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1 Introduction

1.1 Sustainability

Sustainability defines operating such that the needs of the present can be satisfied without compromising the needs of the future, World Commission on Environment & Development 1987.

Although colloquially associated with environmental concerns, sustainability is a wide field with 3 pillars, UN General Assembly 2005,

- Economic
- Social
- Environmental

Environmental sustainability includes consideration of concepts such as energy usage and production, emissions, water usage and quality, food and land usage.

The social aspect includes consideration for the effects of war, labour standards, social justice and poverty among others.

Economic sustainability can define economic growth that takes into account the above concepts. For example, economic development is typically measured in gross domestic product (GDP), however this metric does not include social aspects such as equality, a population's average wage or access to healthcare.

There are many formal initiatives and goals for sustainable development, the main strategies with which this project aligns itself are the United Nation's Sustainable Development Goals.

Part I

Vessel Study

2 Propulsion

2.1 Power Requirements

2.1.1 Hotel Load

The hotel load is defined as the energy usage not related to the propulsion including lighting and power outlets. An estimation of this load for the vessel was modelled and a breakdown can be seen in figure 2.1. The total load was estimated at 680 kWh per day. As can be seen, the oven and food refrigeration make up the majority and so 3 methods for refrigeration were investigated in order to find the most energy efficient solution with SDG 7 in mind. These included a collection of standard upright fridges, all-in-one cold rooms and a bespoke cold room. All-in-one cold-rooms were the most energy efficient and were selected as a result.

3 Efficiency Investigations

3.1 Solar

The scope of the vessel's solar energy capabilities were investigated with the intention of supplementing the chemical energy of the ammonia fuel cells. The capabilities of photovoltaic cells covering an area of

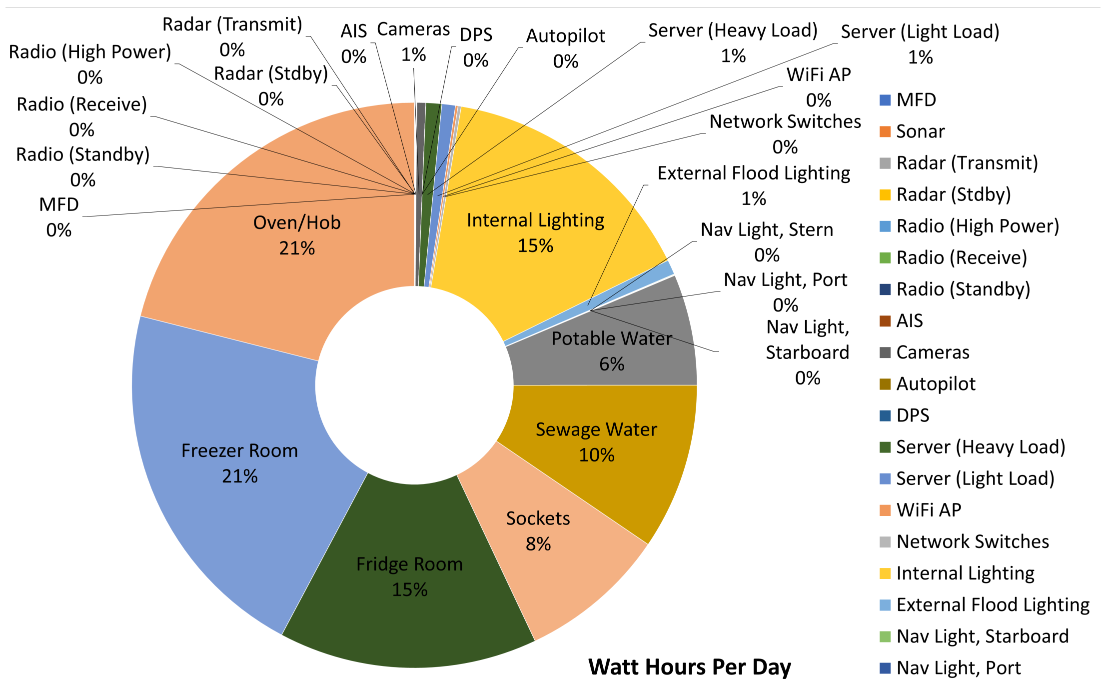

Figure 2.1: Breakdown of hotel load energy for the surface vessel, totals to ≈680 kW

the vessel's footprint are considered and compared with both the financial and carbon cost in an effort to determine whether the proposal would be effective in achieving the goal of net-zero operations and SDG 9 specifically.

The expected available area capable of hosting photovoltaic cells was estimated to be 26m x 30m or 780 m^2. Using the same solar panel modelling of GEORGE, this would equate to 441 panels with a max power of 176 kW, an order of magnitude smaller than the ammonia fuel cell capabilities. This would represent 123 tonnes of embodied carbon which could be reduced to 65 tonnes by recycling following decommission.

As a result of this projection, it is proposed that the vessel is not fitted with solar panels. As the other energy being generated via the ammonia cells is already carbon-zero (assuming the use of *green ammonia*), the embodied carbon of the panels would not be offset through their own use. This carbon cost would need to be offset via the project-level offsetting processes, see JASON. The benefits would be limited to the financial savings of reducing fuel usage, limiting carbon cost is more of a priority for this project.

4 Energy Storage

The use of ammonia fuel cells for power generation on the vessel provides the opportunity to eliminate direct CO_2 emissions from the vessel; when produced using renewable energy (*green ammonia*), the entire fuel supply chain from production to use can be made carbon-neutral. From an electrical perspective, however, the current-voltage characteristics of such a system must be considered.

Figure 4.1 presents the I-V characteristics for a typical fuel cell, it can be seen that drawing more current from a cell reduces its voltage. As $P = IV$, this inverse relationship results in an optimum current draw to operate with the highest efficiency or power density. Operating outside of this area will accentuate losses, the dominant effects of each operating region can be seen in figure 4.2. Comparing the two graphs, it can be seen that the optimum operating state would be in R-2 (figure 4.2); in fact drawing excess current and pushing into R-3 can damage the cell, Faizan 2018.

From these figures, fuel cells could be described as being sensitive to a noisy or dynamic load such as changes in thrust and therefore the required power can vary quickly. For example, when using dynamic

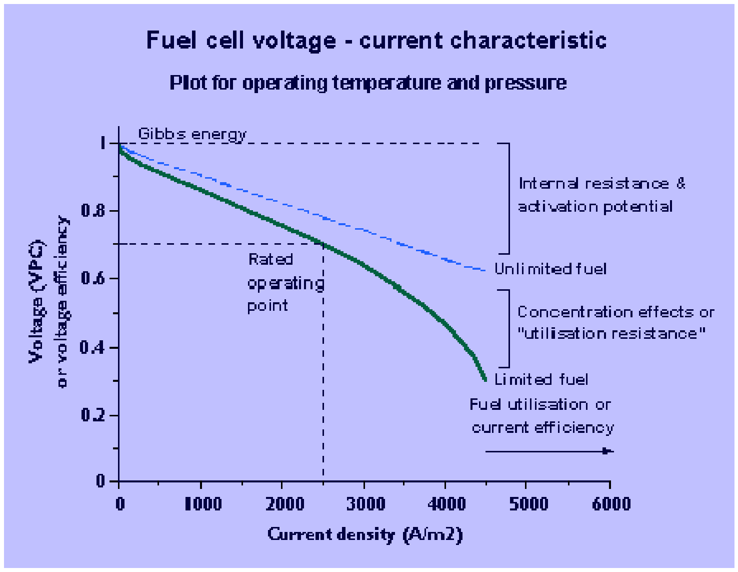

Figure 4.1: Current-Voltage characteristics for a typical fuel cell, rated operating point highlighted, Green Box Systems Group 2000

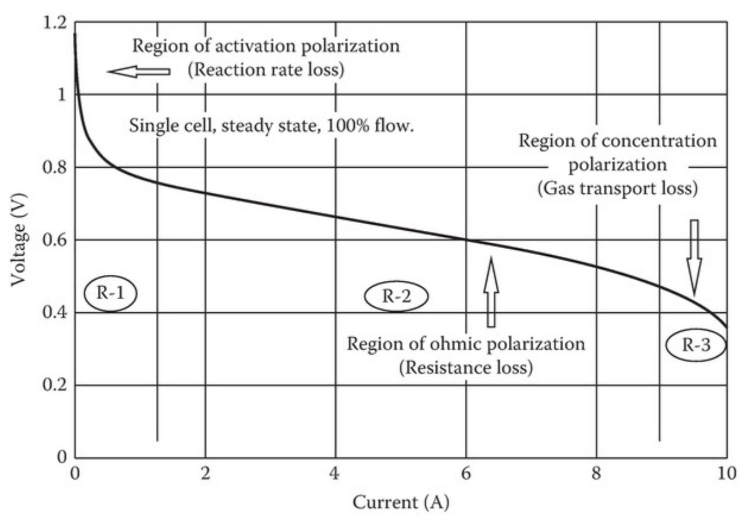

Figure 4.2: Current-Voltage characteristics for a fuel cell with dominant losses highlighted in each operating region, Faizan 2018

	NiCd	**NiMH**	**Lead Acid**	**Li-ion**	**Li-ion Polymer**	**Reusable Alkaline**
Gravimetric Energy Density **(Wh/kg)**	45 - 80	60 - 120	30 - 50	110 - 160	100 - 130	80 (initial)
Cycle Life **(to 80% of initial)**	1500	300 - 500	200 - 300	500 - 1000	300 - 500	50
Self-discharge / Month **(room temperature)**	20%	30%	5%	10%	~10%	0.3%
Load Current **(Peak)**	20C	5C	5C	>2C	>2C	0.5C
Load Current **(Ideal)**	1C	≤0.5C	0.2C	≤1C	≤1C	≤0.2C
Operating Temperature **(discharge only)**	-40 - 60°C	-20 - 60°C	-20 - 60°C	-20 - 60°C	0 - 60°C	0 - 65°C
Commercial Use Since	1950	1990	1970 (sealed lead acid)	1991	1999	1992

(Battery University 2017e)

Table 1: Comparison of physical characteristics for common rechargeable battery chemistry

positioning in a high sea state. Ideally, the use of more cells operating in their optimum state would be preferred over increasing the draw on a smaller population. However, this increase in active cells is not an instantaneous operation and cells require time to reach their optimum state. To allow this focus on efficiency, the load including hotel and propulsion power should be decoupled from the fuel cells with an electrical storage buffer in between. This will allow the buffer to absorb spikes in load draw and allow the fuel cells to increase power output by increasing active cells instead of individual draw. This initiative was conducted with SDGs 7 (Affordable and clean energy) and 12 (Responsible consumption and production) in mind, although goal 14 (Life below the water) is also important due to the materials involved in the considered solutions.

The following section outlines solutions for this described buffer, rechargeable batteries are the natural option and as such this is considered first. Other, innovative solutions are also outlined before the implementation of a suitable solution is presented along with the safety and financial implications of such a system.

4.1 Rechargeable Battery Chemistry

There are many different methods for constructing a traditional rechargeable battery or *secondary cell*; the chemistry of the reactants determines the characteristics of the system as well as having drastic implications on the safety and sustainability. Secondary cells are a consumable item, their components degrade with usage and this lifespan will be reduced if not constructed and maintained correctly. This only accentuates the importance of the solution's sustainability as it constitutes a significant amount of material which will periodically require replacing and disposal.

Table 1 outlines the relevant characteristics for the most common configurations of rechargeable battery. As can be seen, Lithium-ion technology leads the other solutions in most of the categories. While Nickel-Cadmium has a higher lifespan than Li-ion there are other factors that led to this being discounted. NiCd suffers from the *memory effect*, where frequent charge/discharge cycles lead to the battery *remembering* the point at which charging began and experiencing a drop in voltage past this point. Additionally, Cadmium

	Energy Density (WhL^{-1})	Power Density (WL^{-1})
Bromine-polysulphide	20 - 35	60
Vanadium-vanadium	20 - 35	60 - 100
Iron-chromium	20 - 35	6
Vanadium-bromine	20 - 35	50
Zinc-/bromine	20 - 35	40
Zinc-cerium	20 - 35	50
Soluble lead-acid	20 - 35	25
Conventional lead-acid	60 - 80	230
Lithium-ion	150 - 200	275
Nickel-metal-hydride	100 - 150	330

Table 2: Energy and power densities for typical redox flow battery chemistry (top) compared to traditional rechargeable cells (bottom), Mohamed, Sharkh and Walsh 2009

is a highly toxic heavy metal, requiring specialist containment; in fact, many types of Cadmium battery are now banned in the EU, Chatain 2013.

Lithium-ion batteries are a mature domain and one of active research; they are essentially the standard for portable electronics and the growing electric vehicle market.

4.2 Innovative Solutions

Traditional rechargeable batteries of varying chemistry are currently the standard for this domain. However, other systems utilising different technologies were also considered.

4.2.1 Flow Battery

A redox flow battery is a type of electrochemical cell where the energy is stored in two chemicals brought together at a membrane in order to facilitate ion exchange and create a potential difference or voltage, Noak et al. 2020.

This can be structured to function like a rechargeable battery as the chemical reaction is reversible.

There are a number of advantages to a system like this, for example it is less sensitive than Lithium-ion to overcharge and overdischarge with no need for charge balancing, Daggett 2019.

The main disadvantage relevant to the required applications is the required space and weight. Flow batteries typically have a much lower energy and power density than traditional rechargeable batteries, a comparison of values for various structures can be seen in table 2. Both values are critical for the vessel; as a buffer for absorbing large peaks from the propulsion, it is key that a high power can be drawn from the solution. From the presented values, Lithium-ion can provide between about 3 and 7 times as much power draw than redox flow batteries. Looking to energy or capacity density, Li-ion is roughly 4 to 10 times higher.

To achieve the capacity and power requirements defined by the propulsion system, a flow battery would likely need vastly more space and weigh significantly more. The weight penalty would prove more damaging as this would require more fuel for propulsion and lower the efficiency of the vessel.

Although flow batteries have found applications in large-capacity applications including grid services from load balancing to peak shaving, these are typically stationary without as much of a volume restriction.

4.2.2 Solid-State

The previously described traditional rechargeable batteries have a liquid electrolyte in which the electrodes are submerged. This solution allows ions to pass between the electrodes during charge and discharge.

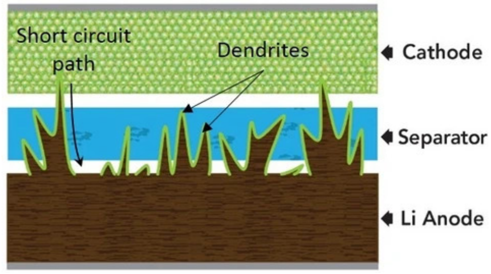

Figure 4.3: Dendrites growing between the Lithium battery electrodes, MSE Supplies 2019

Systems in which this liquid electrolyte is instead a solid are called solid-state batteries (SSB). This provides an advantage in that these liquid electrolytes are typically one of the key causes of safety concerns as they are flammable and sometimes toxic, . These are important considerations for this domain. With less of a concern regarding high operating temperatures, this also allows SSBs to be charged faster.

Additionally, the system has the opportunity to increase energy density, thereby reducing the required space while increasing the available capacity.

Unfortunately, however, there are a number of considerations that, currently, make it unsuitable for the required application. As an active area of research without much commercial availability, the price of solid-state batteries will likely be much higher than that of other formats. Additionally, concerns associated with Lithium-ion batteries including overheating and explosion are not completely removed by transitioning to an SSB. Dendrites are structures of Lithium that can form during charging and discharging as a result of electrodeposition, Cao et al. 2020. While this should occur evenly across the electrode, if uneven it can cause columns to grow towards the separator, figure 4.3. As these grow they can penetrate through this separator and make contact with the cathode. This will cause a short circuit, rapidly increasing heat and potentially causing fire and explosion.

Hutchins 2020 summarises four current challenges to scaling up solid-state batteries as investigated by Tan et al. 2020:

1. Stability of the electrode-electrolyte interface
2. Characterising and analysing this interface in a now opaque structure
3. Sustainable manufacturing processes
4. Designing for recyclability

These last two are critical for the project objectives. With these considerations it is suggested that solid-state batteries will not be ready at the time of construction to supply the scale of storage array required.

4.3 Proposed Solution

For this project, Lithium-ion chemistry was proposed as the solution for the vessel energy storage. As previously mentioned, the domain is an area of fervent research as a result of its importance to consumer electronics and electric vehicles. An important factor in the decision is the scale of system required, this will have significant impacts on the ability to source and dispose of a system as well as the financial and safety implications.

There are a variety of chemical compositions for Lithium-ion batteries depending on the other materials used in the electrodes including Lithium Manganese Oxide and Lithium Cobalt Oxide. Each have specific benefits and associated applications, for our purposes Lithium Nickel Manganese Cobalt Oxide will be used as it is a common chemistry with high specific energy, Battery University 2017d.

	18650 Cell
Voltage, (V)	3.6
Capacity, (mAh)	3500
Ideal Discharge C-Rate, (h^{-1})	1
Ideal Charge C-Rate, (h^{-1})	0.5
Weight, (g)	48

Table 3: General specifications for 18650 Lithium-ion cells

There are many standard Lithium-ion standard cell formats from flat pouches and prismatic cells designed for mobile phones, to the more standard cylindrical cells. For this application, cylindrical cells are a suitable choice as compactness and thinness are not critical design parameters.

The 18650 cell is a mature cylindrical cell with good reliability records and high rates of use among medical equipment, drones and electric vehicles, Neverman 2020; Tesla uses battery packs composed of 18650 cells, Hawley 2017.

As with other battery cells, the voltage is a characteristic of the chemistry, for Lithium this is around 3.6 V, Battery University 2017d. The key parameters that vary amongst producers are the capacity and charge/discharge C-rates. In order to estimate the cell specification for use in this project, the existing range of available cells was taken into account. Typical, mid-range 18650 cells can vary between 2500 - 3000 mAh capacity, Neverman 2020; the highest energy density can currently extend this to 3500 - 3600 mAh. As technology improves, it is expected that by the point of construction this higher range will be more accessible and reliable, and as such, 3500 mAh is used as the cell capacity for further calculations.

The 18650 cell specifications being used herein are described in table 3.

4.3.1 Configuration

The quantity of required cells for the battery system was calculated using the expected propulsion power requirements in conjunction with the expected generation capabilities of the ammonia fuel cells. The quantity of required cells was calculated from the required power draw of the battery and the characteristics of the 18650 Lithium cell being used. The result was 193,600 cells. These cells are arranged into a matrix of parallel and series blocks, all the series blocks connected in parallel must be of the same length. This will provide 2.44 MWh of electrical energy storage for the buffer system.

The balance of parallel to series blocks is not a critical parameter for the application and can instead be tuned for efficiency; as the propulsion units require AC power, transformers can be used to select a desired voltage and current from a given power value. For high power applications high voltage is typically preferred to high current to reduce heat losses which corresponds to a higher weighting of series length.

4.3.2 Challenges

Limited Lifespan Traditional rechargeable battery cells are a consumable item with the capacity and performance decreasing over extended use for a number of reasons. These include electrode corrosion, reduced porosity or a reduction in Lithium ions as a result of side reactions, Hendricks et al. 2015.

When the cells begin to perform below a defined acceptable level, they will require replacement. This poses both financial and environmental implications. As will be discussed in section 4.3.4 this is a significant amount of money. Additionally, the scale of required cells means that the disposal protocols are critical. Options for such disposal procedures are discussed as part of the life cycle analysis in section 4.4.

Safety Although Lithium-ion batteries are typically safe and stable if stored and used correctly, abuse can cause severe safety issues. As previously mentioned, the liquid organic electrolyte is flammable, and combined with the high energy density of Li-ion batteries can lead to thermal runaway and eventually fire if not handled correctly.

There are a couple of causes for such a thermal runaway, these include physical damage, short circuits, overcharging and exposure to high temperature, University of Washington 2018.

Multiple measures must be implemented to ensure safety, University of Washington 2018:

- Reputable manufacturers must be used as defects during construction can cause or exacerbate faults.
- The battery system should be located far from combustible materials
  - Contextually this would primarily be the fuel tanks.
- The cell's temperature should be monitored and controlled.
- Cells of the same age must be grouped and used together
- Cells should be charged intelligently in order to mitigate overcharge and implement charge balancing, see 4.3.3
- The battery system should be stored in an water/air-tight container
- This container should be able to safely vent gases
  - In the event of an emergency, cells can release toxic gases (CO_2, CO, HF)

With regards to the described container, as previously outlined, standard shipping containers will be used. This provides a good base to modify in order to meet the above, i.e. air/water-tight and venting.

4.3.3 Charging & Safety Circuitry

As previously described, Lithium-ion cells are sensitive to stressful electrical conditions such as overcharging, deep discharging and excessive current draw.

In order to protect and enforce operating conditions for the Lithium cells, a battery management system or BMS is used. A BMS implements safety protocols to mitigate the above effects as well as providing information to the load and other monitoring services such as state-of-charge information (remaining capacity), Battery University 2017a.

4.3.4 Extending Lifespan

Lithium-ion cells are a consumable item that degrades. The environmental and financial cost of replacement creates a significant incentive to extend this as much as possible as long as this does not inhibit the operating capabilities beyond the specification.

As previously mentioned, the temperature of the cells is a key parameter affecting both performance and lifespan, Battery University 2017b. Although operating at a higher temperature increases performance it also decreases lifespan. Temperature control is already critical for safety purposes. 20°C provides the ideal temperature for prolonging lifespan and as such will be set as the target temperature, Battery University 2017b.

Another important aspect to the lifespan of Lithium-ion batteries is the depth-of-discharge (DOD) which determines the number of charge cycles that the battery will last for. The depth-of-discharge describes the amount of capacity used each cycle before recharging. Lithium batteries are able to handle moderate DOD without significantly affecting the lifespan, however, frequent deep discharge cycles, completely emptying the battery, will shorten its life, Battery University 2017c.

Similar to frequently completely discharging the battery, storing a battery fully charged for long periods of time can also shorten its lifespan. This can be seen presented in figure 4.4 where higher cell charge voltages can be seen to reduce capacity much faster as time or charge cycles increases[1].

[1] Worth noting that the capacity is initially higher for higher voltages, it is the lifespan that can be extended by picking a more reserved value.

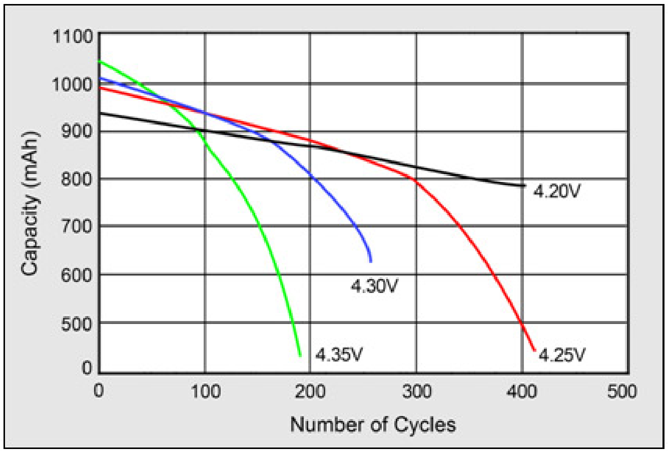

Figure 4.4: The lifespan of Lithium-ion cells described by the max capacity as charge cycles increase for various charge voltages, Battery University 2017c

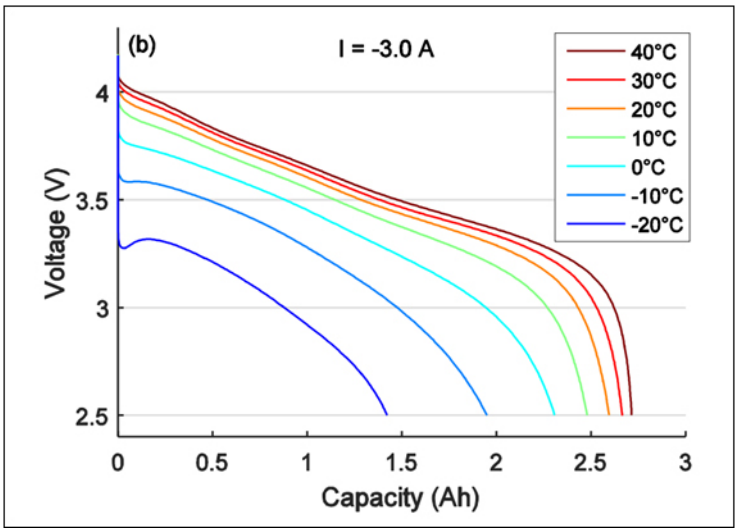

Figure 4.5: Voltage-Capacity characteristics for a 18650 Li-ion cell at varying temperatures, Battery University 2017b

Both of the above points, tempering DOD and charge voltage rely on the BMS. To prevent deep discharges, more ammonia fuel cells should start up as the capacity decreases in order to balance the workload meaning that the ammonia management system will need to interface with the BMS. Additionally, it would be the responsibility of the BMS to charge cells to a reasonable voltage, 3.9 - 4.1 V can provide a balance between higher capacity and longer lifespan, (Battery University 2017c).

4.3.5 Financial

As will be described (section 4.6), a battery array lasts approximately 2.3 years, after which, a new set must be sourced. 18650 cells vary in price across manufacturers and distributors, a range of RRPs were taken from UK distributors, Ecolux 2020; 18650.uk 2020; Fogstar Batteries 2020. In general, a cell's RRP ranged between £4 and £7, and so it is assumed that a procurement department would secure a unit price at the lower end of this for the scale of order required, £5 is used.

A set of 193,600 cells at this cost totals to £968,000 which averages to £420,869 a year for modelling purposes.

Costing a battery management system is complicated by the scale of battery being proposed. A mega-watt

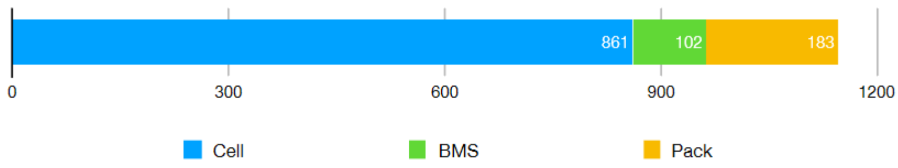

Figure 4.6: CED breakdown for a NCM11 battery pack (MJ/kWh), Melin 2019; Dai et al. 2019

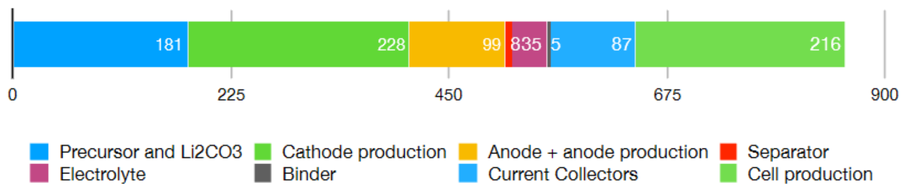

Figure 4.7: CED breakdown for a NCM11 cell without BMS or pack (MJ/kWh), Melin 2019; Dai et al. 2019

scale battery will require a complex BMS without publicly available prices and an estimation must be made. Cluzel, Slater et al. 2012; Cluzel and Douglas 2012 suggests that cells constitute 60% of the total system price. Using this estimate the BMS and pack is estimated to cost £645,000.

4.4 Life-cycle Analysis

The life-cycle analysis (LCA) of Lithium-ion batteries is a complicated process for a couple of reasons. As repeatedly stated, Li-ion batteries have been critical to the explosion of mobile consumer electronics; the development of the fabrication process and the associated environmental effects has changed dramatically. More recent LCAs and meta-analyses of previous data are considered in order to account for this. Additionally, as a global product the values for various greenhouse gas (GHG) and other emissions is contingent on the country within which the cells are made.

Both the cumulative energy demand (CED) and the GHG emissions are considered. Cumulative energy demand allows abstraction of the specific method of energy production and the associated emissions.

Many of the LCA studies on Lithium-ion batteries consider a cradle-to-gate scope without including use or end-of-life. Two end-of-life procedures are considered as well as practices to improve usage lifetime.

4.4.1 Cradle-to-Gate

Figure 4.6 outlines the cumulative energy demand for the major elements of a Nickel/Cobalt/Manganese cathode (NCM11) battery. As Melin 2019 points out, cathodes are tending towards a higher cathode composition of Nickel, however the general proportions are relevant to other chemistry. It can be seen that the production of the cells constitutes the majority of the required CED at 75% of the total. As this is also the element of the battery that requires periodic replacement following degradation, a closer look at the contributing stages should be considered.

This further breakdown can be seen in figure 4.7. The precursors, Li_2CO_3 and cathode production constitute almost 50% of the cell's CED, these are the Lithium intensive processes. By using recycled Lithium, this major contributor could be reduced. As such, a cell manufacturer using recycled Lithium should be identified and used.

The contributions of each stage to the embodied carbon can be seen in figure 4.8. As previously shown, the Lithium-containing NCM powder constitutes the largest contributor. The 73 kg CO2e/kWh quoted value is dependent on the location of manufacture, a slightly more conservative 80 kg CO2e/kWh will be used for calculating the battery systems embodied carbon from production.

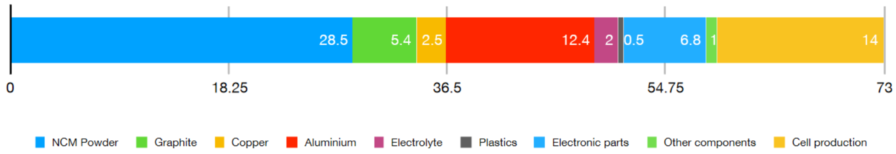

Figure 4.8: Equivalent carbon breakdown for a NCM11 battery pack (kg CO2e/kWh), Melin 2019; Dai et al. 2019

Using this value, a set of cells represents 191 tonnes of embodied carbon. This will be included in the total embodied for the project requiring offset.

4.4.2 Use

The use of Lithium batteries does not inherently incur a Carbon cost; the associated cost of energy stored is accounted for by the source of this energy, in this case ammonia fuel cells.

The use of the batteries does require analysis, however. The source and end-of-life procedures for a battery pack are carbon intensive operations and the ability to extend the time in-between replacement will improve the environmental impact overall.

There are a number of ways to increase the lifespan of a battery pack, these have been outlined in section 4.3.4 and are critical for reducing the environmental impact of the system.

4.4.3 End-of-Life

There are two main approaches to sustainable end-of-life processing for Lithium-ion processing, second-use and recycling.

Second-use describes the use of a battery for new applications after the performance is deemed too low for the vessel's buffer, Melin 2019. By doing so the lifespan of the batteries can be extended and reducing the amount being constructed.

There are many methods for recycling Lithium batteries, and it is important to identify a process that will not use more energy than that required to mine virgin materials. Melin 2019 summarises that up to 48% of the CED and CO_2e could be saved. They identify *direct recycling* as the best option for this. This method allows the electrodes to retain their composition as opposed to breaking it down into constituent parts, Sloop et al. 2020. This has applicability across Lithium-ion chemistry including the form used herein, NCM.

For the vessel battery, the use of an intelligent BMS and tight integration with the ammonia cells should allow it to be treated well such that it is kept in comparably good condition. As such it is proposed that they would be well suited for second-use applications such as energy storage. The battery will not be used until failure but instead until it cannot be used for the high-draw requirements of the buffer. They would likely have good applicability to purposes without such focus on high draw but that will make use of the remaining capacity.

4.5 Sustainability

Although many of the important environmental aspects of sustainability are covered by a life-cycle analysis, there are other elements to consider regarding sustainability. One of the most important aspects is a social one, that of the mining of Lithium and Cobalt. The majority of both minerals are located in two areas of the global south where resource shortages and unethical mining practices lead to dangerous and damaging results both socially and environmentally.

4.5.1 Lithium

The majority of global Lithium deposits can be found in an area of South America referred to as the *Lithium Triangle* covering areas of Chile, Argentina and Bolivia. The area has been estimated to constitute between 54 and 70% of the world's deposits, Katwala 2018; Dickson 2017. The extraction is a water-intensive process in an area already without an adequate supply; in Chile this is as much as 65% of the area's water or 500,000 gallons per tonne of Lithium, Katwala 2018.

The processing can also include dangerous chemicals including various acids that can pollute local water supplies as a result of leaks, leaching and emissions, Katwala 2018.

4.5.2 Cobalt

Over half of the world's Cobalt deposits are found in the Democratic Republic of Congo, Katwala 2018; Webb 2018.

Although not officially designated as such, there are efforts to class Cobalt as a conflict mineral as its importance grows to one of the most notorious countries for other such minerals including Gold and Tungsten.

20% of the exported cobalt has been estimated to come from artisanal mines, Webb 2018. These are small-scale mines known for a lack of safety standards including minimal personal protective equipment, structural requirements and child labour, World Economic Forum 2020.

4.5.3 Summary

The above emphasises the need to identify Lithium cell manufacturers using recycled materials in order to reduce the amount of virgin material being mined and assembled.

4.6 Time-dependent Modelling

In order to validate the buffer configuration, a model was constructed to visualise the capacity of the battery system while in use. Explanations as to the specific behaviour and assumptions made can be seen in appendix A. An example model describing the vessel's dynamic positioning above a cable fault can be seen in figure 4.9.

The top sub-figure describes the power in from the ammonia fuel cells and the load power drawn from the hotel and propulsion systems. The middle figure describes the effect this has on the capacity of the battery. The bottom figure describes the efficiency of this system, the *unused* power describes when more fuel cells than required are turned on and power is drawn below the most efficient state. The *unavailable* power describes when the fuel cells in their most efficient state and the battery combined cannot meet the requirement. As a result, extra power would be drawn from both pulling them into an inefficient or damaging state.

This model was extended to simulate an entire mission with defined power requirements (figure 4.10) including:

- Outbound journey (3 days)
- Manoeuvring to the fault (1 day)
- Dynamic positioning while completing the first splice (2 days)
- Manoeuvring to the other half of the cable (1 day)
- Dynamic positioning while completing the second splice (2 days)
- Homeward journey (3 days)

From these models, the amount of battery charge cycles was estimated to be 2 per day. Extrapolating this to a yearly usage value using the expected vessel usage, a battery array was estimated to last 2.3 years. This is a typical value for the lifespan of Lithium-ion batteries.

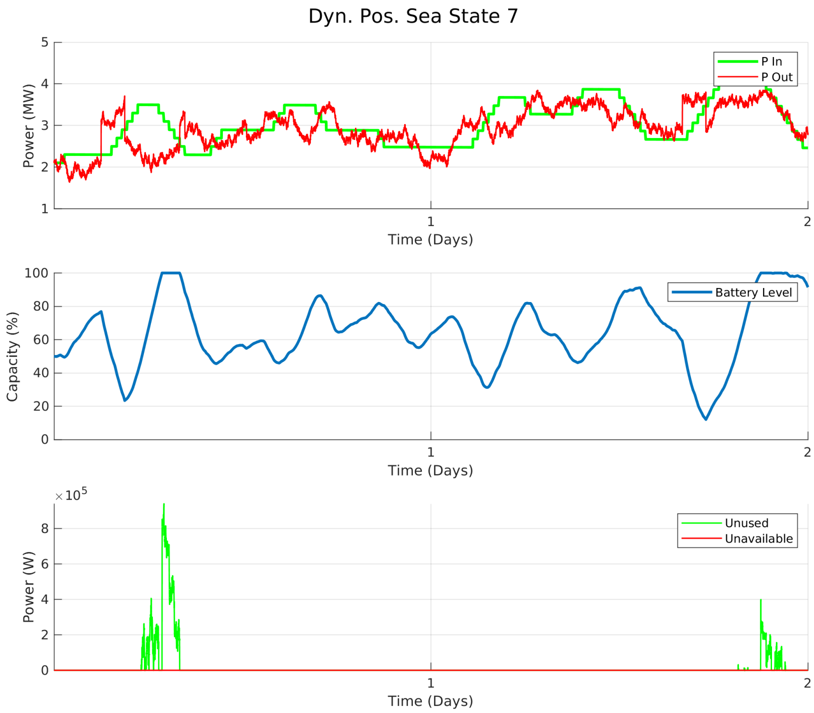

Figure 4.9: Power model describing the vessel dynamic positioning on mission

second

Figure 4.10: Power model describing one mission including travelling and dynamic positioning

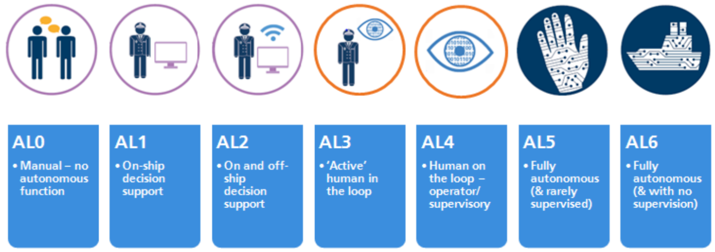

Figure 5.1: Outline of the 6 levels of autonomy for shipping, Jim Covill 2019

4.7 Summary

The proposed 2.44 MWh buffer solution includes 193,600 NCM Lithium-ion cells requiring replacement every 2.3 years. As a result of this replacement rate, it is stipulated that the battery be re-appropriated for second-use such as energy storage following decommission in order to extend their life and reduce the environmental impact. Manufacturers using recycled materials should also be identified in order to reduce the impact of mining virgin materials.

It is worth noting that this is the proposed solution based on the current state of energy storage. One of the only advantages of rechargeable batteries being a consumable item requiring replacement is that when this occurs, it is an opportunity to re-evaluate the system design. With an expected project lifespan of 30 years, it is highly unlikely that the use of Li-ion cells will remain the best option.

Systems based on a solid-state chemistry will likely become more stable and less expensive to the point that the advantages in safety and energy density can be fully utilised without the heavy downsides.

5 Onboard Systems

The vessel will be fitted with a number of operating systems responsible for navigation and communications. Many are required as part of SOLAS regulations chapters IV and V, International Maritime Organization 1974.

5.1 Navigation

A number of standard systems will be fitted for navigation including GPS, radar, sonar and depth finder. These are often combined for display on a multi-function display or MFD at the bridge. The radar will include an automatic identification system (AIS) which allows vessels to identify themselves to each other and include information such as vehicle class and bearing, Bhattacharjee 2019a.

When designing a new ship, the level of autonomy should be considered. The development of robotic navigation in conjunction with machine learning and artificial intelligence have allowed an increase in autonomous operations, a number of projects for independent vessels are already in development, Walker 2019.

The difference in autonomy levels are defined by Lloyd's Register (Lloyd's Register 2017) in figure 5.1. Up to level 2 involves human control with varying degrees of support from the computer. Levels 3 and 4 involve the human supervising the computer's actions and levels 5 and 6 involve the computer operating independently with an optional crew. For this project, level 3 should be targeted, beyond this would be unnecessary considering the domain. The aim is not to remove the crew entirely as a team of specialists will still be required to complete the mission operations including cable splicing.

The benefits of increased autonomy include higher fuel efficiency as a result of the computer's ability to maintain course and a reduction in human error.

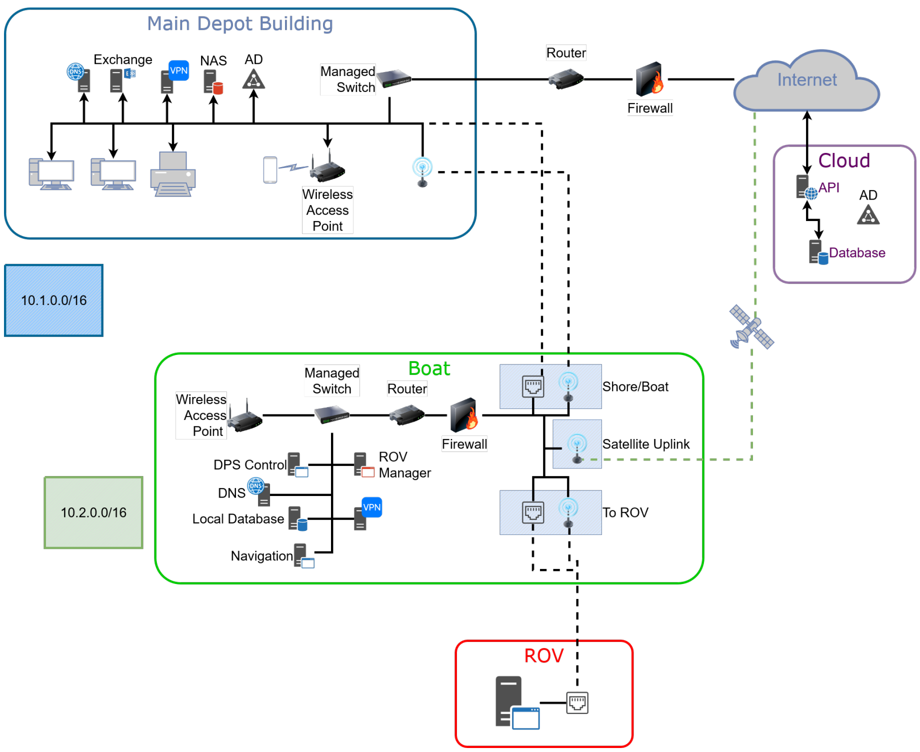

Figure 5.2: Network topology across the depot, vessel and cloud environment; main services highlighted

5.2 Communications

In compliance with chapter 4 of the SOLAS standards, the vessel will be fitted with a very-high-frequency (VHF) radio as well as Emergency Position Indicating Radio Beacons (EPIRBs) and Search and Rescue Transponders (SARTs) in order to meet the Global Maritime Distress Safety System (GMDSS) requirements, Bhattacharjee 2020.

5.2.1 Internet

The surface vessel will be connected to the internet via two gateways. While berthed, the vessel should be able to connect to the depot via Ethernet which can be run alongside the shore power line. For internet connectivity while at sea, the vessel will be equipped with satellite internet apparatus.

A network layout for the whole environment[2] can be seen in figure 5.2.

5.3 Computation

Many of the onboard operating systems including the dynamic positioning control, autonomous navigation services and many of the network services are not provided as hardware units but as software packages that will require hosting. As such, a capacity of server hardware will be required, possibly with GPU-acceleration for deep learning functionality. There are many options for this, for modelling purposes a single Dell R740 would meet the requirements, Dell 2017.

[2]Many business-level services including Active Directory can be seen at the depot, in reality these would likely be based at head office

6 Mission Ops

6.1 Grapnel-based Operations

While the use of robotics has made sub-sea cable repair operations more efficient, there are situations where this is not available and it is worth briefly outlining how grapnels are used in repair operations.

Grapnels are specialised tools attached to lengths of chain which trail the stern of the ship. For cable repair operations, a cut & hold grapnel is used (Ejiri et al. 1991; ETA 2020). With knowledge of the path of the subject cable and the location of the fault, the grapnel is lowered before the boat makes a pass perpendicular to the cable. As the grapnel makes contact it is able to both cut and grip the cable before being raised to the surface vessel.

6.2 Unmanned Underwater Vehicle Operations

The following section outlines how the use of an unmanned underwater vehicle (UUV) can make mission operations more efficient and precise. The state of current UUV usage throughout cable repair operations is outlined in order to identify the critical capabilities, requirements and advantages over traditional grapnel operations. The future of the domain is then explored and the challenges in applying these developments to sub-sea cable repair are identified before exploring how these can be overcome in order to meet the determined requirements. Prior to this, the domain of UUVs as a whole is described in order to outline the scope of available vehicles.

The developments are aligned with UNSDGs 9 (Industry, Innovation and Infrastructure) and 12 (Responsible consumption and production) for the ability to reduce required fuel usage of the surface vessel.

6.2.1 UUV Classes

ROVs and AUVs UUVs can be divided into two categories based on their control scheme. Remotely operated underwater vehicles (ROV) and autonomous underwater vehicles (AUV) are distinguished by whether a human is controlling the vehicle or whether it operates independently; as such they have different applications, NOAA 2020. ROVs have been the vehicle class of choice where complex intervention and actuation is required such as offshore oil and gas operations and cable repair. A human operator controls the vehicle from the surface vessel; bi-directional communication including data, control, video and power are transmitted through an umbilical cord tether between the two vessels, BlueRobotics 2019. AUVs on the other hand have primarily been used for survey and research purposes.

This distinction in responsibilities is not static, however. Like other robotics domains such as auto-mobiles and ships, autonomy is a rapidly developing area of research and development; newer vehicles are able to complete more complex operations without human intervention and with longer endurance.

Physical Configuration The physical layout of a UUV can generally be described by one of two classes, box frames or torpedo shaped, Marine Technology Society ROV Committe 1998. Box frame UUVs are typically larger with more space for instruments and actuators but are not expected to make longer distance journeys as a result of their poor hydrodynamic profile. Torpedo shaped vehicles tend to be smaller without actuators; their hydrodynamic profile makes them well suited for faster, longer distance missions however this comes at the cost of reduced stability and control.

6.2.2 Current ROV Usage

Cable repair operations are currently undertaken, where possible, with human-controlled ROVs. With visual contact and direct actuation at the seabed, the ROV is used to identify, cut and grip the cable for retrieval to the surface-vessel, Burgess 2016. In doing so the need for repeated motions of the ship across the cable is removed, saving time and fuel. Instead, the surface vessel uses dynamic positioning in order to maintain its position above the ROV and cable.

Figure 6.1: SIMEC Technology's HECTOR-7 ROV used on Orange Marine's Pierre de Fermat, SIMEC Technologies 2014

	HECTOR-7	**Atlas**	**ST200**	**QTrencher 600**
Company	SIMEC Technology	Global Marine		SMD
Vessel	Pierre de Fermat	Wave Sentinel C.S Sovereign	Cable Innovator	N/A
Depth Rating	3,000 m	2,000 m	2,500 m	3,000 m
Weight in Air	9 t	10.6 t	6.5 t	11 t
Power	300 kW	300 kW	-	450 kW
Burial Depth	2 m	2 m	1.5 m	3 m

SIMEC Technologies 2014; Global Marine 2019a; Global Marine 2019b; SMD 2017

Table 4: Relevant specifications and operating capabilities for sub-sea cable repair ROVs

While this finer control is a key benefit for ROV use over grapnels, one of the most important benefits is the ability to bury repaired cables in the sea floor using high-powered water jets, SMD 2017. 70% of cable damage is caused by man-made activity, of which over a third is a result of fishing activity; another quarter is as a result ship anchors, Ultramap 2020. As such, the ability to protect sub-sea cables in shallower waters by burying them from human intervention is a key parameter in protecting cables from further damage and extending the time between repairs. While this can be completed with a separate plough, this would require more deck space and motion of the surface vessel.

The need for fine movement control and actuators with which to manipulate cables has led to box frame vehicles dominating this field, figure 6.1 shows SIMEC Technology's HECTOR-7 ROV, a typical design for sub-sea cable repair vehicles.

Table 4 lists the specifications for the ROVs currently being used as part of the ACMA cable repair agreement along with similarly classed vehicles from other providers. As can be seen, current ROVs for this domain have a maximum working depth of about 3 km. This poses a problem to cable repair operations where, further out to sea, the sea floor can extend much further, see figure 6.2. While ROVs could be capable, in theory, of reaching lower depths it is important to balance these working capabilities with other considerations such as price and weight. In practice, while this working depth is a reasonable range to work within, it could be argued that the most important capability of current ROVs is their ability to re-bury the cable post-repair. As described previously, this is in order to protect the cable from human intervention including fishing and anchor operations. These incidents are more prevalent in shallower waters within the operating range of the ROV, therefore it is acceptable to use a grapnel outside of this operating range where burying the cable is less important.

Requirements Specification Using this information, the requirements for a cable repair UUV could be described as the following,

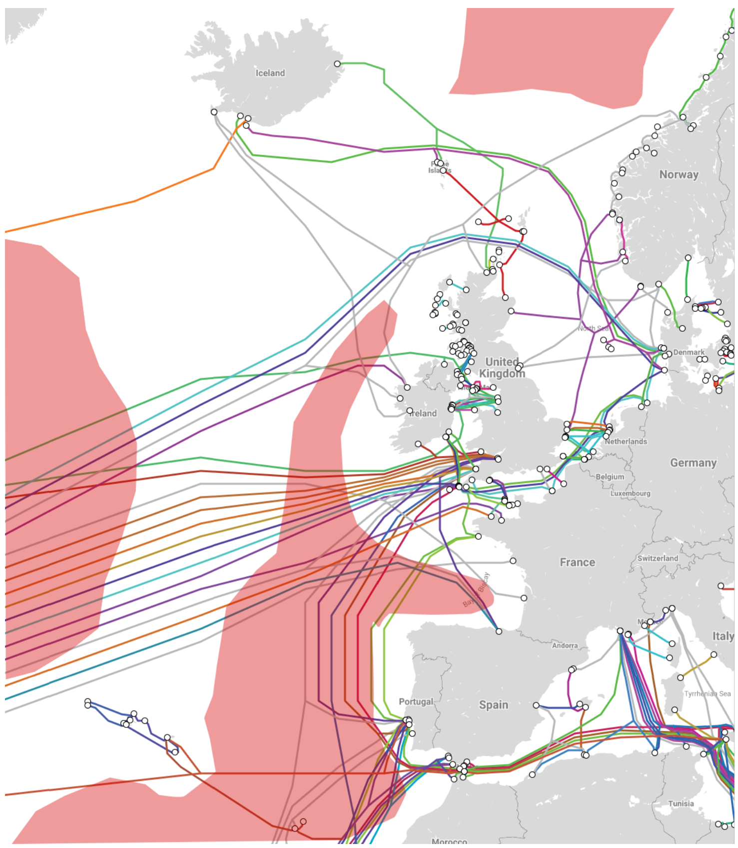

Figure 6.2: An estiamtion as to the operating range of the ROV, shaded red indicates seabed outside of the operating area, NOAA 2008; TeleGeography n.d.

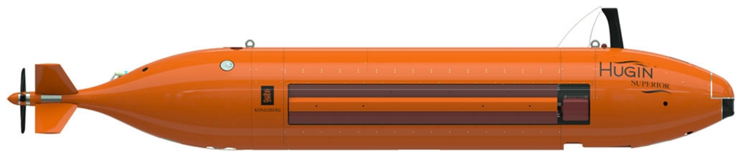

Figure 6.3: Kongsberg Maritime's HUGIN Superior AUV, Kongsberg Maritime 2018

1. The UUV should have actuators in order to both cut and grip cables
2. The UUV should be able to operate to at least 2 km of depth
3. The UUV should be able to locate the cable without visual information i.e. electromagnetically
    (a) In shallower water the cable is buried and will not be able to be visually identified
4. The UUV should be able to re-bury the cable in shallower waters
    (a) This should provide more protection to the cable from interference including fishing operations

6.2.3 Current AUV Usage

Autonomous underwater vehicles are well suited to survey and research operations; without human intervention they sweep a given area collecting data for analysis. This can include bathymetry[3], surveys and chemical composition investigations such as pH and toxin levels, Crimmins and Manley 2008. The HUGIN superior can be seen in figure 6.3, it has a torpedo design as previously described.

6.2.4 Advantages

An advantage of using an autonomous vehicle would be the lack of need for the surface vessel to maintain position directly above the ROV and fault; instead the surface vessel would stay within a larger area only to maintain contact with the UUV. This could reduce the required power directed to dynamic positioning which in higher sea states can become a significant draw. Additionally, as the UUV can move independently, the surface vehicle would not need to directly track the vehicle's movement; for example, when the UUV is re-burying the repaired cable in shallower waters. This would, again, lower the required propulsion power used by the surface vessel.

Another advantage could be a reduction in risk during mission operations. With a traditional tethered ROV, should the umbilical cable be broken the vehicle would likely lose functionality and require specialist recovery. This break could occur as a result of a fault in the tether management system, high storm activity causing too much tension on the system, or in less likely scenarios, animal intervention. An autonomous vehicle has no tether to break and a hybrid ROV/AUV could likely be instructed to take control and return home should the tether break during missions involving direct human control.

6.2.5 Domain Challenges

Navigation As mentioned, one of the main advantages of using an autonomous vehicle for sub-sea cable repairs would be the physical de-coupling of the vehicles, however this also poses the most significant challenge. In typical ROV operations, the operator has knowledge of the location of the ROV relative to the surface vessel. As the surface vessel is GNSS[4]-enabled (Likely GPS) it has knowledge of its position in world co-ordinates and the operator can use this to reduce the ROV's cable search space.

Decoupling the vehicles introduces complications that are not necessarily typical to the existing use cases for AUVs. The frequency of EM waves used by GNSS systems do not penetrate deep through the water

[3]Measurement of the depth of a body of water

[4]Global Navigation Satellite System, the generic term for satellite aided global navigation of which the American GPS, Russian GLONASS and European Galileo systems are examples

Figure 6.4: A top-hat tether management system attached to the top of an ROV, SMD 2016

and an AUV must be able to operate without world co-ordinates provided in this manner, Taraldsen, Reinen and Berg 2011. As such, navigation systems used by AUVs are typically *dead reckoning* systems. This is a form of navigation that operates relative to a known fixed point (where a UUV is deployed for example) as opposed to one relative to world co-ordinates, Bhattacharjee 2019b.

With an accurate system, this will satisfy many surveying and research use cases where relative location data can be transformed to world-coordinates after the fact. This will prove less effective when the vehicle is expected to autonomously navigate to a specific location (the cable fault). A dead reckoning system as described above uses relative sensors to measure speed and infer the current location however these relative sensors have associated measurement errors which accumulate over time, Gebre-Egziabher, Powell and Enge 2010. This would be more pronounced under the water where sea currents are liable to accentuate these errors, the efficacy of an AUV's fault location capabilities may be reduced to the point of unacceptability.

Launch & Recovery By allowing the UUV to operate untethered underwater, complications are introduced to the method by which it is launched and recovered to the surface vessel. A tethered ROV of the size being considered typically has a top-hat tether management system (TMS) responsible for controlling the slack in the umbilical cable, an example can be seen in figure 6.4. Smaller vehicles can also use a garage-style TMS where the tether attaches to a box-like cradle that houses the UUV within.

This results in the UUV being under control by the surface vessel as it is being lifted from the water, especially during the *splash zone*, the area surrounding the average water level. As the UUV is lifted or dropped through this area and it beings to make contact with the water, the weight load on the crane can change dramatically, Mark Tool & Rubber 2012. During this period, the UUV is most at risk of damage as wind and sea forces can make it swing towards the surface vessel.

The TMS and LARS system together aim to protect both vessels as the UUV descends through the splash zone by dampening the lateral movement of the UUV and by limiting the amount of umbilical slack; this keeps it away from the surface vessel's thrusters, Paschoa 2015.

These methods are effective in protecting tethered UUVs during launch and recovery, the challenge comes in defining how the UUV will be deployed when operating autonomously without a tether.

6.2.6 Proposed Design

The vehicle will be designed for hybrid ROV/AUV operations. The vehicle should be able to complete missions independently of the surface vessel with the ability to operate in a similar fashion to existing ROVs (human controller, tethered power and data connection). This will have a number of benefits, primarily that the vehicle should be able to benefit from autonomous operation where possible with the ability for direct human control in missions deemed too complex for autonomous control.

The existing remit of AUV operations is primarily survey, inspection and light intervention, it is likely that the autonomous capabilities of this vehicle would not be capable of conducting all existing cable repair missions which involve more intervention. It is important that enabling autonomous operations does not ultimately reduce its operating capabilities.

As previously described, box frame UUVs are well suited to sub-sea cable operations where fine movement control and space for actuators are critical. As such a box frame of similar specifications to those currently used, (Global Marine 2019a; SIMEC Technologies 2014) will be implemented. The vehicle will likely be at the larger and heavier end of existing ROVs as the vehicle must now have the onboard energy capabilities to complete a mission without a constant power supply from the surface vessel. The vehicle is assumed to have similar dimensions to existing vehicles, an estimation of 4m x 4m x 2m for a volume of 32m^3 is used as well as an estimation of 10 t for weight.

6.2.7 Communication

As the UUV is now expected to operate independently of the surface vessel, it should have the ability to bi-directionally, wirelessly communicate with the surface vessel. Uses for such a communications channel include the UUV reporting its mission status and the surface vessel providing high-level instructions such as *return home* orders. When operating underwater, acoustic signals are the primary medium for wireless communication. JANUS is a NATO standard for underwater communications using modulated audio signals, as such this protocol will be used between the two vessels, Potter et al. 2014.

6.2.8 Navigation

As previously described, the navigation system will primarily be built on the principle of *dead reckoning* using an inertial navigation system (INS). An INS uses input from many types of sensor such as accelerometers and gyroscopes to measure the movement of the vehicle and hence infer its location, Nortek 2020. None of these could individually provide an accurate determination of location and as such *sensor fusion* is employed. Each sensor has an associated measurement uncertainty which compounds over time, sensor fusion allows all the sensor measurements to be combined in such a way as to produce a single output measurement with an uncertainty smaller than any of each sensor individually. A common method for implementing sensor fusion is using a *Kalman filter*, Kalman 1960; Kim and Bang 2019.

However, despite the use of a Kalman filter allowing more precise approximations of the vehicle's relative location, the lack of external calibration means that the overall uncertainty will still increase over time. In land-based robotics this is mitigated through the use of periodic GPS measurements which have low, constant uncertainty and help to place an upper bound on the overall error. As previously mentioned, GNSS systems do not work deep underwater and as such, another method for providing these external updates must be used. A Doppler velocity log is a common sensor with a constant error that can also be used to limit error growth, Nortek 2020.

The following proposes methods for providing global positioning to the UUV without a traditional GNSS system. This will be completed in two stages, the first being to provide the UUV with the ability to measure the location of a fixed point relative to itself. In parallel, the global co-ordinates of this fixed point will be communicated to the UUV in order to infer its own global location.

Underwater Acoustic Positioning Alongside the use of acoustic signals for communications it will also be employed for positioning. One application for this is underwater acoustic positioning which employs the use of time-of-flight measurements to beacons of a known location to triangulate an object's location, Vickery 1998. There are different configurations for such a system depending on how these beacons are laid out, *long-baseline* (LBL) systems involve beacons located on the sea floor, Nortek 2020. Spreading these beacons around the working area of an ROV widens the baseline of the system and provides higher accuracy when triangulating. This configuration is best suited to static areas of research such as ship wrecks where an initial time devoted to deploying and calibrating these underwater beacons is a reasonable expense to pay for the required high accuracy. This is not the case for sub-sea cable repairs where the deployment, calibration and recovery of beacons on the seabed would be prohibitively complex and add significant time to the duration of a mission.

Short-baseline (SBL) systems involve a number of beacons placed at the furthest corners of the surface vessel, this has the benefit of requiring little set-up and pack-down at the cost of reduced accuracy, Vickery 1998; Liang 1999. Relative to the UUV these beacons are all on a similar bearing when operating at a distance, as a result changes in the vehicle's location would be reflected in similar changes to the measurements from all of the beacons. Previously, with a long-baseline, the beacons are ideally surrounding the UUV's working area and changes in its location are reflected in different distance deltas for each beacon allowing tighter triangulation. Accuracy can be improved by extending the beacons away from the vessel to extend the baseline as far as possible.

One method to mitigate the drawbacks of both described methods is by using GPS Intelligent Buoys (GIBs). This configuration, also referred to as an *inverted long-baseline*, allows a much wider baseline than the surface-vessel-mounted beacons by deploying a group of *smart buoys* around the expected working area of the UUV, Vito 2007; Sgorbini et al. 2002. The use of buoys as opposed to beacons on the sea-floor significantly decreases the preparation and clean-up mission phases.

Of these methods it is proposed that the surface vessel be equipped with a short-baseline beacon array as well as a population of GIBs. This will allow the choice between higher accuracy or faster mission turnaround be decided by mission conditions as well as providing redundancy for either system. In shallower waters, the accuracy of the onboard SBL may be deemed sufficient however in deeper water where the UUV is operating far further from the surface vessel, the compactness of the SBL baseline may require the higher accuracy of the GIBs[5]. The GIBs would be considered additional accuracy, the SBL would be used alongside the GIBs and act as an extra node in the array. Additionally the weather and sea conditions could play a factor in the decision. In higher sea states and stormy weather, the deployment and recovery of GIBs may be deemed too risky and the SBL could be used alone.

Global Calibration The above underwater acoustic positioning system will allow the UUV to keep track of its position relative to known points at the surface, however this alone will not provide the UUV with its global location. In order for the UUV to calibrate its local map to global co-ordinates, the global position of these surface points must be provided. This will be conducted over the previously described acoustic communication channel. As it could be expected that this channel has a low bandwidth, these updates need not be excessively frequent.

Acoustic Doppler Current Profiling While accelerometers and gyroscopes would be expected components of any mobile dead reckoning navigation system, additional sensors well-suited to sub-sea localisation will allow the vessel's movement to be more precise. One such sensor is a *Doppler velocity log* (DVL) which estimates the vessel's velocity by tracking the seabed. DVLs apply the broader concept of *acoustic Doppler current profiling* which measures the velocity of water by measuring the change in frequency caused by the Doppler effect. Combined with depth measurements calculated from the signal's echo time, this can be used to estimate the vessel's velocity. DVLs are crucial to a sub-sea INS as, like GPS, their error does not grow when employed correctly unlike other relative sensors. As described in section 6.2.8, a sensor who's measurement error does not compound and grow but stays constant is important as it places an upper bound on the overall error and allows the system to maintain accuracy over time.

[5] In practice the two could be used in conjunction for efficiency. As the UUV is deployed it initially uses the onboard SBL array while the surface vessel makes a pass around the working area deploying GIBs for use as the UUV gets deeper

6.2.9 Power

The ability to operate autonomously without an umbilical cord implies that the UUV must have an onboard power supply.

As mentioned, much of the vehicle specification is being inherited from existing ROV technology and this would include expected operating power. The expansion of the UUV's capabilities to include autonomous operation would primarily be completed through software and not significantly alter the required power.

300 kW was used as the required max power to calculate the energy storage capabilities, an operating time of 10 hours was also defined. An average draw of 50% max power was used to calculate 1.5 MWh of required storage.

The previously described 18650 cells (section 4.3) will be used for the UUV's battery pack, this will allow a single process for sourcing and end-of-life processing and increase efficiency by utilising the economy of scale. As such, the previously mentioned notes on sustainability including processes for second-use and recycling would apply to the UUVs battery pack. Lithium-polymer batteries have found usage in AUVs as a result of their lighter weight than Lithium-ion batteries. While this will increase efficiency, it is proposed that the use of a single supply chain will improve sustainability, a key parameter for this project.

The cell voltage (3.6 V) and capacity (3.5 Ah) were multiplied for 12.6 Wh of power capacity per cell. This would require 119,048 cells to meet the capacity requirements.

The battery system constitutes an extra 5,700 kg of extra weight for the UUV, it is important that the battery be removable for tethered operation in order to increase efficiency when independent operation is not required. This will bring the total weight of the vehicle to 16t when operating in AUV mode and is estimated to take up 2.5 m^3 of space.

As this battery array will experience less usage than the surface vessel's set, it is expected that it will last longer. Despite undergoing less charge cycles, Lithium-ion cells still have a finite lifespan and would not be expected to last beyond 4 years. As such this is defined as the battery replacement time period.

6.2.10 LARS

The proposal for hybrid AUV/ROV capabilities somewhat simplifies the required LARS methods. As the vehicle must still be able to operate while tethered, from the surface vessel's perspective a traditional LARS system with a top-hat TMS will be used. When operating as an ROV, the underwater vehicle will not have the battery system mounted on the top and the tether will directly connect to the vehicle. In these scenarios the LARS processes will be as previously described, see figure 6.5.

When operating autonomously, the battery system will be mounted on the top of the vehicle. It is proposed that the battery system have an interface for the top-hat TMS on the top, see figure 6.6. An acoustic location and communication beacon will be mounted on the underside of the TMS in order to provide a reference to the UUV for navigating towards and docking, Offshore Engineer 2020.

This allows the actual LARS processes to be conducted in the traditional secure manor through the splash zone and then allow detachment for autonomous operation when safely under the water.

6.2.11 Sustainability

With regards to the battery system, the same principles as described for the surface vessel battery in sections 4.4 and 4.5 apply including procurement, and lifespan extension.

However, the difference in usage patterns for the UUV may make the battery's applicability to second-usage less viable. This would be because it would be expected to sustain higher depth-of-discharge without the ability to activate more ammonia cells and keep the capacity higher. As such the direct recycling processes previously described may be more appropriate as an end-of-life procedure.

Using the previous per kilowatt embodied carbon value, a UUV battery set represents 120 tonnes of carbon requiring offset to achieve net-zero.

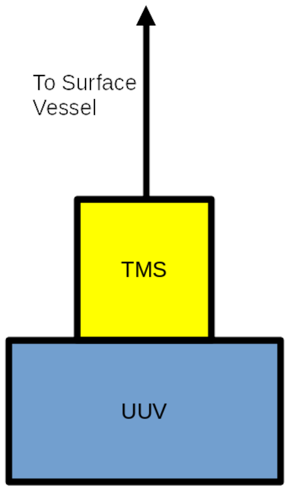

Figure 6.5: TMS and UUV structure when operating tethered

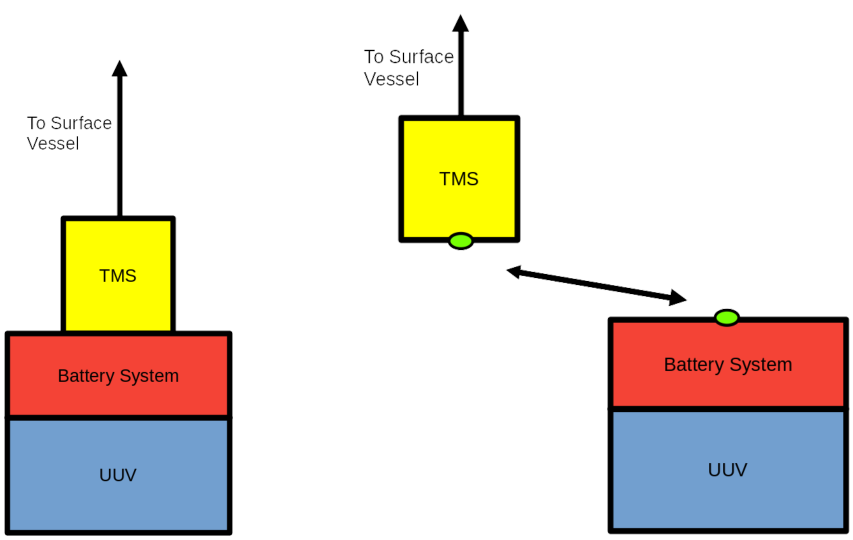

Figure 6.6: TMS and UUV structure when operating autonomously, indicating mount point for re-housing

6.2.12 Financials

UUVs and TMSs are typically bespoke, purpose-built projects without publicly available prices. As such estimations were made in order to cost the entire system. UUVs with publicly available prices tend to be light intervention and autonomous survey vehicles with a max depth of 300m, Amron 2020; Deep Trekker 2020. These vehicles tend to cost between £24,000 and £50,000. The proposed vehicle is far more powerful and is not the same class of vehicle.

Including the advancements of autonomous capabilities it is proposed that an industrial vehicle of the requirements described would cost £2,000,000. Additionally it is proposed that the tether management system would cost £400,000.

As described, a single type of Lithium cell are being used in order to benefit from the economy of scale. Using the previously specified £5 unit price, a set of UUV battery cells will cost £595,240. Modelling this across its lifespan averages to £148,810 per year. For costing the associated BMS, the previously mentioned 60% cell cost contribution would suggest a price of £397,000.

6.2.13 Summary

The proposed UUV describes an extension to existing ROV capabilities by allowing untethered autonomous operations. This requires a wireless communication channel between the surface and underwater vessel which will be completed using acoustic waves. The UUV will effectively be GNSS-enabled by proxy from the surface vessel, allowing it to navigate to the fault locations. In order to operate autonomously, the UUV will require onboard power, a battery system of suitable scale was described along with protocols for decommissioning sustainably.

Part II

Digitalisation

Before discussing how this project aims to leverage *digitalisation* it is worth defining the term and the adjacent term *digitisation*. Digitisation describes the transforming of data or a process from an analogue system to a digital one, Burkett 2017. It is a value-neutral term in of itself and could have positive or negative effects. A simple example would be transitioning from working with pen-and-paper forms to digital documents and PDFs.

Digitalisation describes the use of digitisation to increase efficiency and access new value-producing business opportunities, Burkett 2017; Gartner n.d. To follow the above example, digitalisation could include using groupware in order to collaboratively work on a cloud document as opposed to delivering hard copy revisions of a document between locations.

As a broad concept, there are many ways that the concept of digitalisation could be applied to this project, as a whole, though, the initiative could be described as a *smart ship*. Many of the features rely on interconnected sites, the internet network topology has been discussed in section 5.2.

With a fully connected environment, head-office and the depot will be able to monitor and control aspects of the vessel. In theory, head-office would be able to remotely command both the vessel and UUV, although proper authorisation, safety and business practices would need to be defined for where this is appropriate.

Live access will be available for information about the vessels including location data, course information, battery capacity information and remaining fuel levels. This could be used in order to sync depot operations with the vessels mission status, for example by preparing the local electrical supply for cold-ironing the vessel.

Within the vessels, machine learning (ML) and AI will have varying applicability. The UUV, for example, would likely apply both for applications such as image recognition from the visual cameras. Kalman filters have already been discussed for calculating the vessel's location.

Part III

Design Summary

7 Vessel

7.1 Electrical Energy Storage

The surface will be fitted with 2.44 MWh of electrical energy storage acting as a buffer between the ammonia fuel cells and the thrusters. This will allow the power from the ammonia cells to be generated in the most efficient manner possible with this primarily being varied by changing the population of active cells instead of the draw on a fixed group. The system will be repurposed following decommission in order to extend the life of the system and reduce the environmental impact.

7.2 Autonomous Underwater Vehicle Capabilities

The proposed UUV inherits the operating capabilities of existing ROVs used in the domain while proposing extensions to allow autonomous operations. This allows an increase in efficiency while decoupling the two vessels in order to save fuel for the ship. The UUV has 1.5 MWh of removable onboard power storage for autonomous missions in order to allow a 20 hour operating time.

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A Time-dependent Power Modelling

A.1 Power In

As described in the premise for why a buffer is needed (section 4), the power from the ammonia fuel cells will primarily be varied by changing the population of active cells as opposed to drawing varied power from each individually. This allows the cells to operate as much as possible in their most efficient state. However, cells require time to turn on and reach this efficient state, about 20 minutes. This was modelled by having the input power move in discrete steps as cells are turned on and off. This step value was defined as 200 kW, the most efficient state for a single fuel cell.

As time increases, every twenty minutes the amount of active cells can be incremented or decremented. This over-simplifies the actual behaviour as this would, in reality, be a gradual process as opposed to one of discrete steps, however, it was deemed acceptable in order to enforce the time penalty in changing the number of powering cells.

A.2 Power Out

In order to model the load draw from the propulsion and hotel load, a random power load delta was added or subtracted each second. This was done in order to provide a dynamic environment, were the load power to stay the same the battery would either charge or discharge entirely and then stay in this state. A random change each second more closely matches the expected power requirements as the wind and currents required a dynamic load to be drawn.

The max load delta was defined as 10 kW. This means that each second the load could change by a maximum of ± 10 kW with a random number between -1 and 1 used as a scale factor.

The different stages of a mission were defined as having a maximum and minimum load power which the random function was able to fluctuate between. When dynamic positioning, it could be expected that more power would be used than when completing either the out or home-bound journey.

A.3 Efficiencies

The charging and discharging of the battery is not a completely efficient process. In order to take this into account, both processes were treated as 80% efficient.

A.4 Validity

In terms of applicability, the model provides a good high-level approximation of the relationship between the fuel cells and the battery usage. In reality, however, the system would be far more complex. For example, the model only increments or decrements the active fuel cells by one at each twenty minute interval when in reality many could be activated or deactivated simultaneously. The model was also entirely reactive, acting only on the current capacity of the battery. In practice, knowledge of other factors including the upcoming mission stages and weather forecast would allow the system to be more pro-active.