1/1/2022

Sustainable Energy Storage Honoka'a, Hawaii

Energy Supply to Proposed New Google Data Centre

Table of Contents

Project Goals & Objectives

The aim of the project is to develop an uninterruptable low-cost energy supply, for a proposed new Google data centre in Honoka'a, HI. It consists of a renewable energy storage system, using energy from wind farms when there is a surplus, to store energy for use when the wind is low. Island Power Inc. has been contracted to meet this goal by overseeing the project on the behalf of Google. The project involves assessing a means by which energy can be stored for peak shaving, and selecting one of these based on cost, environmental impact, and benefit for the local community. Following the Assess stage, it was determined that either hydropower or green hydrogen are to be selected for the energy storage. Specific objectives include the project delivering power within 3.5 years from project sanction, and the energy storage providing 20 MW per hour, continuously for 6 hours. The objectives that must be quantified to meet the project goal are price and economic benefit to the local community. A qualitative Life Cycle Assessment (LCA) must be completed. The energy storage's electricity must be cheaper than the cost of electricity from the interconnector to be profitable. Critical success factors to ensure the project is achievable include detailed cost estimates, performing LCAs to evaluate carbon footprints, the preservation of Hawaiian wildlife, and employing local workers and materials where possible. The relevancy of the project must be upheld through a triple bottom line assessment.

Project Description & Strategic Fit

The data centre requires 20 MW per hour, for 6 hours. Due to the changing wind conditions, energy from the wind farms on The Big Island is not sufficient. The energy from the interconnector is too expensive for the project to be profitable. The motivation for the project is the data centre's requirement for a continuous source of cheap energy. This energy must be sustainable, and the project should benefit the local community. From the SWOT analysis in Table 1B (Appendix B), the selected strategy builds on strengths and opportunities by hiring specialist companies to develop the energy storage system, and combats threats and weaknesses by hiring locally and minimising environmental impact through Life Cycle Assessments. The project is managed by IPL, although Google's approval is required at each stage gate at the end of the Assess, Select and Define stages. SMART objectives are outlined to ensure the goal is met. To select the method of energy storage, each option must be compared through a triple bottom line assessment, including cost estimates, technical comparisons, LCAs, social impacts, contracting and execution strategies. Lessons must be reviewed at the start of each project stage and captured at the end.

Description of Options 1 & 2

Option 1 involves "High-Density Hydro™" – hydropower using the fluid R-19™, which is 2.5 times denser than water, allowing for a lower head. The vertical distance between tanks is 200 m, thus the project only requires a hill rather than a mountain that would be necessary for a lower-density fluid. The company that would engineer this option is RheEnergise, a London-based company specialising in pumped hydro storage (1). When the wind farms on The Big Island are producing a surplus of energy due to favourable wind conditions, energy is used to pump the fluid to the top storage tank, thus storing energy in the form of potential energy. When energy is required, the fluid is released, passing down the penstock and through turbines, generating electricity. The data centre uses this electricity rather than the more expensive and fossil-fuel-originated electricity from the interconnector. The site involves an inactive volcano in a tropical coastal area. The top and bottom storage tanks are each $100 \times 100 \times 7.5\ m$ (total volume $75{,}000\ m^3$, with working fluid volume $72{,}000\ m^3$), each of the two penstocks have 0.8 m diameter and 200 m length. The power-house contains master safety valves, reversible pump-turbines, electrical equipment, and ancillary systems. Other components of the system include manifolds joining the tanks and valves to control flowrate. The system provides 20 MW per hour, continuously for 6 hours, totalling 120 MW. The storage tanks and power-house require reinforced concrete foundations, the penstock requires 'thrust blocks'. Trenches reduce the visual impact of the penstock. A powerline and pylon system connects to the grid. Risks involve pumping malfunction and leaks. These can be mitigated through backup pumping, regular checks, and maintenance. Uncertainties include the materials used in producing the fluid and their environmental footprint.

Option 2 involves green hydrogen, produced through electrolysis, and used in PEM fuel cells to generate electricity. When the wind is high, energy is used to convert water into hydrogen and oxygen through electrolysis. These are stored in tanks and used when the wind is low to generate electricity in the fuel cells. GreenHydrogen Ltd would engineer this option. The electrolyser can operate at standard conditions, whilst the fuel cell operates at 80°C. Hydrogen is compressed to 1.5 bar for storage and use in the fuel cell. The fuel cell stack produces $20.032MWh$, each of the 289 cells produces $19.2539\ W$, the stack's dimensions are $1.235 \times 0.988 \times 0.2594\ m$. The hydrogen tank is $25\ m^3$, the oxygen tank is $20\ m^3$, with radius $1\ m$, lengths $8\ and\ 6.5\ m$ respectively. The chosen material for the tanks is type 316 steel. The current for the whole electrolyser stack is $10{,}990\ A$, each of the 275 cells requires $40\ A$. The total dimension of the stack is $0.17 \times 0.16 \times 16.5\ m$. The pipes for the water and oxygen are concrete, whilst the pipes for the hydrogen are basalt-derived fibre reinforced polymer pipes. The capacity of the water storage tank is 10,000 L, which stores acidified water for use in electrolysis. This comprises deionized water and dilute sulfuric acid, in a ratio of 10:1. The fuel cell requires a heating and cooling system, as well as a humidifier. There is a control and alarm system, as well as valves and isolation valves for safety. Simple electrical enclosures house the stacks and heating/cooling/humidifiers. A compressor is required for the hydrogen storage. A powerline and pylon system connects to the grid. Risks involve the use of hydrogen, which is highly flammable, as well as leaks. Mitigation involves the use of isolation valves, minimising the diameter, length, and number of joints in pipes - thus straight pipes. Uncertainties include whether heating/cooling/humidification is required for the electrolyser stack.

Adverse effects on wildlife would prevent the execution of the project; it is thus imperative that nature is protected; the high-density fluid or hydrogen must be contained, any leaks must be addressed immediately. The project must have a minimal carbon footprint, and noise or waste pollution must be minimised – walls of enclosures must have adequate thickness, decommissioned equipment recycled.

Project Frame

The scope of the hydropower includes a High-Density Hydro energy storage system, consisting of top storage tanks, manifolds, valves, penstocks, a power-house, lower storage tanks, foundations, ‘thrust blocks’, trenches, the area, and connection to the grid. Ancillary systems are outside of scope as detail is not given. The scope of work involves construction of the tanks, penstocks and power-house, as well as their foundations, an overhead powerline and pylon system to connect to the grid, and the excavation of trenches. Givens include the site being on an inactive volcano with 200 metres of head, the volume of both top and bottom storage tanks is 75,000 m^3, the penstocks have diameter 0.8 m, and the system provides 20 MW for up to 6 hours. It is assumed the length of penstocks is 200 m.

The scope of the green hydrogen includes a water electrolysis and hydrogen fuel energy storage system, consisting of an electrolyser stack of 275 cells, a fuel cell stack of 289 cells, enclosures for the stacks, two storage tanks, connecting pipelines, valves, an alarm system, heating/cooling, humidifier, compressor, water tank, the area, and connection to the grid. Any power conditioners, valves, pumps, alarm/control systems are outside of scope, to simplify design. The scope of work involves construction of the enclosures, laying down pipes and tanks, assembling the stacks and heating/cooling/humidification, and an overhead powerline and pylon system to connect to the grid. Givens include the site being coastal land near the data centre, and the system provides 20 MW for up to 6 hours. It is assumed heating, cooling and humidification are not required for the electrolyser.

The strategy involves HSE (Health and Safety Executive), quality management, design management, project controls strategy, ICT strategy, risk, change, value, and lessons management. HSE strategy involves the safety case, where all major hazards are identified, their risks considered during the Select stage, and mitigated by Front End Engineering Design. Safety processes must make risks as low as reasonably possible. Quality management involves quality assurance by both IPL and Google; for the former by pre-commissioning checks, tests, and preparation activities – including loop checking on control systems, alarms and set point, as well as Verification of Readiness (VoR) Certificates; for the latter through regular testing and maintenance of the plant and equipment to ensure it is working as expected. Quality control requires IPL to check the energy storage system produces at least 20 MWh, quality surveillance requires Google to check that the energy supply from either the storage or the wind farms is continuous, and that the interconnector is not required. Design management strategy includes codes and standards as well as design philosophy, the standard ISO 22734-1:2008 applies for the safety of hydrogen generators using water electrolysis (2). Project controls strategy involves cost estimation, engineering, and planning. ICT strategy involves document management, IT support, and communication protocol. Risk management requires a risk response action plan and a risk matrix. Change management requires data decided as ‘frozen’ to be changed if required for an improvement. Value management includes peer assists and reviews. Lessons management requires lesson review and capture, as well as paying attention to lessons from similar projects; approval can take 5 years – this project must be running in 3.5 years.

Project Schedule

As demonstrated in Figure 1B, both projects are estimated to be running before 3.5 years (42 months) after project sanction – the projects should be running before 2025. The Gantt chart is based on typical hydrogen and hydropower project durations – for the former between 18 and 24 months and for the latter minimum 24 months (3),(4), although contingency has been added. For both options, permits and consents must be obtained before the rest of the project can be completed. Contracts and investigations must also be carried out before any further work. For the hydrogen option, stack assembly must precede the alarm, control, and temperature/humidity systems.

Contracts & Procurement Strategy

Tables 2B and 3B demonstrate the proposed work scope packaging. RheEnergise/GreenHydrogen could contract others for procurement/fabrication, or deal with piping/electricals/construction themselves. However, it is recommended that they are responsible for procurement and fabrication, so that the technology's standards are met, and that external contractors are hired for piping, electricals, and construction as these must meet safety standards and regulations – this requires specialists. The chosen contracting strategy has Google responsible for operation, IPL who define preliminary engineering as well as commissioning, and a contractor (RheEnergise/GreenHydrogen) for the detailed engineering through to construction. In this way Google take responsibility for the plant once it is completed, and IPL are responsible for organizing contractors to build the plant according to Google's specifications. A market survey report is required, to assess the capability of potential contractors to meet the required standards. Various contractors should be listed, thus improving the selection; contractors can be compared, and the contractor deemed the best can be hired. An EPCM contract type would be suitable for RheEnergise/GreenHydrogen, as they are responsible for engineering and procurement, and manage construction. A Project Management Contract would be suitable for IPL, as they define preliminary engineering and are responsible for overseeing and testing the system. Smaller contractors such as for piping and electricals are hired by RheEnergise/GreenHydrogen.

Stakeholder Engagement & Alignment Strategy

Table 4B demonstrates the various stakeholders (5),(6). The external stakeholders are environmental, political, and climate movements; the internal stakeholders are the hired companies and workers, as well as the landowner, Google's upper management, and project board members. For the external stakeholders, the project is of interest to those concerned with green energy, although it may be seen as a threat to independence movements, who may not want large foreign corporations taking their land. It may be a threat to Hawaiian wildlife groups, who may be concerned about its impact on nature and the environment. The internal stakeholders are in favour as they will make money. The variations in influence of the external stakeholders depends on the size of the group, the most influential groups have authoritative power. Those strongly against are independence movements, those against are environmental groups. The balanced groups may be swayed depending on if the project supports the economy and does not contribute to waste. The stakeholders in favour may be aligned though demonstrating the low carbon footprint of the selected option. The project's sustainability should be advertised before January 1st, 2023, once permits and consents are obtained, to draw positive attention and gain the support of the stakeholders. Stakeholders who are balanced or against may be aligned if the project benefits the Native Hawaiians and if it has minimal impact on wildlife. Where possible, local workers and materials should be used. Before March 1st, 2022, job advertisements should be published for local construction workers. Before January 1st, 2023, they should be published for local engineers. Any waste must not be discharged into nature. The effectiveness of these actions must be assessed, an alternative approach may be required if stakeholders are not aligned.

Operations & Maintenance Philosophy

Production

Fluids used to generate energy shall be recycled. Open flames shall not be present on-site, ignition sources must be isolated or eliminated. Earthing must be in place for electrical equipment (7). Electrical equipment shall be stored in an enclosure for shelter against the environment. Electricity from the interconnector shall only be used in the event of failure of the storage system.

Maintenance

Daily checks shall be performed. Abnormalities shall be reported immediately. Damaged equipment shall be repaired where possible, otherwise replaced. Cleaning shall be during periods of inactivity. In the event of a shutdown, Google shall be informed immediately.

Organisation

Workers shall be employed locally where possible. Smoking is prohibited on-site.

The Operations Assurance and Readiness (OAR) manager must report to the project manager. The OAR team will comprise 6 people, including the manager, for the Define and Execute stages. Risk assessments are presented in the following section, as well as in the Description of Options.

Technical Comparison of Options 1 & 2

Hydropower's advantages include energy efficiency & losses, and safety. For the former due to near 100% energy conversion from mechanical to electrical (8). For the latter as the fluid is "environmentally benign, non-toxic, non-corrosive, and non-reactive" (1). Disadvantages include wildlife impact and operating costs. For the former as hydropower takes up more space, the construction of the site will be more disruptive to nature than that of hydrogen, for example a storage tank is 75,000 m^3 compared to the hydrogen storage tank of 25 m^3. For the latter as pumping the fluid is energy intensive, thus increasing costs. Hydrogen's advantages include wildlife impact and operating costs. The system is more compact than that of the hydropower, thus less land is required. Although hydrogen's flammability and need to be compressed add to cost (9), in this case it does not need much compression as there is relatively little. Disadvantages include energy efficiency & losses, and safety. The fuel cell must be heated to 80°C, and the hydrogen gas compressed to 1.5 bar, thus it does not operate at standard conditions. 30-35% of the energy used to produce hydrogen is lost during electrolysis, the use of hydrogen in fuel cells adds a further 40-50% loss (9). Hydrogen is highly flammable and appropriate safety measures must be taken. The lifetime of an electrolyser is around 30,000 hours (10), assuming 12 hours of use per day, a replacement should be required after about 7 years. The mechanical equipment for the hydropower however only requires replacing after 40 years (11), thus less maintenance is required for this option. Downtime because of repairs or replacements must be taken into consideration, in this case electricity from the interconnector will be required. This should not be an issue for the hydrogen storage as by the time the electrolyser requires replacing, around 2035, the new subsea interconnector should be completed. This would supply cheaper electricity than the current interconnector, thus the shorter lifespan of the hydrogen equipment should not pose an issue.

The criteria have been selected to satisfy a triple bottom line assessment as safety and wildlife impact consider life and society, energy efficiency & losses consider the environment, and operating costs consider economics.

Technological risks:

- Hydropower requires pumps, which can explode or rupture if over pressurised. Mitigation involves backup pumping, as well as regular maintenance.
- An opportunity is the high-density fluid, which allows for less head, thus the site can be on a smaller scale.
- Optimisation of green hydrogen systems is costly and complex due to limited knowledge as it is a new technology (9). This can be mitigated through further research; Google has the wealth to fund research into green hydrogen.
- Hydrogen is flammable and is stored in a pressurised vessel, thus there is the risk of explosion. Mitigating strategies include alarm systems, regular inspection of the tank and replacing any embrittled parts.
- An opportunity is the cycling of the materials – water is converted into hydrogen and oxygen, which are then converted back to water which can be recycled back to the electrolyser. The concept of ‘circular economy’ applies.

Environmental Assessment

An Environmental Impact Assessment (EIA) considers consequences and ensures environmental implications of decisions are considered. Public consultation is a key feature, the public participates in decision-making (12). A Life-Cycle Assessment (LCA) is the best framework for assessing potential environmental impacts of products, according to the European Commission. It is an internationally standardised method (ISO 14040 ff). It considers the full-life cycle of the product, environmental pressures, and benefits (13). Whilst the EIA focuses on public opinion and general consequences, LCA follows an international standard and considers each stage, from material origin to disposal, of a product. Their similarities lie in their concern over consequences to the environment. EIA has the benefit of considering public opinion, which is valuable considering the stakeholders and the Native population, who may feel the project is invasive to their land and the wildlife. The benefit of LCA is its consideration of every stage, beyond the process, involving materials, transport, disposal. EIA considers direct consequences, not every stage of the life cycle.

- Functional unit: high-density hydropower or green hydrogen system of 20MW for up to 6 hours.
- Impact category: climate change (kg CO_2-eq).
- LCA system boundary: the hydropower or hydrogen energy storage system, excluding the wind farms, interconnector, and pylons.
- Not assessing valves, pumps, compressors, alarm/control/temperature/heating systems, ancillary systems, as well as some construction materials in the LCA.

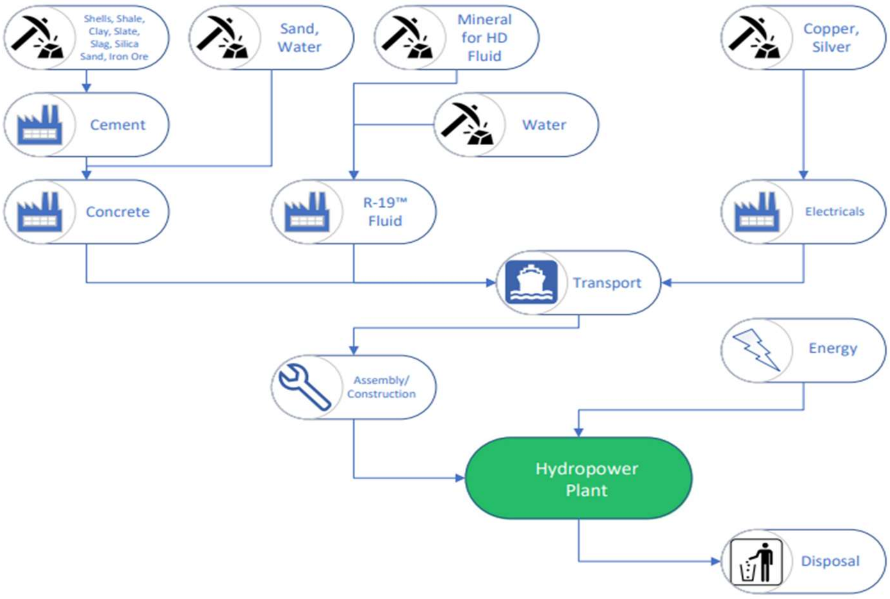

Figure 1. Life Cycle Inventory for Hydropower (14,15,16,17,18)

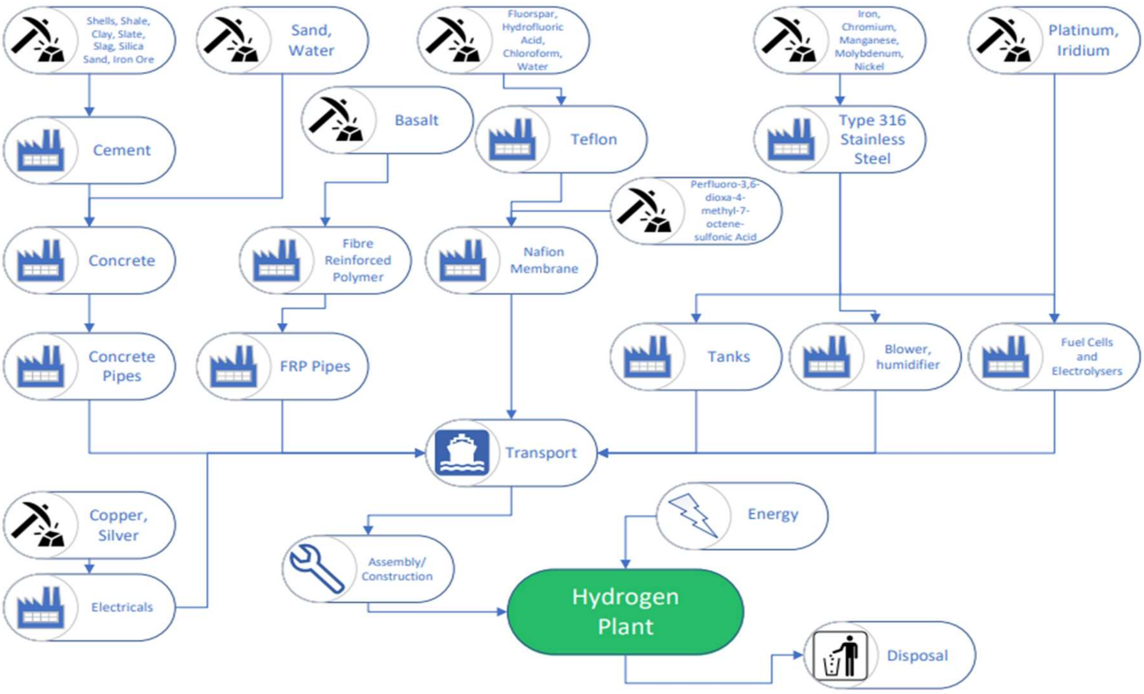

Figure 2. Life Cycle Inventory for Green Hydrogen (14,15,16,17,18)

- Transportation: by air or boat for imports, otherwise by road or boat. Hawaii is rich in basalt, FRP and concrete pipes made locally (19). Most technology such as tanks and stacks are imported.
- Disposal: an acid process can recuperate the platinum and membrane; hydrometallurgical treatment can recuperate the iridium (18). For the hydropower, the high-density fluid is “environmentally benign” (1), and disposal is assumed simple.

The main impacts have been identified as follows:

- Mining – deforestation to clear space for mines to acquire raw materials.
- Transportation – emissions by vehicles, considerable as Hawaii is in the middle of the Pacific Ocean.
- Construction – deforestation to clear building space.

- The hydropower Life Cycle Inventory (LCI) shows a need for fewer resources, thus it may have a smaller environmental impact, although this may be due to limitations in given information on the process. Despite this, it is concluded that the hydropower system has a smaller environmental footprint in terms of emissions. It also relies more on local materials such as concrete, and less on imported technology (e.g., stacks), thus minimising transportation emissions. However, in terms of wildlife impact, the hydrogen system may have a smaller impact due to being smaller in size.
- The LCA does not consider certain components thus is incomplete, and any conclusions may be affected by this. Limitations include the fact that the analysis is solely qualitative, and information is missing. A quantitative LCA is recommended as a more suitable indicator of climate impact.

Societal Aspects & Impact Assessment

The development of the data centre and its energy storage may be seen negatively by the local population, who may not want a large corporation building on the land and impacting the wildlife. Others may view the project positively due to the job opportunities generated, and the use of Hawaiian materials such as gravel, basalt and concrete would benefit the economy. The counterfactual for the project entails no jobs generated for the local community, no use of Hawaiian gravel, basalt, and concrete, although land would be conserved – benefitting the wildlife. The impact on wildlife of the project must be reduced, whilst benefiting the local community. This can be done through using local equipment, materials, transport, and workers. The size of the site should be minimised to reduce the destruction of natural habitats. To monitor societal impact, the local community could be surveyed on their opinion of the project, the benefit to the Hawaiian economy could be determined through the number of employees and workers hired locally, and whether materials are sourced locally. Environmental impacts can be determined through LCA. The project must be ethical, through protection of public health and safety. The energy storage system must be isolated from populated areas, and regular checks must be carried out. Laws must be respected, and all necessary permits and consents must be obtained before construction begins. Any waste shall not be released into the environment. The use of renewable energy applies to the protection of the environment and life, electricity from the interconnector should be avoided as it may be petrochemical-derived. Honesty and integrity must be maintained through informing the public and authorities of any associated hazards. Accuracy and rigour shall be ensured through hiring competent engineers. Diversity, equality, and inclusion shall be promoted.

Cost Estimate, Economics, & Business Case

Assuming the 3 wind farms produce sufficient energy for the data centre when it is windy, generally between 6 am and 6 pm (20), thus two 6-hour cycles are necessary per day – thus 240 MW per day. Assuming a cost of £10 per MWh (21). The cost of the chosen energy storage system must be cheaper than the price of electricity from the interconnector: $\$275.50 \times 0.75 = £206.63\ per\ MWh$

Thus £49,591.20 per day, or around £18 million per year.

Hydropower Operating Costs:

Assuming a pump efficiency of 90%, head of 200 m, fluid density of 2500 kg m^{-3}, flowrate of 12,000 m^3 hr^{-1}; pump power required: 18 MW (for 6 hours) (22).

Thus £180 per 'cycle', or £360 per day. Assuming 3 staff members (1 each for repairs, electromechanical controls, and supervision). The average salary for a hydropower engineer (US) is \$90,529 (23):

$\frac{90{,}500 \times 0.75}{365} = £185.96\ per\ day$: total of £557.88 for all 3 workers

Total operating costs: £917.88 per day; £335,026 per year.

Comparing to the price of electricity from the interconnector, shown in Figure 2B, the hydropower saves over £30 million after 6 years. Assuming all electricity produced is used and not sold, and reducing rate of 25% on capital tax allowances, tax rate 30%, discount factor 7%.

Hydrogen Costs:

CONSTRUCTION & ENGINEERING		
Investigations		£60,000
Excavation & Filling		£1,000,000
Piling & Retaining		£500,000
Concrete		£100,000
Sundry Brick/Block/Stonework		£10,000
Steel		£50,000
Tanking		£5,000
Simple electrical enclosures		£250,000
Control room		£150,000
Chain-link fence		£1,200
Automatic gate		£2,000
Misc. Works		£50,000
Access roads		£200,000
Gravel parking		£5,000
Electrical Works		£100,000
Specialist Data & Security		£20,000
	TOTAL CONSTRUCTION	£2,501,200
	Including 10% Contingency	£2,751,320

CAPEX (PLANT)	
Pipework, Valves	£20,000
Tanks	£17,700
Humidifier	£850
Blower	£100
Fuel Cell Stack	£42,000
Electrolyser Stack	£52,500
Compressor	£600
Electrical (main)	£500,000
Transformers / Grid	£500,000
Balance of Plant, including Control, Alarm & Heating systems	£250,000

TOTAL PLANT CAPEX	£1,383,750
CAPEX (Acidified water)	
Acidified water	
Deionized water	
Sulfuric acid	
TOTAL ACIDIFIED WATER CAPEX	£35,000
Contractor	
Contingency 7.5%	£200,532
Overhead contractor 10%	£263,875
TOTAL Contractor	£464,407
Total CAPEX	£4,634,477
INITIAL DEVEX	
Design (for consents)	
Initial investigations	
Legal fees (acquisition)	
DEVEX (High risk Capital)	£122,222
DEVEX (FEES AND CONSENTS)	
Design (detailed)	
Planning & Consents	
Licences	
Landowner	
Land Acquisition	
Agent Fees (acquisition)	
Grid (connection fees)	
Grid (inspection fees)	
TOTAL FEES & LICENCES	£572,222
TOTAL CAPEX & DEVEX	£5,206,699

The price of hydrogen is £5/kg H_2 produced (24). For a 'cycle' of 6 hours running:

$m_{H_2} = n_{H_2} \times Mr_{H_2} = 1230\ mol \times 0.002016\ kg\ mol^{-1} = 2.480\ kg$; £24.80 per day.

The cost of hydrogen compression is calculated using $W = -2.303nRT \log \frac{V_2}{V_1}$

$$W = -2.303(1230\ mol)(8.314\ J\ mol^{-1} K^{-1})(293\ K) \log \frac{24.07\ m^3}{36.10\ m^3} = 1.215\ MW$$

Giving £24.30 per day. For heating/cooling:

$c_{p_{H_2}} \approx 14.3\ kJ\ kg^{-1}\ K^{-1}$ (25) $\qquad c_{p_{O_2}} \approx 0.917\ kJ\ kg^{-1}\ K^{-1}$ (25)

$$(14.3\ kJ\ kg^{-1}\ K^{-1})(2.48\ kg)(293\ K)2 = 20.78\ MW\ per\ day$$

$$(0.917\ kJ\ kg^{-1}\ K^{-1})(615\ mol)(0.016\ kg\ mol^{-1})(293\ K)2 = 5.287\ MW\ per\ day$$

Cooling requires 23.58 MW per day:

$20.78\ MW + 5.287\ MW - 23.58\ MW = 2.487\ MW$ or £24.87 per day.

Water used up per day: $m_{H_2O} = (1230\ mol)(0.01802\ kg\ mol^{-1})(1\ kg\ L^{-1})2 = 44.32\ L$

Assuming a 1:10 ratio of sulfuric acid to water: 4.4 L sulfuric acid required per day, assuming £44 per day. Assuming 3 staff members, the average US salary of a hydrogen systems project engineer is $80,070: £164.38 per day, total £493.14.

Total operating costs: £611.11 per day; £223,055 per year. Figure 3B demonstrates the cash flow of hydropower compared to hydrogen; after 6 years the hydrogen saves around £15 million. Thus, green hydrogen is the cheapest option, cheaper than both hydropower and the energy from the interconnector, thus it is worth investing in green hydrogen. To assess the companies' trustworthiness, their customers can be asked about financial reliability and the quality of their work. To ensure the work deliver meets the required standard there must be adequate communication between Google, IPL and the companies, a service level agreement, and measurement of metrics such as delivery in full and on time, quality, and compliance.

Project Execution Strategy

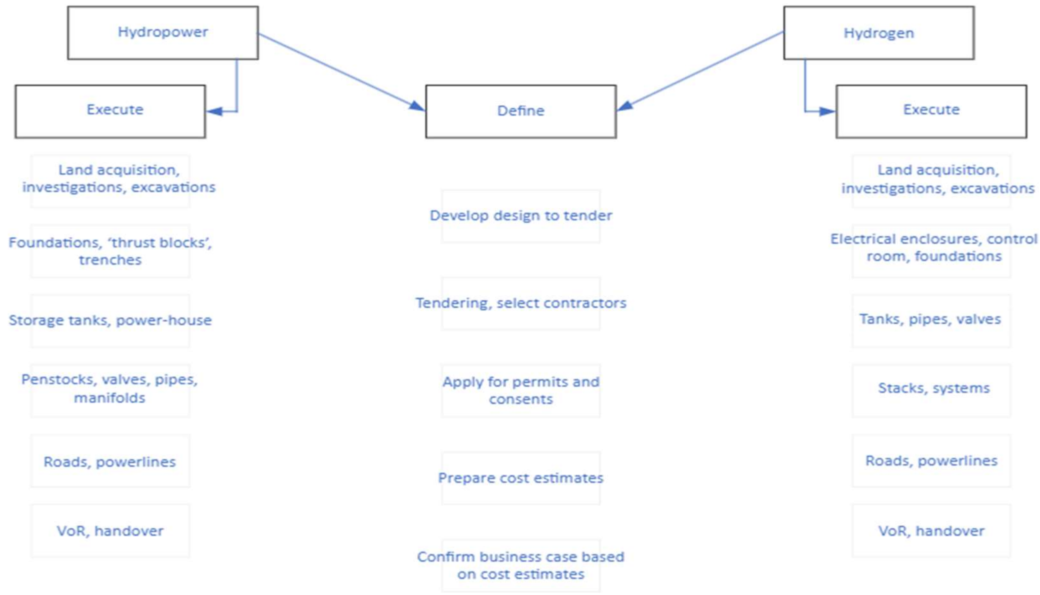

Figure 3. Work Breakdown Structure & Strategic Approaches for each Option

Conclusions

Based on a triple bottom line assessment, the green hydrogen energy storage system has been selected. Compared to the hydropower, it is a better option financially, saving £15 million by 2028. Environmentally, although hydropower appears to have a smaller footprint, the smaller scale of the hydrogen may have less of an impact on wildlife. Socially, either option can be justified through employing locally. Both options are renewable and provide benefit to the local community, this the difference in cost is the most important factor. The difference is very significant; thus, the preferred option is the hydrogen system.

References

1. RheEnergise (2022) *LinkedIn*. Available at: https://www.linkedin.com/company/rheenergise/ (Accessed: 8 January 2022).
2. Pritchard, D.K., Royle, M. and Willoughby, D. (2009) *Installation permitting guidance for hydrogen and fuel cell stationary applications: UK version*. Buxton: Crown.
3. California Fuel Cell Partnership (2017) *July 2017 Hydrogen Station Update Webinar – Questions & Answers.* Available at: https://cafcp.org/blog/july-2017-hydrogen-station-update-webinar-questions-answers (Accessed: 8 January 2022).

4. Renewables First (2022) *How long will a hydro project take?* Available at: https://www.renewablesfirst.co.uk/hydropower/hydropower-learning-centre/how-long-will-a-hydro-project-take/ (Accessed: 8 January 2022).
5. University of Hawaii (2022) *Environmental Organizations in Hawai'i*. Available at: https://www.honolulu.hawaii.edu/sites/www.honolulu.hawaii.edu/files/sustainability-orgs-hawaii.pdf (Accessed: 8 January 2022).
6. Wikipedia (2021) *Hawaiian sovereignty movement*. Available at: https://en.wikipedia.org/wiki/Hawaiian_sovereignty_movement (Accessed: 8 January 2022).
7. HyResponse (2022) *Sources of hydrogen ignition and prevention measures*. Available at: http://www.hyresponse.eu/files/Lectures/Sources_of_hydrogen_ignition_notes.pdf (Accessed: 8 January 2022).
8. University of Calgary (2022) *Hydropower*. Available at: https://energyeducation.ca/encyclopedia/Hydropower (Accessed: 8 January 2022).
9. World Economic Forum (2021) *4 technologies that are accelerating the green hydrogen revolution*. Available at: https://www.weforum.org/agenda/2021/06/4-technologies-accelerating-green-hydrogen-revolution/ (Accessed: 8 January 2022).
10. pv magazine (2020) *Electrolyzer overview: Lowering the cost of hydrogen and distributing its production.* Available at: https://pv-magazine-usa.com/2020/03/26/electrolyzer-overview-lowering-the-cost-of-hydrogen-and-distributing-its-productionhydrogen-industry-overview-lowering-the-cost-and-distributing-production/ (Accessed: 8 January 2022).
11. GE Renewable Energy (2022) *Pumped Hydro storage.* Available at: https://www.ge.com/renewableenergy/hydro-power/hydro-pumped-storage#:~:text=Renewable%20and%20Sustainable%3A%20Hydropower%20uses,100%20years%20for%20the%20dam (Accessed: 8 January 2022).
12. European Commission (2022) *Environmental Assessment.* Available at: https://ec.europa.eu/environment/eia/index_en.htm (Accessed: 8 January 2022).
13. European Commission (2022) *European Platform on Life Cycle Assessment.* Available at: *https://ec.europa.eu/environment/ipp/lca.htm* (Accessed: 8 January 2022).
14. ThoughtCo. (2020) *Type 316 and 316L Stainless Steels*. Available at: https://www.thoughtco.com/type-316-and-316l-stainless-steel-2340262 (Accessed: 8 January 2022).
15. Mecadi (2022) *Nafion*. Available at: https://www.mecadi.com/en/uncategorized/nafion_copolymer_made_from_ptfe_and_perflourinate/ (Accessed: 8 January 2022).
16. Orion Industries (2016) *How is PTFE (Teflon) Made?* Available at: https://www.orioncoat.com/blog/how-is-ptfe-teflon-made/#:~:text=Polytetrafluoroethylene%2C%20also%20known%20as%20Teflon,590%2D900%C2%B0C (Accessed: 8 January 2022).
17. Lucideon (2022) *Concrete Testing.* Available at: https://www.lucideon.com/construction/concrete/raw-material-evaluations (Accessed: 8 January 2022).
18. Valente, A., Iribarren, D. and Dufour, J. (2019) End of life of fuel cells and hydrogen products: From technologies to strategies, *International Journal of Hydrogen Energy,* 44(38), pp. 20965-20977.

19. Britannica (2022) *Economy of Hawaii*. Available at: https://www.britannica.com/place/Hawaii-state/Economy (Accessed: 8 January 2022).
20. Weather Spark (2022) *2021 Weather History in Kailua-Kona*. Available at: https://weatherspark.com/h/y/166/2021/Historical-Weather-during-2021-in-Kailua-Kona-Hawaii-United-States#Figures-WindSpeed (Accessed: 8 January 2022).
21. Office of Energy Efficiency & Renewable Energy (2022) *Advantages and Challenges of Wind Energy*. Available at: https://www.energy.gov/eere/wind/advantages-and-challenges-wind-energy (Accessed: 8 January 2022).
22. Electrical For You (2022) *Pump Power Calculator.* Available at: https://www.electrical4u.net/energy-calculation/pump-power-calculator-formula-example-calculation/ (Accessed: 8 January 2022).
23. Glassdoor (2022) Available at: https://fr.glassdoor.be/index.htm?countryRedirect=true (Accessed: 8 January 2022).
24. Euractiv (2020) *What is the real cost of green hydrogen?* Available at: https://www.euractiv.com/section/energy/opinion/what-is-the-real-cost-of-green-hydrogen/ (Accessed: 8 January 2022).
25. Engineering ToolBox (2001) Available at: https://www.engineeringtoolbox.com (Accessed: 8 January 2022).
26. Rahim, A.H.A., Tijani, A., Shukri, F.H., Sainan, I., Hanapi, H. (2014) Mathematical modelling and simulation analysis of PEM electrolyzer system for hydrogen production, 3rd IET International Conference on *Clean Energy and Technology (CEAT) 2014,* Kuching.
27. Luo, Y., Shi, Y. and Cai, N. (2021) Bridging a bi-directional connection between electricity and fuels in hybrid multienergy systems, *Hybrid Systems and Multi-energy Networks for the Future Energy Internet*, pp. 41-84.
28. Alibaba (2022) Available at: https://www.alibaba.com/ (Accessed: 8 January 2022).
29. Air Supplies (2022) *Professional/Industrial Compressors.* Available at: https://www.airsupplies.co.uk/air-compressors/professional-industrial-compressors (Accessed: 8 January 2022).
30. San Marchi, C. and Somerday B.P. (2014) ASME 2014 Pressure Vessels and Piping Conference, *Comparison of Stainless Steels for High-Pressure Hydrogen Service.*
31. Alberto, L. (2010) Controlling Operating Temperature in PEM fuel cells, *20th International Congress of Mechanical Engineering,* Gramado, RS, Brazil.
32. Mahmah, B., Mraoui, A., Belhamel, M., Ben Moussa, H. (2006) Experimental study and modelling of a fuel cell PEMFC fed directly with hydrogen / oxygen, *16th World Hydrogen Energy Conference 2006,* Lyon.
33. Pourmovahed, A. (2005) Performance of a PEM Fuel Cell System, *Proceedings of the 2005 American Society for Engineering Education Annual Conference & Exposition.*
34. Picclick (2022) *2000m3/h Industrial Centrifugal Blower Fan + 500Watt Speed Controller Extractor. Available at: https://picclick.co.uk/2000m3-h-Industrial-Centrifugal-Blower-Fan-500Watt-Speed-163090138522.html* (Accessed: 8 January 2022).

35. Office of Energy Efficiency & Renewable Energy (2022) Available at: https://www.energy.gov/eere/office-energy-efficiency-renewable-energy (Accessed: 8 January 2022).
36. FuelCellStore (2022) Available at: https://www.fuelcellstore.com/ (Accessed: 8 January 2022).

Appendix A

Polymer Electrolyte Membrane (PEM) fuel cells, operating at 80°C with a platinum catalyst. For a single cell: $V_{FC} = E_{Nernst} - V_{act} - V_{ohmic} - V_{con}$ **[Eq. 1]** (31)

$$E_{Nernst} = 1.229 - 0.85 \times 10^{-3}(T - 298.15) + 4.31 \times 10^{-5} T \left[\ln(P_{H_2}) + \tfrac{1}{2}\ln(P_{O_2})\right]$$ **[Eq. 2]** (31)

$$V_{act} = -\left(\xi_1 + \xi_2 T + \xi_3 T \ln(c_{O_2}) + \xi_4 T \ln(I_{FC})\right)$$ **[Eq. 3]** (31)

$$V_{ohmic} = I_{FC}(R_M + R_C)$$ **[Eq. 4]** (31)

$$V_{con} = -B \ln\left(1 - \frac{J}{J_{max}}\right)$$ **[Eq. 5]** (31)

$$J = J_{out} + J_n$$ **[Eq. 6]** (31)

$$J_{out} = \frac{I}{A}$$ **[Eq. 7]** (31)

$$R_M = \frac{r_M L}{A}$$ **[Eq. 8]** (31)

$$r_M = \frac{181.6\left[1 + 0.03\left(\frac{I_{FC}}{A}\right) + 0.062\left(\frac{T}{303}\right)^2 \left(\frac{I_{FC}}{A}\right)^{2.5}\right]}{\left[\lambda - 0.634 - 3\left(\frac{I_{FC}}{A}\right)\right] e^{4.18\left(\frac{T-303}{T}\right)}}$$ **[Eq. 9]** (32)

$$c_{O_2} = \frac{P_{O_2}}{5.08 \times 10^6 \times e^{\frac{-498}{T}}}$$ **[Eq. 10]** (32)

$$Pow = VI$$ **[Eq. 12]** (33)

$$\xi_2 = 0.00286 + 0.0002 \ln A + (4.3 \times 10^{-5}) \ln c_{H_2}$$ **[Eq. 11]** (31)

From MATLAB, optimal current was 38 A. It was calculated that $V_{FC} = 0.4407\ V$, thus $Pow = 19.2539\ W$. The stack is composed of 289 cells, each with power $19.2539\ W$, the stack produces $20.032 MWh$. Assuming a $4500\ W$ fuel cell stack costs £34,000 (dimensions $100 \times 80 \times 21\ cm$) (32). As 234 cells would give about $4500\ W$:

$\frac{289}{234} = 1.235$ thus £$34{,}000 \times 1.235 \approx$ £$42{,}000$. Thus, the cost of the stack is £42,000.

Its dimensions are $1.235 \times 0.988 \times 0.2594\ m$. For a single cell: $6.97\ ml\ min^{-1}$ of hydrogen are required per amp produced (33): $F_{H_2} = 38 \times 6.97 = 264.9\ ml\ min^{-1}$

$$Q_{H_2} = \frac{264.9 \times 10^{-6} m^3 min^{-1}}{0.02241 \quad {}^3mol^{-1}} = 0.01182\ mol\ min^{-1}$$ (assuming STP)

From stoichiometry: $F_{O_2} = F_{H_2} \div 2 = 132.5\ ml\ min^{-1}$ or $Q_{O_2} = 5.911 \times 10^{-3}\ mol\ min^{-1}$

For the stack, which runs for $360\ minutes$:

$$n_{H_2} = 0.01182 \times 360 \times 289 = 1230\ mol \text{ and } n_{O_2} = 615\ mol$$

Assuming ideal gases, considering high pressures are not used: $PV = nRT$

For the hydrogen storage at 1.5 bar:

$$V_{H_2} = \frac{1230\ mol \times 8.314\ J\ mol^{-1}\ K^{-1} \times 353\ K}{1.5 \times 10^5 Pa} = 24.07\ m^3\text{, tank size } 25\ m^3$$

The density of hydrogen at 1.5 bar and 20°C: $0.1241\ kg\ m^{-3}$ (25)

$$m_{H_2} = 24.07\ m^3 \times 0.1241\ kg\ m^{-3} = 2.987\ kg$$

For the oxygen storage at atmospheric pressure:

$$V_{O_2} = \frac{615\ mol \times 8.314\ J\ mol^{-1}\ K^{-1} \times 353\ K}{1.01325 \times 10^5 Pa} = 17.81\ m^3\text{, tank size } 20\ m^3$$

The density of oxygen at 1 bar and 20°C: $1.314\ kg\ m^{-3}$ (25)

$$m_{O_2} = 17.81\ m^3 \times 1.314\ kg\ m^{-3} = 23.40\ kg$$

For the refrigeration blower: the rate of heat generated in the fuel cell stack:

$$Q_{gen} = Pow_s\left(\frac{1.48}{V_{FC}} - 1\right) = 13{,}100\ W \qquad \textbf{[Eq. 13]}\ (31)$$

Assuming the refrigeration maintains the stack at constant temperature, $Q_{gen} = Q_{rem}$

Where $Q_{rem} = \eta_{blower} Pow_{blower} \Delta T$ **[Eq. 14]** (31)

Blower efficiency is 0.4 (31), operating and ambient temperature difference is 60°C:

$$Pow_{blower} = \frac{Q_{rem}}{\eta_{blower}\Delta T} = 545.8\ W$$

Assuming the cost of the unit is £100 (35). The water produced in the fuel cell can be recycled through a humidifier to prevent the PEM drying out (36), the cost of this is about £850 (37). Assuming the molar flowrates required by the fuel cell stack are those required by the electrolyser:

$$Q_{H_2} = 0.01182 \times 289 = 3.416\ mol\ min^{-1} = 0.05693\ mol\ s^{-1}$$

The current for the whole stack:

$I_{elec} = 2FQ_{H_2} = 2 \times 96485.3\ coulombs\ mol^{-1} \times 0.05693\ mol\ s^{-1} = 10{,}990\ A$ **[Eq. 15]** (26)

Area is typically $50\ to\ 150\ cm^2$, assuming $100\ cm^2$ (26). The maximum operable current density for an electrolyser cell is around $0.4\ A\ cm^{-2}$(27). This would mean $40\ A$ cells. The stack is composed of 275 cells. Assuming cost of electrolyser stack £52,500 (28). Dimensions $0.17 \times 0.16 \times 16.5\ m$. The cost of a compressor is assumed £600 (29). Type 316 stainless steel is resistant to embrittlement (30), thus it is used for the tanks. The costs of the hydrogen and oxygen tanks are £9,000 and £7,500, respectively. Radius $1\ m$, lengths $8\ and\ 6.5\ m$. The 10,000L water tank is assumed to cost £1,200.

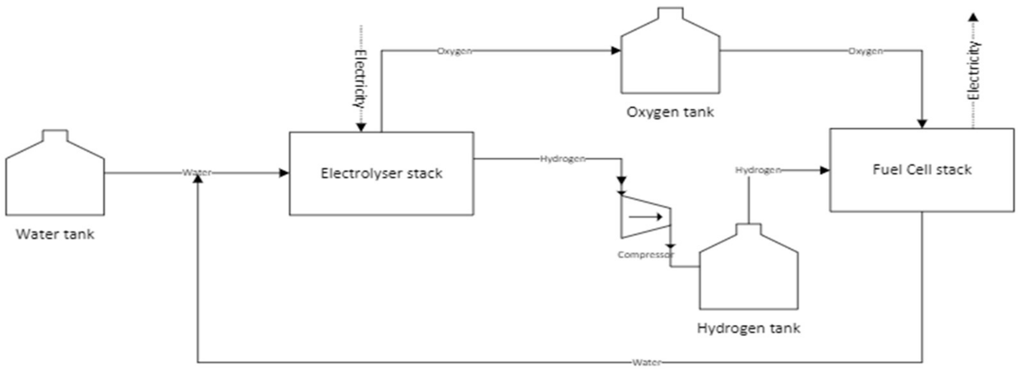

Figure 1A. Process Flow Diagram of the Hydrogen System

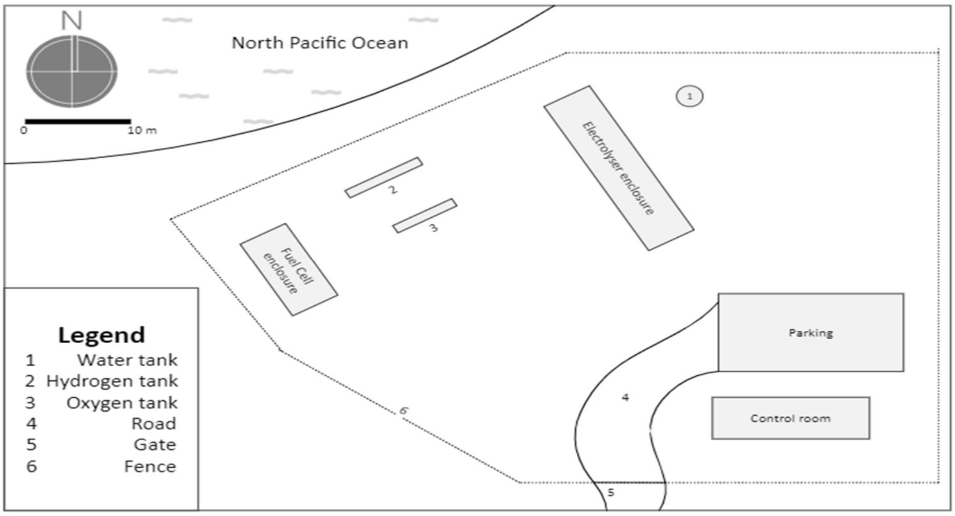

Figure 2A. Site Footprint of the Hydrogen System

Appendix B

Table 1B. SWOT analysis

Strengths	**Weaknesses**
• Google has the wealth to hire IPL, develop an energy storage system	• Large corporations may be seen negatively by the locals
Opportunities	**Threats**
• Surplus wind energy can be stored and re-used, this energy is cheap • The sites have access to the interconnector • The geography of each site makes both options feasible	• Electricity from the interconnector is expensive • Energy projects on The Big Island have taken years to be approved by the authorities. The project will be affected by its environmental and social impact

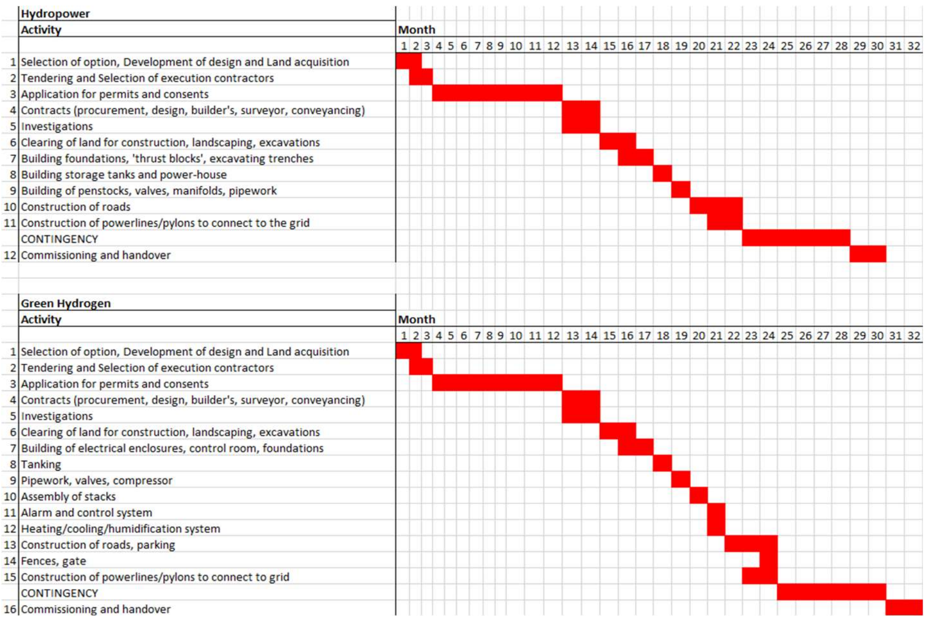

Figure 1B. Project Schedule for both Options

Table 2B. Navajo Blanket Matrix for Hydropower

Element	Define preliminary engineering	Execute detailed engineering	Execute procurement	Execute fabrication	Execute construction	Execute test and commission	Start-up and operate
Valves, fittings	IPL	RheEnergise				IPL	Google
Tanks							
Pump-turbines							
Piping		Piping contractor					
Electricals		Electricals contractor					
Construction	Construction contractor						

Table 3B. Navajo Blanket Matrix for Green Hydrogen

Element	Define preliminary engineering	Execute detailed engineering	Execute procurement	Execute fabrication	Execute construction	Execute test and commission	Start-up and operate
Valves, fittings	IPL	GreenHydrogen Ltd				IPL	Google
Tanks							
Fuel cell, electrolyser							
Piping		Piping contractor					
Electricals		Electricals contractor					
Water tank			Minor projects contractor				
Construction	Construction contractor						

Table 4B. Stakeholder Analysis Matrix

	Strongly against	Against	Balanced	In favour	Strongly in favour
Significant influence	Ka Lahui	HEPA	Hawaiian Development Trust	Landowner	Office of Climate Change, Sustainability and Resiliency RheEnergise/GreenHydrogen Workers Google, Project board members
Some influence	ALOHA	Conservation Council for Hawaii Hawaiian Islands Land Trust		Sierra Club of Hawaii	Blue Planet Hawaii US Green Building Council
Little influence	Kahea – The Hawaiian Environmental Alliance	Hawaii Audubon Society	Zero Waste O'ahu	Elemental Excelerator	

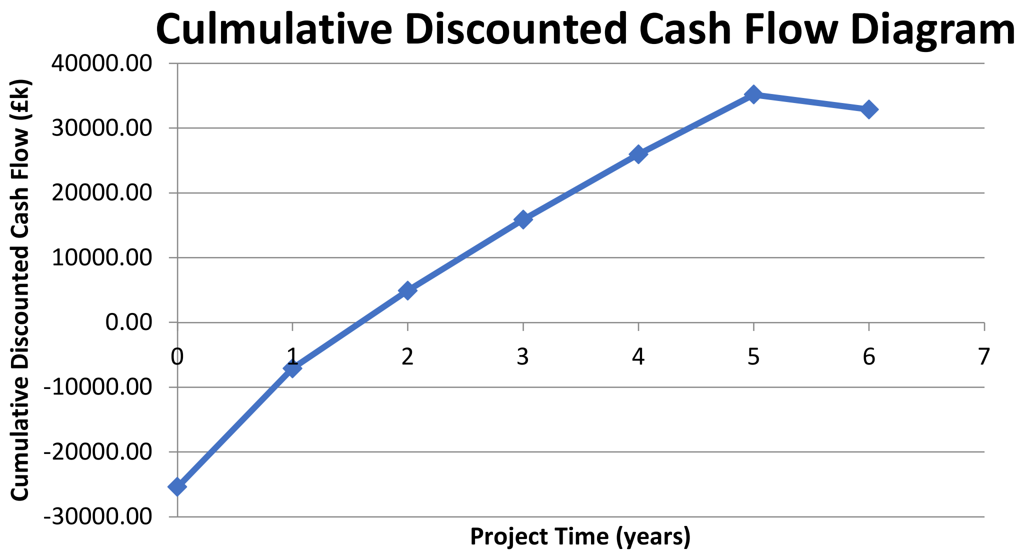

Figure 2B. Cash Flow Diagram for Hydropower, compared to base case of using electricity from the Interconnector

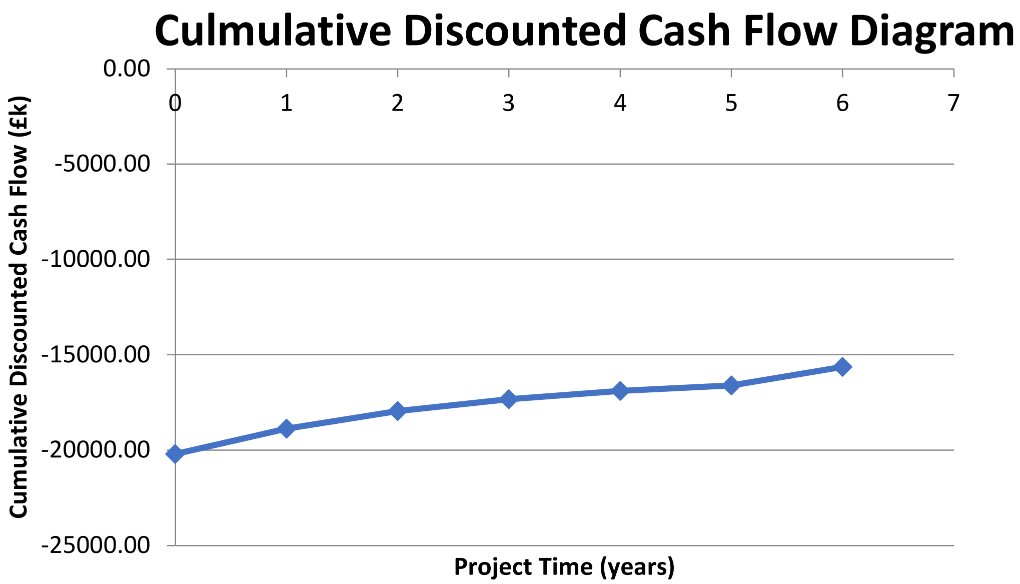

Figure 3B. Cash Flow Diagram for Hydropower, compared to base case of Hydrogen

It is assumed $\$1 = £0.75$ in all calculations.