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Iron Powder as a Fuel on Service Vessels

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ABSTRACT

This paper investigates the feasibility of iron powder energy generation systems on board a semi-submersible crane vessel. This is done using a design model that integrates design information and a simulated mission profile to determine a hybrid iron powder setup split. This setup is then placed within a set of vessel designs to calculate a base level feasibility looking at the draft, stability, and emissions decrease. For those concepts that were technically feasible, the new hybrid iron powder setup contributed to a reduction of CO_2 *up to 25-50% and a reduction of* NO_x *emissions between 15-50%, depending on the mission profile.*

KEY WORDS

Iron powder; alternative fuel; semi-submersible crane vessel design; feasibility study

INTRODUCTION

This paper explores the use of metal powder as a fuel on service vessels because they are a promising sustainable alternative to conventional energy sources since they are dense energy carriers. The main feature attributed to the iron powder power generation process that makes it such a high potential alternative fuel source is the fact that the combustion of this powder results in no CO_2 by-product (van Rooij et al., 2019). This paper is a follow on feasibility study to de Kwant et al (2023), who looked at the iron powder as a potential fuel on shipping vessels. De Kwant et al (2023) determined that short sea container vessels would be the most promising vessel class for shipping vessels, and that iron powder would could be technically feasible, however, it will likely not be as economically feasible as other alternative fuels.

This paper extends that research by looking into the feasibility within service vessels. This paper will start with a evaluation of the state-of-the-art of iron powder energy generation to determine the most optimal setup to be installed aboard a marine vessel. This will be followed by a study of the marine service vessels to determine which is best suited for an iron powder powertrain installation. The conclusions from these two studies will result in the creation of a design method to test iron powder feasibility on the chosen service vessel type. This method of testing feasibility will then be applied to a set of case study vessels.

Introduction to iron powder as fuel

Metal powder combustion is one of the promising sustainable power generating alternatives to conventional sources of power such as fossil fuels. Metal powders are dense energy carriers that can be turned into a power source using two processes (Bergthorson, 2018). The first is known as the wet cycle in which the metal is reacted with water at high temperatures for heat and hydrogen production (Dirven et al., 2018). The product can be used either in heat engines or in fuel cells. The second process is the dry cycle in which the metals are directly combusted in an external combustion chamber and converted into mechanical energy directly (Dirven et al., 2018). The dry cycle is a more direct form of energy generation as opposed to the two-step process of the wet cycle. This means that the dry cycle will be more compact in practical use than the wet cycle and require less volume. Therefore, the use of the dry cycle is far more practical onboard a ship with limited area and volume and will be the only one researched.

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Iron powder characteristics

The iron powder energy generation process has multiple characteristics that make it unique, such as its availability, recyclability, and zero-emission aspects of iron powder as an energy source. There are also other characteristics that serve as advantages such as low safety risks, ease of retrofit opportunities, and a significant energy density. Other characteristics such as abrasivity, moisture sensitivity, and a generally low efficiency serve as characteristics that will require further attention.

A key advantage of using iron as a power source is its overall abundance as a resource. Iron makes up around 5% of the earth's crust making it the 4th most common element in the crust (Bergthorson, 2018). This means that there will be enough resource availability for this particular use alongside the conventional uses of iron in construction and other sectors. Other metals that can be considered for electrofuels such as cobalt are far less abundant and more difficult to obtain, making them more expensive and less attractive as an alternative fuel.

As can be done with several other metal fuel sources, iron can be fully recycled after the process of energy generation. When iron powder is burned in a combustion chamber, the remaining products are iron oxides. These iron oxides cannot be used again for combustion in the state they are in as they have already been oxidized. Using either coke (a high-carbon distillate of coal) or hydrogen it is possible to reduce the iron oxides back into iron powder making the energy generation process fully circular process, as shown in Figure 1.

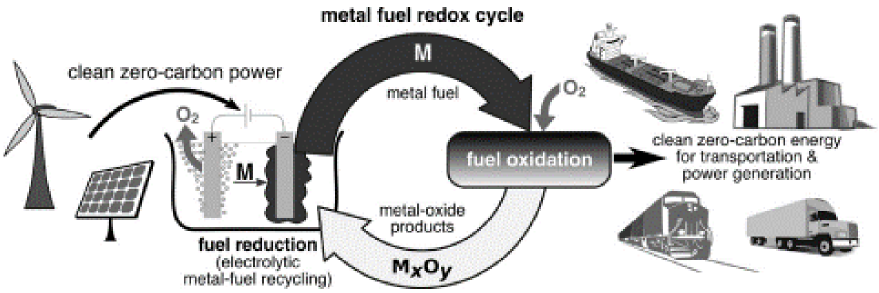

Figure 1: Metal reduction cycle applicable for iron (Bergthorson, 2018)

This has the main advantage that generally only one supply of iron powder is required for a specific application as this source can be infinitely reused through the reduction process. This is, of course, not possible with fossil fuels as their combustion products cannot be reduced back into the fuel.

The main advantage of using iron as a fuel source over fossil fuels is of course its extremely low emission in combustion. The combustion of iron releases no CO_2 as a by-product and very low levels of nitrous oxide with a maximum of 94 ppm of nitric oxide and 1 ppm of nitrogen oxide measured in a 100kW test setup by TU Eindhoven (van Rooij et al., 2019). The low level of nitrous oxide by-product is dependent on both the temperature of the combustion as well as the amount of hydrogen atoms present in combustion. For iron powder the temperature still reaches levels where some nitrous oxide may be released however the lack of hydrogen atoms in this combustion ensure this level is extremely low especially when compared to conventional diesel engine combustion (van Rooij et al., 2019).

Iron powder components

The iron powder powertrain consists of multiple systems to complete the entire cycle of power generation. A large array of infrastructure, systems and equipment are required both on land and onboard to complete the process (see Figure 2).

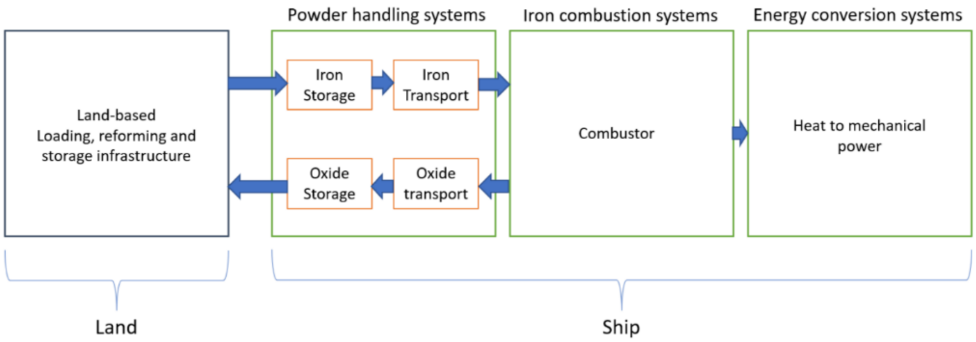

Figure 2: An overview of the components in the iron powder powertrain (de Kwant, 2021)

The land-based components are mainly the storage areas and regeneration plants. These are less important for the ship processes and will therefore not be further investigated in this paper. The components onboard the ship can be split into four different systems: storage, transport, combustion, and energy conversion systems. These systems will be further explored looking at the current state-of-the-art and will be analyzed in context of the challenges that arise with placement onboard a ship.

The storage of iron powder is fundamentally different to the storage of conventional liquid fuels such as marine diesel oil (MDO) and heavy fuel oil (HFO). Whereas liquid fuels are stored in tanks at around 40 degrees, iron powder cannot be stored in tanks and does not necessarily require a specific minimum temperature level (Seijger, 2020). As with all other bulk goods, iron powder is best stored in silos (van Rooij et al., 2019). The powdered form of the iron powder results in a higher volume requirement as well as high mass levels. There are two types of silos that can be used for iron powder storage, a horizontal or vertical silo. A horizontal silo is more comparable to the shape of a tank allowing for much lower placement to ensure a low center of gravity for the vessel. A key disadvantage of the horizontal silo, however, is its lower discharge level in comparison with the vertical silo. The vertical silo can discharge its bulk content through the hopper system mainly through gravitational forces and flow design. Due to its far more limited failure points, the vertical silo is currently preferred over the horizontal silo.

Transport of iron powder particles is best done using a two-phase pneumatic transport system. This transport system transports the bulk material through an air stream rather than direct contact. This air stream is created inside a tubular enclosed piping by a pump or high-power fan to push the bulk materials through the piping. This system can provide transport with sharp turns in any direction. Its high transport speed in the air stream makes it possible to minimize the size of the transport tubes while maintaining the minimum level of flow required. Flow level may need to be reduced to ensure minimal damage due to abrasiveness of the iron powder and oxide powder. The pneumatic two-phase transport system is also able to provide a homogeneous flow rate for transport from the dispersal system to the combustion chamber (van Rooij et al., 2019). This system has already been used for zinc transport whose properties are highly comparable to iron powder (Air-Tech System, 2024). The main concern with this system is the high amount of power required to operate in comparison to most other bulk transport systems.

The process of iron powder combustion is done in an external combustion chamber. This is because the combustion process for iron powder is much longer than is possible in an internal combustion chamber. This is coupled with the possibility of clogging of the iron powder particles in an internal combustion engine. To collect the iron oxide particles for storage and reduction back into iron powder, a combination of a cyclone filter and bag house filter setup are used. These are deemed sufficient to match the requirements for an iron powder system with an efficiency of around 38% to reach an oxide collection rate of 99.999% (van Rooij et al., 2019).

The energy generation from this combustion process is best done using a Mitsubishi (Ultra Steam Turbine) UST cycle (de Kwant, 2021). This is a reheated Rankine steam cycle. This setup is pictured in Figure 3. Is fitted with an economiser, evaporator, superheater and reheater. These are connected to a series of three turbines: a high-pressure turbine, intermediate pressure turbine, and a low-pressure turbine. This reheating of the working fluid and passing through this series of turbines increases the efficiency up to 15% compared to standard steam cycles. These systems are in commercial operation and are seen as suitable for iron powder application as well (van Rooij et al., 2019).

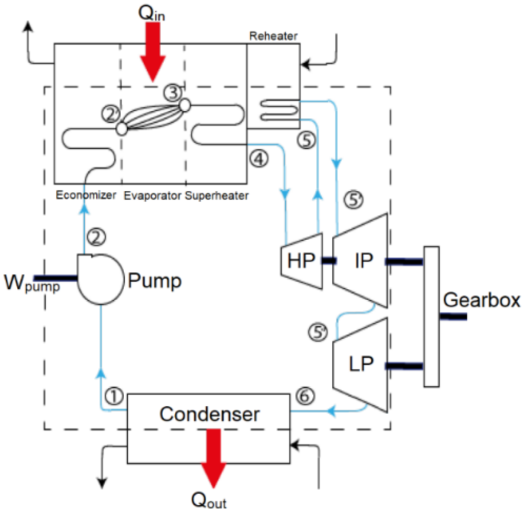

Figure 3: Schematic of Mitsubishi's UST plant, (de Kwant, 2021, Seijger, 2020)

Iron powder limitations
There are certain limitations that dictate the iron powder powertrain's output capability. These key limiters are the volume and mass concerns that come with iron powder storage systems, the part load and dynamic load issues that come with energy conversion, and potential filtration issues concerning the heat collection from oxides in the combustion system. Regardless of what combustion process, storage system, transport system or energy conversion system is used, there will be a high volume and mass requirement for the iron powder powertrain. From vertical storage silos to filtering systems to the boiler system and turbine the total volume taken up by the entire powertrain becomes significant with regards to ship stability. This requires a deep dive into the possibilities for different configurations of this system keeping in mind the high energy cost for pneumatic two-phase transport between these systems.

One of the main drawbacks of using a steam cycle for energy conversion is the low capability for part load conditions as well as dynamic loading. When the ship is in part load condition, the power requirement is lower than the design point of the power generation and conversion system. At this point the system is no longer working at optimum efficiency as this is only the case at the design point. This is the case with most power units however the drop in efficiency for a steam cycle can be quite stark. One of the most prominent solutions to the part load concern pertaining specifically to transit is the use of a controllable pitch propellers (van Rooij et al., 2019). This allows the ship to travel at different speeds without changing the steam cycle from its nominal power output. A hybrid configuration can be used to make up for the load variations (van Rooij et al., 2019). The main power source can be used for propulsive power and the secondary power source can be used for additional loads such as hotel, equipment, and crane loads.

Introduction to Service Vessels

The term service vessel encompasses a large variety of ship types with varying sizes and functions. These vessels were put through a two-phase down selection starting with the wide range of service vessels and ending with one, most optimal service vessel type. First, a list of different types of service vessels was made and their feasibility for an iron powder powertrain was determined based upon size and range. A select few vessel types were then further analyzed based on their operational modes and missions. These operational profiles were used to make an estimated load variation over the course of a mission and of the total output requirements along with their initial iron powder volume and mass requirements.

Phase one
Phase one of the down selection starts with a list of the service vessels to be considered, categorized into four areas: Transport, Support, Construction and Specialty, see Table 1.

Table 1: List of commonly used service vessels.

Transport Vessels	Support Vessels
- Walk-to-work Vessel - Platform Support Vessel - Heavy Lifting Cargo Vessel - Daughter Craft/Crew Transfer Vessel	- Tugboat - Anchor Handling Tug Supplier
Construction Vessels	**Specialty Vessels**
- Offshore Subsea Construction Vessel - Semi-submersible Crane Vessel (SSCV) - Jack-up Vessel	- Pipe-laying Vessel - Research Vessel - Dredger

These vessels were assessed for potential compatibility with an iron powder setup based upon their size, range, and functions. This very basic assessment allows certain vessels such as the daughter craft, tugboat, and pipe-laying vessels to be filtered out due to size and volume constraints. Long range research vessels can also be eliminated due to their likely high bunker requirement in comparison to their shape and size. Certain remaining vessels such as the walk-to-work and platform supply vessels are combined as they are highly similar in size and function.

Phase Two
From this first phase of the down selection, only four different vessel types remained: the platform supply vessel, the jack-up vessel, the semi-submersible crane vessel (SSCV) and the (limited range) research vessel. These vessel types were singled out in the 1st phase due to opportunities presented regarding either their size, their typical range of operation or the complexity of their functions. While all of these vessel types provided opportunities in one or two of these categories, none were ideal and would require a deeper dive to determine whether the opportunities presented were enough to make the idea potentially feasible. Through a further analysis of operational profile and load profile, an optimal vessel type of these four can be determined.

The main concern with platform supply vessels and research vessels is the relatively small capacity for extra volume and mass. These vessels are largely under 100m in length with largely varying loads over the course of a mission. Another issue is the densely packed state of the hulls of these smaller supply vessels, with minimal room on deck and below deck, placement of the silos will prove difficult. The main issue with the jack-up vessel is the high mass level in relation to its jacking-up process. The extra mass of an iron powder setup is considered too high for the jacking mechanism to still be able to lift the vessel.

The overall size and lightweight of the SSCV and its hull form make it far more ideal for iron powder powertrain implementation. From previous research testing the iron powder setup on short sea shipping vessels, one of the conclusions drawn from the results were that the volume and mass of the setup had a significant impact on the arrangement and performance of the vessel. These results were interpreted as, in order to minimize the impact of the mass and volume requirements of the iron powder powertrain a vessel with appropriate dimensions and tonnage is required. The large pillars connecting its pontoons to the deck box are ideal for silo placement. The general size of these SSCVs ranging from $130m$ up to $210m$ will likely decrease the total impact of the iron powder powertrain on the design of the vessel with regards to volume and mass constraints. While the level of power and energy required by a SSCV cannot be fully supplied by the iron powder powertrain, the load profiles have shown a potential for a hybrid installation which will ensure the power requirement of the vessel is satisfied while still decreasing the GHG emission. Therefore, the choice is made to test an iron powder setup on a SSCV.

METHOD

To test the feasibility of a hybrid iron powder setup on a SSCV, information is required on both the characteristics of the SSCVs as well as the systems to be placed aboard. The main inputs are the main dimensions and operating profiles of a selection of SSCVs. These are used to generate load profiles from which the hybrid split can be determined. With this hybrid split the weight estimations are made and used to test for stability and feasibility. Finally, an emissions comparison is made to assess the environmental impact of the hybrid setup. This process (Figure 4) is structured in a way that will maximize the limited inputs available for SSCVs where only main vessel dimensions, and high-level operating profile and load profile data is available.

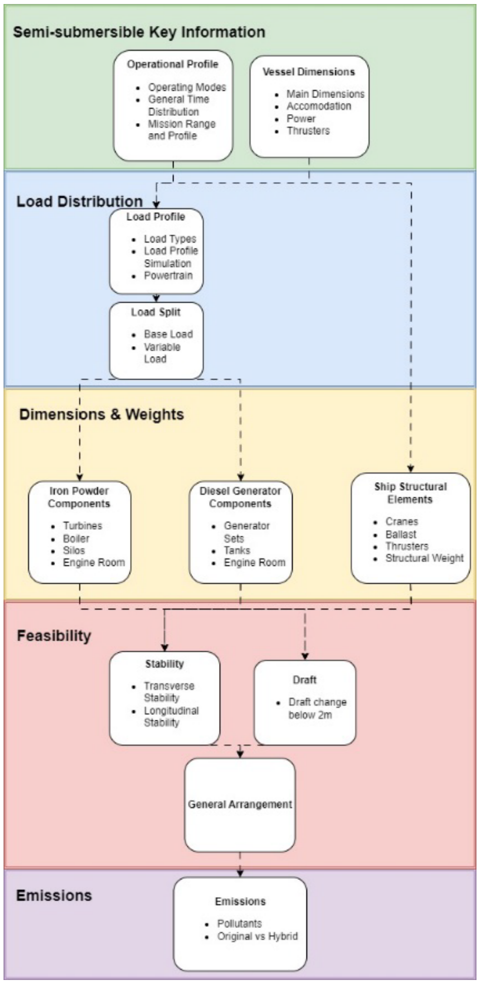

Figure 4: Method diagram showing steps to determine base feasibility.

Key Information

To ensure the reliability of results, existing vessel information is needed. In this case, a market study has been performed on the existing worldwide fleet of SSCVs. From this study, a set of four SSCV designs, each with differing main dimensions, power outputs and crane capacities were selected to form a case study. The information from these vessels is crucial in determining load distributions, weight estimations and stability calculations. Determining the operational profile of SSCVs means looking at the operating modes of the vessel, the distribution of time spent in a particular operating mode and using this information to create a realistic mission profile with an accurate range.

The operational profile of a semi-submersible crane vessel can be viewed over two timespans, over the space of a year and over the space of one mission. The standard SSCV has three operating modes; idle and repair, sailing, and working mode (Hagen, 2021). The idle and repair mode is assumed to be split between three sub modes: repair, idle at port and idle at sea. A SSCV mission can be described using a long and short cycle. In this case the 'long cycle' consists of the time spent loading, bunkering, and unloading at port coupled with the time taken to sail from port to the working area. The 'short cycle' then consists of all the time spent in the working area, this includes the time spent installing the offshore structures as well as potential idle times at sea and sailing time between offshore construction locations. This cycle is visualized in Figure 5.

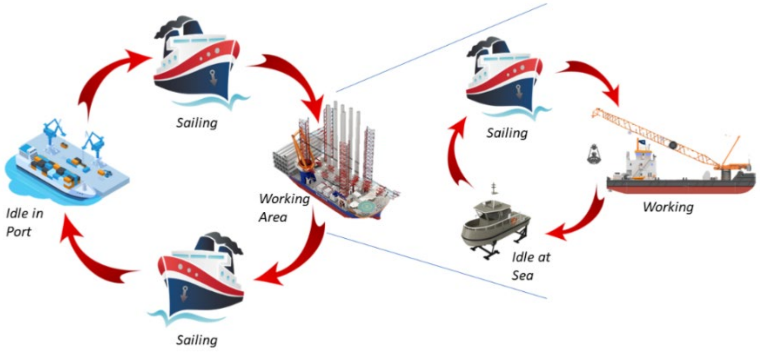

Figure 5: Diagram of the short and long cycles performed by a SSCV over the course of a mission.

The mission duration for SSCVs can vary greatly ranging from 7 weeks up to 15+, with bunkering occurring every 7-12 weeks. (personal communication, March 10, 2023). The missions for SSCVs vary significantly based upon what structures need to be installed, changed, or decommissioned. The sheer variety in operations makes it near impossible to simply take an average of all mission types and create a generic load profile. Therefore, the choice was made to focus on one specific mission type that is becoming increasingly common with installation vessels: wind turbine and mono-pile installation.

Load Distribution

Using the information provided about operating profiles, and general mission durations, the power and energy demands of the vessels can be estimated. The load profile determination starts with an understanding of the load types and how these power demands can be estimated from existing information to generate a time vs power graph. According to the results of the load profile simulations, the existing powertrain can be adapted to a hybrid powertrain. There are three main load types to be considered on a SSCV: the hotel load, thruster load, and crane load.

The load per operating profile is determined based upon the data available for one SSCV, to be used as a reference. The power level required for each operating mode is available for this vessel but not for the rest of the vessels. Due to most hotel systems being aimed at crew comfort or are systems used by the crew it is most likely that the hotel load can be scaled according to the crew capacity of the vessel. Using this reference vessel as a base, half of the factor difference in crew capacity is used as the difference in hotel load. This is because apart from the extra crew quarters, many areas such as the mess hall will not require as significant an increase in hotel load to accommodate for more crew. The thruster load of a vessel is mainly dependent on the installed thruster power. This is available for all vessels and can therefore be scaled to the same level as for the reference vessel. This can be assumed because of the tier III DP requirements applicable to all SSCV available reference vessels The thruster loads in dynamic positioning mode will be determined by a maximum thruster load and a base thruster load. Finally, the crane load is scaled based on the total powertrain of the vessel as the hotel load and thruster load have already been determined. This means that the remaining load for each operating mode is covered by the cranes. The variable crane loads are determined by a maximum crane load and a base crane load.

These loads per operating mode are the basis of the load profile estimation. Each operating mode is simulated for the previously determined mission type for the determined mission length. As the operating mode of the simulation varies over the mission, so does the power requirement of the vessel. This gives an indication of the total power requirement needed for each vessel as well as where the hybrid split should be made. Firstly, a load profile containing the three main consumers is created to show the variation of the power requirement over the course of a mission as well as where the peak loads occur. These are then summed up to create an estimation of the total power requirement of the vessel.

It is important to note that these load profiles are generated from assumptions made for the load requirement of each consumer. While the simulation of a relatively constant load such as the hotel load is quite simple, the simulation of a varying load is more complex and results in a wider range of results with each simulation. This is mainly the case for the thruster and crane load when the vessel is in working mode. With the base and peak load estimations made, the probability of the load requirement being any value between the base and peak load must be determined. This was done based on the existing crane energy demand data available from one of reference SSCVs, shown in Figure 6.

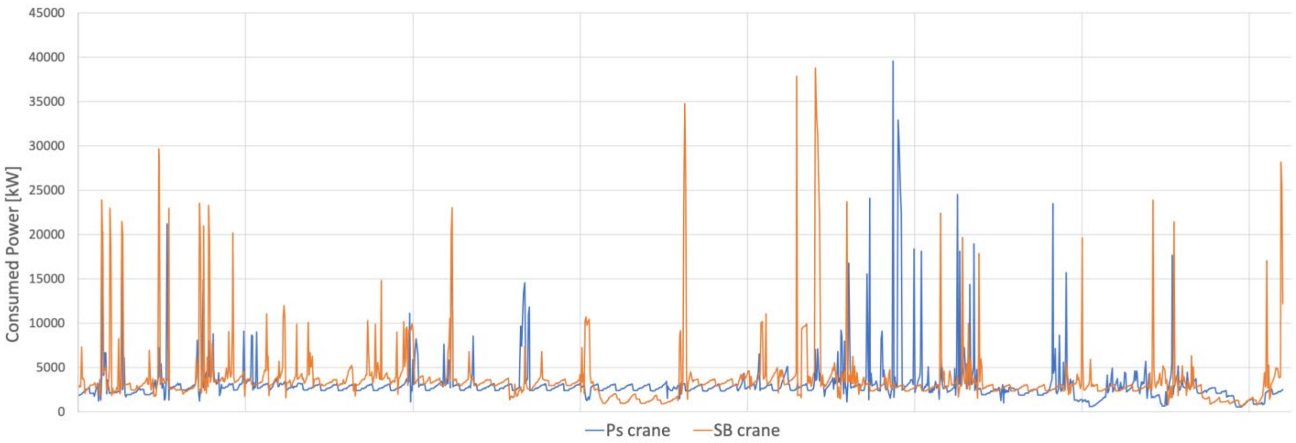

Figure 6: The energy demand of the reference SSCV's cranes during one day in working mode, (Hagen, 2021)

This frequency of peak power demand over one day for each crane was extrapolated for an entire operation in working mode. By calculating the number of times certain power demands were reached over the course of a day, a probability of a certain power demand could be generated and applied to each vessel. While this does not perfectly reflect the reality of the power demand for each vessel, it does give sufficient and reliable indication of the distribution of power demand for both the cranes and the thrusters. The thrusters in working mode are set to dynamic positioning mode and these often work in tandem with the crane operations. When the crane undergoes a large movement, it requires a large amount of power for lifting but also for the dynamic positioning to stabilise the vessel. This coupling of the thruster and crane in working mode allows this distribution of power demand to be used not only for the crane loads but also the thruster loads.

A full depiction of a typical powertrain from power generation to power consumption is given in Figure 7 depicting the full powertrain of one the reference SSCVs with 3 engine rooms. In this schematic the red, blue, and yellow components describe the generator sets in their respective engine rooms while the green components are the main power consumers such as the cranes and thrusters. This general layout of the powertrain systems will be used in the hybrid setup.

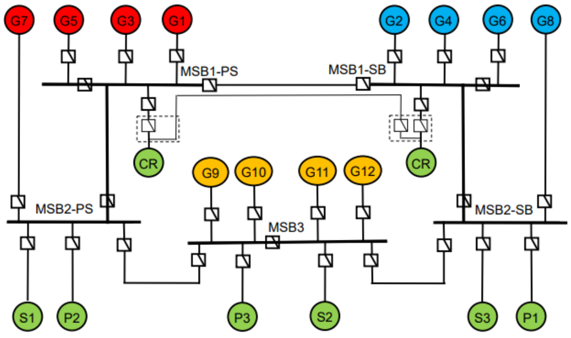

Figure 7: Powertrain schematic for one the SSCVs, (Lyu, 2016)

Keeping in mind that the power levels will differ significantly per vessel, an outline is made of the general layout of the hybrid powertrain. The main difference between the original powertrain and the hybrid powertrain is the addition of an extra engine room with an iron powder setup. Each vessel will consist of four engine rooms. Three of these engine rooms will be similar to the original engine rooms in that they will be equipped with diesel generator sets to provide the variable load required for the vessel. The iron powder engine room will be equipped with two boilers and turbine sets to provide redundancy. The rated power of each setup will be equal to the base load determined from the load profile. The rated power of the remaining diesel generator sets in the other three engine rooms will be determined based on the redundancy requirements used for the original powertrain design. Two of the remaining three engine rooms must be capable of providing the peak load requirement minus the output of the iron powder setup. The layout of this hybrid powertrain is modelled in Figure 8.

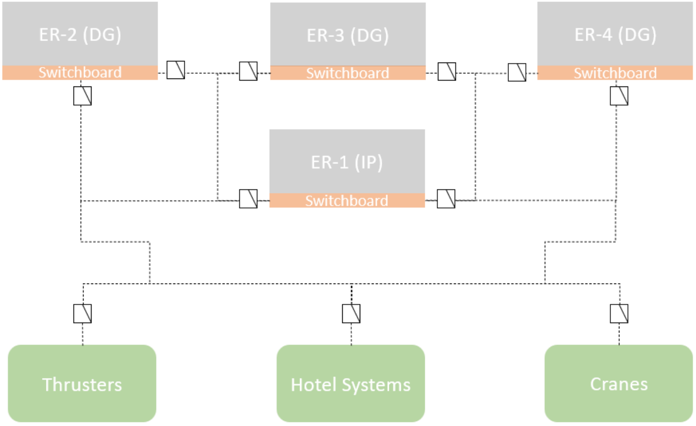

Figure 8: Simplified diagram of hybrid powertrain

Dimensions and weights

The load profiles show both the power and energy requirements of the vessels, the key information needed in order to properly size the powertrain components. The dimensioning and weight estimation is split into three main categories. First, the estimation of the iron powder components is done including everything in the engine room as well as the silos and filters. Next, the diesel generator sets are estimated as well as the bunker tanks. Finally, the main elements of the ship are estimated.

Iron powder components

The iron powder components to be estimated are the steam turbines, boiler, filters, and silos. These dimensions will vary per vessel as they are dependent on the base load required for each vessel as well as the overall kWh needed over the course of a mission. The method of dimensioning and weight estimation is based largely on the methods used by de Kwant er al (2023) for a similar iron powder setup.

Diesel generator components

The diesel generator components are far simpler to estimate as these are far more common and readily available for commercial use. This is also the case for the bunker tanks for the marine diesel fuel as the tanks have far more flexibility for placement compared to the silos for iron powder storage.

Ship main elements components

The ship structural elements consist of the remaining weights on the vessel required for an accurate stability calculation. These include the cranes, the ballast, thrusters, and the structural weight of the vessel. These elements are estimated separately despite the lightweight of all four reference vessels being given due to their varying placement aboard the vessel, these weights and their centres of gravity are required for a more accurate stability evaluation.

Feasibility

Using the information from the dimensioning and weight calculations, some base stability calculations can be made to determine both the feasibility of a hybrid setup on a SSCV as well as how this would look like. Due to a lack of information regarding the motions of these types of vessels as well as the exact internal layout of the vessels only the intact stability will be evaluated. Firstly, a look at the impact of the hybrid setup on the draft of the vessel is investigated. This is followed by the intact stability evaluation which is comprised of a transverse meta-centre height check and a longitudinal balancing leading to a general arrangement of the feasible vessels.

Draft

The draft of SSCV is used as a variable that can increase a vessels stability in working condition. The draft is lowest in sailing condition to minimize the underwater surface area and therefore resistance of the vessel. The draft is highest when performing heavy crane operations as the increased draft ensures a lower ship response to wave loading. The draft is essentially altered through creation of extra deadweight through pumping ballast water into the pontoons and occasionally pillars of the vessel. This increase in vessel weight increases the draft of the vessel. This change in draft is estimated for each vessel depending on their increased mass due to the iron powder setup.

This value is especially important for the transit draft condition as this cannot be compensated by simply pumping less ballast as is the case for the vessel's maximum draft. This increase in draft will certainly increase the underwater surface area which in turn will increase the resistance of the vessel changing its transit speed. This is an issue that may require a redesign of the vessel geometry to account for the added weight. If the draft at transit level increases to above the height of the pontoons, the issue is deemed serious and requiring significant redesign considerations. If the draft at transit level increases but not above the height of the pontoons, it is considered an issue requiring lass significant and far-reaching redesign considerations.

Transverse stability

The transverse stability of SSCVs is generally quite high to accommodate for large moments caused by crane operations. Although the vessel motions due to wave loading are significantly reduced at maximum draft, the metacentre height (GM) is significantly reduced. Therefore, the assumption is made that if the GM is acceptable at maximum draft in fully loaded condition, the GM will be acceptable for all other drafts and conditions as well. According to classification rules for heavy lift vessels in Part 5: Ship Types, Chapter 10: Vessels for special operations, 2021, the 'GM at equilibrium shall not be less than 0.3 m'. Further criteria include that the 'positive range of the GZ curve shall be minimum 15° in conjunction with a height of not less than 0.1 m within this range'. Finally, the 'maximum righting arm shall occur at an angle of heel not less than 7°'. To determine whether this vessel fulfils these criteria, the GM is determined as well as the GZ-curve for the first 15 degrees.

Longitudinal stability and general arrangement

The longitudinal stability is largely dictated by the distribution of ballast across the length of the vessel. This allows the trim of the vessel to be managed in different circumstances and drafts. The general arrangement of the vessel dictates to what degree the ship will trim and to what extent this trim must be controlled.

This placement of the various components to fulfil transverse and longitudinal stability creates a general arrangement of the vessel. The components are placed within the bounds of the geometry of the vessel at various heights along the length of the vessel. The placement will be symmetrical along the breadth of the vessel as is the case with almost all seagoing vessels. This general arrangement will be displayed in the 3D Rhinoceros model made for each vessel with side and top views of each level shown as well.

Emissions

The key advantage of iron powder as a power source is its significantly lower greenhouse gas emission in comparison the marine diesel fuels being used. It is assumed that the installation of an iron powder hybrid setup will likely incur technical concerns regarding the vessel design. The emissions decrease is weighed against these concerns to determine whether the degree of feasibility of installing an iron powder hybrid setup on a particular vessel is worth the effort and cost. This is done by having the emission reduction potential be a key factor alongside feasibility in making a final recommendation in the conclusion. Firstly, the pollutants to be considered are determined as well as their output for each power source and then the original powertrain is compared to the hybrid powertrain to determine the level of emissions reduction.

CASE STUDY

For this case study, a set of four semi-submersible vessel (SSCV) designs was chosen to be a representation of the SSCV fleet. Each vessel design has a slightly different geometry, size, and crane capacity. These four vessel designs are considered sufficient to represent the global SSCV fleet. The differing geometry and capacity allow for a clearer comparison between the vessels when evaluating the reasons for technical feasibility.

Key information

The four vessels have varying main dimensions, carrying/lifting capacities, and powertrain setups. The main information on each vessel is provided in Table 2, and will be used to help create suitable load profiles and general arrangements.

The only missing base information regarding these vessels was the powertrain configuration and total power output capability of Vessel C. The main features shared by all four vessels is the tier III dynamic positioning capability since this is a requirement for the heavy lifting operations. This means that the thrusters for each vessel are azimuth thrusters. All vessels have a transit depth of 11-12m with maximum depths ranging from $25m$ to $32m$. These maximum depths are only reached during heavy lifting operations in which the dynamic positioning is also active. The crew accommodation also vary from 400 persons up to 736 persons. These main points of information are used to determine the expected power requirements for each operating mode.

Table 2. SSCV main dimensions and key information

Dimension	Symbol	Vessel A	Vessel B	Vessel C	Vessel D	Unit
Length	L	220	201.6	154	137	m
Breadth	B	102	88.4	106	81	
Min Draft	T_{min}	12	11.9	11	11.28	m
Max Draft	T_{max}	32	31.6	25	26.4	m
Depth	D	49.5	49.5	42	39	m
Crane Capacity	C_{cap}	2x10,000	2x7,100	2,721 + 3,628	2x1,800	T
Transit Speed	V_{tr}	10	7	5	8	Kts
Thrusters	T	8x5.5	6x5.5	7x3.5	6x3.8	MW
Powertrain	P_E	12x8	6x4.9, 4x4.5, 2x5.5	N/A	8x3.86	MW
Total Power	P_T	96	58.4	N/A	30.88	MW
Accommodation	N_{per}	400	736	394	618	-

Load Distribution

Taking information from the power requirements of an existing SSCV (Hagen, 2021), the power ranges were extrapolated to each of the four vessels based on the information in Table 2 on each vessel. These estimated power requirements were split over the three main consumers: the thrusters, cranes, and hotel load, and are presented in Table 3.

Table 3: Estimated power ranges for each vessel

	Hotel Load [MW]				Thruster Load [MW]				Crane Load [MW]			
	Vessel											
Vessel	A	B	C	D	A	B	C	D	A	B	C	D
Idle	4-5	6-7	4-5	5-6	0.15-0.3	0.15-0.3	0.15-0.3	0.15-0.3	0-3	0-2	0-1	0-1
Sailing	6-7	9-10	6-7	8-9	29-31	22-23	16-17	15-16	0	0	0	0
Working	1-4	1-6	1-4	1-5	5-22	4-16	3-12	2-12	2-40	2-15	1-4	1-3

Using this information and the distribution of time spent in working, sailing and idle mode, the following load profiles were created shown in Figure 9. Each vessel was given the same mission time of 12 weeks and the loads were split between each main consumer; cranes, thrusters, and hotel load. From this split, a total power profile was created by summing the load requirements of each consumer. The total power consumption for each vessel was determined as the average over the 10,000 load profile simulations run.

Through further analysis of the range of load profile simulations of each vessel, the general split between iron powder and MDO power can be shown in the form of a percentage range of the total power requirement of the vessel. These values are shown in Table 4 for all four vessels.

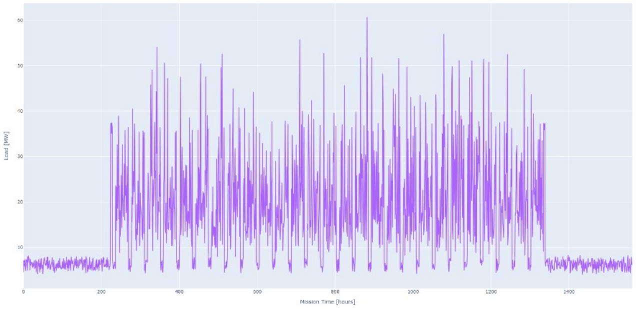

Figure 9a: Vessel A

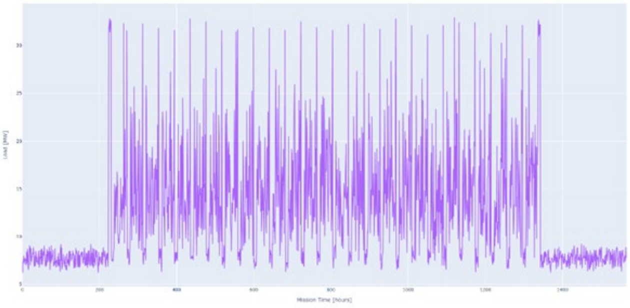

Figure 9b: Vessel B

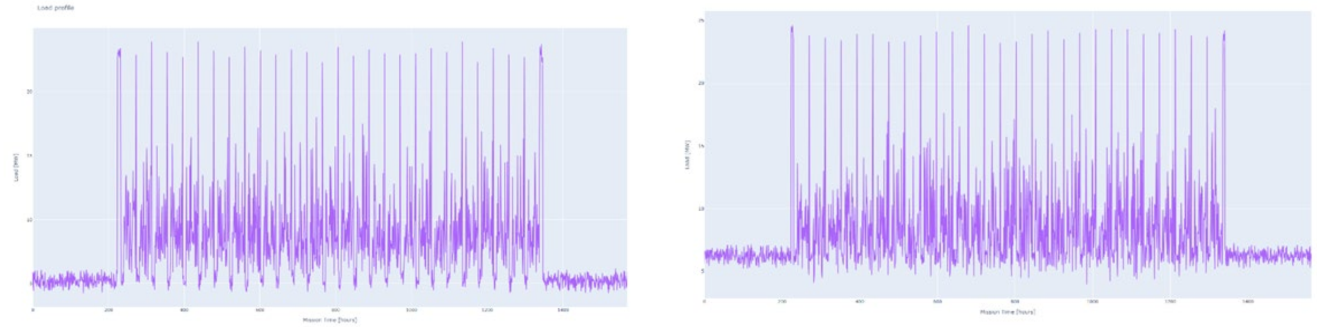

Figure 9c: Vessel C **Figure 9d: Vessel D**

Figure 9: The power profile of each vessel as the total load required

Table 4: Range of percentage total power demand covered by base and variable load.

	Base Load % of Total Demand	Variable Load % of Total Demand
Vessel A	18-45	55-82
Vessel B	31-63	37-69
Vessel C	41-67	33-59
Vessel D	45-73	27-55

Dimensions and Weights

The dimensions and weights were categorized into the engine room weights, bunker weights, and ship element weights.

Engine Rooms

One of the four engine rooms on each vessel will be fitted with the iron powder setup. This engine room will contain the turbines, boiler, and the electrical motor. The dimensions of the engine room are therefore determined by the dimensions of the turbines, boiler and electrical motor combined. A minimum additional margin 10% of length, breadth and height is added for other components as well as to give space for engineers. The length, breadth, height, and the total mass of each engine room is listed in Table 5.

Table 5: Main dimensions for each iron powder engine room

	Length [m]	Breadth [m]	Height [m]	Total Mass [t]
Vessel A	14	6	7	572
Vessel B	16	10	7	734
Vessel C	14	6	7	572
Vessel D	15	9	7	662

The breadth and total mass are double the amount needed for one UST setup as the engine room will need to fit two setups to ensure the strict redundancy criteria of semi-submersible crane vessels are fulfilled.

The diesel generator engine rooms are determined by the size and number of generator sets assigned to each vessel. Three of the four engine rooms to be placed on the vessels will be fitted with diesel generators. As with the iron powder engine room, a margin of at least 10% extra length, breadth and height are added for the remaining smaller components as well as room for engineers. The length, breadth, height and total mass of each engine room is listed in Table 6.

Table 6: Main dimensions for each diesel-powered engine room.

	Length [m]	Breadth [m]	Height [m]	Total Mass [t]
Vessel A	13.5	15	5	616
Vessel B	12	10	5	363
Vessel C	11	9	5	228
Vessel D	11	10.5	5	327

The mass and breadth of Vessel A are multiplied by four as this is the number of engines to be fitted in one engine room. The mass and breadth of the remaining vessels is multiplied by three as these engine rooms are fitted with one less generator set each.

Bunker

The design of the silos is dependent mainly on the dimensions of the vessels. These silos will be placed in the pillars of the main structures of each vessel and each vessel has different sized pillars. The height of the pillars is the main factor in determining the dimensions. The number of silos is taken as the number of silos needed to carry the required bunker including the bunker margin plus the additional 4 empty silos required for initial oxide deposit. The total number of silos must be an even number to allow for even distribution among the pillars on each side of the vessel. The main dimensions and volume of one silo as well as the number of silos required and total iron powder bunker mass for each vessel are listed in Table 7.

Table 7: Main dimensions for the silos on each vessel.

	Total Height [m]	Diameter [m]	Number of Silos	Total Mass [t]
Vessel A	21.6	3.93	34	16600
Vessel B	21.5	3.91	46	23200
Vessel C	20.7	3.76	38	16600
Vessel D	18	3.27	66	19900

The bunker level is determined based off of the specific fuel consumption of the chosen generator sets. The bunker will be placed in the remaining available area in the pillars. The total MDO bunker level required for each vessel as well as its mass are listed in Table 8.

Table 8: Required weight and volume of the MDO bunker on each vessel.

	Bunker Mass [t]	Bunker Volume [m^3]
Vessel A	5030	5650
Vessel B	2610	2930
Vessel C	2140	2400
Vessel D	1930	2170

Ship Elements

The ship structural elements contain the remaining significant elements of the vessel who have a significant mass and therefore significant impact on the ship stability calculations. These include the crane, ballast, thrusters, and structural weight of the vessel. The total mass of each of these elements are listed in Table 9.

Table 9: Mass estimations of key ship elements.

	Crane [t]	Ballast [t]	Thruster [t]	Structural [t]
Vessel A	6850	113000	512	83500
Vessel B	5980	120000	384	66100
Vessel C	5160	30000	329	44100
Vessel D	2240	21000	282	31100

These values alongside the other estimated masses for each engine room will be used to calculate an initial static stability to evaluate the feasibility of a hybrid iron powder configuration and to visualize how this would best fit.

Feasibility

The feasibility of an iron powder hybrid configuration on a SSCV can be measured in many ways. In this case, due to a limited amount of information about these vessels and their dynamic seakeeping behavior, the choice was made to keep to a base feasibility determination. This means that the main static stability criteria will be evaluated such as the draft, transverse stability, and longitudinal stability. Calculations will be made for each of these categories and the results will be compared to either the original powertrain setup of the vessel or the Det Norkse Veritas (DNV) classification bureau stability requirements for SSCVs [Part 5: Ship Types, Chapter 10: Vessels for special operations, 2021].

Draft

The draft is one of a SSCV's key feature in that it should be able to increase and decrease its draft according to its operating mode. A significant change in the total mass of the bunker will increase the draft of the vessel. By comparing the hybrid bunker mass level with a marine diesel fuel only mass level, the change in draft due to the increased bunker mass can be calculated. This is most important in the transit mode as ballast reduction is not possible in this mode meaning the draft increase cannot be simply compensated. The resulting draft increase is listed in Table 10.

Table 10: Draft increase due to increased bunker mass.

	Increase in Bunker Mass [t]	Increase in Draft [m]
Vessel A	15200	1.16
Vessel B	21200	2.22
Vessel C	15200	6.02
Vessel D	18300	8.06

The results are quite varied for each vessel as could be expected. This change in draft depends on both the mass increase as well as the ship's waterline area. The draft change was measured at minimum or transit draft as this is where the change in draft has the most impact. The maximum draft level can be much more easily maintained by adjusting the level of ballast. This is not the case for transit draft as there is no ballast to adjust. Of the four vessels, the only vessel indicating that the increased bunker will not necessarily require a redesign of the pillars and pontoons is Vessel A. The draft increase on Vessel C and Vessel D are mainly due to their small waterline area over all their pillars especially when compared to Vessel B and Vessel A. The substantial draft increase on these two vessels points to a need for a pontoon and pillar redesign if it is to accommodate the expected iron powder bunker level. While the increase in draft is not as severe as for Vessel C and Vessel D, Vessel B will likely also require a redesign of the vessel to a lesser extent. This is due to the draft now being above the pontoon height.

Transverse Stability

The metacentric height (GM) can be calculated for each vessel. Due to the limited information available for these vessels, only a base static transverse stability calculation can be made from which any reasonable conclusions can be drawn. Table 11 lists the KB, KG, BM, and GM values for each vessel in a fully loaded condition at the maximum draft.

Table 11: Transverse stability values for each vessel

	KB [m]	KG [m]	BM [m]	GM [m]
Vessel A	11.4	35.7	28	3.62
Vessel B	12.2	30.9	25.1	6.35
Vessel C	9.05	30.8	26.8	5.11
Vessel D	7.61	26.7	19.6	0.52

According to the classification rules by DNV [Part 5: Ship Types, Chapter 10: Vessels for special operations, 2021], the minimum allowed GM of 0.3m at maximum operating draft has been met by all four vessels. Vessels A, B and C even have a wide margin of safety above the minimum required GM value. This indicates that it may be possible for the iron powder hybrid configuration to be installed without negatively impacting the transverse static stability of the vessel. It must be considered that these GM values are determined based off rough estimations and may in fact not reflect reality. There are certain extra mass elements aboard the vessel that may not be as large as the ones considered but may add up alter the estimated KG value. This is why the margin of a few meters regarding the GM values of Vessels A, B and C are more promising than the 0.2m margin for Vessel D. If these estimations were to be altered and the GM were to lower, the chances of Vessels A, B and C still fulfilling the initial transverse stability criteria are far higher than that of Vessel D. On top of this, Vessel D has a righting arm that reaches only a maximum of 0.05m at 15 degrees of heel, which is only 50% of the minimum requirement stated by DNV. This means that Vessel D does not meet the stability requirements and cannot be deemed feasible with an iron powder setup.

Longitudinal Stability

The longitudinal stability of each vessel is largely determined by the trimming moment created by the vessel. The trimming moment is dependent on the longitudinal center of gravity of each component/element placed on the vessel. Each vessel has its own longitudinal center of buoyancy and its own structural longitudinal center of gravity. These elements cannot be altered same as the longitudinal center of gravity of the cranes, thrusters, and ballast. The trimming moment is minimized by keeping the total longitudinal center of gravity of each vessel within one meter of the longitudinal center of buoyancy of each vessel. The longitudinal center of gravity of the engine rooms and bunker tanks/silos have the largest impact on the longitudinal center of gravity of the vessel. Table 12 shows the needed longitudinal centers of gravity of the engine rooms, fuel bunker and iron powder bunker to ensure this minimal trimming moment.

Table 12: Longitudinal centers of gravity for each element that can be placed for each vessel.

	LCG Engine Rooms [m]	LCG MFO [m]	LCG Iron Powder [m]
Vessel A	75	156	90
Vessel B	70	163	80
Vessel C	50	100	60

These conditions alongside the vertical component placement conditions determined for the transverse stability can be used to create a general arrangement for Vessels A, B and C shown in figures 13, 14, and 15.

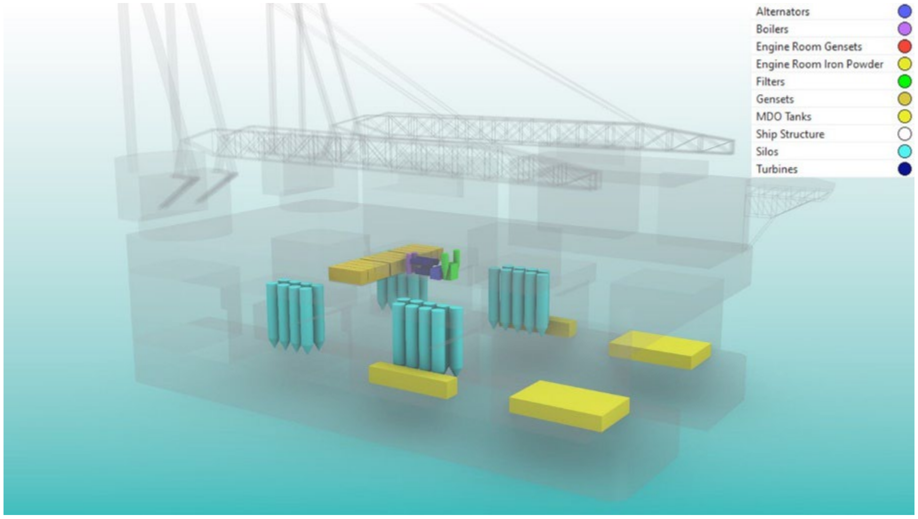

Figure 10a: Vessel A

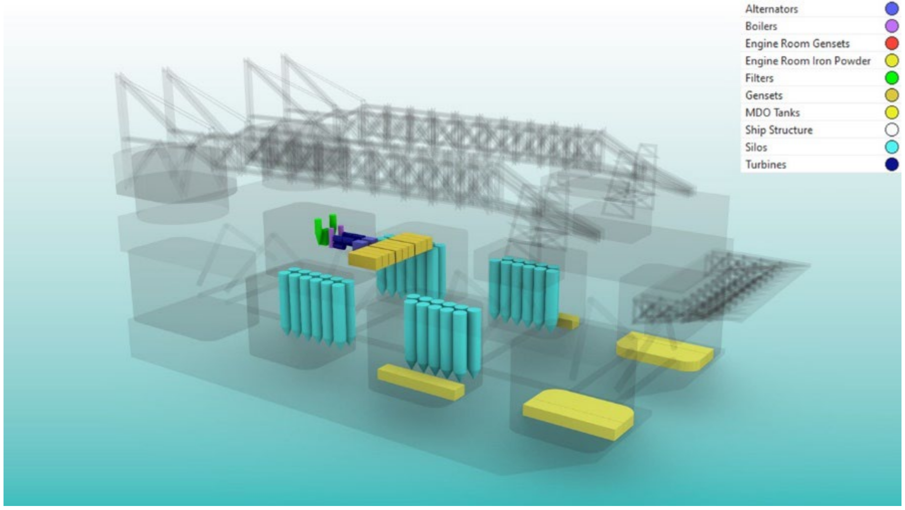

Figure 10b: Vessel B

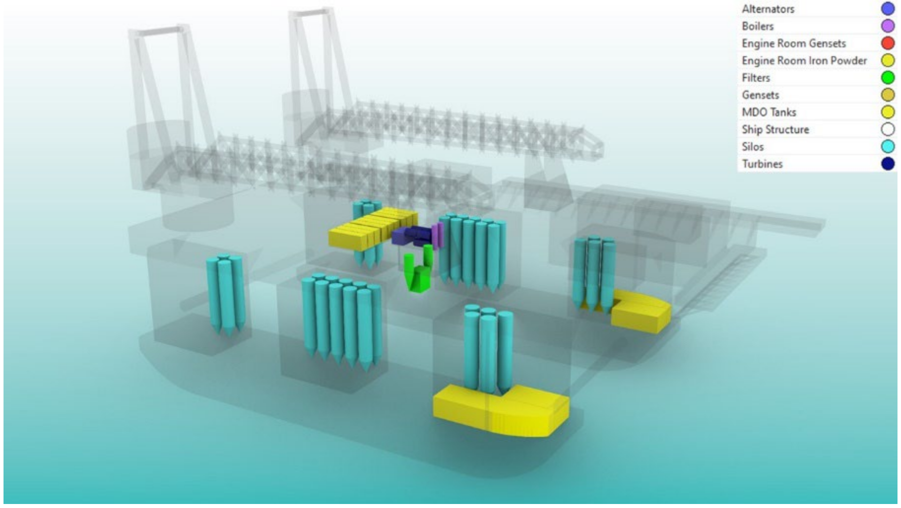

Figure 10c: Vessel C

Figure 10: Perspective view of each vessel’s hybrid general arrangement

Emissions

The environmental impact of installing a hybrid iron powder powertrain on these SSCVs can be determined through an emissions comparison. The distribution of base versus variable power varies significantly for each vessel and is in this case taken as a range of output values as opposed to a singular value. This is due to the high variance in the variable load as it is simulated using probabilities of peak loads occurring. Table 13 shows the total calculated emissions output comparison for both carbon dioxide as well as nitrous oxide.

Table 13: Total CO2 and NOx output comparison for single year of 3 missions.

	CO_2 Total Output [kg/kWh]		NO_x Total Output [kg/kWh]	
Vessel	Hybrid	Original	Hybrid	Original
Vessel A	44100	66900	175	226
Vessel B	27900	46800	93	162
Vessel C	18300	31500	61	116

This comparison is based off of the assumption that three 12-week missions will be completed in a year to leave over 10 weeks for non-mission transit and potential maintenance and repair. The total CO_2 reduction is significant reaching around 20,000 tons of CO_2 a year for each vessel. The total NO_x reduction is not as large as the total output values are far lower than the CO_2 output. A reduction of around 50 tons of NO_x yearly can still be achieved which is in the case of Vessel C is around half of its total expected NO_x output.

CONCLUSION

Based on the results, certain feasibility evaluations can be made. First, it was determined that there is an optimal iron powder setup that can feasibly be placed aboard a marine service vessel. Furthermore, it was determined that a SSCV would be the most optimal vessel on which to place this iron powder setup. From this literature level research, the importance of implementing a hybrid setup was made clear. Through application of a model and simulation of said model on a case study of a set of SSCVs, the level of base feasibility can be determined for each vessel as shown in Table 14. In this table, the impact of the hybrid setup on the draft, stability and emissions of each vessel is compared. In the case of the draft, '1' indicates the lowest increase in vessel draft due to the increased mass while in the case of the stability '1' indicates the highest level of metacentric height and initial righting arm. In case of the emissions, '1' indicates the largest estimated decrease in CO_2 and NO_x emissions.

Table 14: Short comparison table ranking the feasibility of each case study vessel.

	Draft	Stability	Emissions
Vessel A	1	3	2
Vessel B	2	1	1
Vessel C	3	2	3
Vessel D	4	4	N/A

Vessel A claims the second highest feasibility level as it is least affected by the mass increase in terms of both draft and stability while still seeing significant emissions reductions. Vessel B has highest feasibility with only a minor concern regarding draft increase and satisfying the initial stability estimations whilst having an estimated highest emissions decrease. Vessel C is still considered base level feasible despite its issues with increased draft as its initial stability levels are more than sufficient. Vessel D is considered not feasible at a base level due to its lack of stability coupled with a high draft increase at a higher mass making an emissions comparison unnecessary. This leads to the main conclusion that the larger SSCVs are generally considered to be more feasible candidates for iron powder hybrid powertrain installation as they generally shaped to provide a larger water-plane area and equipped with a far larger deadweight carrying capacity. The key points of concern when trying to implement an iron powder powertrain on a SSCV include:

- Hybridization will be required due to the high variability in SSCV load profiles as well as increased mass of the iron powder bunker
- Balance needs to be found regarding the amount of power delivered by the iron powder powertrain (emissions saved) and the impact of its bunker on the vessel's stability and operability
- Larger SSCVs provide more sizing possibilities with comparatively lower vessel stability impact

FUTURE WORK

As the main concerns regarding iron powder implementation on marine vessels lies largely in the technical feasibility study, it was this area that was focused on most. There was not sufficient time to conduct a proper cost estimation for the vessels. This would provide interesting context to the technical feasibility as the initial costs of the setup can be compared to conventional energy sources as well as the yearly bunker costs. This is especially interesting considering the iron powder cycle and the possibility of becoming a fully cyclical energy source meaning only one initial bunker cost is made for the lifetime of the powertrain. Redesign costs and port infrastructure costs can also be considered in this economic feasibility analysis to provide a full picture of the potential of iron powder as an energy source.

This research was done as an in-house project meaning that there was no continuous contact with companies within this field during the research. This meant that the information provided about certain iron powder powertrain components and the SSCVs was generally quite limited. The key information used as the main inputs of the method in were taken from official vessel brochures and reports that highlight the operating profile of select SSCVs. This information was then taken and extrapolated as carefully as possible to be applied to a wider range of SSCVs with the knowledge that the results would not be a complete reflection of reality. While these results were considered sufficient for evaluating a base level of feasibility for each vessel, more base information would allow for a more in-depth analysis of the impact of a hybrid iron powder setup. This includes a look at the impact of crane operations on the stability with a hybrid setup as well as a potential damage stability simulation to provide a more rigorous analysis of the stability of the vessel. More information regarding the performance and output of the existing SSCVs would contextualize the emissions results outside simply the estimated original setup for each vessel. With continuous contact with experts in these fields, it is likely that even more measures of feasibility can be considered to go beyond simply a base level feasibility.

CONTRIBUTION STATEMENT

Erik Scherpenhuijsen Rom: Conceptualization; Investigation, Methodology, Software, Writing – Original Draft, Review and Editing. **Austin Kana:** Conceptualization; Interpretation of data; Supervision; Writing – Review and Editing.

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