YRKESHÖGSKOLAN NOVIA

Creation of a Prototype Savings & CO2 Reduction Calculation Tool with Node-RED

With an Introduction to Marine Power Systems

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DEGREE THESIS

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Abstract

Emissions from the shipping industry make up roughly 3 % of the world's greenhouse gas emissions, and industry leaders are seeking ways to reduce this. One way of reducing these is by installing a shaft generator system. Assessing the financial viability of implementing these systems requires calculation tools. These tools are often very complicated and require highly technical information, which might not be available at an early sales stage. A simpler method of calculating a reference value was needed.

The thesis introduced marine power systems, their parts, and how they work, and then focused on the process of creating a prototype for calculating emissions and fuel cost savings. This tool was constructed using Node-RED, which was selected for its beginner-friendly approach to creating functions and user interfaces.

As a result, a prototype was built, capable of calculating fuel consumption, CO2 emissions, CII, and savings. As of now, the prototype is fully functional but lacks a fuel matrix for 4-stroke engines. This means the fuel consumption calculations will not be fully accurate for the auxiliary generators. However, this is mitigated by the fact that auxiliary generators usually run at low load, resulting in suboptimal fuel consumption, to be able to cope with sudden load changes. The prototype will be further developed in the future, and the tool can act as a reference for programming a new tool in a more sophisticated language.

Language: English
Key Words: Shaft generator, Frequency converter, Node-RED, Energy Technology, CII

EXAMENSARBETE

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Titel: Utveckling av ett prototypverktyg för beräkning av CO2-reduktion och kostnadsbesparingar i Node-RED

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Abstrakt

Utsläpp från sjöfartsindustrin utgör ungefär 3 % av världens växthusgasutsläpp, och branschledarna letar ständigt efter ekonomiskt genomförbara sätt att minska dessa. Ett sätt att minska utsläppen är installationen av ett axelgeneratorssystem. Att bedöma den inbesparningarna och utsläppningsminskningarna man får av ett axelgeneratorsystem kräver beräkningsverktyg. Dessa verktyg är ofta mycket komplicerade och kräver omfattande teknisk information som kanske inte är tillgänglig i ett tidigt försäljningsstadium. En enklare metod för att beräkna ett referensvärde behövdes.

Examensarbetet introducerade marina kraftsystem, deras komponenter och hur de fungerar, och fokuserar sedan på processen hur prototypen för att beräkna utsläpp och bränslekostnadsbesparingar byggdes. Detta verktyg programmerades i Node-RED, som valdes för dess nybörjarvänliga metoder att skapa funktioner och användargränssnitt.

Resultatet är en prototyp som kan beräkna bränsleförbrukning, koldioxidutsläpp, CII och förbrukningsbesparingar. För närvarande är prototypen fullt fungerande, men saknar en bränslematris för hjälpgeneratorn. Detta innebär att resultaten inte är helt korrekta för hjälpgeneratorerna. Dock balanseras detta av det faktum att hjälpgeneratorer vanligtvis körs på låg belastning, vilket resulterar i suboptimal bränsleförbrukning för att kunna hantera plötsliga belastningsförändringar. I framtiden kommer prototypen vidareutvecklas och kan användas som referens vid programmering av ett verktyg i ett mer sofistikerat språk.

Språk: Engelska
Nyckelord: axelgenerator, frekvensomvandlare, Node- RED, CII

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Nimike: Prototyyppisen säästö- ja CO2-vähennyslaskurin luominen Node-RED:llä

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Merenkulkualan päästöt muodostavat noin 3 % maailman kasvihuonekaasupäästöistä, ja alan johtavat yritykset etsivät jatkuvasti keinoja niiden vähentämiseksi. Yksi tapa vähentää päästöjä on akseligeneraattorijärjestelmän asentaminen. Näiden järjestelmien taloudellisen kannattavuuden arvioimiseksi tarvitaan laskentatyökaluja. Nämä työkalut ovat usein erittäin monimutkaisia ja vaativat paljon teknistä tietoa, joka ei ehkä ole saatavilla varhaisessa myyntivaiheessa. Yksinkertaisempi menetelmä referenssiarvon laskemiseksi tarvitaan.

Opinnäytetyössä esitellään merivoimatekniikan järjestelmät, niiden osat ja toiminta, ja keskityttiin sitten prototyypin luomisprosessiin päästöjen ja polttoainekustannusten säästöjen laskemiseksi. Tämä työkalu rakennettiin käyttäen Node-RED-ohjelmaa, joka valittiin sen aloittelijaystävällisten menetelmien vuoksi toimintojen ja käyttöliittymän luomiseen.

Tuloksena syntyi prototyyppi, joka pystyy laskemaan polttoaineenkulutuksen, CO2-päästöt, CII-arvon ja säästöt. Tällä hetkellä prototyyppi on täysin toimiva, mutta siitä puuttuu polttoainematriisi 4-tahtimoottoria varten. Tämä tarkoittaa, että tulokset eivät ole täysin tarkkoja apugeneraattoreiden osalta. Tätä tasapainottaa kuitenkin se, että apugeneraattorit toimivat yleensä pienellä kuormituksella, mikä johtaa epäoptimaaliseen polttoaineen kulutukseen, jotta ne selviytyisivät äkillisistä kuormituksen muutoksista. Prototyyppiä kehitetään edelleen tulevaisuudessa, ja työkalua voidaan käyttää viitteenä ohjelmoitaessa uutta työkalua kehittyneemmällä kielellä.

Kieli: englanti
Avainsanat: akseligeneraattori, merivoimateknikka, Node-RED, taajuusmuuttaja, CII

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1 Introduction

In 2022, the global shipping industry made up roughly 3% of the world's greenhouse gas emissions. The shipping industry is searching for ways to reduce this by various means, be it through the adaption of carbon-neutral fuels, optimisation of propulsion, or effectivization of the ship’s power system.

One way of optimizing the ship's power system is installing a shaft generator. The shaft generator uses the superior fuel efficiency of the main engine to produce electrical power. This reduces the fuel consumption of the vessel, which in turn reduces the greenhouse gases emitted. Reducing the fuel consumption of the vessel is beneficial both for the environment and for the charterer, as fuel consumption makes up a vast majority of the vessel's operating expenditures.

This thesis was made on behalf of WE Tech Solutions, to make a tool which can be used to provide the potential customer with a savings figure. The company already has simulation software that can give these values, but the software is complicated and uses technical information that might not be available at a sales stage. Thus, the idea to make a simpler tool was born.

To help the reader understand the reason for installing a shaft generator system, this thesis will also act as an introduction to marine power systems, their components, and their functions.

1.1 Introduction to the company

WE Tech Solutions is a Finnish company, founded in 2009, that specializes in supplying solutions based on variable frequency drives, permanent magnet generators, DC-link power distribution and energy management systems. The company is situated in Vasa and has over 50 employees.

WE Tech's primary solution consists of attaching a permanent magnet generator to the ship's propeller shaft to generate power. To allow the generator to operate at a wider rpm range, it is connected to the main switchboard via a set of frequency drives and filters, called the WE Drive.

The purpose of the WE Drive is to stabilize the varying voltage and frequency from the generator into a set voltage and frequency, as the output varies significantly with the rotations of the propeller shaft.

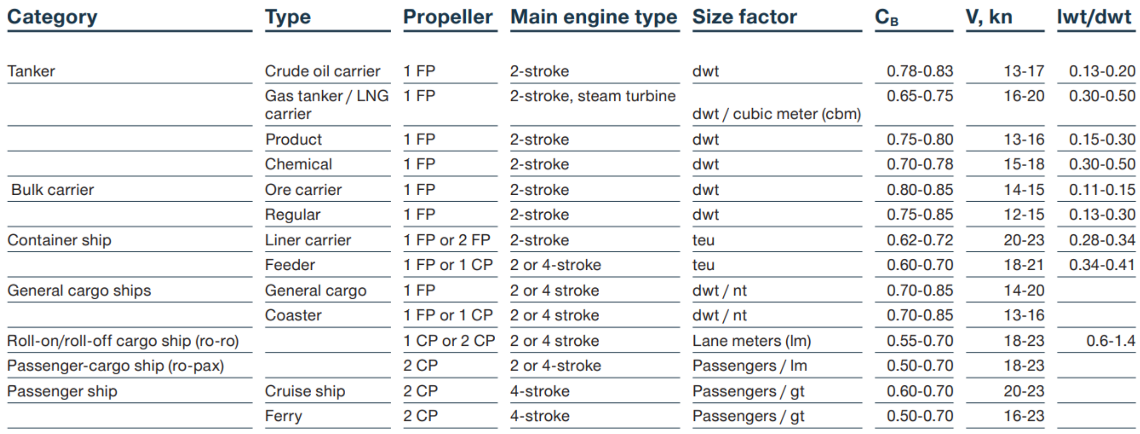
It does this by first sending the power through a rectifier, which turns the AC power from the generator into DC, with a set voltage. It is then sent into an inverter where it is converted back into AC power with a set frequency and voltage and synchronized with the main switchboard. This stabilization ensures a consistent and reliable power supply to the ship's electrical systems.

Additionally, the WE Drive enables heavier consumers, such as electrical propulsion motors and pumps, to be connected directly to the DC link via inverters. This enables the soft starting of motors, better power management, and a more compact main switchboard. The DC link can also be used to integrate battery packs into the ship's electrical system, where they can both be charged and used as a power source. This power can then be fed into the main switchboard, heavier consumers or in some cases, back into the shaft generator to reduce load on the main engine.

2 Marine Propulsion

2.1 Main Engines

The Main engine lies at the centre of the ship's power system. In most cases, the main engine propels the ship forward by driving the propeller shaft. Main engines are usually categorized into three different speed categories, low- or slow-speed, medium-speed, and high-speed. These ranges are loosely defined, and they vary from manufacturer to manufacturer.



Category	Type	Propeller	Main engine type	Size factor	C_B	V, kn	lwt/dwt
Tanker	Crude oil carrier	1 FP	2-stroke	dwt	0.78-0.83	13-17	0.13-0.20
	Gas tanker / LNG carrier	1 FP	2-stroke, steam turbine	dwt / cubic meter (cbm)	0.65-0.75	16-20	0.30-0.50
	Product	1 FP	2-stroke	dwt	0.75-0.80	13-16	0.15-0.30
	Chemical	1 FP	2-stroke	dwt	0.70-0.78	15-18	0.30-0.50
Bulk carrier	Ore carrier	1 FP	2-stroke	dwt	0.80-0.85	14-15	0.11-0.15
	Regular	1 FP	2-stroke	dwt	0.75-0.85	12-15	0.13-0.30
Container ship	Liner carrier	1 FP or 2 FP	2-stroke	teu	0.62-0.72	20-23	0.28-0.34
	Feeder	1 FP or 1 CP	2 or 4-stroke	teu	0.60-0.70	18-21	0.34-0.41
General cargo ships	General cargo	1 FP	2 or 4 stroke	dwt / nt	0.70-0.85	14-20	
	Coaster	1 FP or 1 CP	2 or 4 stroke	dwt / nt	0.70-0.85	13-16	
Roll-on/roll-off cargo ship (ro-ro)		1 CP or 2 CP	2 or 4 stroke	Lane meters (lm)	0.55-0.70	18-23	0.6-1.4
Passenger-cargo ship (ro-pax)		2 CP	2 or 4-stroke	Passengers / lm	0.50-0.70	18-23	
Passenger ship	Cruise ship	2 CP	4-stroke	Passengers / gt	0.60-0.70	20-23	
	Ferry	2 CP	4-stroke	Passengers / gt	0.50-0.70	16-23	

Figure 1: Typical characteristics of different ship types (MAN Energy Solutions, 2023)

2.1.1 2-stroke Engines

Large marine 2-stroke engines are usually low-speed engines, which in a marine setting usually refers to anything under 250 or 300 rpm. However, in practice, they rarely exceed speeds of 120 rpm. The slow speed allows the propeller shaft to be connected directly to the crankshaft of the engine, as propellers for large vessels are generally more efficient at this speed, due to various hydrodynamic and design factors.

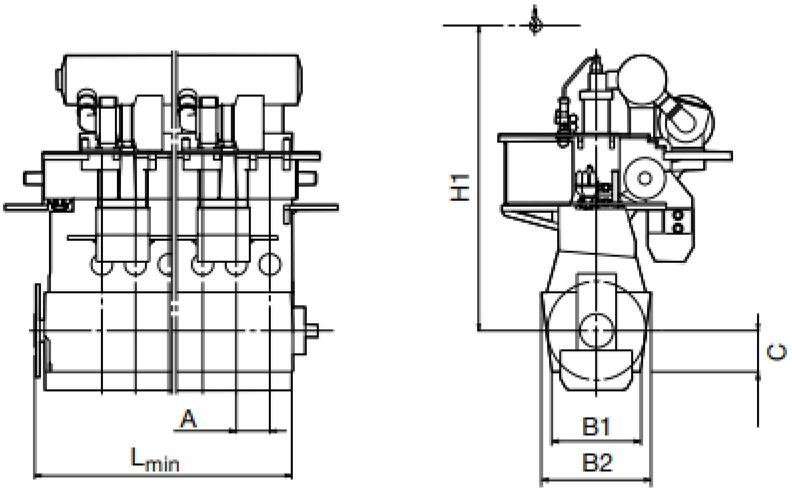


Figure 2: Marine 2-stroke engine drawing (MAN Energy Solutions, 2024)

All the largest engines are 2-stroke low-speed diesel engines. As a comparison, the most powerful 4-stroke engine, the Wärtsilä 18V50SG produced 18 320 kW at 500 rpm, with an efficiency of about 46%, or 183 g/kWh (Sutkowski, 2011). The largest 2-stroke engine ever produced, the Wärtsilä-Sulzer RTA96-C, produced 80 080 kW at 102 rpm, with a break specific fuel consumption, or BSFC, of 171 g/kWh at full power (Demmerle, 1997).

This highlights one of the main benefits of the slow-speed 2-stroke engine, fuel economy. Although, this has less to do with it being a 2-stroke engine and more with it being a slow-speed engine. This comes down to several factors, such as longer stroke, which allows for a more complete expansion of gases, higher compression ratios, which allow more heat to be extracted from the fuel, and improved combustion control from the relatively low speed of the process (Ashok, 2022).

The reason, all large slow-speed engines are 2-strokes, comes down to the fact that the 2-stroke engine produces power every crankshaft rotation, while the 4-stroke produces power every other crankshaft rotation. This means that in theory, the 2-stroke can produce twice as much power and torque, compared to a 4-stroke.

In practice, however, they usually achieve half of that, but it still makes a huge difference in the power-to-weight ratio. The lighter, and smaller engine allows the ship to load more cargo. The 2-stroke engine being able to generate higher torque at low rpms is also especially helpful for ensuring efficient propulsion of the vessel.

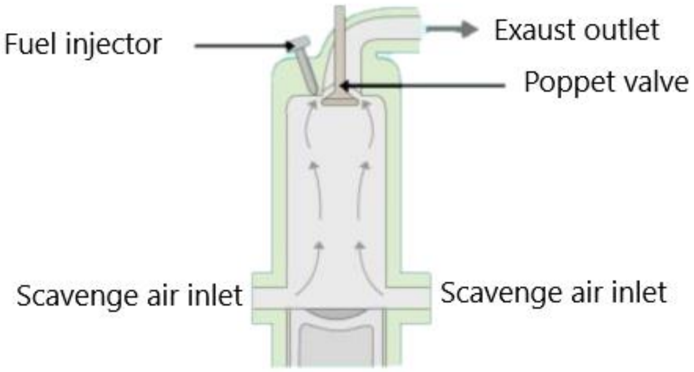


Figure 3: Diagram of a uniflow scavenging engine (Metta Naveen Kumar, 2020)

Another advantage of using 2-stroke engines is that the engines have significantly fewer moving parts, such as intake valves, compared to the 4-stroke engine. This means that the 2-stroke engine has less chance of failure and requires less maintenance.

The disadvantage with 2-stroke engines mainly comes down to them being more polluting, as the combustion often leaves more unburnt hydrocarbons and particulates in the exhaust gas. Another factor is, the high compression, as stated earlier, does lead to increased thermal efficiency, but this comes at the cost of increased NOx emissions (Ashok, 2022). There is also the matter of the 2-stroke burning more lubrication oil compared to the 4-stroke.

2.1.2 4-stroke Engines

Large 4-stroke engines usually operate at medium speed, which in marine terms is generally between 250-1200, in practice however, this rpm is rarely below 500 rpm.

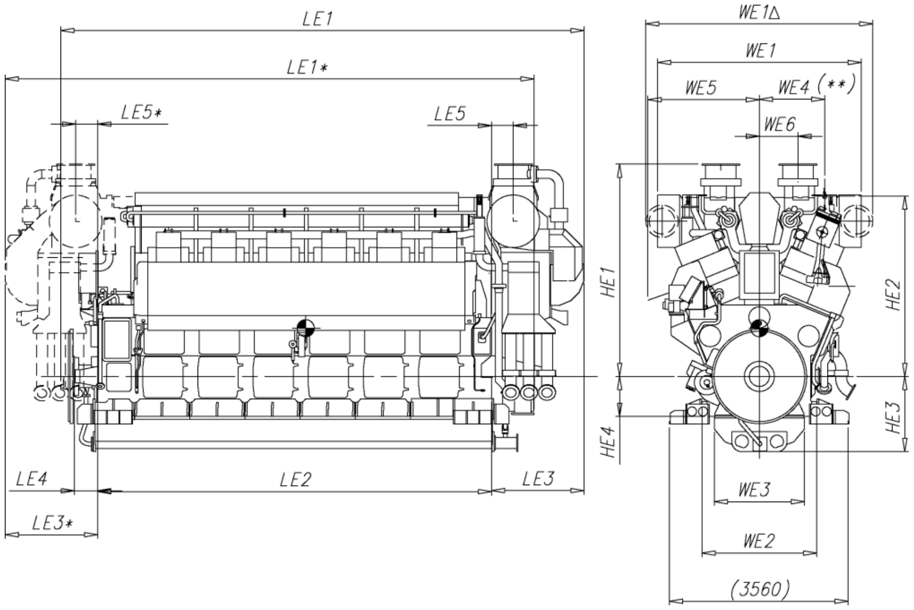
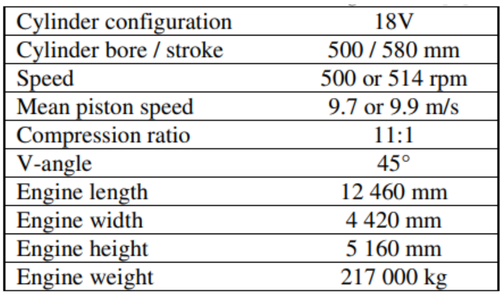


Figure 4: Wärtsilä 50 drawing (Wärtsilä Finland OY, 2016)

Due to marine 4-stroke engines usually operating at much higher rpm than 2-strokes, they can use a smaller displacement volume. To shrink the engine's footprint even further, they often utilize the V-layout, as seen in Figure 4. This makes the medium-speed 4-stroke engine much more compact compared to a slow-speed 2-stroke of similar power output. This comes with the downside of having to install a step-down gearbox for the propeller, to achieve optimal propulsion efficiency, this of course leads to some gearbox losses as well. Due to the smaller size and weight of the engine and its parts, the construction price will generally be less than that of the slow-speed two-stroke engine.

As an example, the engine mentioned in the previous chapter, Wartsila 18V50SG, has a total displacement of 2050 l, while a slow-speed 2-stroke engine of similar power output, MAN B&W S60ME-C10.7, has a total displacement of 5429 l (MAN Energy Solutions, 2024).



Cylinder configuration	18V
Cylinder bore / stroke	500 / 580 mm
Speed	500 or 514 rpm
Mean piston speed	9.7 or 9.9 m/s
Compression ratio	11:1
V-angle	45°
Engine length	12 460 mm
Engine width	4 420 mm
Engine height	5 160 mm
Engine weight	217 000 kg

Figure 5:Wärtsilä 18V50SG Specifications (Sutkowski, 2011)

Due to the 2-stroke having four times longer stroke, this difference will be in engine height and width. The 4-stroke engine in this example is 4 meters longer, but if size is a constraint, length is much more manageable than height. The weight will also be half compared to the slow-speed 2-stroke engine.

The introduction of new types of fuel systems that provide fuel injection under high pressures, the optimization of mixing processes in the combustion chambers, and new approaches to organizing the working process in medium and high-speed engines make them more environmentally friendly, especially in terms of nitrogen oxides NOx in the exhaust gases (Bilousov et al., 2020). This factor makes these engines attractive for vessels working in waters with restrictions on emissions of harmful substances, such as ferries and cruise ships.

2.1.3 Propulsion with Electricity

Main engines are generally used for propulsion, but electrical motors can also serve this function. There are three main ways of utilizing electricity for propulsion, diesel-electric, electrical, and hybrid propulsion.

Diesel-electric propulsion is when multiple large generators generate the electricity needed to power the electrical propulsion motors. Diesel-electric propulsion is commonly used in cruise ships, ferries, and utility vessels due to its flexibility and efficiency in managing power distribution.

In electrical propulsion, the electricity for the propulsion system is instead taken from an energy storage system, such as a battery pack or a fuel cell. This has become more common in vessels operating over short distances, such as ferries.

Hybrid propulsion is when these two systems are combined. This allows the ship to turn off its generators when operating near e.g., harbours, reducing its emissions significantly. The battery pack can then be recharged at port and be used to propel the ship from the harbour to more open waters, where the generators are activated again.

These propulsion systems are rarely used in large cargo vessels but are common in cruise ships, ferries, and utility vessels. The reason this is not used in larger oceangoing vessels is due to the high cost, the relatively low power density of batteries, combined with the lower fuel efficiency of the generators, compared to a large two-stroke engine.

2.2 Marine Fuels

What fuel the ship uses makes a large impact on both emissions and operational costs. There are various types of fuels, each with different properties and impacts on the environment and expenses.

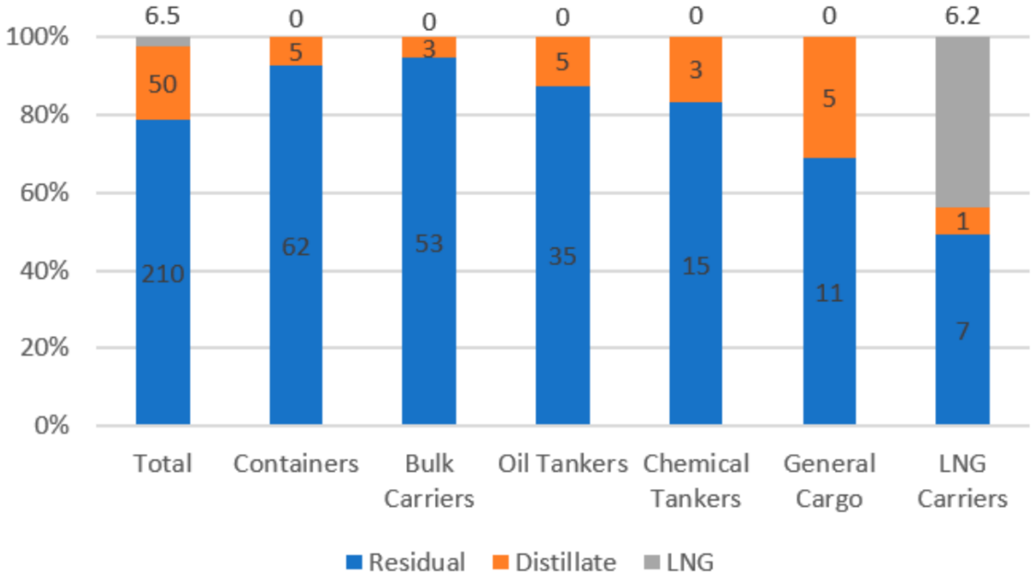


Figure 6: Fuel usage by vessel type (Czermański et al., 2021)

Residual oils, or heavy fuel oils, are the common type of marine fuel. These are the heavy, tarlike oils left over when refining crude oil into lighter fuels like diesel or petrol. Due to it being a byproduct of this process, heavy fuel oils are contaminated with higher amounts of sulphur. Due to their high viscosity, residual oils require heating before they can be used as fuel in an engine. While these oils are much cheaper than more refined fuels, such as diesel, their combustion results in more particulate matter and SOx emissions.

These are generally classified into 3 categories based on sulphur content, high-, low-, and ultra-low sulphur fuel oil. As of 2017, high sulphur has a maximal sulphur content of 3.5%, while low has a sulphur content of 1%, and ultra-low sulphur oil has a sulphur content of 0.1% (Heavy Fuel Oil (HFO) | Lubmarine TotalEnergies, 2020). While these oils are less expensive than their more refined counterparts, their combustion results in more particulate matter and soot. Sulphur oxide, or SOx, emissions are of course largely dependent on the sulphur content of the oil.

Distillates, such as marine gas oil, are the second most common type of marine fuel. These fuels produce less particulates and soot, compared to their heavy fuel oil counterparts. They still, however, produce roughly the same amount of CO2 as their residual oil counterparts.

The third most common marine fuel is liquified natural gas, or LNG. LNG is natural gas, which has been cooled down to -160 °C, where the natural gas liquifies. In its liquid state, the volume of the gas is 600 times less compared to its gaseous state at standard temperature and pressure. This fuel's carbon footprint and emissions of sulphur and nitrogen compounds are significantly better than those of marine fuels based on crude oil (Marine Fuels (Bunker Fuels), 2015).

As shown in Figure 6, this fuel type is most used in vessels transporting LNG. The reason for this is that utilizing, and storing LNG, requires a more advanced fuel system than the various oils. As LNG carriers are built to transport LNG, they already have most of the system required to utilize it as a fuel installed.

Various carbon-neutral fuels have also been looked at as a way to reduce the emissions of the shipping sector. The most likely future fuels are hydrogen and ammonia, but both of these have their issues.

Hydrogen can either be combusted, producing no CO2 emissions, or used in fuel cells to generate electricity with water as the only byproduct. Hydrogen’s primary issue is its low volumetric energy density, about half that of LNG in its liquid state. It is also very difficult to store, as hydrogen’s small molecular size, tends to make it leak easily.

Ammonia, which can also be synthesized using renewable energy, is another potential fuel due to its high energy density and carbon-free combustion. However, ammonia has its difficulties, as it poses safety risks due to its toxicity and corrosiveness. This means that it will require a much more advanced storage system compared to traditional fuels.

Both hydrogen and ammonia have been tested and proven to work as alternative fuels. However, they still require further refinement, innovation, and development of their respective supply chains before they can become economically feasible.

3 Marine Electrical Systems

The electrical system is a critical part of running a modern ship. Electricity on board a ship powers a wide array of essential systems and equipment vital for operating the vessel, such as navigation and communication.

A modern ship is essentially incapable of operating if there is not any electrical power available. Therefore, these systems are made with great care to ensure operational availability, longevity, and safety.

3.1 Auxiliary & Emergency Generators

Auxiliary generators, or gensets, are designed to supply electrical power for the ship's auxiliary systems. These systems include lighting, air conditioning, refrigeration, water desalination, and communication equipment. They also provide power for the cargo handling equipment when loading or unloading.

For this application smaller 4-stroke diesel engines generally operating above 750 rpm are used. As mentioned earlier, in Chapter 2.1.2, at that size and speed, they are more compact, efficient, and produce less pollution.

When running auxiliary generators during the operation of the ship, the load is often split between multiple gensets, even if it could be covered by one. This is called load-sharing, and it helps to manage sudden load changes and ensures redundancy in case of generator failure. This means that the generator often operates at a low load when sailing, which leads to suboptimal fuel consumption.

There are always more auxiliary generators in the ship than is needed to cover the load, for example, if a ship has two auxiliary generators running during operation, it usually also has two backup generators. This is so that, even in case of an emergency, where the two generators stop working, it can continue operating. The power generated from the generator is usually fed directly to the main switchboard, where it is distributed.

3.2 Emergency Generators

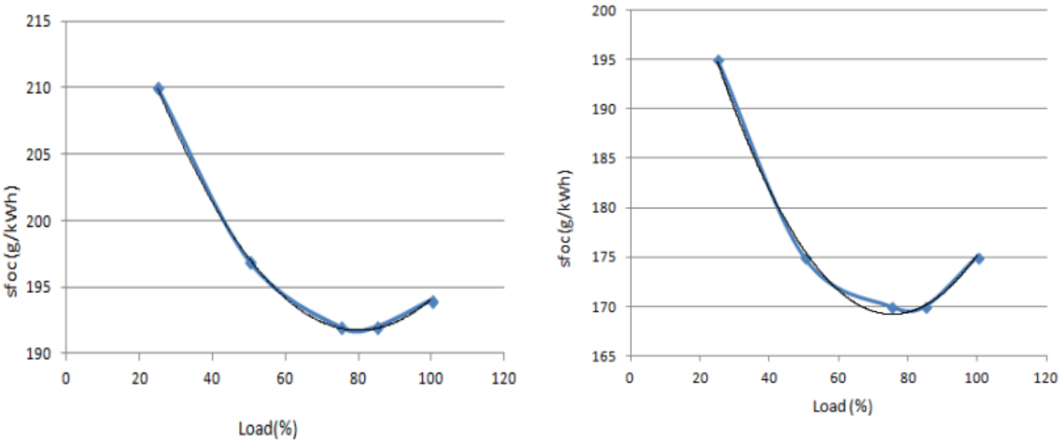
Emergency generators are essential for safety onboard ships. They provide power during unexpected emergencies or outages and ensure critical systems like emergency lighting, communication, and navigation stay operational. They are located strategically, generally above the waterline and away from potential hazards, such as fuel storages. The emergency generators are regularly maintained and started to ensure that they remain operational.

3.3 Shaft Generators

A shaft generator is a generator connected directly to the crankshaft of the main engine and using it to generate power. This mode of operation is called PTO, or Power Take Off, referring to power being taken off the main engine.

In the case of large 2-stroke engines, this is usually done by attaching the generator directly to the propeller shaft, this is called an inline shaft generator. In 4-stroke engines, they are usually connected to the gearbox which drives the propeller shaft.

Other than those, there is also the front-end mounted shaft generator, which is a shaft generator usually consisting of multiple smaller generators connected to the flywheel of the engine. This type of generator has a much smaller footprint than the other options, with the downside of needing more maintenance.



(a) (b)

Figure 7: SFOC with load for the AG (a) and the ME (b) for a passenger ship (Sarigiannidis et al., 2015)

This is done as the fuel efficiency of the main engine is much higher than that of the smaller auxiliary generators. An example of this difference in fuel consumption is illustrated in Figure 7. The shaft generator is usually also dimensioned so that it covers the hotel load. Hotel load refers to the power needed to supply the domestic loads of the ship such as lighting, galleys, and air-conditioning, of the vessel during sailing (Rawson & Tupper, 2001).

Covering the hotel load with a shaft generator so that you can completely, or partly turn off your auxiliary generators while sailing. This creates savings, and improves efficiency, for the ship by both utilizing the higher fuel efficiency of the main engine and reducing maintenance costs for the auxiliary generators.

Shaft generators for marine power generation were originally developed in the 1960s. In the early adaptations of the technology, shaft generators were connected directly to the main switchboard of the ship. As the frequency and voltage of the electricity generated by the generator fluctuates depending on the rotation of the rotor, these generators could only be used to produce electricity to the grid during a very specific engine speed. Thus, it was only feasible to install these on large vessels, sailing at steady speeds, over longer distances.

Nowadays, this issue is bypassed by running the electricity from the generator through a series of frequency converters, where it is output at a set frequency and voltage. This process, which will be discussed more in detail in Chapter 3.4, allows the shaft generator to operate over a wide rpm range.

This combined with, stricter emissions regulations and the use of highly efficient permanent magnet generators, has led to a drastic increase in the number of shaft generator systems installed in newbuild vessels, during the last years.

Other than being used for power generation, the shaft generator can also be used as a motor. This of course requires energy being fed to it from the main switchboard. Depending on the context, this is either called PTI or PTH.

PTI, or Power Take In, mode is when the shaft generator is used as a motor to reduce load on the main engine, to keep it running at its most efficient point.

PTH, or Power Take Home, mode on the other hand, is when only the shaft generator is used to drive the propeller shaft. This might be needed in the case of a main engine failure. The shaft generator can then be used to sail the vessel to the nearest port.

If a PTH solution is installed, there is usually a clutch on the propeller shaft between the main engine and the shaft generator, that can be disconnected. This is so the shaft generator does not have to turn the engine to rotate the propeller shaft.

3.4 Frequency Converters

As the frequency and voltage vary depending on the rotational speed of the generator, frequency converters are used to stabilize it into a set voltage and frequency, as well as to synchronize it with the main switchboard. This allows the shaft generator to be usable over a large power window.

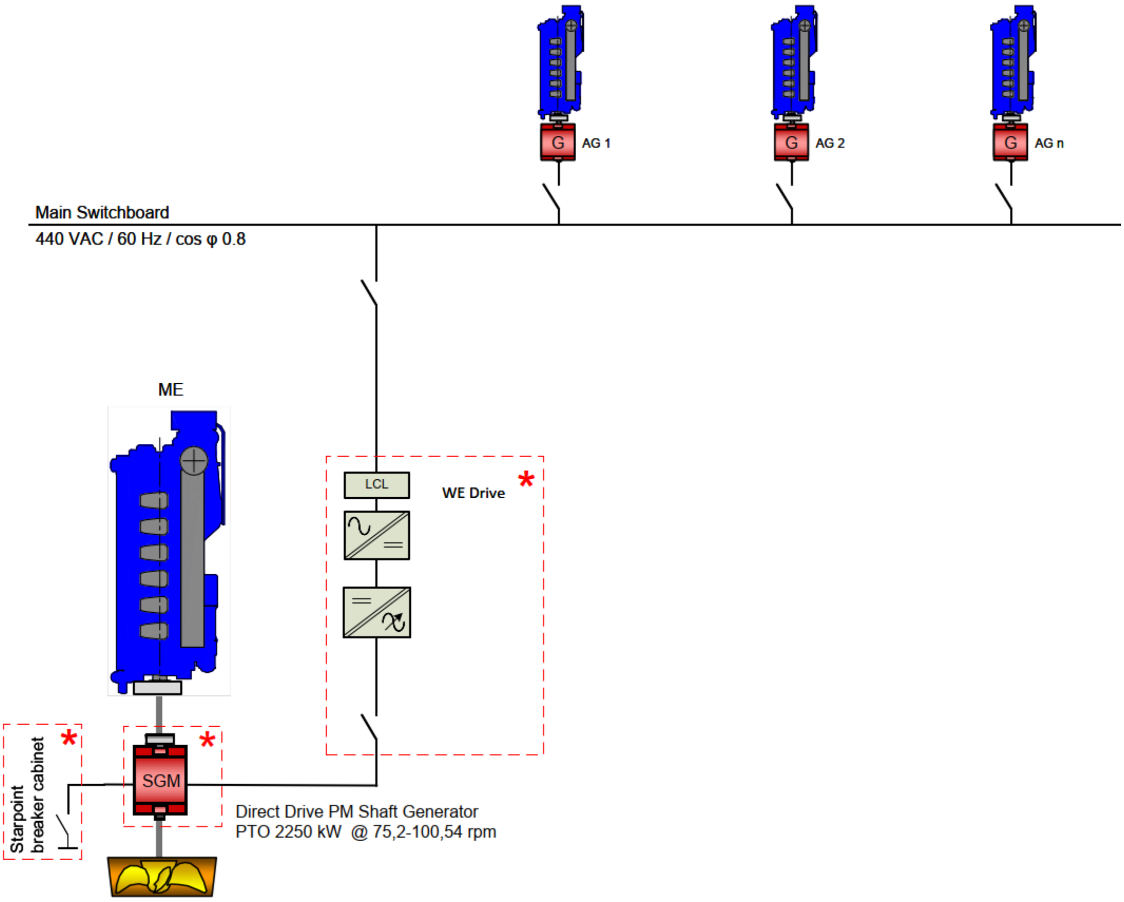


Figure 8: Simple Single line diagram of a shaft generator system.

The frequency converter system used in modern shaft generator applications consists of a rectifier, an inverter, a filter, and sometimes a transformer. The inverter transforms the varying AC voltage from the shaft generator to a set DC voltage. The DC voltage is then sent to the inverter, where it is converted to AC voltage and synchronized with the grid. These units are usually bidirectional, which means they can both send and receive power.

Before the AC voltage is fed into the main switchboard, it is sent through a filter. This filter reduces the harmonic content of the power. Power converters, like inverters and rectifiers, often produce high-frequency switching harmonics. These harmonics can cause interference and reduce the efficiency and reliability of the power system.

Depending on the main switchboard, or generator voltage the power might finally be sent through a transformer. This could be the case if the main switchboard voltage is 6.6 kV. This is common with large vessels, or vessels with high power consumption, where cable losses are a concern, such as in large LNG carriers.

3.5 DC-Links

The frequency converter systems used in modern shaft generator applications are connected via a DC voltage link. Heavier consumers, such as thrusters and pump motors, can be connected to this link with an inverter. This configuration allows for soft starting and better power management. Additionally, connecting heavier consumers to the DC-link enables a more compact main switchboard design.

Another advantage of using a DC-link is the ability to integrate additional power sources, such as battery packs or fuel cells. The power electronics used are usually bidirectional, allowing power to both be sent to and received from the main switchboard. This is useful for various electrical or hybrid propulsion solutions, as it can further reduce emissions when operating near a harbour, or other sensitive areas.

3.6 Main & Emergency Switchboard

The main switchboard is responsible for receiving power from multiple sources, such as auxiliary generators and a shaft generator, and distributing it to various loads. Other than distribution, the main switchboard is also responsible for the control, protection, and isolation of electrical circuits.

Main switchboards on large ships generally use one of 3 voltage levels, 450 V, 690 V, and 6.6 kV. 450 V and 690 V main switchboards are generally used in all except the largest vessels, or those with a large electrical load. The reason for this is that maintenance, commissioning, and the parts themselves tend to be cheaper for these voltages. It is also easier to find qualified technicians to install and maintain them.

6.6 kV main switchboards are generally used in large vessels with either, long cables or large electrical loads. Using higher voltages leads to lower cable losses, which further increases the efficiency of these vessels.

The main switchboard also usually has a power management system built in. This is then responsible for dividing the load between various power sources, as well as starting and stopping them when needed.

Modern main switchboards are often equipped with advanced features such as remote monitoring and control capabilities, allowing them to be monitored and adjusted from a centralized location on the ship, such as the control room.

The main switchboard is usually located as close as possible to where the power is generated, to minimize cable losses. This usually means the main engine room or machinery control room (*Statx*, 2024).

These locations are usually below the ship’s waterline, which means that in the case of flooding or a fire, the main switchboard would likely be disabled. Therefore, an emergency switchboard is needed.

The emergency switchboard, combined with the emergency generator is designed to keep the ship's vital functions working during emergency conditions. These systems include lighting, safety and communication systems, and power necessary for dead ship starting (Abed & Rashid, 2024).

3.7 Shore Power

Shore power, also called cold ironing or shore connection, is when the ship utilizes electrical power from land when docked at port. This allows the ship to turn off its auxiliary generators, thus reducing emissions and operating expenditures.

This makes a significant difference in the ship’s greenhouse, and particulate emissions when in harbour. In addition to its environmental benefits, shore power can lead to significant cost savings. The cost of electricity from land is often lower than the cost of fuel needed to run auxiliary generators, especially when maintenance and operational expenses are considered.

To be used in the vessel, the shore power must first be galvanically isolated with the help of an isolation transformer. Without an isolation transformer, there is a direct connection between the earth ground of the dock and the ship's electrical system. This could cause galvanic corrosion of the submerged parts of vessels.

After the isolation transformer, the electricity is synchronized with the main grid, using frequency converters. In addition to covering the electrical load of the vessel, the shore power can also be used to charge a battery pack, if such is available.

4 CII, EEXI & EEDI

The maritime industry is undergoing significant regulatory changes to both map and reduce its environmental impact. The requirements for EEXI, EEDI, and CII were introduced by the International Maritime Organization, a specialized agency of the United Nations focused on maritime transport (International Maritime Organization, 2022). EEXI, EEDI, and CII aim to map and regulate the energy efficiency of existing vessels and vessels being built.

The CII, or Carbon Intensity Indicator, was introduced in November 2022. It is a measure of a ship's energy efficiency and is given in grams of CO2 emitted per cargo-carrying capacity and nautical mile (*CII - Carbon Intensity Indicator*, 2021). The number is then converted into a performance rating ranging from A to E.

Ships are rated from A to E every year, with A being the best. A D-rating three years in a row or a single E-rating means non-compliance in which case a corrective plan is required (Sustainable Ships, 2024).

$$\mathbf{CII} = \frac{[\mathrm{AnnualFuelConsumtion}] \times [\mathrm{CO2emissionsfactor}]}{\mathrm{TransportWork} : [\mathrm{DistSailed}] \times [\mathrm{Capacity}]}$$

Figure 9: CII Calculation Formula (StormGEO, 2023)

As seen in Figure 9, the base formula for CII is quite simple, and only takes 4 constants into account. These are, annual fuel consumption, CO2 emission factor of the fuel, distance sailed and cargo capacity.

Annual fuel consumption is the total fuel consumption of the vessel over a year. The CO2 emission factor represents the amount of CO2 released when one ton of fuel is combusted, which varies depending on the fuel type. Distance sailed is a measure of the total nautical miles travelled by the ship annually.

Cargo capacity refers to either deadweight tonnage, in the case of a cargo vessel, or gross tonnage in the case of a passenger vessel. Gross tonnage refers to the internal volume of the ship while deadweight tonnage refers to the vessel's load-carrying capacity (Deadweight Tonnage | Shipa Freight, 2020).

The EEDI, or Energy Efficiency Design Index was introduced in July 2011 and became mandatory at the start of 2013. Its primary purpose is to ensure that new vessels are built as energy efficient as possible. It does this by setting mandatory energy efficiency standards that must be met during the design and construction stages of a vessel.

The EEDI evaluates energy efficiency based on the design parameters of a ship, such as hull form, propulsion system, and cruising speed. This means the evaluation is rooted in the ship’s technical specifications rather than real-time operational data.

How the ship reaches these efficiency targets, is up to the shipbuilder. Therefore, EEDI prompts innovation by encouraging shipbuilders to adopt more efficient engines, optimized hull designs, and other energy-saving features (Improving the Energy Efficiency of Ships, 2021).

If the ship matches the efficiency standards set by the IMO, it gets a permanent EEDI certification. Not meeting these efficiency standards may lead to difficulties in financing the vessel, fines, or operational restrictions.

The EEXI, or Energy Efficiency Existing Ship Index, was introduced at the same time as CII. Similarly to the EEDI, it evaluates the energy efficiency of a vessel based on its technical specification, but instead for vessels already existing.

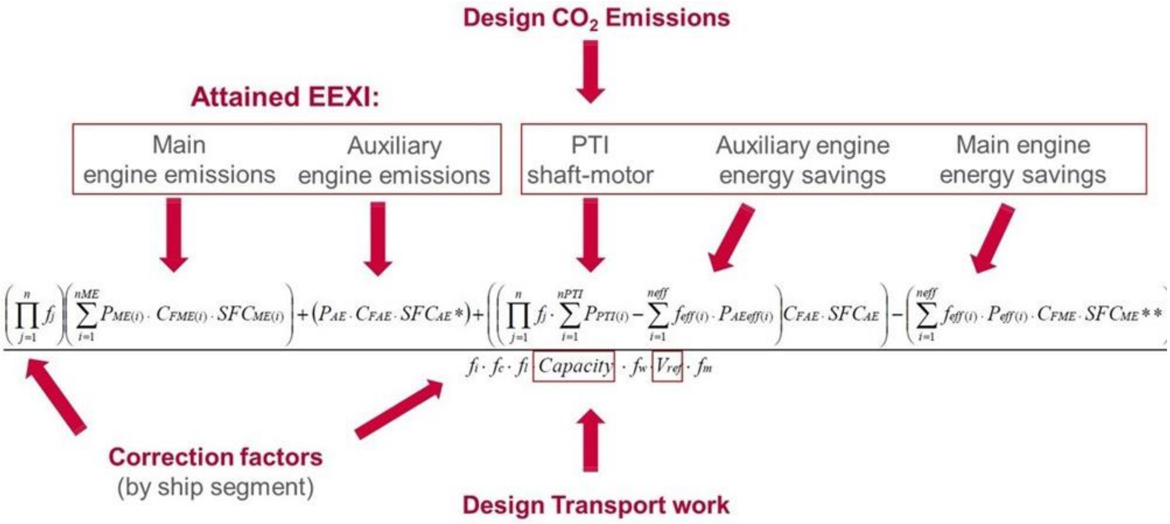


Figure 10: EEXI Calculation Formula (Burau Veritas, 2023)

By mandating that existing ships meet these energy efficiency standards, the EEXI promotes the retrofitting and upgrading of vessels with more efficient technologies (Furustam, 2021).

Unlike the EEDI, EEXI certification involves periodic assessments to ensure that existing ships maintain energy efficiency standards, as these standards will get gradually stricter.

Both EEDI and EEXI are based on technical and design data, while CII is based on operational data. This combined with the simpler formula, means that CII will be used in the calculation tool.

5 Node-RED

Node-RED is an open-source flow-based programming tool designed for visual programming. It was developed by IBM Emerging Technology and the JS Foundation. Primarily, it is a visual tool designed for the Internet of Things but can also be used for other applications to very quickly assemble flows of various services (Info Impulse Embedded Limited, 2022).

The coding takes place in a browser-based editor that allows users to wire together different nodes. The nodes are blocks of JavaScript-based software code. The nodes are visually dragged and dropped to where they can then be edited.

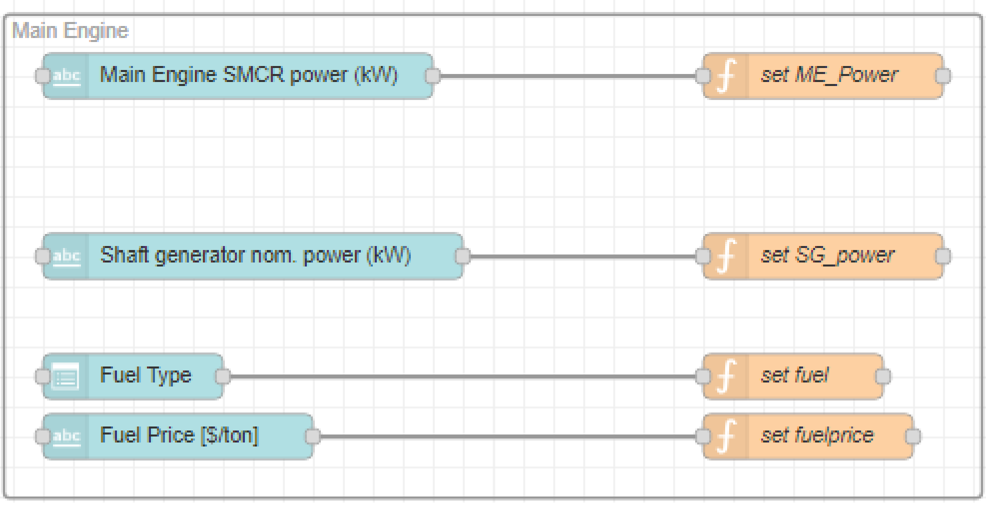


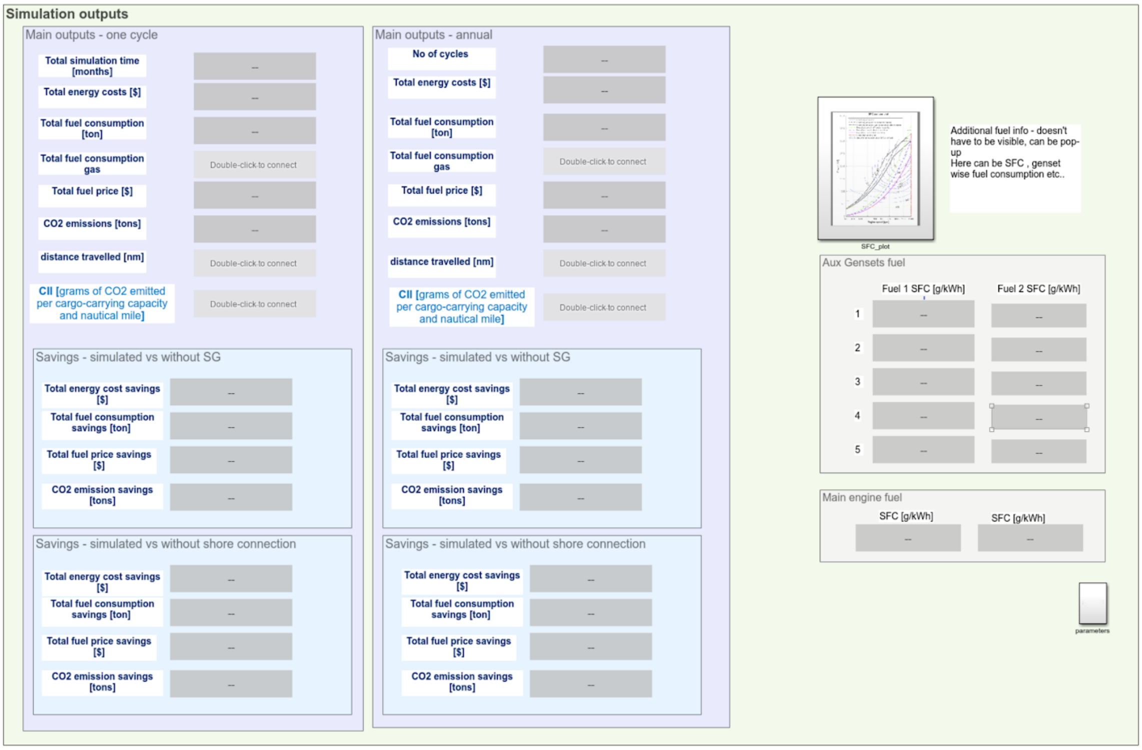
Figure 11: Input nodes connected to function nodes, which save the data.

Node-red also comes with a wide variety of add-ons, these can be used to greatly improve the base functionality. One of the most popular add-ons, Node-RED Dashboard, enables users to design simple user interfaces with ease. This addon provides a range of UI components, such as charts, gauges, and sliders, which can be used to create interactive dashboards for monitoring and controlling applications. Node-RED's ease of use and extensive addon library make it a powerful tool for quick development, even in the hands of an inexperienced user.

6 Early Development

The development of the prototype started after a meeting, where the scope and desired functionality were discussed. The main purpose of the tool was to make a simple calculation tool, capable of calculating savings, as well as emissions.

After the meeting, the following additional features were singled out as essential, graphic user interface, saving, and loading of data, calculations based on operational cycles, as well as a code with comments explaining its functionality. To make the creation of the interface simpler and provide an easy way to both upload and download data, Node-RED was chosen as the programming language.



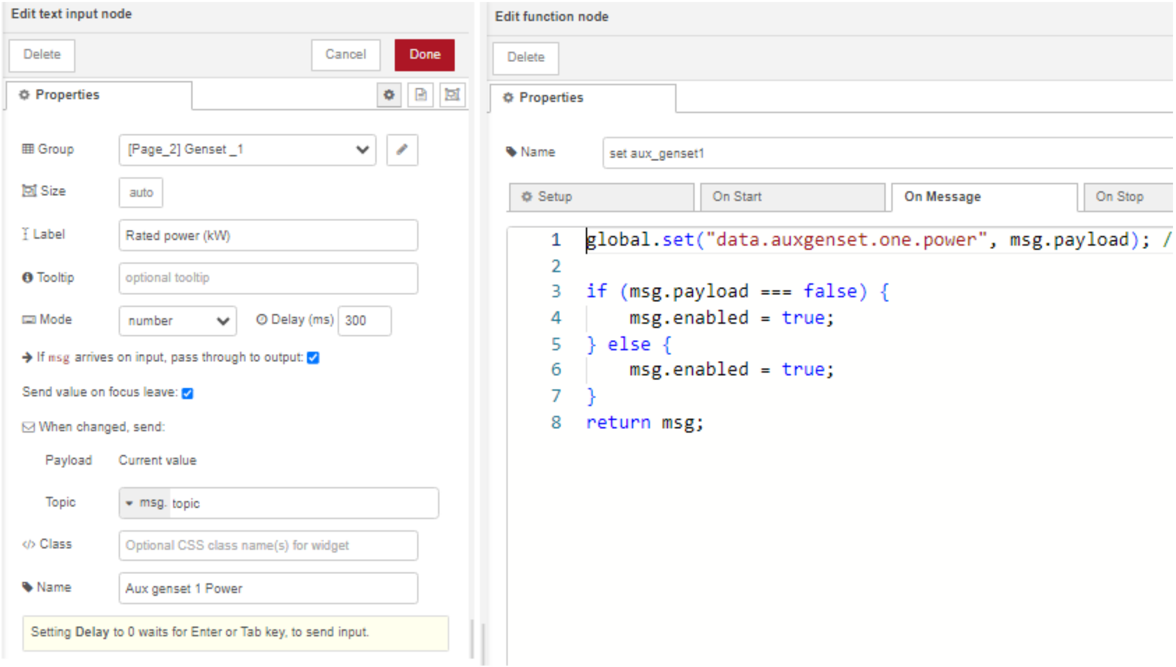
Additional fuel info - doesn't have to be visible, can be pop-up
Here can be SFC , genset wise fuel consumption etc..

Figure 12: Concept image for the result page.

Before the meeting took place, another employee at WE Tech Solutions had made concept images for the proposed prototype. Figure 12 is one such concept, presenting a potential design for the result page. These concept images served as the foundation for the user interface and as a starting point for the data inputs.

7 Functionality

Most of the code is built with the use of input-nodes, which make up the UI, and function-nodes, which run when the input nodes are interacted with. The input-nodes are used to collect user inputs, such as fuel prices and electrical loads. These inputs are then processed by the function-nodes to both store the data globally and perform calculations.



Group: [Page_2] Genset _1
Size: auto
Label: Rated power (kW)
Tooltip: optional tooltip
Mode: number
Delay (ms): 300
If msg arrives on input, pass through to output: ☑
Send value on focus leave: ☑
When changed, send:
Payload: Current value
Topic: msg. topic
Class: Optional CSS class name(s) for widget
Name: Aux genset 1 Power

Setting Delay to 0 waits for Enter or Tab key, to send input.

Name: set aux_genset1

```
global.set("data.auxgenset.one.power", msg.payload); /

if (msg.payload === false) {
    msg.enabled = true;
} else {
    msg.enabled = true;
}
return msg;
```

Figure 13: Input-node next to a function-node

7.1 Page 1

The program starts on Page 1. As can be seen in Figure 14: Page 1 , the user is given two options, either they can upload previously saved data into the Upload data field or start inputting new data in the Project Data field.

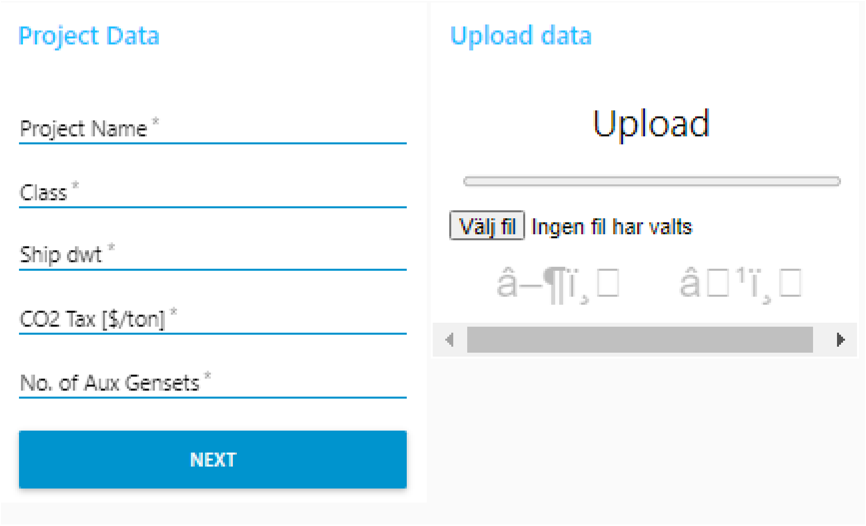


Figure 14: Page 1

When either the " NEXT” button is pressed, or old data is uploaded, multiple functions are executed in the background. One of these functions creates a global JavaScript object where all the projects’ data is stored. The data from the input fields is then stored in this JavaScript object, which for simplicity’s sake is called data. As the JavaScript object is global, it can be accessed from anywhere in the code using the right command.

Simultaneously, two other functions are executed in the background. These functions define two additional global JavaScript objects: one for the fuel matrix of the main engine and another for the fuel consumption of the gensets. If the "NEXT" button is pressed, the user is forwarded to Page 2. If data is uploaded, the user is directly sent to Page 4, where the results are presented.

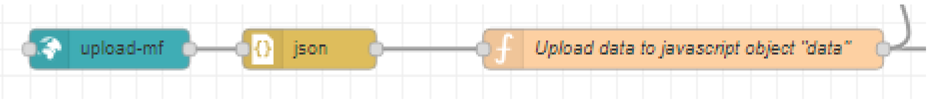
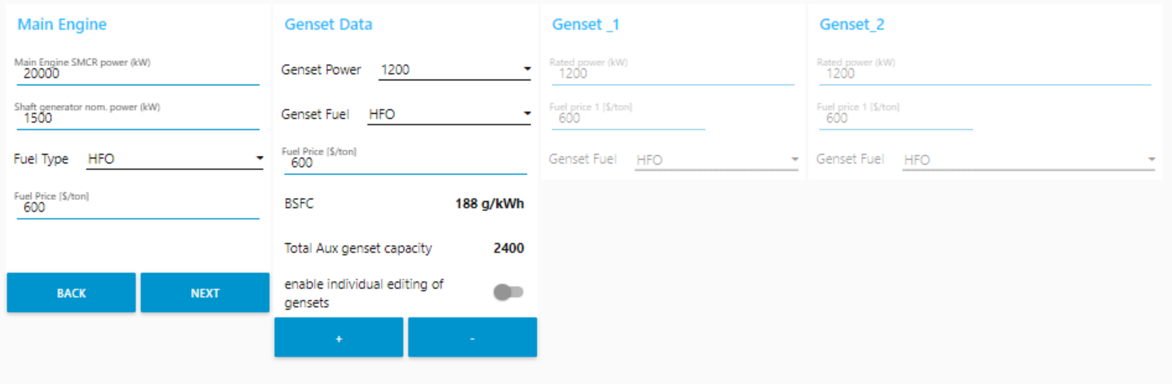


Figure 15: The nodes responsible for uploading data.

The uploading of data is handled by the addon “ui-upload-mf,” which adds a separate node where you can drag and drop data. After the file has been uploaded, the JSON node converts the JSON data in the save file into a JavaScript object, which is then uploaded to the tool using a function node. How the function node accomplishes this will be discussed in more detail in the following chapter.

7.2 Page 2

After the user has been directed to page 2, they are once again met with multiple input fields. These fields are responsible for giving the technical information needed on the main engine and auxiliary generators. This information will be crucial for the calculations on Page 3 and 4.



Main Engine

Main Engine SMCR power (kW): 20000

Shaft generator nom. power (kW): 1500

Fuel Type: HFO

Fuel Price [$/ton]: 600

Genset Data

Genset Power: 1200

Genset Fuel: HFO

Fuel Price [$/ton]: 600

BSFC: 188 g/kWh

Total Aux genset capacity: 2400

enable individual editing of gensets

Genset _1

Rated power (kW): 1200

Fuel price 1 [$/ton]: 600

Genset Fuel: HFO

Genset_2

Rated power (kW): 1200

Fuel price 1 [$/ton]: 600

Genset Fuel: HFO

Figure 16: Page 2

As can be seen in Figure 17: The nodes used to set the main engine's data. when data is in input, or changed, the input nodes send the data as a payload to the function nodes. The function nodes then save the payload data in the JavaScript object "data" under a chosen name.

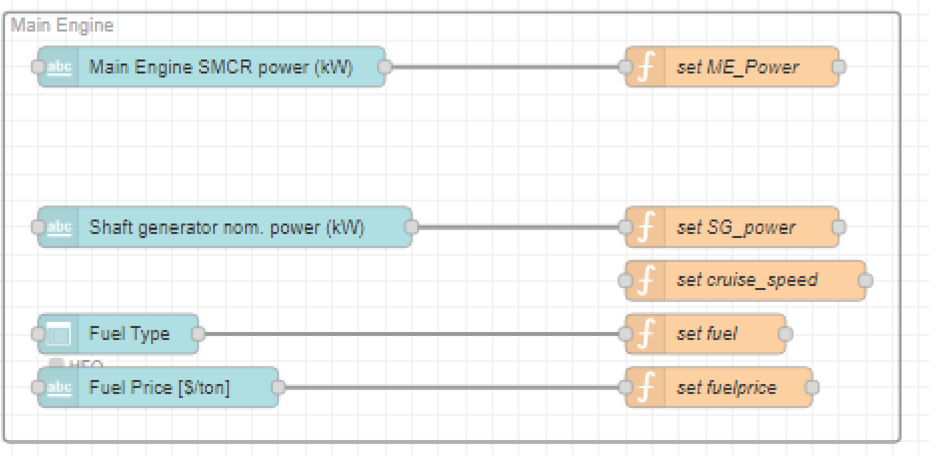


Figure 17: The nodes used to set the main engine's data.

Name: set ME_Power

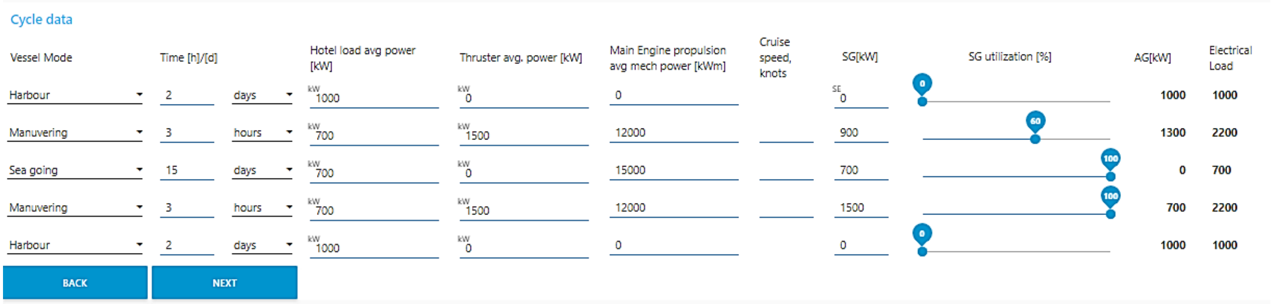
```
global.set("data.mainengine.power", msg.payload); //set global variable data

return msg;
```

Figure 18: The code inside the function ME_Power.

The function that saves data is very simple and only consists of two lines of code. The code inside the function “ME_Power”, which can be seen in Figure 18: The code inside the function ME_Power saves the main engine power sent from the input node to the JavaScript object “data” using the “global.set” function. In this case, the data is saved under “data.mainengine.power”. A similar data saving function-node is connected to nearly all the input-nodes in this tool. A benefit of saving the data in a JavaScript object is that you can store all the data needed for the tool under one variable. This simplifies the code and makes utilization of these variables much easier.

7.3 Page 3

On Page 3 the user inputs an example operational cycle for the ship. The complete operational cycle, in this case, is from harbour to harbour. The complete operational cycle is split into five parts. Two for harbour and manoeuvring, and one for sea-going.



Vessel Mode	Time [h]/[d]		Hotel load avg power [kW]	Thruster avg. power [kW]	Main Engine propulsion avg mech power [kWm]	Cruise speed, knots	SG[kW]	SG utilization [%]	AG[kW]	Electrical Load
Harbour	2	days	1000	0	0		0	0	1000	1000
Manuvering	3	hours	700	1500	12000		900	60	1300	2200
Sea going	15	days	700	0	15000		700	100	0	700
Manuvering	3	hours	700	1500	12000		1500	100	700	2200
Harbour	2	days	1000	0	0		0	0	1000	1000

Figure 19: Page 3 UI

The data inputs in each of the operational cycles are what determine the fuel consumption of both the main engine and the auxiliary generator. “Hotel load avg. power”, and “Thruster avg. power" are responsible for calculating the total electrical load during the cycle. "SG utilization" determines how much of the available shaft generator power is utilized, and updates "SG[kW]" to represent that amount. This then in turn updates the data under "AG[kW], which displays how the electrical load is distributed between the shaft generator and the auxiliary generators.

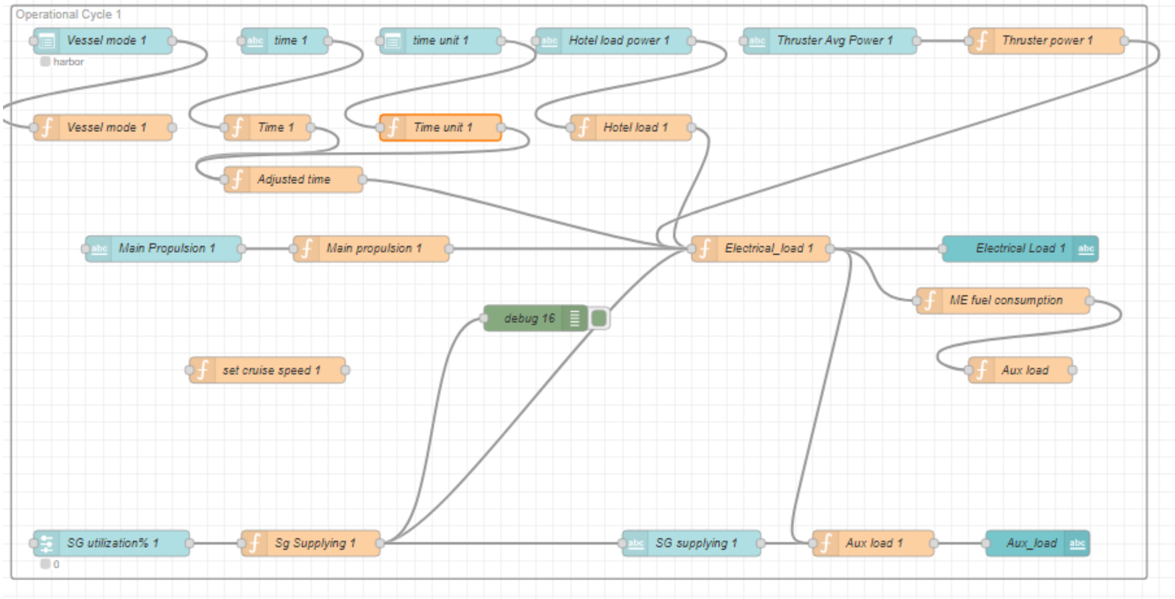


Figure 20: The nodes used to set operational cycle one.

The data under "Main Engine propulsion avg mech power [kWm]" combined with "SG[kW] is used to calculate the total load on the main engine. Both time inputs are connected to the function-node "Adjusted time", which converts the time into hours, in case the time unit is set to days. The data from "Adjusted time" can then be used to calculate the total power consumption, duration and sailing distance, of each cycle.

```
var time = global.get("data.operationalcycle.one.adjustedtime");

var me_load = global.get("data.operationalcycle.one.meload");
var me_power = global.get("data.mainengine.power");
var me_loadprecentage = (Math.round(me_load/me_power*10))/10; //rounds to nearest first decimal
var fuelmatrix = global.get("fuelmatrix2st");
// Define power based on main engine power
var power;
if (me_power <= 15000) {
  power = 10;
} else if (me_power <= 25000) {
  power = 20;
} else if (me_power <= 45000) {
  power = 40;
} else {
  power = 80;
}

// Function to get BSFC value based on engine power and load percentage
function getBSFC(power, loadPercentage) {
  // Access BSFC value from fuelmatrix using power and load percentage
  // Returns null if no value found
  return fuelmatrix[power] && fuelmatrix[power][loadPercentage.toFixed(1)];
}

// Get BSFC value based on power and load percentage
var bsfc = getBSFC(power, me_loadprecentage);

// Calculate fuel consumption
var fuelconsumptionme = (bsfc / 1000) * me_load*time
global.set("data.operationalcycle.one.fuelconsumptionme",fuelconsumptionme)
var sg_load = global.get("data.operationalcycle.one.sgsupplying");
var kwhsg = sg_load * time; //Calculate sg kwh
var fuelconsumptionsg = (bsfc / 1000) * sg_load * time; //Calculate sg fuel consumption

global.set("data.operationalcycle.one.fuelconsumptionsg", [fuelconsumptionsg, bsfc,kwhsg]);


return msg;
```

Figure 21: The code used to calculate main engine fuel consumption.

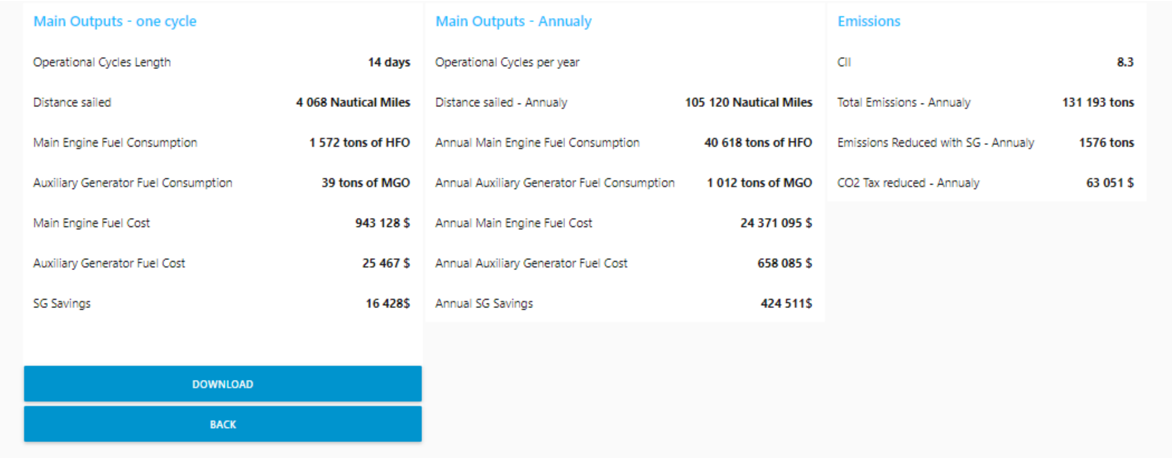
The code shown in Figure 21: The code used to calculate main engine fuel consumption. is responsible for computing fuel consumption of the main engine, and the shaft generator within an operational cycle. It begins by retrieving the needed data from the global Javascript object “data”. The “time″ variable represents the adjusted time for the operational cycle, while “me_load” and “me_power” represent the main engine's load and power, respectively. Additionally, “me_loadprecentage” calculates the percentage of the main engine load relative to its power, rounded to the nearest first decimal. The “fuelmatrix” variable imports the fuel matrix for the main engine defined on Page 1.

The function “getBSFC” is used to retrieve the BSFC, or brake-specific fuel consumption, value based on the main engine's power and load percentage, from the earlier defined “fuelmatrix”. If no corresponding value is found, it returns “null”. When the BSFC value has been determined, it is then stored in the “bsfc” variable.

This variable, along with the main engine's load, and the adjusted time is used to calculate the fuel consumption of the main engine, after which it is stored under “fuelconsumptionme”. The fuel consumption that the SG added to the main engine is also calculated and stored as a separate variable under “fuelconsumptionsg”, which will be used to calculate savings on Page 4. The results of the calculations are then stored in the JavaScript object “data”. A similar function-node is used to calculate the fuel consumption for the other operational cycles as well.

7.4 Page 4

On Page 4, the results of the calculations are presented. The first column displays the calculation results of one complete operational cycle. The second column adjusts these values to represent an annual basis, offering a long-term perspective. The third column presents the data on emissions, CII, and CO2 reduction with the shaft generator, as well as CO2 taxes reduced.



Main Outputs - one cycle	
Operational Cycles Length	14 days
Distance sailed	4 068 Nautical Miles
Main Engine Fuel Consumption	1 572 tons of HFO
Auxiliary Generator Fuel Consumption	39 tons of MGO
Main Engine Fuel Cost	943 128 $
Auxiliary Generator Fuel Cost	25 467 $
SG Savings	16 428$

Main Outputs - Annualy	
Operational Cycles per year	
Distance sailed - Annualy	105 120 Nautical Miles
Annual Main Engine Fuel Consumption	40 618 tons of HFO
Annual Auxiliary Generator Fuel Consumption	1 012 tons of MGO
Annual Main Engine Fuel Cost	24 371 095 $
Annual Auxiliary Generator Fuel Cost	658 085 $
Annual SG Savings	424 511$

Emissions	
CII	8.3
Total Emissions - Annualy	131 193 tons
Emissions Reduced with SG - Annualy	1576 tons
CO2 Tax reduced - Annualy	63 051 $

Figure 22: Page 4 UI

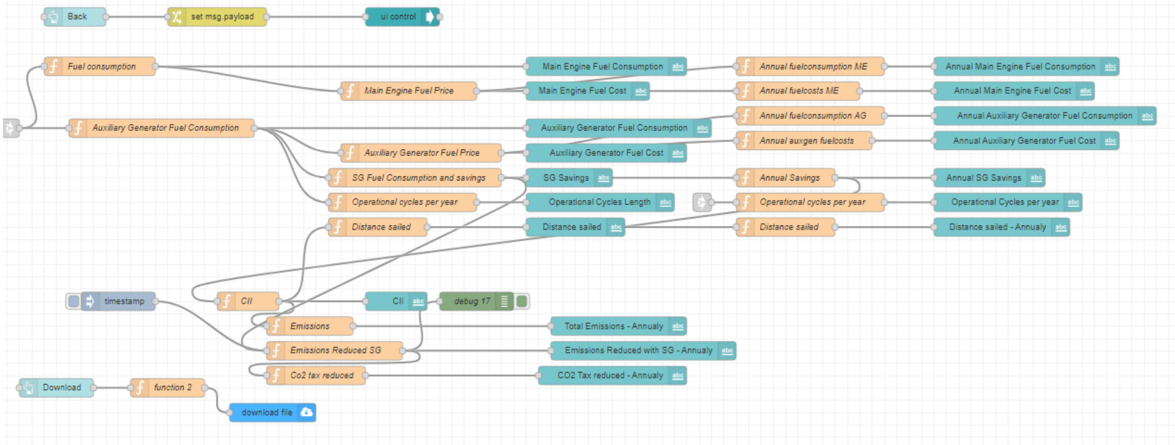


Figure 23: The different nodes used to build Page 4

Most of the values presented on the result page are simply calculated. An example of this is the main engine fuel consumption and fuel costs.

The fuel consumption of the main engine is calculated by first calculating the sum of the main engine's fuel consumption during each operational cycle. This is then multiplied by the fuel price. The same process is repeated for the auxiliary generator.

Similarly, the emissions of the main engine are calculated by multiplying its total fuel consumption by the CO2 emission factor of the fuel being used. Dividing this with the distance sailed multiplied by the vessel's capacity gives us the CII value. Where it gets more complicated is in trying to calculate the savings produced by installing a shaft generator.

```
var fuelconsumptionsg =
  global.get("data.operationalcycle.one.fuelconsumptionsg[0]") +
  global.get("data.operationalcycle.two.fuelconsumptionsg[0]") +
  global.get("data.operationalcycle.three.fuelconsumptionsg[0]") +
  global.get("data.operationalcycle.four.fuelconsumptionsg[0]") +
  global.get("data.operationalcycle.five.fuelconsumptionsg[0]");

var fuelprice = global.get("data.mainengine.fuelprice");

global.set("data.results.fuelconsumptionsg", fuelconsumptionsg);
var fuelcostsg = Math.round((fuelconsumptionsg / 1000) * fuelprice);


var electricalload = [global.get("data.operationalcycle.one.electricalload"),
global.get("data.operationalcycle.two.electricalload"),
global.get("data.operationalcycle.three.electricalload"),
global.get("data.operationalcycle.four.electricalload"),
global.get("data.operationalcycle.five.electricalload")];
// electricalload array

var adjustedtime = [global.get("data.operationalcycle.one.adjustedtime"),
global.get("data.operationalcycle.two.adjustedtime"),
global.get("data.operationalcycle.three.adjustedtime"),
global.get("data.operationalcycle.four.adjustedtime"),
global.get("data.operationalcycle.five.adjustedtime")];
// Adjustedtime array

var bsfc = global.get("data.auxgenset.bsfc") / 1000;
var agfuelprice = global.get("data.auxgenset.fuelprice");

let agconsumptions = []; // Array to store the agconsumption values
let totalAgConsumption = 0;

for (let i = 0; i < electricalload.length; i++) {
  const agconsumption = electricalload[i] * adjustedtime[i] * (bsfc / 1000);
  agconsumptions.push(agconsumption); // Store the calculated value in the array
  totalAgConsumption += agconsumption; // Add current agconsumption to total
}
var fuelcostag = totalAgConsumption * agfuelprice //cost of fuel without sg
global.set("data.results.totalAgConsumption",totalAgConsumption);

var fuelconsumptionag = global.get("data.results.fuelconsumptionag"); //ag fuelconsumption when load is
divided between ag and sg
var fuelcostagwithsg = (fuelconsumptionag / 1000) * agfuelprice //combined fuelcosts for ag + sg

var sgsavings = fuelcostag - (fuelcostsg + fuelcostagwithsg);

global.set("data.results.sgsavings",sgsavings);
var formattedSavings = sgsavings.toLocaleString(); // Format savings with spaces every third digit

msg.payload = formattedSavings;
return msg;
```

Figure 24: Formula used to calculate the savings produced by installing a shaft generator

The script in Figure 24 calculates the fuel consumption and fuel costs for each operational cycle, comparing them with and without the use of a shaft generator.

The script begins by importing the shaft generator's fuel consumption values from the five operational cycles. The fuel consumption for each cycle is then summed to calculate the total fuel consumption of the shaft generator, this is stored in "fuelconsumptionsg".

Next, the fuel cost for operating with the shaft generator is calculated. This is done by, first, retrieving the price of the main engine's fuel. This is followed by converting the fuel consumption into tons by dividing it by 1000 and then multiplying it by the fuel price. The result is then rounded to the nearest integer and stored in the variable “fuelcostsg”.

The script proceeds by retrieving the electrical load and adjusted time for each operational cycle, storing these in "electricalload" and "adjustedtime". It then retrieves the brake-specific fuel consumption of the auxiliary genset and the price of its fuel.

Simply put, with these values, the script calculates the fuel consumption of the auxiliary genset for each cycle, if it were to supply all the power needed for the electrical load with the auxiliary generators. This is then multiplied by the fuel price for the auxiliary generator and stored in the value “fuelcostag”.

Next, the script retrieves the auxiliary genset fuel consumption when the electrical load is shared with the shaft generator. It then calculates the combined fuel costs for this scenario and stores it in “fuelcostswithsg”.

Finally, the script determines the savings by first combining the variables “fuelcostwithsg” and “fuelcostsg” and subtracting it from “fuelcostag”. This value is then formatted with spaces for every third digit for readability and set as the payload of the output message.

The data used for the calculations, except fuel matrixes, as well as the results can then be saved by pressing the download button. This is done with the help of an addon called “prescient-devices/node-red-contrib-downloadfile”. The download is in the form of a .txt file that contains the JavaScript object “data”. This data can then be used to quickly resume calculations, or for presenting savings.

8 Results and Future Development

As a result, a prototype tool capable of calculating fuel consumption, CO2 emissions, CII, sailing distance, and savings, was built. The tool utilizes a fuel matrix to determine the load profile for the main engine, calculated from the mechanical energy needed for propulsion, and the shaft generator. This makes the fuel-consumption calculations for the main engine side fairly accurate for all newbuild vessels, which in turn makes the emission calculations quite accurate for the main engine.

This makes the CII calculations accurate, as the main engine accounts for the vast majority of the emissions, as long as the user provides accurate information for the mechanical energy needed for propulsion and the cruise speed.

However, the absence of support for fuel consumption based on load percentage for the auxiliary generators slightly diminishes the accuracy of the tool. However, in ships, the load is generally divided between multiple auxiliary generators, where they are kept at a low load, to be able to cope with sudden power demands that might occur. This then also means that the generator will not be running at an optimal load for a low fuel consumption.

As of now, the shaft-generator savings estimate is only calculated based on fuel savings. This will be further developed to include an estimate on maintenance cost reductions from the shaft generator, as the auxiliary generators have much higher maintenance costs per running hour compared to the main engine. This will make a large difference in savings, especially, when operating at lower loads. In the future, a feature to add a shore connection will be added, as well as support for a 4-stroke main engine, and a fuel matrix for both auxiliary generator and main engine.

Despite this, the prototype is fully functional, in giving an estimate of both fuel consumption, emissions, CII, savings, and sailing distance. The prototype is also quite simple to use and supports both loading and saving of data. Overall, I see this prototype as a success, as it does what it was set out to do, and I will probably continue developing it on the side of my normal work.

9 References

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