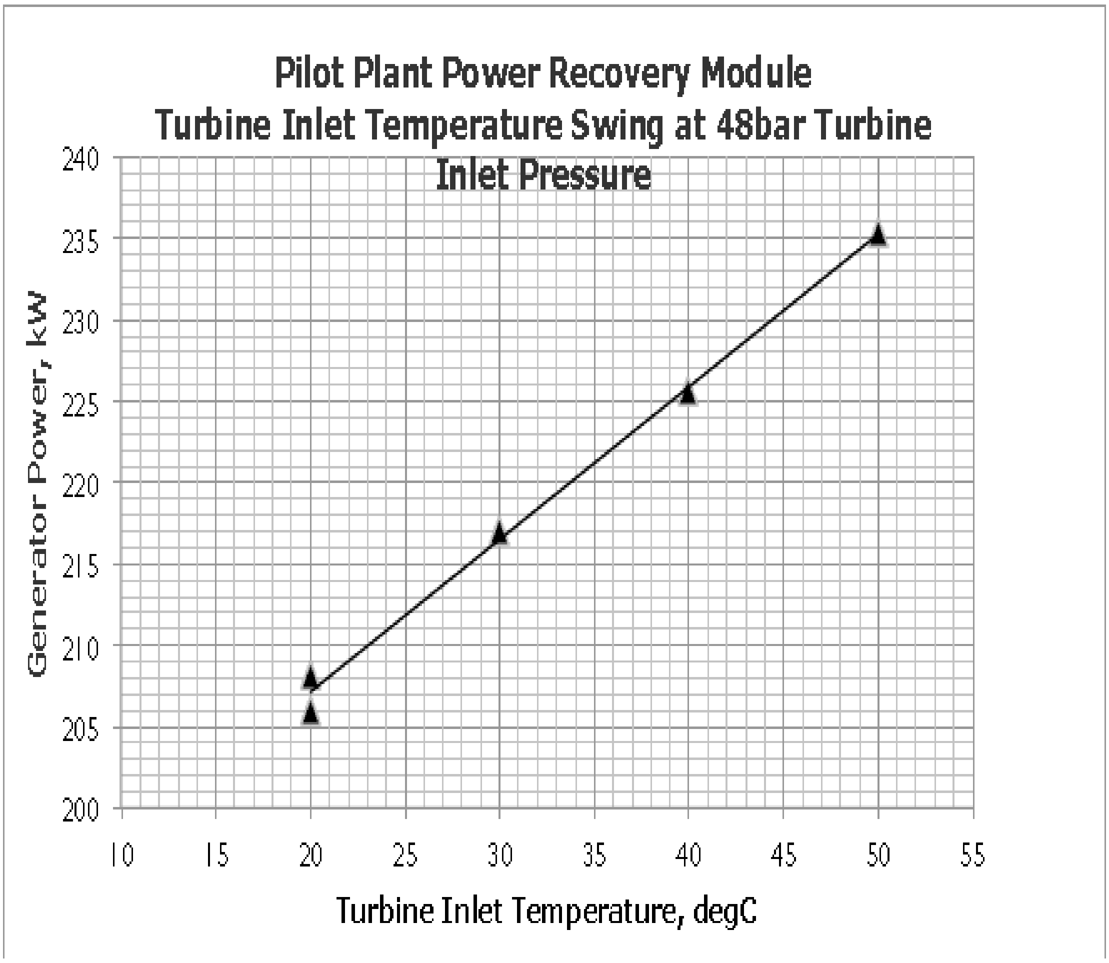


Figure 23: Pilot Plant heat to power relationship (25)[27] :

This indicates that a 1 °C increase in temperature of the waste heat gives a 1KW increase in power output at this scale of plant. In addition to this additional analysis[28] has indicated that modelling this further to evaluate a full range of waste heat temperatures, enables a view of a general LAES system with a range of waste heat

[27] *Source - HIGHVIEW POWER STORAGE TECHNOLOGY AND PERFORMANCE REVIEW MARCH 2012.*

temperatures from 50 C to 300 C and demonstrated the round trip efficiency as a function of the temperature (°C) of the waste heat stream:

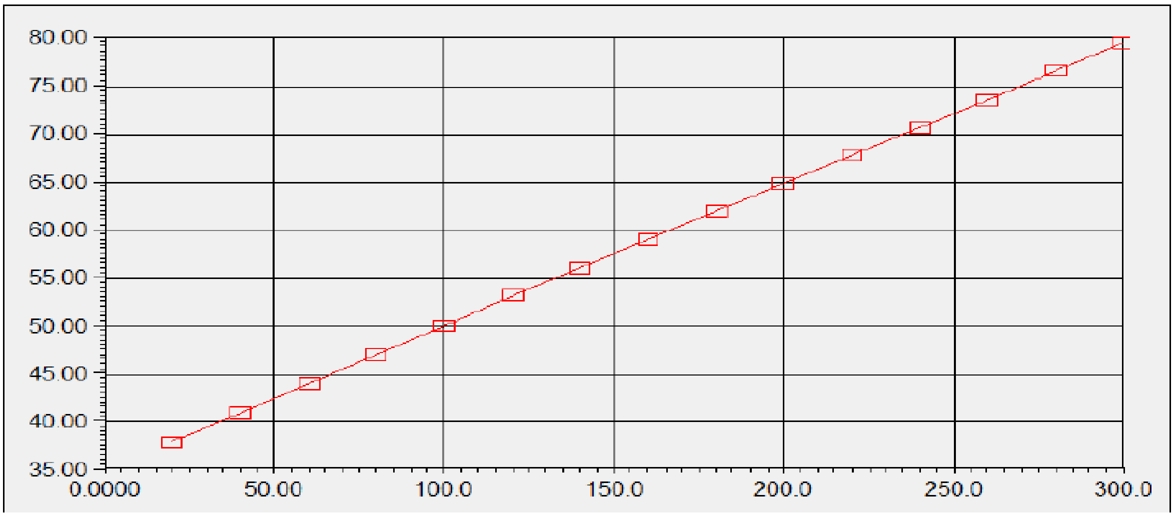


Figure 24 : Round trip efficiency of liquid air energy storage system in comparison to waste heat temperature (°C). Analysis via Aspen HYSYS (23)[28].

Cold Recycle

In addition to the efficiency benefit experience with utilising waste heat a similar efficiency benefit is noted when cold recycle is incorporated into the system. Figure Figure 25 : Results[27] below shows that pilot trials are in parallel with the profiled guarantees for the liquefaction equipment and have also these and modelled efficiency improvements. With lower temperature and losses within the cold recycle lower the amount of work required by the liquefier per Kg of output.

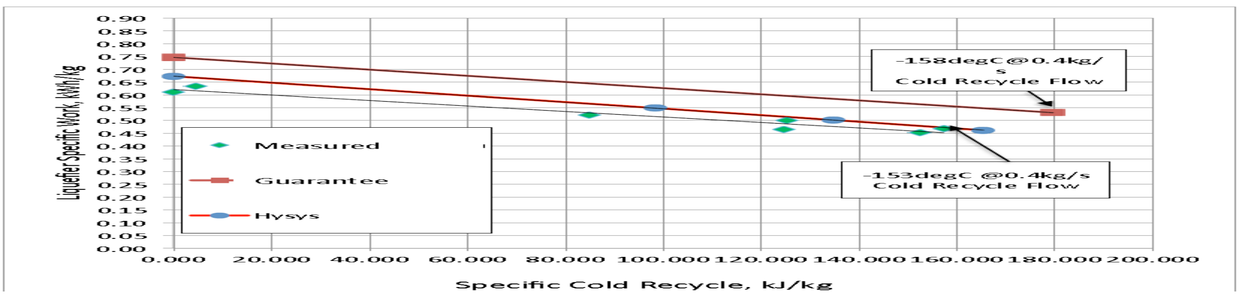


Figure 25 : Results (25)[27]

[28] Thermodynamic modelling in MEI's Liquid Air Energy Storage System Study: Emma Edwards, Dr. Roger Dargaville, Professor Paul Webley, 2 April 2014

3. Start-up response time

Response time – The system is said to have a response time of approximately 2.5 minutes when starting from standby to full power out. If starting from shutdown the system is able to achieve full power output within < 20 minutes. Both scenarios assume that there is a charged liquid energy store (18)[25.] The benefit of this fast response time relate to the ability to claim STOR, where a 20 minute response time to reach the set point output from an instruction is generally considered to be acceptable for a STOR provider[27].

4. Standing Losses

The liquid air energy storage system looses charge energy by heat loss to the surrounding environment mainly from the bulk cryogenic store. To mitigate against excessive losses the design of the insulation around these tanks is critical to ensure overall efficiency of the system, (losses of less than 0.2% per day are typical and compare favourably to energy losses from other technologies such as batteries) (18)[25.]

5. Flexibility

The nature of the plant and equipment is such that it can be configures in a modular approach and liquefaction units, storage vessels, cold store and cryo-generation equipment can all be sized independently. Although in general losses are lower with the increase in size of turbo machinery and standing thermal losses are lower in larger storage tanks. This inevitably improves the efficiency of large installations (18)[25].

5.3. Assessment of the Site

From analysis of the GSK site supply and demand model, as discussed in section 0 the various sizing options for the energy storage plant were reviewed and the most optimal units assessed via a savings model. The model was used to analyse the business case for an energy storage plant.

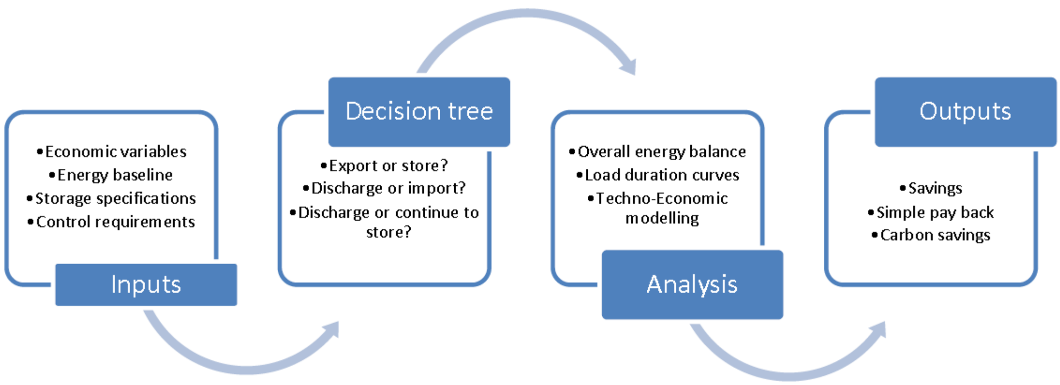


Figure 26 Modelling overview

The basic architecture starts with a number of input streams, including the energy demand and generation on an hourly basis, as developed with GSK for the biomass CHP project.

Input	Units	Description
Baseline demand	*kWh*	Total forecast demand on site (hourly data)
On-site generation	*kWh*	Total forecast generation by on-site generators (hourly data)
Storage capacity	*kWh*	Volume of storage the plant is able to store
Storage minimum	*kWh*	Desired minimum level of storage (e.g. if required for black start)
Storage charge power	*kW*	Maximum power storage can charge with
Storage discharge power	*kW*	Maximum power storage can provide while discharging
Export limit	*kW*	Any export limit that is in place on site
Electricity to spill	-	Select whether biomass / wind / nat. gas CHP are spilled if over
Prefer discharge to grid?	*Y/N*	Determine a preference to export storage or use it to displace

Figure 27 : Key inputs to the energy storage model

Each of the 8760 hours in the year are then taken through a number of calculation steps in the form of a decision tree, and the resulting profiles are then analysed to provide a series of outputs.

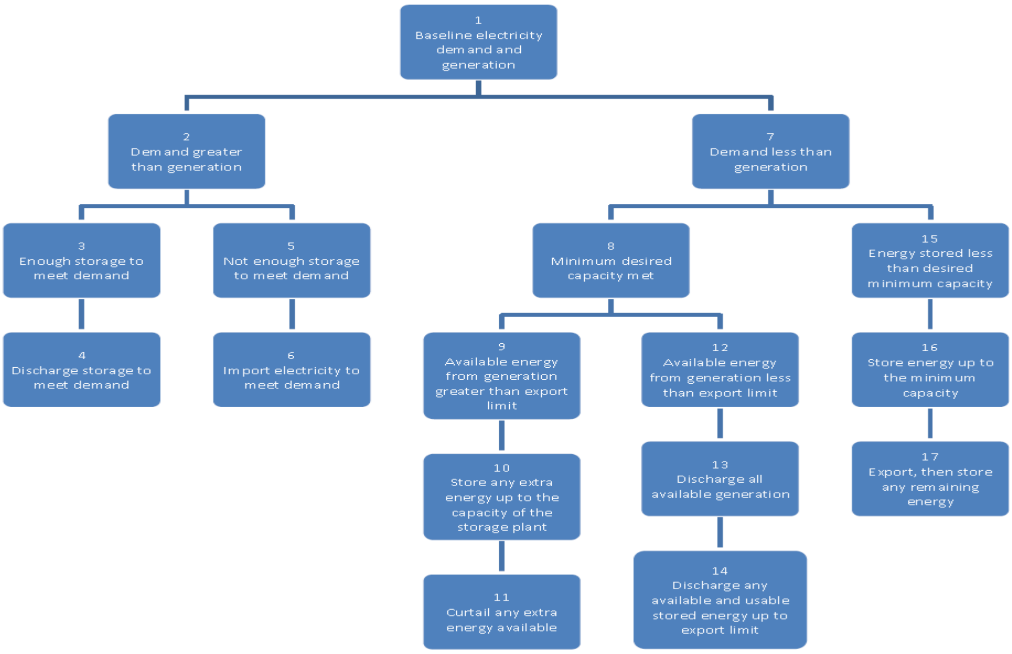


Figure 28 : Key inputs to the energy storage model The above process was used to determine the most appropriate use for excess renewable energy that would have been curtailed without energy storage.

The opportunities for maximising benefit from this energy were given a priority:

1. Charge the storage LAES tanks by using excess Renewable Energy.
2. Supplement site demand with stored energy, minimising electricity import.
3. Top-up existing export to 9MW

From this data the minimum recommended size for the liquefaction plant was determined to be 300 tonnes of air per day, corresponding to a 2.5MW liquefaction plant and a 5MW expansion turbine power recovery unit (PRU). This will enable an appropriate volume of storage to be installed, which was estimated at 140 MWh.

Equipment Costs

The liquefaction equipment is found to be the most expensive item within the overall system with the power recovery unit and storage equipment being relatively cheap in comparison. The following data is derived from supplier information and factored for scale the main items of equipment are commercially available and the costs below include all balance of plant items and construction costs (25)[29].

LAES CAPEX		Liquefaction [kW]		
[million £]		1250	2500	5000
PRU [MW]	5000	11.61	14.51	19.41
	10000	14.06	16.96	21.86
	15000	16.08	19.55	24.8

Figure 29: Cost profile for liquefaction and power recovery unit configurations.

The costs above reflect the early stage of this technology and reflect the "first of a kind". Hence there is an expectation that costs will reduce substantially on full development of the energy storage system. For this assessment I have used the initial costs for a current realistic appraisal of the technology.
The following table displays the required equipment to support a LAES system sized around the base case (all planned onsite generation installed & 100% utilised), with the likely unit costs as described above.

Equipment	Item Cost (£m)
Liquefier (Charging Device)	**9.6**
PRU (Discharging Device)	**4.4**
Energy Store	**0.2**
Waste Heat Recovery	**0.3**
Total Basic unit	**14.5**
Additional Storage	**3.9**
Total Cost	**18.4**

Figure 30 : Expected costs for a 2.5MW/5MW plant with 140MWh of storage.

The above analysis indicated a total installed capital cost of £ 18.4 million.

[29] Source - HIGHVIEW POWER STORAGE TECHNOLOGY AND PERFORMANCE REVIEW MARCH 2012.

Benefit analysis

There are several key sources of income from the use of LAES in this configuration. These include the (1) **generation of renewable electricity** from wind turbine generators that would otherwise have been prevented due to the export cap. The value of (2) **Renewable Obligation certificates** for this additional generation. The (3) **power recovered** from this renewable electricity through the LAES system. The value saved by using this power rather than (4) **importing electricity** from the grid. There are further saving opportunities expected such as eliminating import of electricity during (5) **TRIAD** periods and the income available for maintaining a readiness for (6) **STOR** standby by generation for grid supply.

Cost/Benefit	Unit	Value (p.a.)
1. Curtailed Elec Gen (>9MW)	KWh	10,273,386
2. ROC Value for Additional	£	£ 397,580
3. Recovered Elec post LAES	KWh	6,677,701
4. Import Saving	£	£ 641,059
5. TRIAD Saving	£	£ 198,000
6. STOR Income	£	£ 54,269
7. O&M Cost of LAES	£	-£ 135,000
8. Net Saving from LAES	£	**£ 1,155,908**

Table 8 : Cost benefits summary of proposed system.

These benefits are combined with expected annual (7) **operational and maintenance** costs, associated with the running of the LAES plant and equipment to give an overall annual saving of (8) **£1.1m.**

Following on from this analysis a Net Present Value (NPV) of the installation, during the total lifetime of the project (20 years), assuming a discount rate of 7% was carried out. The NPV obtained for this case study is negative, highlighting that the project is not viable within the current economic model.

	Discount rate	7.0%
year	Absolute cost	PV
0	£ 18,400,000	-£ 18,400,000
1	£ 1,155,908	£ 1,080,288
2	£ 1,155,908	£ 1,009,615
3	£ 1,155,908	£ 943,565
4	£ 1,155,908	£ 881,837
5	£ 1,155,908	£ 824,147
6	£ 1,155,908	£ 770,230
7	£ 1,155,908	£ 719,842
8	£ 1,155,908	£ 672,749
9	£ 1,155,908	£ 628,738
10	£ 1,155,908	£ 587,605
11	£ 1,155,908	£ 549,164
12	£ 1,155,908	£ 513,237
13	£ 1,155,908	£ 479,661
14	£ 1,155,908	£ 448,281
15	£ 1,155,908	£ 418,954
16	£ 1,155,908	£ 391,546
17	£ 1,155,908	£ 365,931
18	£ 1,155,908	£ 341,992
19	£ 1,155,908	£ 319,618
20	£ 1,155,908	£ 298,709
	NPV	**-£ 6,154,291**
	Simple Payback	**15.9**

Table 9 : Economical feasibility of the system over 20 years

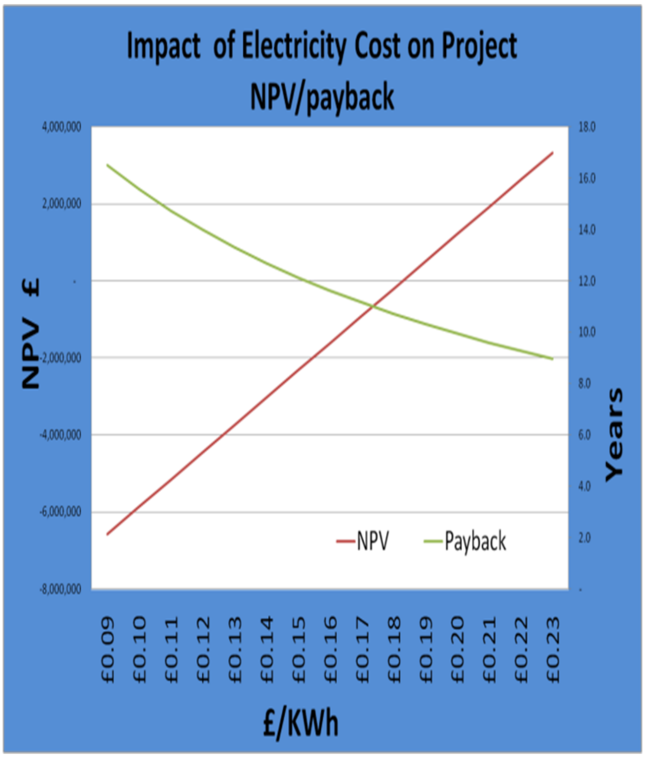
From this data a sensitivity analysis was carried out to investigate the impact of the following 2 factors:

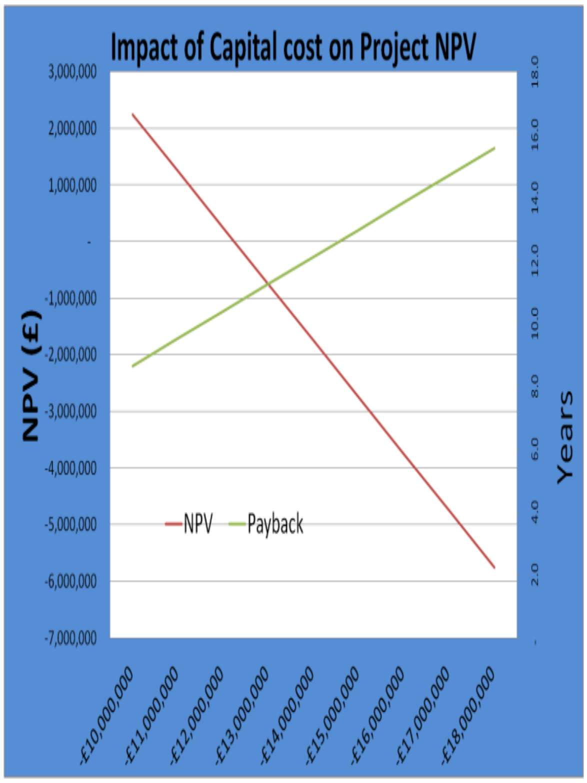
1. Reduction in capital cost of the plant and equipment.
2. Increase in the import electricity value.

From this analysis it is seen that either an independent reduction in the capital cost of the plant of £18.4m to £12 m or and separate increase in cost of grid electricity to £0.19 /KWh, provides a positive NPV.

A more likely scenario is a combined an optimisation of the capital cost with a smaller increase in grid electricity cost to make the project commercially viable.

Graph 7 : NPV sensitivity analysis of the system for varying capital cost and grid Electricity price.





Environmental Saving

The environmental saving is also noted in that the quantity of electricity off-set by the additional renewable energy generated by the wind turbine generator is approximately 3,000 tonnes. This is based on a power recovery unit output of 6,700 MWh and a CO_2 grid electricity conversion factor of 0.4585 (26)[30].

[30] **Government conversion factors for company reporting, DEFRA / DECC,** http://www.ukconversionfactorscarbonsmart.co.uk/

6. Conclusion

The Irvine site can benefit from the implementation of an electrical energy storage technology, designed to enable greater utilisation of all implemented and planned renewable energy technologies. Form the data above it can be seen that the site could offset imported electricity by storing excess or curtailed renewable electricity.

Assessment of a range of electrical energy storage technologies has identified that there are limited applicable technologies available. This is due to the location, scale and response time of the technology, in relation to the modelled site demands and volume of generated electricity.

One technology that does technically achieve the delivery requirements is liquid air energy storage, (LAES) and has the potential to deliver various benefits to the Irvine site, including almost 3,000 tonnes per year of CO2 reductions and £1m of energy cost benefits in addition to enhanced security of supply.However, the capital cost requirements of a LAES plant currently prove prohibitively high for this application, due to the development status of the technology package.

Due to the various and significant benefits available to the site with an energy storage facility, it is recommended that further work is carried out to investigate the alternative emerging storage technology of power to gas. This looks to be a viable alternative for the use of unused renewable energy and as the site has a considerable heat demand it may well be a suitable alternative.

Both technologies are at key development stages and the adoption of either will be dependent on the future commercial equipment costs. Future feasibility activity should keep an overview of these technologies along with the third option of battery technology that is likely to develop more quickly and will reduced in prices significantly (currently reducing at 15-20% per annum (14)) over the next few years to become a very competitive option.

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