Mobile Marine Fuel Generation Based on a Micro Nuclear Reactor

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Synopsis

Geopolitical and macroeconomic uncertainty, supply chain risks and the growing pressure for carbon-intensive industries to reduce emissions has resulted in great interest in synthetic fuels in recent years. Electrofuels are a type of synthetic fuel which are produced by combining hydrogen and carbon dioxide. This paper explores the use of a 5MWe micro nuclear reactor in order to provide energy to produce electrofuels onboard a vessel. This paper uses empirical data to determine the relationships between characteristics of various components in order to determine of electrical and thermal power and produce the maximum possible amount of fuel, as well as to determine the volume and mass of equipment. The paper concludes with discussion of ship impact and an outline of a possible synthetic fuel generating replenishment vessel.

Keywords: Electrofuels, Shipping, Transportation, Nuclear Energy, Sustainability

1. Introduction

Traditional fuels and refuelling infrastructure present certain limitations for both naval and commercial ships, including in areas such as sustainability, logistics and storage. Electrofuels offer an alternative which shows promise in addressing some of these concerns. An electrofuel is a type of synthetic fuel which is created by combining captured carbon dioxide and hydrogen extracted from water with the use of electricity (Royal Society, 2023). Electrofuels offer a number of advantages when compared to traditional petroleum products. One such advantage is the flexibility which comes with generating fuel on demand. Only the amount of fuel which will be consumed needs to be generated, potentially leading to weight and volume savings. Further, different fuels can be created depending on the type of fuel required e.g. either aviation fuels or marine fuels. They may also allow for a simpler and more robust supply chain, as there will be a lesser reliance on imported oil.

Another crucial aspect which must be considered is environmental impact. Electrofuels allow for a significant reduction in carbon dioxide emissions of 20-47% (considering an electricity supply with a low carbon intensity of 25 gCO2 e/MJ) when compared to traditional fuels (Malins, 2017). This is noteworthy given the maritime industry's historical difficulty in decarbonising, where existing alternatives like batteries prove impractical. The strategic importance of Navies combating climate change can be seen with the US Navy targeting a 65% reduction in greenhouse gas emissions by 2030 as compared to 2008 levels (USN, 2022). More broadly, the UK is at present committed to achieving Net-Zero by 2050 (Gov.uk, 2008), a process which does require a significant reduction in emissions from organisations including the Royal Navy.

The primary aim of this paper is to examine whether a micro-nuclear reactor, based on a device under development by Rolls Royce, is suitable for electrofuels generation aboard a naval support ship or a commercial vessel or platform. This paper examines whether the output of the reactor is sufficient to allow for the generation of the required electrofuels on board the ship. It will also consider the volume and mass of equipment required for such a process to occur, and thus whether it is viable. The paper also discusses different methods of obtaining and delivering the raw materials to the ship for electrofuels generation. One method involves storing a highly dense form of carbon on board, most likely derived from biological material, which can be hydrogenated and subsequently used in the creation of electrofuels. The other involves directly extracting carbon in situ, in the form of carbon dioxide in the air or water.

2. Literature review

2.1 *Nuclear Energy in a marine context*

Nuclear energy has a long history of being implemented in a maritime setting, typically as a source of propulsive power. The use of nuclear reactors in providing sea-faring vessels with power dates back to the 1950s, when a PWR (Pressure Water Reactor) prototype for use in a submarine was first developed by Westinghouse

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Rachel Pawling is Programme Director for the MSc Marine Engineering and Naval Architecture courses and a Lecturer in Ship Design at UCL, teaching the subject of ship design to undergraduate and postgraduate students. She obtained her PhD in computer aided ship design in 2007 and has subsequently continued her research in projects funded by the EC, UK and US governments.

(Barré et al, 2016) and Ragheb (2016) notes that the 'largest experience in operating nuclear power plants has been in nuclear naval propulsion, particularly aircraft carriers and submarines'.

2.2 The Heat-Pipe Micro Reactor

This paper considers the use of an onboard micro-nuclear reactor to provide the electricity required to generate electrofuel. The specific reactor being considered is a 5MWe Nuclear Gas Turbine, sized by the second author based on information from Rolls Royce (2023). Whilst reactors of a similar power level have been employed in marine contexts, such as the propulsion system of the NR-1 submarine (Barré et al, 2016), none have been used to generate electrofuels on board a ship for the purpose of refuelling. Micro-reactors typically output between 1 and 10 Megawatts of power, with dimensions that allow for portability (Rolls-Royce, 2023). This contrasts with the small modular reactor (SMR), which provide around 0.5 Gigawatts of power.

The UCL concept micro-reactor was described by the second author for a submarine application in Pawling (2023) and is an engineering estimate based on published Rolls-Royce information (2023) and the specifications of other proposals, such as the eVinci (Arafat, 2019). It has not been subject to detailed nucleonic or thermodynamic analysis and so the overall parameters are estimates. The micro-reactor is a high-temperature reactor using TRISO fuel, with reactivity control via control drums and heat transfer through multiple heat pipes. These transfer heat from the core to Brayton cycle generators (essentially gas turbine generators). These can be used in a simple open cycle mode or potentially incorporate recuperation, waste heat steam generation, or be closed-cycle. A closed-cycle option for submarines is illustrated in Figure 1 (Pawling, 2023).

The reactor module achieves a small size (8.1m x 2.3m x 2.3m) and weight (80 tonnes) via a "shrink-wrapped" shielding geometry, repair and refuel by replacement, and compact power conversion systems, compared to the saturated steam plants of Pressurised Water Reactors. With a core life of 5 years it provides 5MWe of electricity and approximately 12MWth of waste heat. With core temperatures of 600-1000^{o}C, the exhaust is expected to be 200-300^{o}C. Incorporation of recuperation is estimated to allow for an increase in electrical output by 37%, from 5MWe to 6.85 MWe, whilst based on combined cycle gas turbine generating plants (Karaağaç et al, 2019) it is assumed that approximately half of the waste heat could be recovered by an exhaust gas boiler – 6MWth, which could be used for process heating or additional power generation.

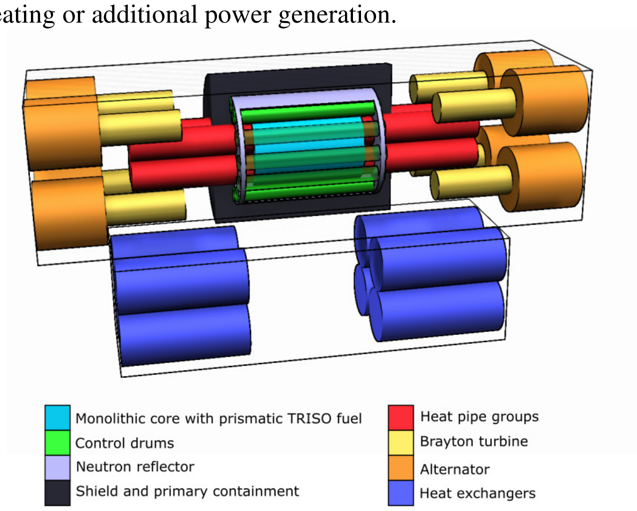

Figure 1: The notional UCL 5MWe Heat Pipe Gas Turbine Reactor (Pawling, 2023)

2.3 Electrofuels

With respect to commercial shipping, there has been widespread interest in various sustainable fuels, which allow for both a sustainable source of propulsion as well as a reduction in pollution attributed to the commercial shipping industry. Greenhouse gas emissions from the global shipping industry reached 1,076 million tonnes of CO_2 equivalent in 2018, a 9.6% increase with respect to emissions in 2012 (IMO, 2021).

One fuel widely considered to be a promising alternative is Methanol. Replacing traditional marine fuels with Methanol eliminates the emissions of sulphur oxides and reduces the emission of nitrogen oxides by 60% (Argus Media, 2020). This, in combination with the preexisting standards and regulations surrounding the fuel, makes it an attractive alternative for shipping companies. There is already significant interest in Methanol from major

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commercial players - as of 2023, Maersk has 24 container vessels on order, all of which are capable of operating on green Methanol (Maersk, 2023). This also suggests Methanol is an appropriate contender.

Ammonia is another fuel which has captured attention amongst those looking to decarbonise the commercial shipping industry. Like methane, ammonia is less energy dense than diesel but greater than hydrogen, a competing green fuel. Ammonia also has the advantage of already being a reasonably common cargo and so the maritime industry has experience in handling the fuel in bulk. It emits no carbon when burned and has a low range of flammability, enhancing safety. In spite of the fuel's otherwise green credentials, NOx emissions and particularly water use in production remain environmental concerns, (Ghavam et al, 2021).

While both fuels are of interest to the shipping industry, for the purposes of this paper, methanol was chosen as the fuel of interest for commercial purposes. One reason for this is that methanol already has regulatory acceptance under the International Marine Organisation's IGF Code, which ammonia does not. Another is that methanol can be stored as a liquid in much the same way as traditional marine fuels, whilst ammonia must be stored in a compressed state. Finally, the interest expressed in methanol by key players such as Maersk and Stena Bulk (Argus Media, 2020) suggests that methanol will gain traction among firms operating in the commercial shipping industry at a faster rate.

Regarding naval ships and other military use cases, the favoured choice is synthetic diesel. At present, Diesel Fuel Marine, which is commonly known via the NATO specification F-76, is the primary fuel used for propulsion by the US Navy (Sermarini, 2000). It is important to recognise that the desired characteristics of the optimal fuel differs between military and commercial uses. For example, F-76 contains stability additives which are not typically present in commercial fuels. It also has a minimum flash point specification of 140° F (60° C), as well as limits on particulates and water and corrosiveness to promote safety and limit engine damage over long periods of time (Sermarini, 2000).

There have been attempts to produce and implement various synthetic diesels in military contexts. Once such example is RediDiesel, a renewable biofuel developed by Applied Research Associates (ARA, 2016). One of the key advantages of this type of fuel is that is serves as a drop-in replacement for F-76, and so requires no additional equipment or operational modifications when used. The lack of requirement to retrofit is attractive in a military context, with this being a costly and time-consuming process which can impact fleet availability.

3. Theory and Calculation

3.1 Method

The overall methodology employed to carry out this project is outlined below. This process allows for the amount of a specific fuel which can be produced in a day aboard a refuelling ship to be found.

1. Determine which fuels are to be considered for electrofuel production.
2. Research key components, identifying key characteristics: volume, power input and output
3. Non-dimensionalise output of component.
4. Rebalance power to ensure optimal allocation of power input to components, allowing for optimal fuel production.
5. Determine the overall amount of fuel produced in a certain timeframe e.g. a day.
6. Repeat for all considered fuels

From the literature review, it was determined that Methanol was most appropriate for commercial purposes, whilst synthetic diesel is of interest for military vessels. Thus these are the fuels which will be considered in this paper. The process of electrofuel generation is illustrated in Figure 2, with the key components listed in Table 1.

In order to non-dimensionalise the key components, data can be collected and trendlines developed to describe the relationship between the output of a component and its power input. This allows for the optimal power distribution among components, and thereby the maximum amount of fuel produced for a given energy. Similarly the volume or weight of the component can be plotted against its output.

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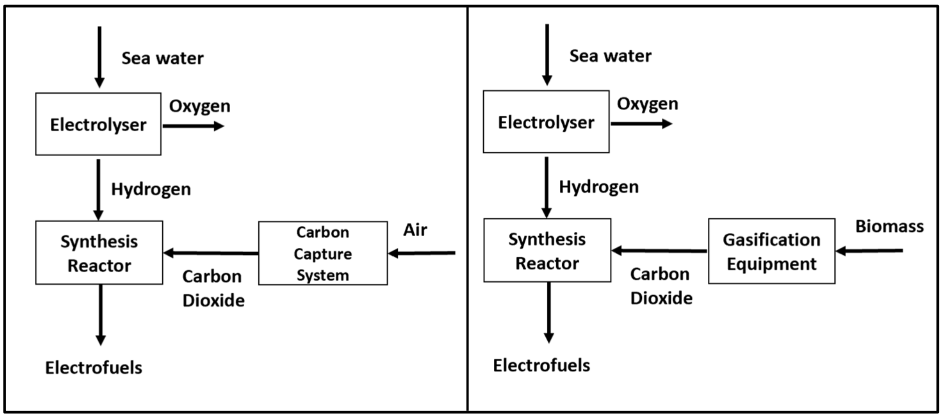

Figure 2: Diagram showing simplified overall process of electrofuel generation with carbon sourced from the air (L) and from Biomass (R)

Table 1: Key components required for electrofuel generation

Key Component	**Function/Description**
Electrolyser (including Gas separation unit)	Convert water into hydrogen and oxygen. Ensure hydrogen and oxygen are fully separated and pure
Synthesis Reactor	Combine hydrogen and carbon dioxide into electrofuels
Carbon Capture System	Capture carbon in situ (Not required for biomass carbon concept)
Gasification equipment	Convert biomass stock into carbon dioxide (not required for carbon capture concept)

3.2 Electrolyser

Whilst electrolysis has alternative processes which could theoretically achieve the same outcome (converting water into hydrogen and oxygen) such as thermal decomposition, electrolysis was preferred as thermal decomposition of water requires temperatures of between 500° to 2,000 ° C (energy.gov, 2020), whilst the micro-nuclear reactor being considered is only capable of providing exhaust gas at a temperature of 200-300° C and core temperatures of 600-1000° C. Electrolysers for hydrogen production are becoming more widely available and data on modular and unitised systems is readily available, for example the data sheet from Bloom (2023) summarised in Figure 3.

MODULAR BLOOM ELECTROLYZER KEY DATA

Power (MW)	Hydrogen Output			
	kg/hr	mt/day	mt/year	Nm^3/hr
1.2#	32	0.77	280	356
2.4	64	1.5	560	712
50	1,344	32	11,772	14,957
1000**	26,685	640	233,759	297,002

Figure 3: Key data table sourced from the Bloom Electrolyser Data Sheet (Bloom, 2023)

Some manufacturers provide performance metrics more useful for scaling. For example the ME450 from H-Tec (2023) has an efficiency of 53 kWh/kg and an output of 450 kg/day. Data from several sources can be compiled to derive a generic relationship between power and output, as illustrated in Figure 4. The trendline shows a linear relationship between hydrogen production and electrical power input, with an equation y = 0.5603x. We would expect a broadly linear relationship as, for a given technology, electrolysers use the same electrochemisty regardless of size and do not have the complexities of, say, a diesel engine. The Bloom datasheet was used to derive a thermal load of 0.345MWth per tonne H_2 per day for steam generation, if a high temperature cell is used.

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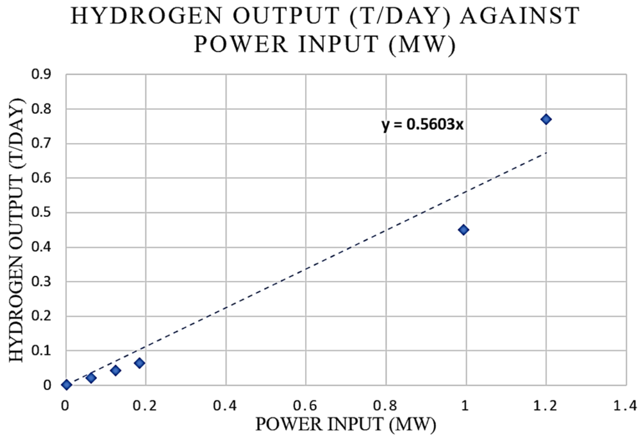

Figure 4: Graph showing relationship between hydrogen output and power input, with the trendline and equation shown

The volume of the equipment is also of interest. The Bloom data sheet quotes a size of 12.04 x 1.86 m for a 1.2MW module. As the height is not given, we can make a rough estimate by analysing the render depicted on the datasheet, as below:

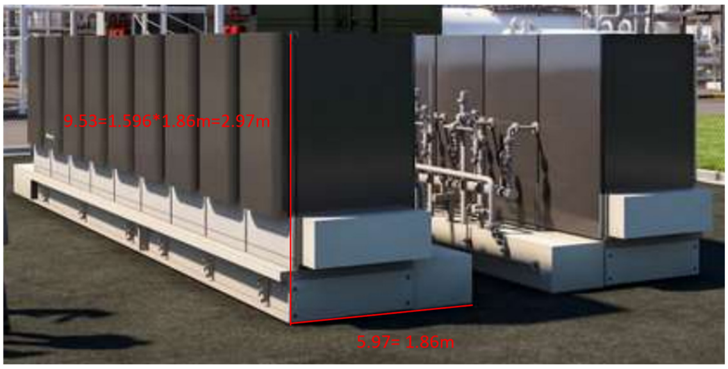

Figure 5: Depiction of how the height of the Bloom electrolyser was estimated by comparing lines (Bloom, 2023)

In Figure 5, the width of the electrolyser is known to be 1.86 m as per the data sheet. We can draw a line on a software such as PowerPoint along the width. As PowerPoint gives the length of the drawn line to be 5.97 cm, we can compare this with the length of the line drawn along the height of the electrolyser in order to determine its true height. The vertical line in PowerPoint comes to 9.53 cm. Thus the true height of the electrolyser is:

$$1.86\ m \times \frac{9.53\ cm}{5.97\ cm} = 2.97\ m$$

Thus we have dimensions of 12.04m * 1.86m * 2.97m giving a volume of 66.5 m^3. The relationship between volume and hydrogen output can thus be plotted as shown in Figure 6. Here we would expect a power relationship, with the exponent below 1, as a result of the greater efficiency achieved at greater equipment volumes, due to aspects such as the surface area to volume ratio.

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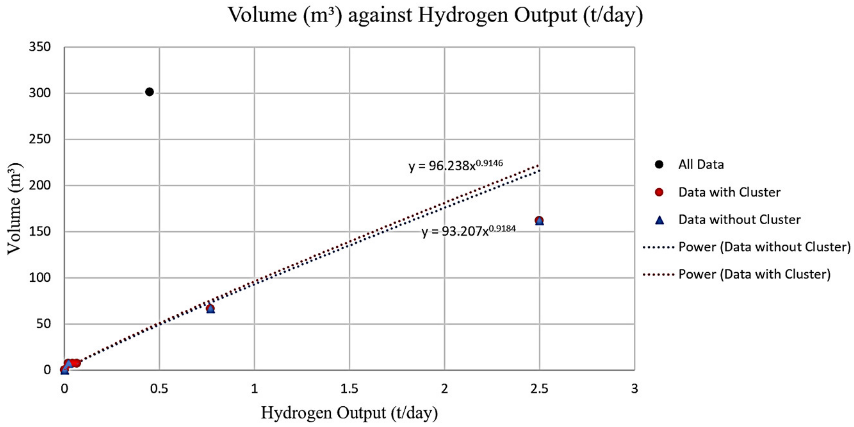

Figure 6: graph showing relationship between volume and hydrogen output. Note the outlier (black) and data with the cluster (red)

Note that there is a clear anomaly which was not included when creating the trendline. This anomaly is due to the electrolyser being used in a land-based industrial context where there is less incentive for the manufacturer to minimise volume. Also note that there are a cluster of red data points near the origin. The presence of several data points very close to each other disproportionately influences the power trendline (red), and so the 'data without cluster' dataset was created (blue triangles) and a trendline (blue) was subsequently found with the equation $y = 93.207x^{0.9184}$. This gives a more representative relationship.

As most electrolysers for the production of hydrogen use fresh water as their input to the electrolysis cell, Reverse Osmosis (RO) or Multistage Flash distillation (MSF) will be required. Some commercial units may already have this equipment fitted, but to be conservative it was assumed to be an additional item. From an energy and power perspective, the electrical loads of modern RO plants are small compared to the electrolysis loads above, with academic literature (Wade, 2001) and product specification sheets e.g. (Evac, 2016), indicating values between 4 and 8 kWhr/m^3 fresh water produced via RO, with a similarly small additional size and weight for the equipment.

3.3 Carbon Capture System: Air

Direct Air Capture (DAC) extracts carbon dioxide from the atmosphere, primarily through chemical processes. The energy requirements for these systems are generally a mix of thermal and electrical, although a unitised system such as Airthena uses internal heaters to provide the former, with only electrical input to the device. Sadiq et al (2020) provide an energy type breakdown for an Airthena type device, with 70% of the internal energy use being thermal, with temperatures around 80 degrees C.

Typically, direct air capture involves using an air contacting medium which exposes a sorbent to airflow, which results in the CO_2 being absorbed. One example is aqueous hydroxide sorbents, which result in following chemical reaction (Eloy et al, 2016).

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

Following the capture, the sorbent is then regenerated by heating. Here, the carbon dioxide is removed and the sorbent is able to absorb further carbon dioxide. Direct air capture is a technology which is expected to receive much investment in the coming years as more attention is paid to extracting carbon dioxide out of the atmosphere. In this regard, this component of the electrofuel generation system is certain to significantly improve in efficiency and performance in time. Table 2 compares the key characteristics of several carbon capture systems. The average density of a DAC unit was assumed to be similar to the air filtration units of a naval HVAC system (Bronswerk, 2017), at approximately 0.4 te/m^3.

Table 2: Characteristics of some selected DAC systems

Source	Power in MWe	CO_2 out t/day	Volume m^3	Input kWeh/t	Output t/day/MWe	Notes
Keith, 2006	1.4	208.219	1140398	161	148.7	Uses air handling tower
Casaban, 2023	0.2283125	10.959	450	500	48.0	
Kulkarni, 2012	0.009968	1.1	69.12	217	110.4	
Lackner, 2009	0.012732	1	90	306	78.5	
Sadiq, 2020	0.04	0.00042	3.9312	2285714	0.011	Modularised

Using a graphical method as described in section 3.2, the relationship between CO_2 output (t/day) and Power input (MW) was found to be y = 146.11x. However, as Table 2 shows, the single industrial-scale entry dominated this analysis of power demand. Removing the largest value led to relationship of y = 46.78x, and it is speculated that the lower performance of the smaller plants is due to their inclusion of mechanical air handling systems. Whilst the relationship between the volume of carbon capture system and the CO_2 output was $y=76.406x^{0.9184}$. These relationships are very similar to the equivalent relationships of the electrolyser, with direct air capture seeing similar volumetric efficiency gains as output increases.

While the total energy requirements for DAC are reasonable, due to the low concentration of carbon dioxide in the atmosphere a large amount of air must be handled. With a mass fraction of 0.0626% (Engineering Toolbox, 2024) a 100% efficient capture system would need to process 1597 tonnes of air per tonne of CO_2 captured, or approximately 1.3 million m^3. For land based, or static floating installations, this amount of air can easily be handled using large tower structures, with the example in Keith et al (2006) being over 100m in diameter and height. Spread over a 24-hour period, this equates to volume flow of approximately 54000m^3/hour, which is equivalent to the total ventilation capacity (excluding machinery spaces) of the RNLN Holland class OPVs (Heinen & Hopman, n.d.). Data for naval air handling units was used to derive a value of 8 x 10^{-4} kW/m^3/hr for air handling. Efficiency values for DAC vary significantly, with systems for scrubbing flue gas being 80-90% efficient but those for atmospheric extraction being much lower (Sodiq et al, 2023). For this study, an extraction efficiency of 50% was assumed.

3.3 Carbon Capture System: Water

Carbon dioxide is present in much higher proportions in seawater, although mostly in various compounds (Zeebe & Wolf-Gladrow, 2008), however our notional 100% efficient system would still need to process around 11,100 tonnes (10,800m^3) of seawater to extract one tonne of CO_2. Whilst this is still a very large volume, it is approximately equivalent to the flow through a 0.86m diameter tube, moving at 10 knots, for a day, small compared to the amount of water that would be moved through a waterjet propulsion system for example.

Most of the CO_2 in seawater is bound in other compounds, e.g. and an electrolysis process is used to drive a series of reactions leading to yields of around 87% extraction at an energy requirement of 122kJ/mol CO_2 (Kim et al, 2022). Whilst various experimental systems have been tested, seawater CO_2 extraction is not at the same level of development as DAC. As it uses a system of electrolysis, for the purposes of this study it was assumed that a notional CO_2 extraction system could be scaled from the hydrogen extraction system, scaling with the input water mass flow rate.

3.4 Gasification Equipment

A potential alternative source of carbon dioxide is through the gasification of biomass. For example, the 2.5 MW(e) biomass gasification module described by McLellan (2000). Here, the gas produced from woodchip with a 37% weight moisture content is only 4.4% carbon dioxide by volume, an inefficient means of producing carbon.

This method of sourcing carbon does have certain disadvantages when compared to direct air capture. Direct air capture extracts carbon in situ, whilst gasification requires biomass to be processed externally and loaded onto the vessel, making the supply chain inherently less robust and thus secure. The biomass may also present a fire risk, as it consists of flammable material. One method to mitigate this risk is to store it as bricks, where the surface area to volume ratio of the matter is lower than that of chips or pellets, for example. However, this then requires the bricks to be broken down before gasification, adding to capital costs, maintenance requirements and taking up space on board. For these reasons, as well as that there is more robust and applicable data available on direct air capture, this study proceeded in its calculations considering in-situ capture as the source of carbon.

3.5 Synthesis Reactor

The synthesis reactor is a vessel in which the electrofuel is synthesised. Alongside the well-known Fischer–Tropsch process for producing hydrocarbons from a mix of carbon monoxide and hydrogen, there are two primary methods of generating hydrocarbons from hydrogen and carbon dioxide. The first method, known as the two-step synthesis method, involves first converting carbon dioxide into carbon monoxide through the reverse water gas shift process:

$$CO_2 + H_2 \leftrightharpoons H_2O + CO$$

This process usually occurs with the use of a catalyst, typically ZnO or Al_2O_3. The second step is the methanol synthesis, which takes place in a second reactor, and involves three reactions which occur simultaneously (Anicic et al. 2014):

$$\begin{gathered} CO_2 + 3H_2 \rightleftharpoons CH_3OH + H_2O \\ CO + 2H_2 \rightleftharpoons CH_3OH \\ CO_2 + H_2 \rightleftharpoons CO + H_2O \end{gathered}$$

The mixture obtained from this product is cooled and a flash separator is used to separate the components. The non-reactive components which are not of use can be discarded. The second method, hydrogenation of carbon dioxide, allows for direct methanol synthesis. Carbon dioxide and hydrogen are fed into a reactor and, in the presence of a catalyst such as zinc oxide react to form methanol and water as products. Other products include DME and methane (Anicic et al. 2014):

$$CO_2 + 3H_2 \rightleftharpoons CH_3OH + H_2O$$

Estimating the energy required for this process from the literature is difficult as power is needed for pumps, pressurisation, heating and cooling (as some of the reactions are exothermic), and in many industrial contexts the thermal energy is provided as steam, which may be “taken for granted” in applications where waste heat is plentiful and the main concern is the additional mechanical work. A further complication is the use of heat exchangers to recover heat lost in cooling, which can significantly improve the thermal efficiency in a large synthesis plant. Table 3 summarises a sample of energy requirements for hydrocarbon synthesis.

Table 3: Thermal and electrical energy requirements for some synthesis studies

Input	Produces	Electrical MWhr/t	Thermal MWhr/t	Total MW	Th:El ratio	Notes	Reference
CO_2, H_2	meOH	0.748	-	0.748	-	Synthesis only	Sollai et al, 2023
	meOH single step	11.07	-	11.07	-	Complete system	Anicic et al, 2014
	meOH two step	10.63	-	10.63	-	Complete system	
	meOH	0.169	0.439	0.608	2.60	Synthesis only	Mar Pérez-Fortes, 2016
NH_4, CO_2	meOH	0.529	0.481	1.01	0.91	Synthesis only	Er-rbib et al, 2012
	Diesel	0.529	0.111	0.64	0.21	Synthesis only	
	Diesel	0.529	8.347	8.876	15.78	Synthesis only	

Combining these with other references, the methanol yield in tonnes per day was found to scale with input electrical power with the relationship y = 36.67x, with the thermal requirements being assumed to be twice the electrical. For diesel fuel the relationship was y = 17.17x, with the thermal requirements again varying significantly so assumed to be twice the electrical. The trendline for the data corresponding to synthesiser volume against methanol output was not found to be based on a power relationship, but a linear one, with an equation of y=0.0598x. This suggests that the volumetric efficiency gains encountered when the size of the synthesis reactor is increased is less significant than that of the electrolyser or direct air capture. Another potential explanation is that this improvement simply did not manifest itself in the selection of data.

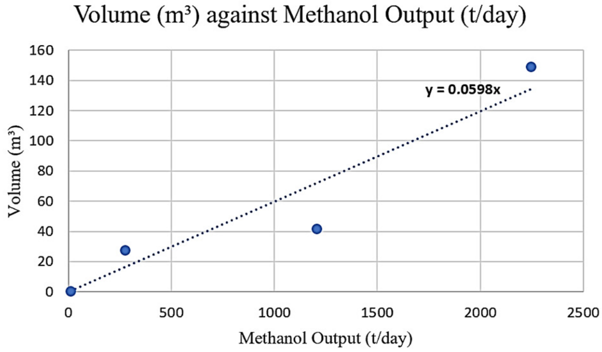

Figure 7: Graph showing linear relationship between methanol output and volume

3.6 Summary of relationships

The relationships between key characteristics of key equipment are shown in the table below, with references where these have not already been mentioned in the text.

Table 4: Relationships between key characteristics of components

Item	y	x	Relationship
RO plant	FW output (t/day)	Power input (MW)	y = 4307.6x
	Volume of RO plant (m^3)	FW output (t/day)	$y = 0.1499x^{0.93}$
	Mass of RO plant (te)	Volume of RO plant (m^3)	y = 0.2x
Electrolyser	Hydrogen output (t/day)	Power input (MW)	y = 0.5603x
	Heat input (MWth)	Hydrogen output (t/day)	y = 0.344x
	Volume of electrolyser (m^3)	Hydrogen output (t/day)	$y = 93.207x^{0.9184}$
	Mass of electrolyser (te)	Volume of electrolyser (m^3)	y = 0.46x
	Water required (t/day)	Hydrogen output (t/day)	y = 10x
DAC system	CO_2 output (t/day)	Power input (MWe)	y = 146.11x
	Heat input (MWth)	Power input (MWe)	y = 5.87x
	Volume of DAC (m^3)	CO_2 output (t/day)	$y = 76.406x^{0.9184}$
	Mass of DAC	Volume of DAC (m^3)	y = 0.4x
	Air required (t/day)	CO_2 output (t/day)	y = 3194x
Air handling	Power input (kW)	Air handled (t/day)	y = 0.027297x
Water CO_2 capture system (WCS)	CO_2 output (t/day)	Power input (MW)	y = 31.17x
	Water required (t/day)	CO_2 output (t/day)	y = 9643x
	Volume of WCS (m^3)	Water required (t/day)	y = 9.32x
	Mass of WCS (te)	Volume of WCS (m^3)	y = 0.46x
H_2O pumps	Power input (kW)	Water handled (t/day)	y = 0.02x
Synthesis reactor	Electrofuel Output (t/day)	Power Input (MWe)	y =36.67 x
	Heat Input (MWth)	Power Input (MWe)	y = 2x
	Volume of Synthesis Reactor (m^3)	Electrofuel Output (t/day)	y = 0.0598 x
	Mass of synthesis reactor (te)	Volume of Synthesis Reactor (m^3)	y = 1.25x

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3.7 Output and Volume Calculations for methanol, DAC method

The synthesis reactor is not 100% efficient in terms of use of feed gasses, and the ratio of gas input to gas used in the product varies significantly depending on the catalyst and reactor design. Anicic et al (2014) and Pérez-Fortes (2015) were used to derive ratios of 1.98 (50.5% efficiency) for CO_2 and 1.6 (62.5%) for H_2 in methanol synthesis. According to literature, H_2 and CO_2 should enter the synthesis reactor at a molar ratio of 3:1 Anicic et al (2014). Hence, the mass flow ratio can be determined as follows:

$$mass\ flow\ ratio(H_2{:}CO_2) = (3)2.016\ g/mol : (1)44.01 g/mol$$

Therefore, the mass flow rate of CO_2 entering the synthesis reactor exceeds that of H_2 by a factor of 44.01/6.048=7.2767. This agrees with Anicic et al (2014), where the expected ratio of reactants per unit of methanol are 1.3758/0.1892=7.2717. From this, the rate at which each reactant must be generated:

$$\frac{1.98 \times 7.2767}{8.2767} \text{ tonnes/day of } CO_2 \text{ and } \frac{1.6 \times 1}{8.2767} \text{ tonnes/day of } H_2.$$

Applying the relevant relationships from Table 4, it therefore takes a constant 0.01191 MW to generate the required CO_2 to create 1 tonne of methanol per day, with a throughput of approximately 4.54 million m^3 of air per day or 189,000m^3 per hour with a parasitic load of 151kW. Similarly for hydrogen, 0.19331 tonnes per day are required, at a constant electrical load of 0.345MW, and a heat load of 66.5kWth for steam generation, requiring 1.933 tonnes of fresh water per day with a parasitic load of 0.45kW. Considering Methanol, for the synthesis reactor:

$$y_{MeOH} = 36.67 x_{MeOH}$$
$$x_{MeOH} = \frac{1}{36.67} = 0.02727\ MW\text{e}$$

Therefore, producing 1 tonne of Methanol a day requires:

$$11.91 + 151.77 + 345.02 + 0.45 + 0.039 + 27.27 = 536.46\ kW = 0.536 MW$$

Given the micro nuclear reactor produces 5MWe, this allows for the production of 9.32 tonnes per day, and a thermal load of 1.78MWth, requiring an exhaust gas boiler. We can now apply the mass volume relationships to determine the volume of equipment required, resulting in plant equipment of 1385m^3 and 570te (minus the nuclear reactor, power conversion equipment etc).

3.7 Output and Volume Calculations for synthetic diesel, DAC method

Synthetic diesel with a chemical formula of $C_{12}H_{23}$ can be produced in reactors largely similar to methanol, such as tubular reactors (Awogbemi & Kallon, 2022). The molar ratio between hydrogen and carbon is reduced to 2:1. This is because a lower H_2:CO_2 ratio increases the probability of chain growth, as required for forming longer chain hydrocarbons such as diesel (Garcina et al, 2023). This is equivalent to a mass ratio of 10.92. Following the same method as for methanol, the ratio of CO_2 and H_2 required is:

$$\frac{10.92}{11.92}\frac{tonnes}{day}\ of\ CO_2\quad \frac{1}{11.92}\frac{tonnes}{day}\ of\ H_2$$

However the efficiency of gas utilisation is much more variable, with values for Fischer-Tropsch synthesis ranging from 60% to 90% carbon utilisation (Luo, 2021). For this analysis a value of 80% is used (i.e. a ratio of 1.25), while hydrogen efficiency also varies, being as low as 6% in some studies (Medrano-García et al, 2022). For a baseline the same efficiency as the meOH process was assumed, a multiplication factor of 1.6. This resulted in a rate of production of 12.32 tonnes per day for a 5MWe reactor, with a total plant volume (excluding reactor) of and mass of 1258m^3 and 519te. A much larger waste heat boiler would be required, of 2.57MWth capacity.

3.8 Output and Volume Calculations for synthetic diesel, water capture method

This system is dominated by the size of the CO_2 extraction system (WCS). To produce one tonne of CO_2 per day we find that the input water flow is 9643 tonnes/day, with a WCS volume of 89880m^3 and WCS mass of

41345 tonnes. This is clearly non-viable for a mobile application, although the volume is broadly consistent with the size of the land-based 300kg/day plant developed by Equatic (2024).

4. Application to an RFA

4.1 Containerisation

The methanol production takes 1385m^3, approximately 36 twenty-foot shipping containers, whilst synthetic diesel would require 33 containers. With each reactor and associated power systems adding 4 containers, even a small coastal container ship (typically around 200 TEU) could in principle support multiple plants.

4.2 Example Design

An example design for a naval "tanker" using the synthetic diesel plant was worked up using the UCL MSc Ship Design Exercise database. A summary of the principal particulars is shown in Table 5 and the simplified layout is in Figure 8. With four reactors in an IFEP configuration and three synthesis plants, this concept can generate 25 tonnes of synthetic diesel per day whilst proceeding at 20 knots and 37 tonnes per day at 15 knots, allowing complete refilling of the storage tanks in 11 days.

Table 5: Principal particulars of the example design

Length, waterline	141m
Beam, waterline	17.76m
Draught	5.46m
Depth, amidships	12.2m
Displacement, deep	8430te
Accommodation	122
Synfuel storage	500m^3
Synthesis plants	3
5MWe reactors	4
Propulsion motors	2 x 4.6MW
Emergency DG	4 x 1MW
Max Ship hotel load	1000kWe
Maximum speed & power	20 knots, 9.2MW
Cruise speed & power (high)	15 knots, 3.3MW
Cruise speed & power (low)	10 knots, 0.93MW
Helicopter	1 x 5-tonne class
Armament	Sea Ceptor, 30mm, decoys

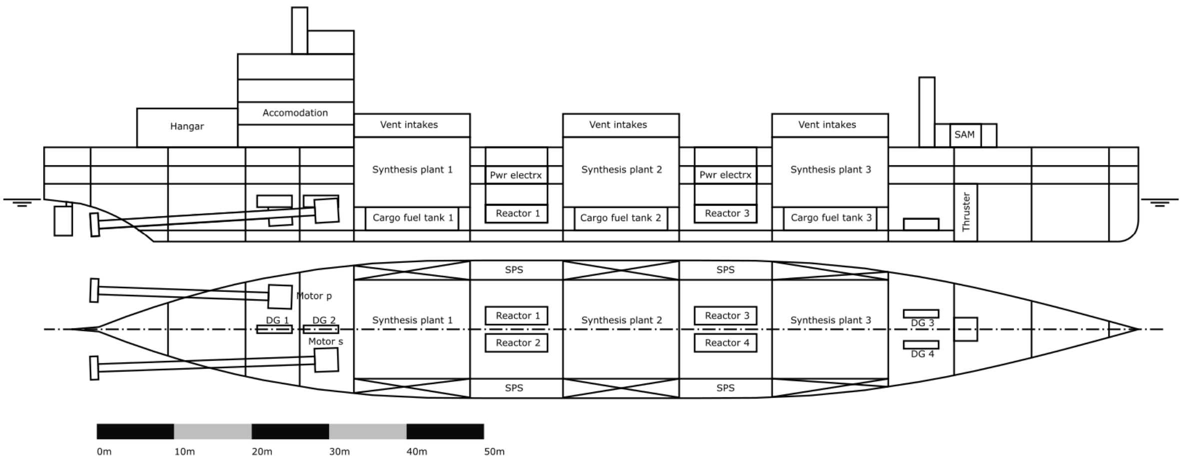

Figure 8: Outline general arrangement of the RFA

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4.4 Comparison with Combatant Fuel Loads

The example tanker is somewhat smaller than existing RFA tankers, the 39,000 tonne Tide class, and the number of reactors and synthesis plants chosen was somewhat arbitrary, simply to provide an illustration. The output of 63 tonnes per day can be compared with some combatant fuel loads shown in Table 6 below. The RFA could refuel a large OPV once a week or, possibly more interestingly, support a large number of USVs up to patrol boat size.

Table 6: Fuel loads of various naval vessels

Vessel	**Fuel (te)**
C-Sweep USV	2
Armidale Class PB	58
Aker PV-85 OPV	306
Aker PV-50 FAC	75
Vosper Mk 10 FF	537

5. Discussion and conclusions

The scoping study described in this paper indicates that a micro-reactor has the potential to generate useful amounts of synthetic fuel at sea; approximately 12.32 tonnes of synthetic diesel can be produced daily, at an overall efficiency of 80% when comparing fuel energy out (using LHV) and plant energy in (electrical and thermal). Table 7 summarises the breakdown by main component. Note that the air handling was treated as part of the parent ship for this analysis.

Table 7: Main component breakdowns as percentages of the total

	Mass	**Volume**	**Electrical**	**Thermal**
DAC	82.06	84.78	1.93	22.06
Air handling			24.60	
Electrolysis	16.07	14.44	59.03	
RO	0.09	0.19	0.08	22.13
Synthesis reactor	1.77	0.59	14.35	55.81

A significant proportion of the volume of equipment was related to capturing carbon dioxide. The characteristics of DAC, both physical and energetic are one of the main areas of uncertainty in this study. As this technology is expected to improve significantly over the coming years, this means that the overall electrofuel generation system has the potential to become more compact over time. The electrical load is dominated by the electrolysis process to generate hydrogen and if this could be reduced further by better utilising waste heat, fuel yields would increase. A high temperature electrolysis machine using steam as an input has electrical power requirements 50-70% those of PEM devices.

The indicative design uses modularised synthesis plants distributed along the ship. An alternative approach to be investigated would be the use of a single integrated plant. This is likely to be more efficient, and make better use of hull volume, but design integration increases design interactions, significantly increasing complexity and risk. There are several practical considerations that would impact a ship installation, including;

- Provision of sufficient air intake ducting and physical arrangement of the ducts on the upperdeck.
- Air treatment required before air is fed to the DAC.
- Sensitivity of systems such as the synthesis reactor to ship motions and shock.
- Additional power requirements due to air and water ducting and piping.
- Additional space requirements for access and maintenance.

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- Buffer tanks for CO_2 and H_2 with associated safety concerns.
- Structural integration such as foundations and seatings

These suggest that the results obtained in the paper serve as a lower bound estimate for the size and weight of the plant.

6. Future work

There are certain limitations with the work outlined in this paper. Many of the components used in the data collection component of this paper have varying applications and scales, including experimental, modular and industrial. As a result, some relationships consider equipment which was designed with differing priorities and thus characteristics. If possible, equipment data should be grouped by industry or technology to obtain a more accurate sizing relationship. A key point that emerged from the literature review is that there are many possible chemical processes to be considered, specifically combinations of catalysts, use of waste heat to improve efficiency etc.

An area of conceptual uncertainty is the cost and cost-benefit of a synthetic fuel generating tanker. Given the complexity of the systems on board, it is likely that such a vessel will be similar to a combatant in UPC/tonne, rather than a fleet tanker. However this has to be weighed against infrastructure and operational savings and advantages.

7. Declarations

This paper is based on, and contains several sections from, the first author’s final report and appendices submitted as part fulfilment of his final year individual project (Kapoor, 2024)

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