D1.1 Relevant identified technical solutions

Synergetics | Synergies for Green Transformation of Inland and Coastal Shipping

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Release Approval

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Abbreviations

CAPEX	Capital Expenditures
CCNR	Central Commission for the Navigation of the Rhine
CCS	Combined Charging System
DAC	Direct Air Capture
ESD	Energy-Saving Device
FAME	Fatty Acid Methyl Esters
GTL	Gas to Liquid
HVO	Hydrotreated Vegetable Oil
IMO	International Maritime Organisation
IWT	Inland Waterway Transport
LBM	Liquified Bio-Methane
LMG	Liquified Methane Gas
LNG	Liquified Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
MCS	Megawatt Charging System
MGO	Marine Gas Oil
NRMM	Non-road Mobile Machinery
OPEX	Operational Expenditures
TCO	Total Cost of Ownership
TRL	Technology Readiness Level
TTW	Tank-to-Wake
VLSFO	Very Low Sulphur Fuel Oil
WTW	Well-to-Wake

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Executive Summary

SYNERGETICS is an Innovation Action aiming at the green transformation of the existing inland and coastal fleet by creating synergies. On the one hand, synergies are sought with pilot and demonstration projects that are carried out outside of SYNERGETICS. Consortium partners are involved in many of these projects assessed within WP2, so that appropriate cross-linking is ensured. On the other hand, the findings from the project's own demonstrators (WP3) are compared and made available to the industry.

This deliverable "D1.1 Relevant identified technical solution" is the first deliverable of WP1 Exploration. It documents the findings of "Task 1.2 Inventory of technical solutions, including other industrial (transport) sectors, that are promising for use in the waterborne transport". This deliverable provides a compilation of knowledge available within the consortium and from external references on relevant technical solutions for reducing the specific energy demand or substituting fossil fuels. It includes an overview of developments and applications from other sectors as well.

Since the call topic HORIZON-CL5-2022-D5-01-04 focuses on "retrofit solutions to reduce GHG emissions that are developed and ready to deploy", technologies that may take a relevant role in the decarbonisation but have a low TRL today, such as ammonia or solid-state and redox-flow batteries, are left out of scope of SYNERGETICS and thus also out of scope of this deliverable.

Deliverable 1.1 shows that the special requirements of inland and coastal vessels are matched by a variety of technical solutions for reducing the specific energy demand and/or substituting fossil fuels. Some technologies offer a significant reduction in greenhouse gases (combustion engines with diesel pilot ignition) but may still emit a certain volume of air pollutants emissions. Others can achieve low or even below net-zero emission greenhouse gas in the well-to-wake cycle (especially bio-fuels made from substrates such as manure, green methanol, HVO from renewable resources) and can drastically reduce air pollutant emissions as well. Some options lead to zero-emission solutions (both for climate and air pollutant emissions), such as pure battery operation with electricity from renewable energies or fuel cell systems using (compressed) hydrogen made from renewable energy.

Since inland and coastal shipping as a sector is not a development driver in the true sense of the word, it can be more efficient to adapt technologies with already relatively high TRL to the requirements on board, i.e. to carry out marinisation. The resulting synergy effects between the sectors are a core topic of the SYNERGETICS project.

In addition to the introduction of new propulsion systems and/or renewable energy carriers, further improvements of the energy efficiency are highly relevant. There are different approaches to reach higher energy efficiency, such as optimised voyage planning (smart navigation and reduced speeds) and optimising the load factor and avoiding empty trips. One of the approaches is also to optimise the vessel capacity (dimensions), the hull shape and propulsors (hydrodynamics). All vessels, independent of type, size, transport task or even their energy system (fuel, green gas, battery, ….) will directly benefit from a reduced ship resistance. Primarily, less power and hence less energy are required to drive the vessel. Secondary or indirect effect is, that reduced power demand will lead to smaller engine sizes, hence less engine weight, smaller energy storages and, thus, less investment. The research performed within the project and the studies reported herein confirmed why shipping is listed among the hard-to-abate sectors. Due to the boundary conditions and special requirements for safe and economic navigation, even technologies with a high TRL or a positive business case in other sectors come with additional technical challenges in waterborne transport and/or significantly increased total costs of ownership in most applications. Therefore, greening the fleet requires careful case-by-case analysis and optimised selection and combination of measures.

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1. Introduction

1.1 Background

Mitigating climate change is a major social challenge and requires massive changes, not least in the transport sector. In combination with the need to reduce emissions of air pollutants that are harmful to health and the environment, considerable efforts are required to increase environmental performance of inland and coastal vessels. It is well-known that fossil fuel resources are finite and burning the fossil fuels is the main cause of global warming due to the related CO_2 emission. It is therefore well-known that a transition to alternative energy sources is necessary. A few decades ago, it was assumed that this energy transition would mainly be driven by the scarcity of oil reserves and the associated rise in costs. However, improved extraction methods and newly discovered, partly unconventional deposits, as well as global market conditions, are strongly dampening the price development. At the same time the urgency increases to take measures on short term to stay at least in the range of 1.5 degrees global warming. And in order to mitigate these climate change effects, the energy transition must take place while large fossil fuel resources are still available. The price development of fossil fuels, which are controlled by supply and demand, will not lead to the required transition to sustainable energy sources and technologies needed to reach the climate mitigation goal quickly enough.

Even though many non-fossil energy carriers and energy converters are known today, it is not likely that one technology will prevail like it happened for steam engines and their widespread replacement by Diesel engines. Today, environmentally friendly alternatives come with an economic surcharge in almost all applications and result in additional requirements and risks. To optimise the economic and operational viability, a thorough understanding of the technologies and matching of technical solutions with the requirements of each application is important. This deliverable D1.1 is the first deliverable of WP1 and provides a compilation of knowledge on relevant technical solutions available within the consortium and from external references. It includes an overview of developments and applications from other sectors as well.

The task description from the GA reads as follows:

"Task 1.2: Inventory of technical solutions, including other industrial (transport) sectors, that are promising for use in the waterborne transport (M1 – M12)

Existing and promising technologies and fuels need to be assessed and benchmarked to set the requirements as regards the acceptable costs, both for investment (CAPEX) and operational costs (OPEX). Using desk research and the networks of the consortium partners, alternative propulsion concepts, including sectors like rail, road and non-road, stationary energy generation, are identified and are assessed for their suitability for use in the waterborne transport. The database of the ESSF-SAPS (see https://sustainablepower.application.marin.nl/) will be used as a starting point for the energy carriers. This task elaborates

- *An inventory of technical solutions, including energy converters, hydrodynamic improvements and concepts from other sectors that might be suitable. The network's contacts to other sectors are used to gain in-depth information here.*
- *Formulations of concrete requirements of the waterborne transport industry or of type vessels on an alternative propulsion system.*

With the information gained, suitable future use cases to enable synergetic effects between the waterborne transport applications and other sectors will be identified and verified. This task is led by DST and supported by MARIN, SPB, OST, SNAOS and ANLEG with specific technical expertise on different technologies."

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For the identification of relevant technical solutions, the whole value chain of energy carriers needs to be looked at ("Well-to-Wake"). For the identification of relevant technical solutions, the focus in this document is on the technical part of the vessels, i.e. "Tank-to-Wake". The "Well-to-Tank" part will be described in further detail in Deliverable 1.2. To gain first insights into the full picture, a preliminary assessment for the Well-to-Tank part has been carried out using the Sustainable Power portal, presented in section 2.3. For this, several assumptions and simplifications have been made as described below.

1.2 Structure of this deliverable

The document describes the initial situation against which the SYNERGETICS project is being carried out. The inland and coastal fleets are presented and the general requirements for alternative propulsion systems for these vessels are described. This is followed by a presentation of the Sustainable Power Portal, which also serves as a starting point for the database of alternative energy carriers and the linked tools in WP4. The next part of the report deals with technical solutions that have been deployed in pilots within and outside the sector so far and thus contribute to the project idea of utilising synergies. The last part of the report focusses on the currently available technologies considered in SYNERGETICS: The alternative energy sources and energy converters as well as the implementation of hydrodynamic improvements to increase energy efficiency.

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2. Starting points

This section describes the initial conditions for this deliverable. The inland waterway and coastal fleets are briefly presented. The Sustainable Power Portal is also described. Important insights are gained and analysed from this in the report.

2.1 Classification of Inland and Coastal Fleet

Technical solutions for greening the fleet need to be assessed for their technical suitability and economic viability regarding both the inland waterway transport and the coastal fleet.

2.1.1 Coastal fleet

Within SYNERGETICS the fleet families of inland waterway vessels used for the CCNR-Studies [1] are amended by families for coastal vessels for short-sea shipping (SSS). It should be noted that there is no common definition of "coastal shipping" and "coastal ships" were not specified by the Call for proposals.

Within the context of the SYNERGETICS WP2 activities, the coastal ships were defined as "seagoing ships which operate in ports, along coastlines, between islands and in marginal seas". In the International Transport Workers' Federation (ITF) study on Decarbonisation, Coastal Shipping and Multimodal Transport, coastal shipping is defined as the "maritime transport that takes place between ports on the same continent. Also referred to as intra-continental shipping, short-sea shipping, marine highways, coastal trade and coast-wide trade.".

The ITF definition makes a reference to "short-sea shipping", which is, according to Eurostat, "the maritime transport of goods over relatively short distances, as opposed to the intercontinental cross-ocean deep sea shipping. In the context of European Union (EU) transport statistics it is defined as maritime transport of goods between ports in the EU (sometimes also including candidate countries and EFTA countries) on one hand, and ports situated in geographical Europe, on the Mediterranean and Black Seas on the other hand, i.e., ports in

- EU maritime countries;
- EEA maritime countries (Iceland and Norway);
- candidate countries;
- the Baltic Sea area (Russia);
- the Mediterranean Sea area (Algeria, Bosnia and Herzegovina, Montenegro, Egypt, Israel, Lebanon, Libya, Morocco, Occupied Palestinian territory, Syria, and Tunisia);
- the Black Sea area (Georgia, Moldova, Russia and Ukraine).

This definition is derived from Commission Communication COM (1999) 317 final of June 1999 on the development of SSS in Europe (page 2). As a result, short sea shipping also includes feeder services: a short-sea network between ports with the objective of consolidating or redistributing freight to or from a deep sea service in one of these ports, the so-called hub port."[2]

None of the definitions given above refers to specific vessel characteristics. In that respect, some indications are available from DNV which considers that coastal vessels have a deadweight under 5 000 dwt in common [3]. The largest container feeder vessels deem to be the Baltic max feeders with 1400 TEU (Sietas Type 178). Another indication is given in the German Funding programme for coastal vessels (*Nachhaltige Modernisierung von Küstenschiffen*) where a coastal vessel is defined as a seagoing ship that fits through the Kiel canal and, therefore, does not exceed the dimensions of 235 m length, 32.5 m width, 40 m height and 9.5 m depth. Both definitions are rather wide and do not specify the vessel types. To further underline the variety of ships which may be regarded as coastal vessels, a study on

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greening of Norwegian coastal shipping may be used which analysed three vessel types: a ferry, a fishing vessel, and an offshore supply ship.

Figure 1 shows the distribution of freight transported by SSS per sea region in 2015, showing the significance of this segment of maritime shipping for Europe. The map in Figure 2 shows the main SSS corridors.

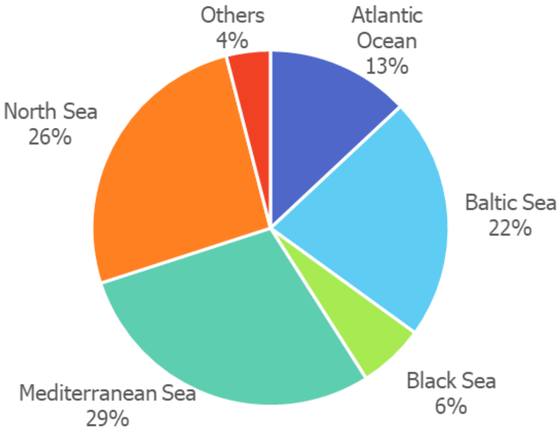

Figure 1 Short Sea Shipping (SSS) of goods by sea region of partner ports in 2015 (in % of total gross weight of goods transported)[5]

Figure 2 Short sea routes [6]

An overview of the shortsea shipping fleet is given in table 1. Russia holds the highest number of short sea shipping vessels, followed by Germany and Norway. Table 3 provides information on the annual fuel consumptions in thousand tons for some vessel categories mentioned in the 4th IMO GHG study. For the twelve countries listed in table 2, the fleet consists of a total number of 7,205 vessels which shows that the greening of coastal ships may have a significant impact.

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1 Distribution of the SSS fleet per country [5]

Residence of shipowner	Number of ships
Russia	1,265
Germany	1,199
Norway	930
Netherlands	737
Turkey	612
Greece	601
UK	522
Denmark	338
Italy	333
Ukraine	265
Spain	211
Sweden	192
TOTAL	7,205

2 Fuel use in kt/a of small vessels up to 5000 dwt [4]

	Size (dwt)	Avg. main engine power (kW)	Main	Aux	Boiler
Bulk Carrier	0-9999	1,796	1	0.3	0.1
Chemical Tanker	0-4999	987	0.8	0.3	0.9
Container	0-999	5077	2.6	0.7	0.4
	1000-1999	12,083	5.1	1.5	0.4
General Cargo		1454	0.6	0.1	0
Ferry (pax only)	0-449	1,152	0.4	0.3	0
	500-1499	3,182	0.7	0.3	0
	1500-2999	2,623	0.6	0.3	0
	3000+	6,539	3.5	0.9	0
Cruise	0-3000		0.1	0.4	2.2
Ferry Ro-Pax	0-3000	1,383	0.6	0.2	0.5
Refrigerated bulk	0-3000	793	0.4	1	0.5
Service-tug		1,086	0.3	0.2	0

It follows that, depending on the scope of the analysis, the coastal ships may include a wide variety of ship types operating on domestic as well as international routes, or even in fisheries. It is worth noting that the 4th IMO GHG study – which represents the most comprehensive inventory of maritime shipping emissions – considers international, domestic and fishing trips separately, which makes hardly possible to single out the emissions of coastal ships or even to pinpoint the "coastal fleet". Thus, SYNERGETICS shall focus on those segments of coastal fleet which can be adequately addressed in terms of greening and supported by sufficient experience from the pilot studies.

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2.1.2 Inland waterway transport fleet

Inland vessels are limited in size by the infrastructure of waterways, bridges and locks. However, the fleet of inland waterway vessels is far from homogeneous in its subdivisions. In fact, it is often heard that “each vessel in IWT is different” regarding its dimensions and its operational profile. With more than 12,000 vessels identified in 2015 [7] this showcases the difficulties in fulfilling all specific needs and requirements of the IWT fleet for decreasing the carbon footprint and further shows that a set of versatile technical solutions is needed to accomplish this. Hereunder, some examples of the diversity of the IWT fleet are presented.

When building an IWT vessel, a key question is how it is going to be used by its intended operator. Only a limited part of the fleet is operating as a liner service for its entire life. A majority is sailing on a constant O/D relation for limited time spans only, or as tramp service most of the time. Nevertheless, before ordering a new vessel, an operator will have a plan on how to operate the vessel in a profitable way, which will generally include a certain geographical area of operations and type of service. For example, cargo vessels are only profitable if they are effective at transporting cargo. Passenger vessels not only need to be effective, but also should be attractive and offer a high safety standard. Therefore, the operator will have plans regarding the origin and destination of the cargo he or she is going to transport with the vessel. In other words: he or she knows where the vessel has to sail and the volume of the cargo. Therefore, it will anticipate to needs of the client of the service and to the physical conditions it will encounter at a typical journey (such as the dimensions of the fairway and objects such as locks and bridges).

This area of operation can be general or very specific, but will determine the dimensions and technical equipment of the vessel. Given economies of scale, if the payload volume would be infinite, it would almost always be optimal to build each vessel as large as possible. However, as soon as an area of operation is identified, practical limitations become clear: available volume of payload (clients demand) and the physical limitations such as locks, bridges, canals, depth, and bends in rivers. All those parameters limit the size of a vessel. Since European inland waterways have a total length of 41,500 kilometres, divided into navigable rivers, lakes and artificial canals, this transport network is also very diverse. It has been classified in seven waterway classes by the European Conference of Ministers of Transport (ECMT). This gives users of the IWT network the overview of the dimensions on entire fairway stretches, which gives them the information needed to fit the size of the vessel to those of the intended fairways to be used.

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3 | Classification of the European Inland Waterways into CEMT Classes

	Motor Vessels			Pushed Convoys			Clearance height
Class	Length	Breadth	Depth	Length	Breadth	Depth	
	[m]	[m]	[m]	[m]	[m]	[m]	[m]
I	38.5	5.05	1.8 – 2.2				4.0
II	50 – 55	6.60	2.5				4.0 – 5.0
III	67 – 80	8.20	2.5				4.0 – 5.0
IV	80 – 85	9.50	2.5	85	9.5	2.5 – 2.8	5.25
Va	95 – 110	11.40	2.5 – 2.8	95	11.4	2.5 – 4.5	5.25
Vb				172	11.4	2.5 – 4.5	5.25
VIa				95	22.8	2.5 – 4.5	7.0
VIb	140	15.0		185	22.8	2.5 – 4.5	7.0
VIc				270 195	22.8 33.0	2.5 – 4.5	9.1
VII				285	33.0	2.5 – 4.5	9.1

As can be seen, the CEMT Classes give maximum values for Length, Breadth, Depth and Clearance Height for Motor Vessels and Pushed Convoys. Cargo flow destinations might be reachable through fairways of one or more specific CEMT classes, which thus limit the size of the vessel that might be used to service that destination. Since economies of scale dictate that it will often be the low-cost option to use the largest vessel (instead of using a smaller vessel for more trips), it is reasonable to expect that over time many vessels will be built dimensioned up to the limits of a specific CEMT category.

However, dimensions are not the only differentiating factor between vessel types. Vessels also significantly differ from each other following the type of cargo they are designed to transport. Cargo can be dry (e.g. dry bulks like sand, coal, ore et cetera and unitised cargo, like containers), usually transported in regular cargo vessels consisting of a large open hold that might be closed. However, liquid cargo is moved in tankers, vessels that contain large tanks inside their structure that are always closed. Pushers and tugs see use in and around ports where they are moving dumb barges for shorter distances, but large loads of coal, ore and other commodities are also being moved by push boats on larger distances. These freight transport categories are complemented by the different types of ferries and cabin vessels that transport passengers over short stretches (ferries across waterways) or during longer trips (river-cruise vessels of different sizes and dimensions).

Similarly, the age of vessels will differ a lot. Which can be distilled by looking at the two images below.

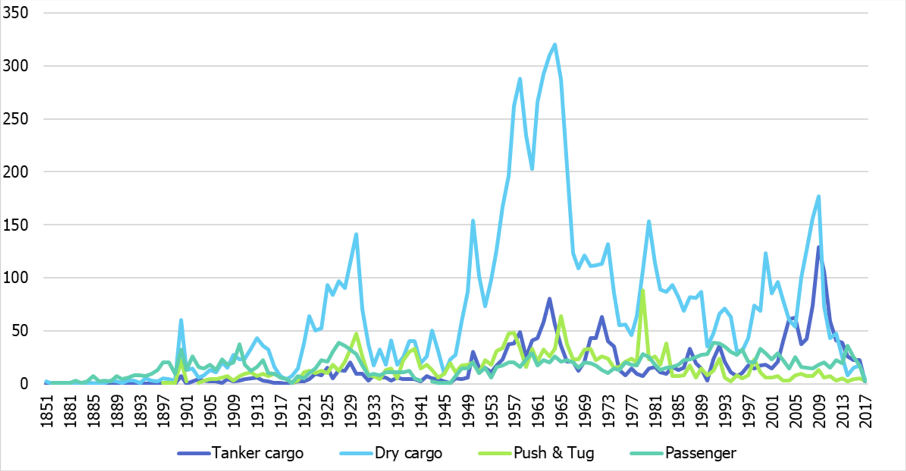

Figure 3 Commissioning activity for the Rhine fleet [1]

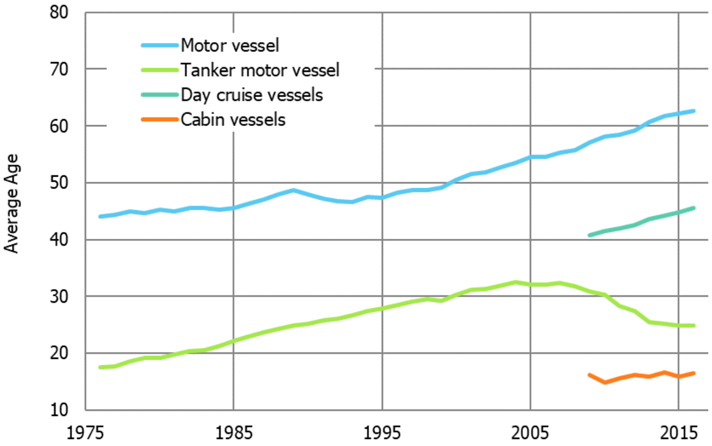

Figure 4 Age development of the German inland fleet [1]

Figure 3 illustrates the different periods vessel types were built. Fluctuation is heavy for all types, but especially Dry Cargo vessels have seen peaks around 1927, 1960, 1982, 2000 and 2010. Together with Figure 4, where the average age of the German IWT fleet is shown, it is made clear that some types of vessels are on average relatively old. Other types are younger, but variation is significant over the fleet. During the lifetime of these vessels, several significant alterations are sometimes made to fit new transportation demands.

The background information above explained the diversity and heterogeneity of the IWT fleet in terms of dimensions, outfitting for different goods to transport and age. Within the H2020 PROMINENT [8] project, research on these topics has led to the identification of a number of Fleet Families. These are shown in the table below, including a then-assessed number of operational vessels in Europe per fleet family.

4 | Fleet Families and Number of Vessels per Fleet Family , as identified in the PROMINENT project. [7]

Fleet families identified in PROMINENT	Total number of operational vessels in Europe
Passenger vessels (hotel/cruise vessels)	2,553
Push boats < 500 kW (total engine power)	890
Push boats 500-2,000 kW (total engine power)	520
Push boats ≥ 2,000 kW (total engine power)	36
Motor vessels dry cargo ≥ 110 m length	610
Motor vessels liquid cargo ≥ 110 m length	602
Motor vessels dry cargo 80-109 m length	1,802
Motor vessels liquid cargo 80-109 m length	647
Motor vessels < 80 m length	4,463
Coupled convoy (mainly class Va+Europe II lighter)	140
Total	12,263

Another important aspect of differentiation between IWT vessels is the lay-out of the engine room. The figure below shows the power installed on different IWT push boats. Here, we see a large diversity between what is essentially one specific subset of IWT vessels. The different levels of power installed further suggest significant differences between the dimensions of the engine rooms of these vessels.

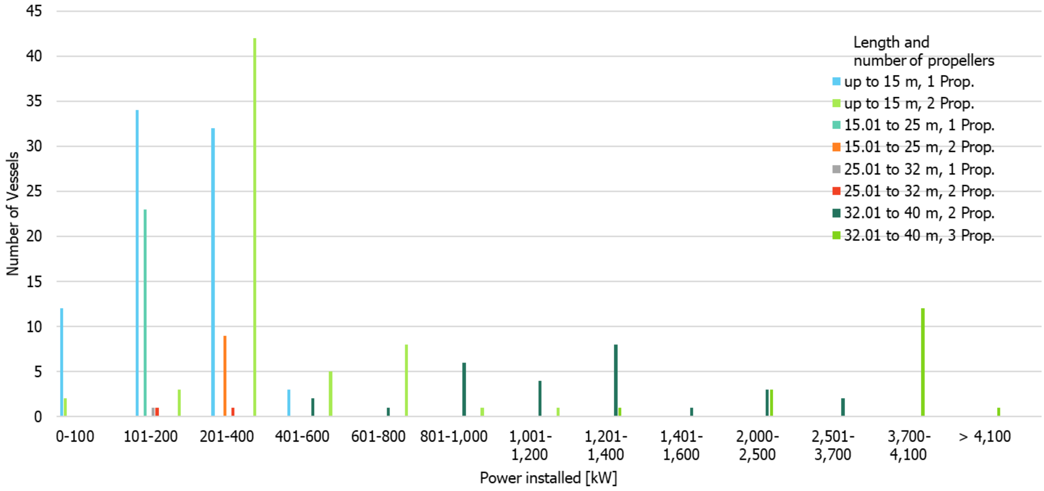

Figure 5 European push boat fleet: Installed power, number of propellers and length distribution of the fleet family [1]

Such a level of diversity between one subset of IWT vessels suggests also significant diversity between installed power in other subsets of IWT vessels and thus in IWT as a whole. Since the dimensions of the engine room are relevant for retrofitting a vessel and thus have direct impacts on the wants and needs of operators of specific vessels, it is another point that showcases the fact that multiple versatile solutions are needed.

This underlines the relevance of the SYNERGETICS project, which will match potential solutions with the many different types of vessels operating on inland waterways and/or coastal waters.

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2.2 Requirements for Alternative Propulsion Systems

The section describes the status quo of a conventional diesel-direct propulsion system and the derived requirements for low-emission alternatives. A conventional vessel's main engine room contains the engines for the main propulsion systems as well as a significant number of auxiliary engines and units. The steering gear, on-board power generators, compressors and pumps as well as the main electrical switchboard are typically located here. The drive engines determine the room layout because they have to be aligned according to the propeller arrangement. The other units and systems are positioned around these machines and grouped according to function.

As combustion engines may lose certain amounts of lubricants and oil over time, which must not be released into the environment, there has to be a collection container underneath the engine. The same applies to all other units in the engine room that can lose oil, such as the steering gear or the shaft bearings. Given the number of possible oil sources, the entire engine room is designed so that any leaking oil runs into the bilge of the engine room. Its contents are pumped out from time to time and disposed as hazardous waste.

Vibrations, noise and heat are generated when combustion engines are in operation. This affects the crew's workplace and often also the accommodation if no special precautions are taken. As a result, the engine room must be insulated against noise and heat and a low transmission of vibrations must be ensured.

For some alternative drive systems (especially those without combustion engines) these requirements or some of them might be reduced. On the other hand, it must be expected that other requirements will arise: For example, a gas-tight cabinet for a fuel cell or a battery management system and fire extinguisher that limits the risk of thermal runaway.

In general, a different safety philosophy applies to marine systems than to land-based systems. The acceptable consequences of a fatal failure or accident with the system may therefore be different. In addition to human damage, environmental damage can also have a different impact (water damage). Another important question is the time it takes for help to arrive at the scene of the accident. It is therefore possible that higher demands are placed on the system to contain the effects of damage.

In order to select suitable systems for inland and coastal shipping, these must also be available in the corresponding performance classes. In terms of range, the shipping industry may have to make adjustments, as in most cases it is not possible to cover the energy equivalent of a diesel tank with alternative energy sources on a one-to-one basis. Therefore, for alternative energy sources also the availability of bunker/recharging/swapping locations plays a role as well as the time loss as result of the bunker/recharging/swapping process. In this regard it can be noted that conventional vessels bunkering diesel can even be bunkered while sailing, resulting in no operational time loss at all. This is not (yet) possible with most of alternative energy sources, except for renewable drop-in fuels (or blends) such as HVO and FAME.

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Inland vessels

Costs are the largest hurdle for the energy transition of the inland waterway fleet. Both clean energy carriers as well as alternative energy converters are nowadays more cost-intensive than the Diesel baseline in almost all applications. As stated in the CCNR Studies, the investment cost for a classic diesel engine can be estimated with 375 €/kW. Maintenance costs were estimated with 7 % p.a. of the original investment cost. Current developments show that the estimation of 1 €/l Diesel is realistic. This follows an optimistic interpretation of the high price scenario in the CCNR Study [9]. All explicit cost estimations for investments and operational costs for alternative propulsion systems will be given in SYNERGETICS deliverable D1.2.

Based on the CCNR Studies the conclusion is that the investment, the maintenance and operating costs for all alternative drive systems are higher than for a conventional diesel engine under the current framework conditions. Higher costs result from more expensive energy carriers, equipment, loss of space, additional time requirements for bunkering, a lower range and other factors (often a combination of several). The higher 'Total Costs of Ownership' for the alternatives for diesel inevitably lead to a consideration of the financial situation in inland navigation. In addition to a few large shipping companies, the vast majority of the vessels is owned by many small and family businesses which often own just one vessel. These entrepreneurs are now faced with immense financing costs to make their vessel future proof in terms of greenhouse gas and air pollutant emission performance. According to current financing standards, it can be assumed that no vessel older than 20 years will receive a loan. However, it always is a case-by-case decision of bank, and elements such as the type of contract and the level of own capital play crucial roles here. A stable long-term contract between a vessel owner/operator and the client can make the difference in this regard. However, many vessel owners/ operators on the day-to-day spot market for which the revenues are hard to predict and volatile due to water level fluctuations and the dynamics in the wider economy.

It is therefore even more important that the SYNERGETICS project also emphasises that this financial gap should be brought to the attention of political decision-makers. The modal shift is the declared goal here which requires the inland fleet to be competitive from environmental point of view with road haulage. Here it must be considered that road transport already has an advantage on air pollutant emission performance and it is expected that road haulage will quickly reduce the CO_2 emissions as well by means of electrification of trucks using batteries[1]. A promising financing approach would be an innovation fund, which would be fed both from the sector itself and from external sources.

Since the European inland fleet is very diverse, there is not one-fits-all solution, but a differentiation at least amongst the fleet families must be made. Nonetheless, there are some key factors that apply for all alternative drive systems that are to be employed in inland vessels:

- Appropriate size, power and torque delivery matching the operations profile to ensure safe and efficient operation
- Long lifetime and maintenance intervals as well as short maintenance times and a good availability of spare parts and skilled workers
- Good implementation of redundancy, which is usually straightforward with electrified systems
- Planning certainty with regards to the availability and pricing of renewable energy carriers

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[1] See e.g. TNO report 2022 R11862 – Techno-economic uptake potential of zero-emission trucks in Europe (https://www.transportenvironment.org/articles/electric-trucks-take-charge/)

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Figure 6 shows the example of a profile of power consumption of a large inland vessel navigating upstream with a full load over the time of 5.5h. It shows that the power requirement is often changing during the journey, as the vessel has to manoeuvre on the river through curves and in narrow waters, pass segments with shallow water and therefore added resistance, and at the same time compensate the effects of the current on the course. With an average power of about 800 kW over 5.5h, the energy demand would be about 4.400 kWh or 1120 l of diesel, assumed a fuel demand of 220 g/kWh. This example clearly demonstrates that battery electric propulsion for this short stretch would already be a challenge.

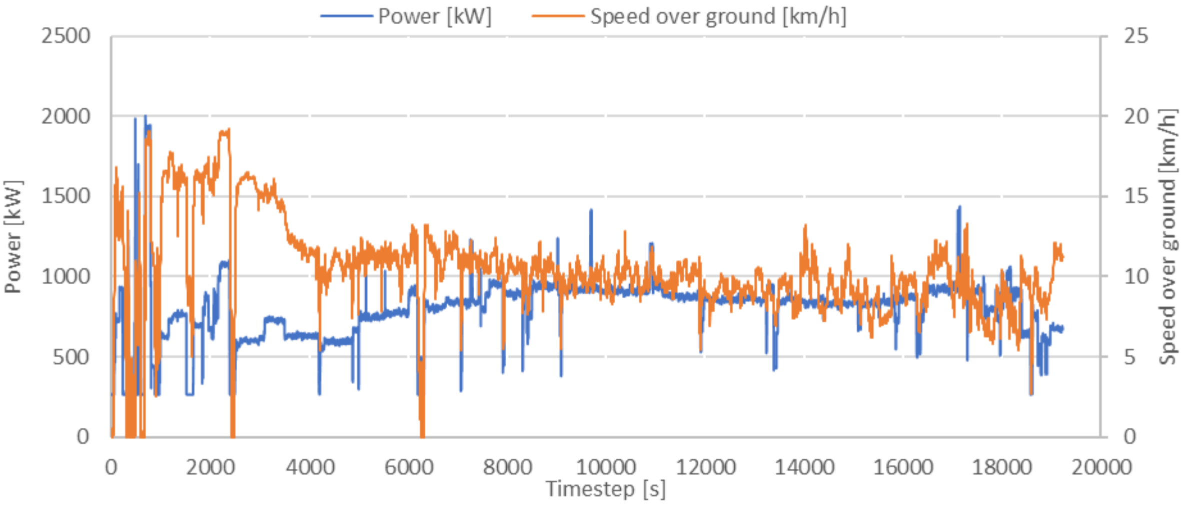

Figure 6 5.5 hours time series of speed and power of a vessel navigating upstream

There are also major differences between sailing upstream and downstream on waterways. Figure 7 shows 10 voyages in ARA-Rhine traffic. It is clear that around 40% of the installed engine power capacity is utilised very frequently. However, it is also clear that it is important that sufficient power reserves are available. The power reserve installed is used for at sailing upstream in high water conditions with currents, emergency stops, or when sailing as coupled convoy with one or more additional barges.

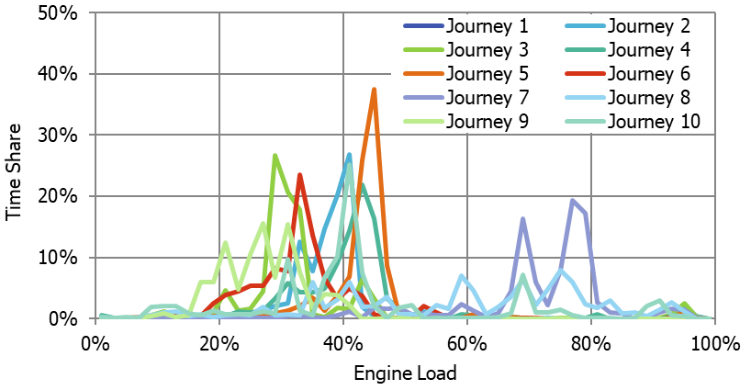

Figure 7 Operational profile of a container vessel during 10 voyages in ARA-Rhine traffic [10]

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In order to create a legal framework for the authorisation of alternative propulsion systems and energy carriers on inland waterway vessels so that the application for a derogation becomes obsolete, the temporary working group CESNI/PT/FC has been working on corresponding chapters for the ES-TRIN since 2020. In Figure 8 an overview of the time plan is given.

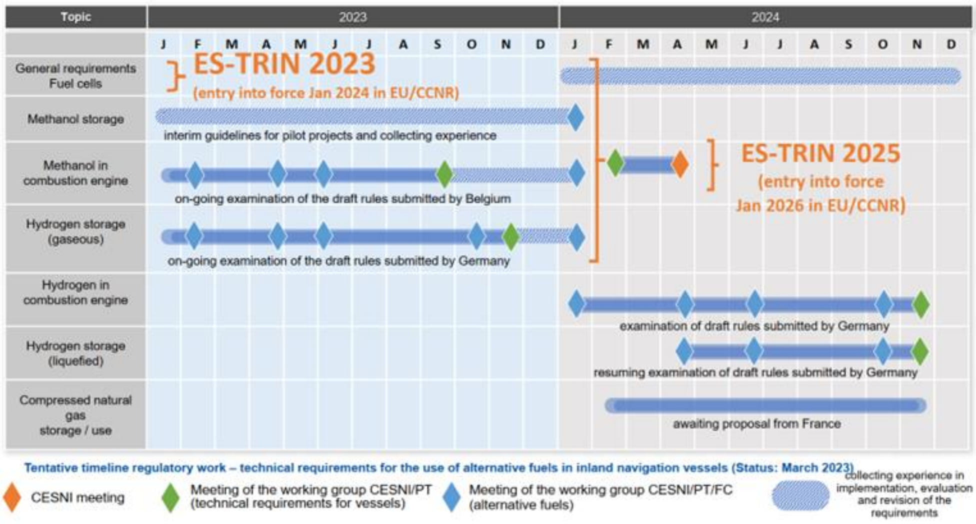

Figure 8 CESNI/PT/FC working plan

Coastal vessels

The cost for the (traditional) main power system per kW installed power is similar for coastal vessels. However, the fuel prices for seagoing were lower for a considerable period due to the use of fuels with high sulphur content (HFO, Heavy Fuel Oil) which is not allowed to be used since 2011 in inland waterway transport. Since the IMO sulphur-cap in 2020, more shipowners are switching towards low-sulphur fuels (VLSFO, Very Low Sulphur Fuel Oil or MGO, Marine Gas Oil), which are similar in cost to diesel fuel used in inland waterway transport. Alternatively, shipowners can also install scrubbers in order to comply with the sulphur cap. To date, alternative fuels like LNG have also been employed to comply with the sulphur cap. Other alternative fuels like methanol and hydrogen can also be used to this end. The same goes for the Tier III NO_X limitations, which alternative power systems can typically comply with without exhaust gas after-treatment, provided that no (or very little) diesel pilot-fuel is used.

In Table 5 the dimensions and a typical operational profile are given for a representative coastal cargo vessel. A high autonomy is listed in this case, and it implies that coastal vessels today are expected to be able to sail for days or weeks without refuelling, even though every few days a port call is made. It is therefore expected that for most vessels the autonomy can be reduced, if sufficient bunkering facilities are available (most coastal vessels are refuelled in port from a bunkering barge).

Most coastal vessels today have an internal combustion system with mechanical propulsion system. For vessels transporting cargo, this is typically the most attractive option from a cost perspective. Next to cost, vessel-owners prioritise RAMS (Reliability, Availability, Maintainability and Safety). When systems are not working as they should, not only high cost is involved, but also safety can be a concern. Unlike in inland waterway transport, where vessels often have redundant propulsion via steerable thrusters (or twin shaft configurations), coastal vessels typically only have a single shaft-line and a fixed tunnel thruster. However, vessels with electrical propulsion are required to have two electric motors on the same shaft [11] (Ch.2, Sec. 14, 2.1.2).

Various classification rules and guidance notes are in place concerning the use of alternative fuels and power systems. For example, when fuel cells are used for the propulsion power generation, also the fuel cell spaces and the energy storage tanks must be made redundant, [12] (Sec. 5 – 2.1.3) unless type C tanks are used, then only a redundant distribution system is required [13] (Sec. 9.3). It must be noted that all classification societies still require HAZID studies to be executed when using alternative fuels. However, unlike in the inland vessels, the engine (or fuel cell) certification process is much simpler. For coastal vessels it is not required to obtain approval in a lab-environment of the whole power system including exhaust gas after treatment.

5 | Typical sailing profile for a coastal cargo vessel running on MGO with a 4-stroke ICE direct power configuration [14]

Length	**Beam**	**Installed power**	**Displace-ment**	**DWT**	**Auton-omy**	**Operational conditions**	**Speed**	**Timeshare**	**Power**
m	**m**	**kW**	**m^3**	**ton**	**days**		**kts**	**%**	**kW**
General Cargo									
112	18.2	4290	12800	9216	30	Transit	13	55	3861
						Manoeuvring	5	10	558
						In port	0	35	0

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2.3 Sustainable Power Portal

As described in the grant agreement SYNERGETICS does not need to start from scratch to collect data on upcoming technologies. One of the most relevant sources, the Sustainable Power Portal (https://sustainablepower.application.marin.nl) was developed together with Sustainable Alternative Power for Ships (SAPS), a working group part of the European Sustainable Shipping Forum (ESSF). In order to support the analysis and assessment of the application of alternative fuels MARIN developed a method to support the concept design phase of a vessel. This method is called the Ship Power & Energy Concepts analyses, in short, the SPEC analysis. This analysis can be used in an early stage of a vessel design or retrofit and will be used within SYNERGETICS in WP3 for all demonstrators. Via this tool it is possible to compare the properties of different energy carriers and power systems, and the greenhouse gas emission reduction of a system.

In parallel the portal is realized in order to share the data on these basic properties of the components of the alternative fuels and related systems for energy storage and energy conversion. Given the mission profile, requirements and the constraints posed on the vessel a subset of "viable solutions" can be selected for further analysis.

In the following the use of the portal is explained.

Goal of the portal

The portal is a single point access to information which is updated on a regular basis based on MARIN research and input from the expert group "Sustainable Alternative Power for Shipping" from the ESSF. The database is not static, feedback from users and gained insights of projects result in updates of the database. In order to ensure a fair and transparent overview, all possible mature and upcoming solutions are gathered, including reference energy carriers based on fossil resources. This data is updated on a regular basis.

This portal provides a summary of the existing scientific knowledge on the performance and potential of different alternative sustainable fuels, energy conversion technologies for shipping, including their environmental performance on a complete well-to-wake approach, complemented, where appropriate, with life cycle considerations.

This overview tries to be as comprehensive as possible in order to be able to identify, where necessary, certain limitations that could hamper the uptake and deployment of the different technology (e.g. costs, lack of available fuel, safety concerns, etc.). A further analysis will indicate the measures necessary to overcome these.

Structure/Overview

In order to determine the Well-to-Tank impact in terms of emissions, the source and production process of an energy carrier are needed. With respect to the vessel the following elements are distinguished; energy carrier, energy conversion and power distribution & drives. This is structured in Figure 9.

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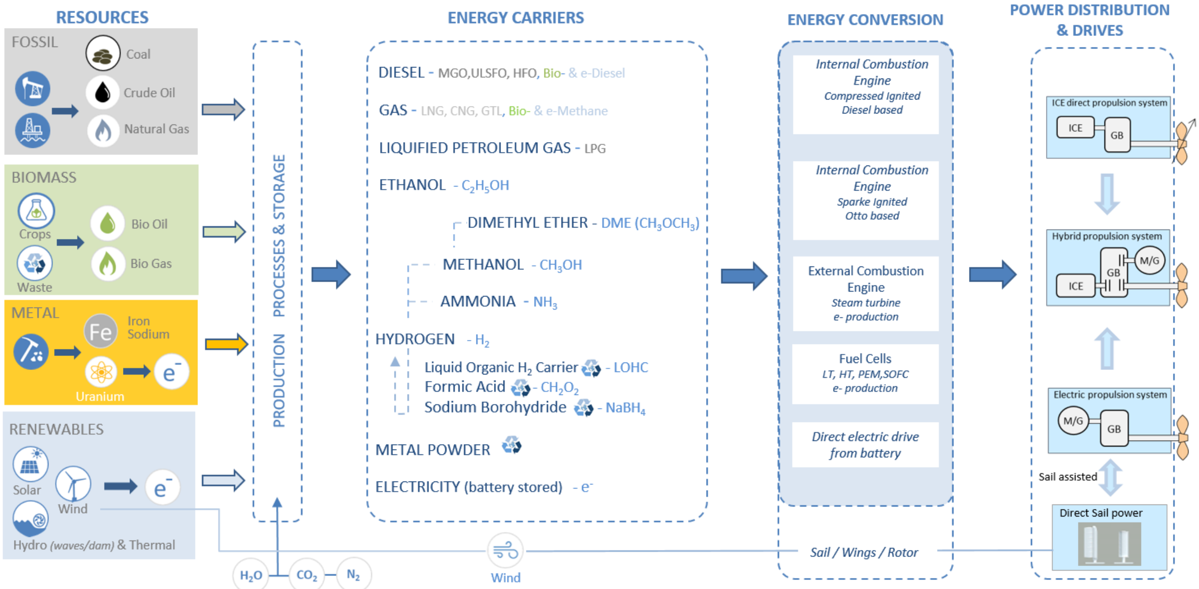

Figure 9 Visual overview of portal structure

The emissions produced by the vessel excluding upstream effects are called the Tank-to-Wake emissions. Overall, the emission caused by a sailing vessel, the Well-to-Wake emissions, are the emissions due to the production of the energy carrier and the emissions caused by operating the vessel:

"WTT emissions + TTW emissions = WTW emission"

Figure 10 shows the different tabs on the home page.

Figure 10 Different tabs on portal home page

1. Home
2. Data Table
3. Energy Carriers
4. Well-to-Wake
5. Pathways

The content of the different tab-pages

The *Home* page provides the overview and the email address to give feedback.

The tab *Data Table* provides an overview of the properties of the different components entered in the database, including the reference in case this is in the public domain. There can be multiple entries for each property, which are averaged to arrive at the values used in the analysis. There is a drop-down menu on "System type" to select the component (energy carriers, power distribution and drives, exhaust after-treatment, carrier pre-treatment, energy conversion). A property from a component can be selected using the "Feature" drop-down menu. The reference of the property can be viewed using the information button on the right.

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The tab *Energy Carriers* shows the averaged properties for each of the alternative fuels. The properties can be viewed in the "Energy carriers data table" shown on the top left. In addition, various plots are available to show the properties of the energy carriers. The CO_2 emissions can be viewed relative to the energy content of the fuel. These are the WTT and TTW emissions. The first are the emissions occurring over the production chain of the fuel. As it can happen that greenhouse gases are absorbed at this stage these emissions can be negative. The TTW emissions give the amount of CO_2 emitted when releasing the energy contained in the fuel. The emission of other greenhouse gases (CH_4 and N_2O) depends on the engine and is therefore not included here. In addition, other properties such as the weight of the fuel and including the tanks (containment) can be shown.

The tab *Well-to-Wake* gives the properties of combined solutions. This includes a fuel (energy carrier), engine (energy conversion) and the transmission. For these combinations the energy efficiency, greenhouse gas emissions and fuel cost are given relative to the energy transferred to the propeller. The energy efficiency gives the ratio of the energy contained in the fuel to the energy transferred to the propeller.

The tab *Pathways* also shows the combined solutions, but with the greenhouse gas emission reduction compared to a reference fuel. The lines indicate the combination of components in a solution and the emission reduction.

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3. Technical solutions

3.1 Concepts and Experience from other Sectors

While all sectors are striving for decarbonisation and economically viable solutions, the boundary conditions can lead to very different solutions even within the transport sector. Nevertheless, it is important to keep track of the development of the technologies and their application in other fields. It is not likely that the shipping sector will lead to significant leaps e.g. in battery technologies, fuel cells or new energy carriers, though methanol and ammonia utilisation are strongly promoted for waterborne applications but less in other sectors today. However, it is very relevant to make use of those developments and the economies of scale. In IWT already today marinised non-road engines with power up to 560 kW or marinised Euro 6 truck engines are deployed. These benefit from the larger market and shorter product cycles, allowing faster integration of clean technologies at moderate costs (see section 3.3.1).

It also helps to monitor the drivers and barriers for market uptake to understand the background of the deployed examples. Local public transport with low-emission buses in cities is often almost without alternative in order to fulfil the requirements of clean air plans. For heavy duty transport on roads the Commission proposed financial penalties of 4,250 EUR per gCO_2/tkm in 2025 and 6,800 EUR per gCO_2/tkm in 2030 in case of non-compliance with the CO_2 targets (amendment of Regulation (EU) 2019/1242). Incentive schemes are applied on various levels to accelerate decarbonisation and to motivate early adopters. This deliverable, however, is focussing on technical solutions.

The ongoing climate crisis and the urgent need for a sustainable energy transition have increasingly focussed attention on alternative drive technologies. These are seen as the key to reducing dependence on fossil fuels and minimising the environmental impact in specific sectors. The targeted selection of the appropriate energy source plays a decisive role in meeting the individual requirements of the respective sector and the diversity of renewable energy sources manifests itself in a wide range of options. This includes, in particular, the different aggregate states of renewable hydrogen, from gaseous to cryogenic liquid, which makes it a key player in the energy transition. In addition to hydrogen, ammonia and methanol other derivatives such as liquid organic hydrogen carriers (LOHC) are also becoming increasingly important. These substances not only represent a safe way of storing and transporting hydrogen with higher energy density, but also expand the form of molecular energy transport of green energy carriers. The integration of biofuels such as HVO, FAME, bio-/e-methanol and bio-/e-ethanol as well as regeneratively produced gases and liquid fuels such as synthetic methane and e-fuels also opens up a wide range of options for environmentally friendly drive systems with combustion engines or fuel cells.

3.1.1 Overview of various sectors

The diversity of green energy sources is reflected not only in their chemical structure, but also in their applicability in various sectors of the economy. In agriculture, alternative energy carriers and partly converters are gaining in importance, particularly through the use of biofuels such as biodiesel and bioethanol. The mining industry is testing and deploying alternative drives, particularly electric and hybrid drives as well as advanced hydrogen technologies. The same holds for some segments of freight transport on roads, where especially in urban logistics electric vans and trucks help to improve air quality with no or small cost penalties. Alternative drive technologies also play a decisive role in stationary applications.

Battery electric vehicles and plug-in hybrids have reached a share of over 15% in global registrations of new light vehicles in 2023. The ongoing development of longer ranges and the expansion of the charging infrastructure are promoting the acceptance and use of these technologies in the private sector. In passenger transport, the focus of the use of alternative drive technologies is on local public transport. Buses with fast-charging systems and hydrogen technologies are helping to improve urban mobility and at the same time reduce dependence on conventional fuels.

Heavy duty road haulage is preparing for the ambitious CO_2 emissions reduction targets (baseline 2019, -15% by 2025, -43% by 2030, -64% by 2035 and the goal of -90% by 2040) and the proposed financial penalties in case of non-compliance. Producers like Scania, Volvo, DAF, MAN and Daimler either have battery electric trucks available today or announced market readiness for 2024. Some new companies are entering the market without extensive background with conventional trucks. All of these HD trucks have a nominal range of 300 to 600 km with battery capacities ranging from 500 to 1000 kWh. It is worth noting that these trucks share the same maximum charging power of 350 kW via CCS (some offering 1,000 kW via MCS as an option) but use a variety of NMC, NCA or LFP cell chemistries. In addition, several countries are testing e-highways with overhead lines which might allow smaller battery capacities. However, the first pilot projects have already been cancelled due to the high infrastructure costs and sophisticated technology.

3.1.2 Non-road mobile machinery – current developments outside of IWT

Engines in IWT are regulated by the Non-Road Mobile Machinery (NRMM) directive (EU) 2016/1628. However, this also includes areas such as agriculture or mining and is currently experiencing significant developments in the field of alternative drive technologies. Adapting these technologies to the specific requirements of this sector is crucial for sustainable and efficient use in the non-road sector.

In agriculture, the use of biofuels such as bioethanol and the integration of electric and hybrid drives not only help to reduce emissions, but also enable an increase in the overall efficiency of agricultural processes through intelligent energy management. This development leads to a more sustainable agriculture by minimising the CO_2 footprint. However, certain requirements of autonomy of the vehicles have to be met as well as charging and energy carrier storing and supply options for the machines and vehicles used in agriculture. The increased use of alternative drive technologies is also having a positive impact in the mining industry. Electric and hybrid drive systems not only reduce air pollution in mines, but can also bring economic benefits in the long term by reducing operating costs through CO_2 compensation payments.

Technological advances and challenges

In the non-road sector, particularly in machines used for construction works, agriculture and mining, technological progress plays a decisive role in the integration of alternative drive technologies. Both electric and hydrogen drives are considered options for the future, whereby innovations in battery storage systems and electric motors are just as important as advances in hydrogen technology. The improvement of battery storage systems and the development of more powerful electric motors are ground-breaking innovations in the field of electric drives. At the same time, hydrogen-based technologies are also making progress. More efficient hydrogen fuel cells and advanced electrolysis processes are helping to further establish hydrogen as an environmentally friendly energy source.

Nevertheless, both technologies face similar challenges. Limited ranges of electric vehicles as well as the need for an efficient charging and hydrogen infrastructure are common hurdles. The integration of these technologies into existing operating processes also requires adjustments and careful planning. Refuelling with hydrogen plays a central role in the integration of hydrogen-based drive technologies in the non-road sector. The construction of hydrogen refuelling stations, especially in rural or remote areas, is an essential measure to ensure the practicality of hydrogen technologies. Another important aspect concerns hydrogen storage. Hydrogen is often stored in pressurised containers or in liquid form. The efficiency and safety of these storage technologies are crucial for the smooth operation of hydrogen-powered vehicles and machines. Advances in hydrogen storage technology, both in terms of storage capacity and safety standards, are necessary to maximise the potential applications of hydrogen in the non-road sector. The standardisation of refuelling protocols and storage technologies plays a central role in ensuring interoperability and efficiency. In principle, however, it can be said that refuelling with subsequent exchange of empty for full storage tanks is particularly advantageous in situations where large quantities of hydrogen are required, as this process often takes so long that it is considered impracticable. An interchangeable storage system must therefore be developed. In addition, it is essential to develop an infrastructure that enables the storage units to be exchanged quickly and efficiently, as the weight of the storage units themselves must not be neglected. A targeted approach to infrastructure and technology development will help to accelerate the integration of hydrogen-based drive technologies in agricultural and mining applications.

Examples of successful implementations

Practical examples of the successful use of alternative drive technologies in agriculture and surface mining demonstrate the potential of these technologies. Some applications for surface mining benefit extremely from regenerative braking systems in combination with batteries. When cargo is transported from a high origin to a destination on a lower level, the energy charged to the batteries downhill can even be sufficient to drive the empty truck uphill. A so-called "Perpetual motion electric truck" never needs to be charged with external electric energy [15], [16]. However, similarly favourable use cases and boundary conditions are unfortunately not to be expected in shipping.

One example is the wheel loader in mining. By integrating pressurised hydrogen storage systems with higher pressures of over 500 bar, it is possible to operate the wheel loader exclusively with hydrogen while driving. This high-pressure technology not only enables efficient storage of hydrogen, but also demonstrates the adaptability of this technology in the three-digit kilowatt range. This enables the hydrogen-powered wheel loader to fulfil its tasks in the mining industry with a minimal ecological footprint and contributes to sustainable development in this sector.

Another example from the non-road sector is the snow crawler, which also relies on pressurised hydrogen for propulsion. Particularly relevant in regions with wintry conditions, where batteries show performance losses, this snow crawler relies on high-pressure hydrogen storage tanks with pressures of over 500 bar. An innovative solution here is the integration of a refuelling station that charges the storage tanks when the snow crawler is not actively in use. This not only emphasises the technological development of hydrogen applications in mining, but also demonstrates the importance of the refuelling infrastructure to ensure continuous availability. These solutions are also in the kilowatt range and contribute to the environmentally friendly design of winter sports regions.

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3.1.3 Progress in passenger transport

Developments in the passenger transport sector are making steady progress with the introduction of alternative drive technologies. The focus here is on bus transport with fast-charging stations for purely battery-electric drives, as well as hydrogen refuelling stations with a high volume-flow when refuelling hydrogen vehicles. This area also includes the use of hydrogen trains as sustainable alternatives in rail transport.

Hydrogen refuelling and fast-charging systems in the context of local public transport

A comprehensive comparison between hydrogen refuelling and general fast charging, as exemplified by electric buses with fast charging technology, is crucial to understanding the advantages and disadvantages of both technologies in public transport. Fast-charging technologies, for example for electric buses, are proving to be particularly effective in urban areas with fixed routes and short stopping times. These allow vehicles to be charged quickly, optimise operating times and are comparatively easy to integrate into existing urban transport networks. Looking at more general use cases of fast charging, other electric vehicles also benefit from it, especially in urban environments.

It is essential to carefully weigh up the differences in infrastructure, range, operating costs and environmental impact in order to identify the optimum solution for each transport situation. This ensures that the selected technology meets the specific requirements and circumstances of local public transport.

Successful projects are already being implemented around the world that focus on the rapid refuelling of hydrogen and the fast charging of electric vehicles in public transport. Cities such as Stockholm and Hamburg, for example, have successfully integrated electric buses with fast-charging stations. Following a German pilot project for a hydrogen train, however, the battery-electric variant was favoured for future trains, as this is currently more economical [17].

Alternative drive technologies play a decisive role in passenger transport and in various modes of transport. Advances in the optimisation of gas control systems and filling station infrastructure have a direct impact on the possible applications and efficiency of these vehicles and vessels. For example, trucks can offer a sustainable and emission-free (tank-to-wheel) transport solution through the integration of optimised gas control systems and efficient refuelling infrastructure as well as fuel cells. The possibility of refuelling vehicles with high-pressure hydrogen and cold refuelling at the same time enables fast refuelling and optimises the use of hydrogen as a fuel. Trains, especially hydrogen trains, also benefit from this technology. With fuel cell applications, they can achieve greater ranges on non-electrified routes than purely electric trains. High pressure levels and cryogenic refuelling and the resulting fast refuelling contribute to efficiency and performance.

Challenges and outlook

The integration of alternative drive technologies represents significant progress, but it also brings common challenges for various sectors with it. A key challenge is the development of cost-effective and efficient energy storage systems. The development of a charging and refuelling infrastructure cross boundaries and the control of material and resource availability play a decisive role here. Equally important is the standardisation of technologies to ensure a smooth transition to sustainable drive solutions. Identifying innovation potential and the need for research is a key step in the further development of alternative drive technologies. Continuous research and development are essential in order to achieve technological breakthroughs and maximise the use of alternative drive technologies in various sectors.

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3.2 Energy Carriers

In the context of the desired decarbonization various alternatives to fossil diesel are discussed regarding their future use in the coastal and inland-waterway shipping sector which all have their individual characteristics, advantages and downsides. This section will discuss the various pros and cons of these energy carriers.

For the identification of relevant technical solutions, the whole value chain of energy carriers needs to be looked at ("Well-to-Wake"). For the identification of relevant technical solutions, the focus in this document is on the technical part of the vessels, i.e. "Tank-to-Wake". However, finally the whole value chain of energy carriers needs to be looked at ("Well-to-Wake"). The "Well-to-tank" part will be described in further detail in Deliverable 1.2. To gain first insights into the full picture, a preliminary assessment for the Well-to-Tank part has been carried out using the Sustainable Power portal, presented in section 2.3. For this, several assumptions and simplifications have been made as described below.

The Figures in this section have been generated with and extracted from the Sustainable Power Portal, and the PDF version of this deliverable has clickable figures, which are linked to additional and up-to-date information.

The energy carriers can be structured in different ways either by their production method, physical state or chemistry. Even though a certain overlap cannot be avoided, the following groups are used here:

- Hydrocarbons with different chain lengths reducing from diesel and diesel-like fuels with ten to twenty carbon molecules to methane with only one.
- Pure hydrogen and liquids used as hydrogen carriers. There is some overlap with the first group, when hydrocarbons or alcohols are used with reformers to separate the hydrogen.
- Electric energy stored "directly", i.e. not being produced on the vessel by means of converters.
- Metal based energy carriers, like iron powder and uranium.

All energy carriers in the groups need to be stored which can be done by different technologies/concepts resulting in different volumetric energy densities and also, due to the containment, different gravimetric energy densities.

All energy carriers can be produced with renewable sources (which is the focus in the SYNERGETICS project) such as renewable electricity or biological substrates, but also by using fossil sources such as oil, gas, coal or radioactive material.

3.2.1 Selection of energy carriers

Many energy carriers are being researched and may play significant roles in the energy transition of the transport sector in the future [18]. An important factor is the energy density, as seen in Figure 11 without containment (only the energy carrier), and including containment in Figure 12 (1 kWh = 3.6 MJ). Containment includes the storage system, but also auxiliary storage required on-board for spent-fuel (where applicable). Figure 11 and Figure 12 also show the Technological Readiness Level (TRL) by means of a bubble chart, in which the bubble-size determines the TRL. The very small bubbles represent TRL 4-5 technologies, which still require a lot of development prior to integration on-board. The larger bubbles indicate TRL 7 energy carriers, which implies they are ready for prototype demonstration in a relevant environment. These are the energy carriers that have focus in SYNERGETICS:

- Drop in-fuels (chemically similar to Diesel including FAME)
- Methane, be it compressed gaseous or liquified
- Methanol
- Hydrogen, be it liquid or compressed
- Electricity (stored in batteries)

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To have an emission reduction from well to wake, it is required that the aforementioned energy carriers are produced from sustainable resources. Moreover, the efficiency of the energy converter and power distribution are not taken into account here (see chapter 0). While methanol and diesel can be stored at ambient pressure and temperature, other solutions require high-pressure tanks and/or thermal insulation. As the proportion of carbon in the energy carrier decreases, so does its volumetric energy density (partly reflected in Figure 12), which is a challenge for mobile applications including inland waterway vessels.

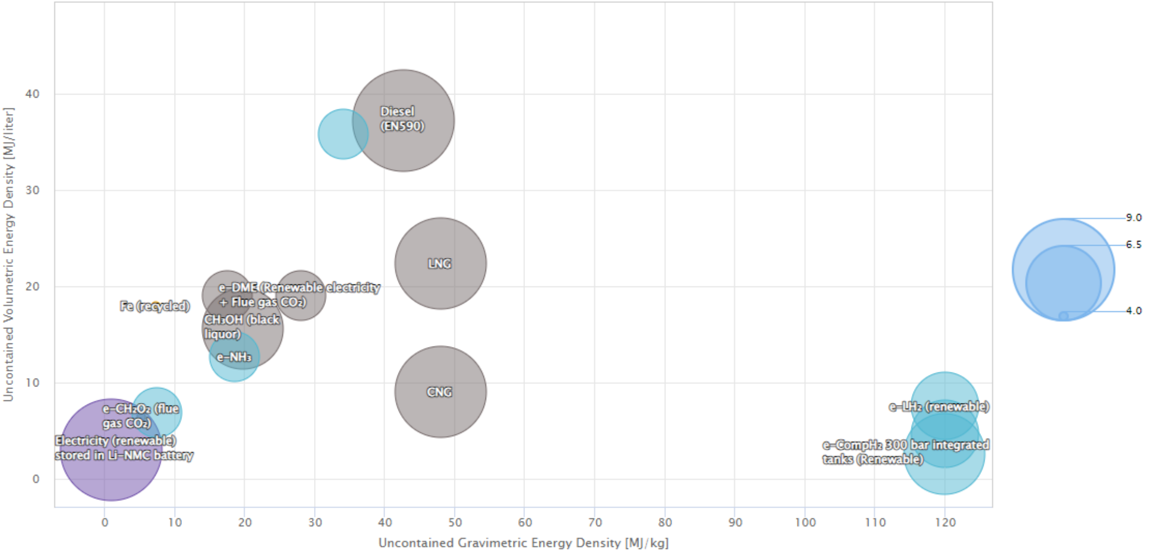
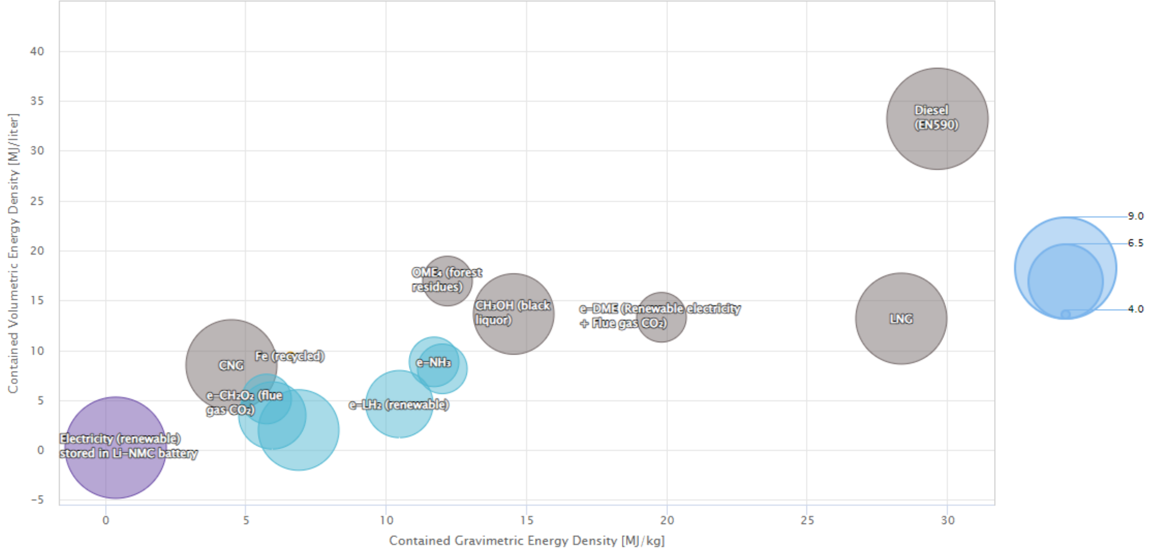


Figure 11 Plot of energy carrier density excluding containment. Bubble size indicates TRL (higher is larger bubble). Note that uranium is not plotted here as it has much higher values than all other energy carriers [19].



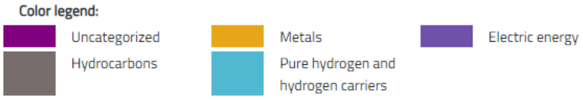


Figure 12 Plot of energy carrier density including containment. Bubble size indicates TRL (higher is larger bubble). Uranium is not plotted here as it has much higher values than all other energy carriers [19].

3.2.2 Comparison of energy carriers

This section will provide a high-level comparison of energy carriers. The following aspects are considered relevant herein, other aspects like availability and land-use issues of feedstocks will be addressed in upcoming reports:

- Energy efficiency of the energy carrier production (well-to-tank production efficiency)
- Greenhouse gas emissions of the energy carrier production (well-to-tank emissions)
- Greenhouse gas emissions of the energy carrier conversion (tank-to-wake emissions)
- Capital cost of the energy storage system
- Energy density
- Operational cost of the energy carrier
- Toxicity of the energy carrier
- Safety aspects of the energy carrier

The comparisons are presented in Figures and Tables in the following.

The well-to-tank production efficiency of various energy carriers was compared considering that all energy carriers were produced from renewable electricity (coming from wind and solar) and flue gas carbon capture (from an existing point source). Figure 13 shows that synthetic diesel (e-diesel) takes a lot of energy to produce. This has to do with the long chain of carbons that must be built. Batteries on the other side have the best performance, because they do not require physical conversion to store energy. The fact that batteries are very energy intensive to produce is not accounted for here. Pure hydrogen is relatively efficient because it is produced by electrolysis, a common step for all e-fuels. Liquefied hydrogen requires a lot of energy to obtain the required liquefication temperature of -253 °C.

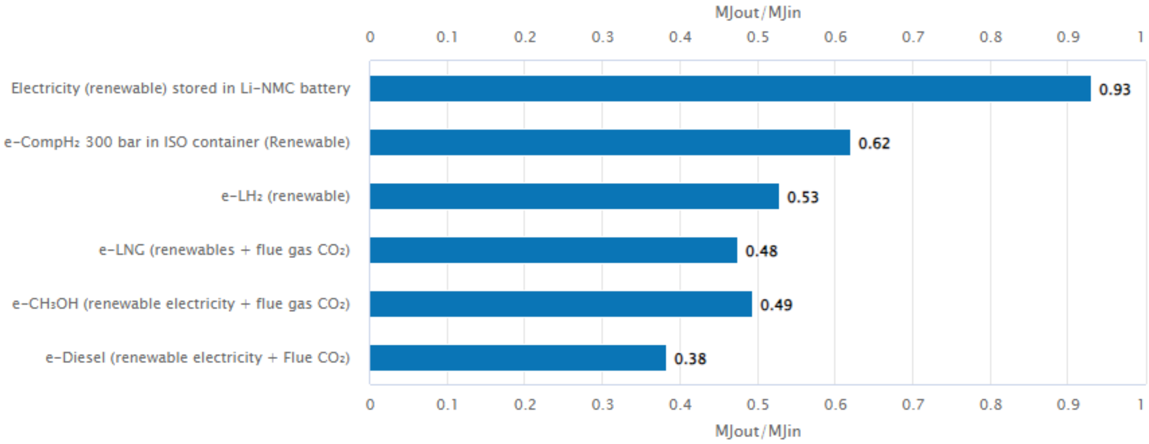


Figure 13 Well-to-tank production efficiency for energy carriers. This chart shows how much energy is required to produce an energy carrier and to get it on-board. Transportation of the energy carrier is not included [19].

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Comparing greenhouse gas emissions for energy carriers is a complex task. The emissions strongly depend on the used resource. Therefore, the comparison is made given a certain resource type; fossil, biomass or renewables. Yet, the comparison for CO_2, as presented in Figure 14 still shows a great scatter. Just considering the production, renewable hydrocarbons have negative emissions in the WTT scope if the carbons are extracted from the atmosphere (direct air capture, DAC) and bound in the fuel while other GHG emissions like methane slip are avoided in the production. When the energy is converted, these carbons are released again which should lead to a low overall CO2 impact resulting from remaining emissions due to processing the energy carrier (production, transport, storage, fuelling etc.).. The large error bars shown in Figure 14 show that a great uncertainty is associated with fuels based on biomass and other feedstocks. This is because different assumptions used for emission calculation are used. Palm oil plantations for instance can have a lot of land use change effects. Therefore, use of palm oil is already limited according FuelEU Maritime and other regulations. Lastly it appears that batteries that were charged with electricity produced using fossil fuels may appear very poor from Figure 14, but when considering that the vessel system efficiency of battery-electric is much higher than the others, it will actually not appear so bad anymore. What is also not considered in these results are other greenhouse gases, like methane slip (CH_4) and dinitrogen monoxide (N_2O, known as laughing gas). The emission of these gases depends not only on the resources used, but also on how the fuel is converted.

Therefore, expanding the energy carrier model with energy converters and including CH_4 and N_2O emissions is necessary to provide a complete picture on the greenhouse gas emissions. This is presented in Figure 15, showing the total greenhouse gas emissions from well-to-wake, using a pre-defined energy converter. More details on these converters are provided in section 3.3. In contrast to Figure 14, battery electric from fossil energy is now not as bad anymore: it even slightly outperforms a vessel running on Diesel EN590. This has to do with the higher system efficiency. It is important to note that energy losses in transportation are not modelled here, and these may be significant. It is also clear that other alternatives, produced from fossil resources are worse than fossil diesel. Biofuels can provide a substantial emission reduction, provided that the right resources are used. It is also clear that very few alternatives are expected to be fully climate neutral.

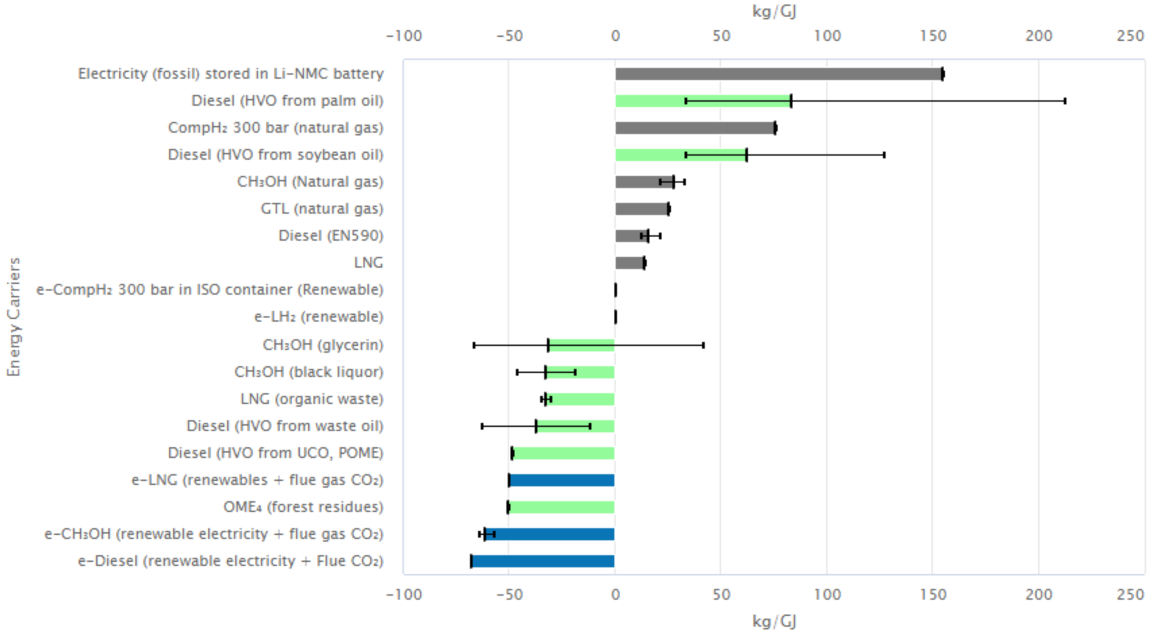

Figure 14 CO_2 emissions from well-to-tank of the energy carriers under consideration, using multiple feedstocks: blue: from renewable electricity and carbon capture, green: from biomass, grey: fossil resources [19]

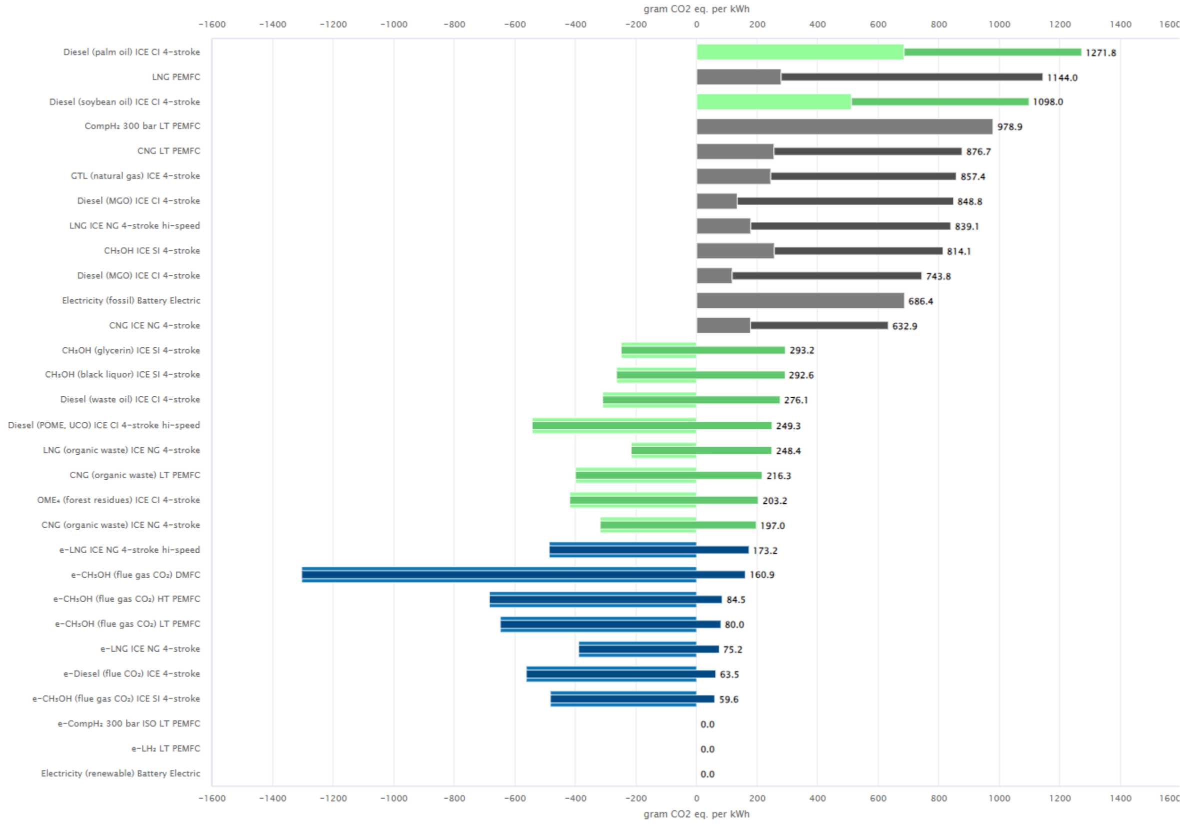

Figure 15 CO_2-eq. emissions from well-to-wake of the energy carriers including energy conversion system and including CH_4 and N_2O emissions according a 100-year global warming potential calculation. The unit is g CO_2-eq/kWh where a kWh is the useable energy at the shaft or auxiliary power system. Thick bars show well-to-tank, thin bars show tank-to-wake [19].

Costs are also an important factor when considering alternatives. In this analysis the focus is on the energy carrier: what does it cost to store (capital expense) and what is the cost of the usage (operational cost). The total cost of ownership can only be calculated when considering the entire system (converter, distribution).

Figure 16 presents the capital expenditure for the energy carrier storage system. Here batteries are significantly more expensive. Note that these values represent an order of magnitude, the variation is large depending on supplier, material and exact scope of supply. Hydrogen is the second most expensive to store due to the cryogenic storage or thick steel tanks required, and methanol storage comes close to diesel storage systems.

Energy carrier cost is also important to consider, though it highly fluctuates depending on market conditions. The Sustainable Power Database includes figures based on costs which were published in various studies over the last years, however, due to market circumstances these costs are no longer representative and therefore excluded in this report. Therefore, upcoming work in SYNERGETICS aims at a database which will be maintained beyond the lifetime of the project with updated figures. To have some idea of future renewable energy costs makes sense to consider the well-to-tank production efficiency as presented in Figure 13. In principle, less conversion steps (i.e. battery-electric) will exhibit the lowest costs. Though other than market circumstances, these factors can also affect energy supply cost: 1. certification and permit needs, for example hydrogen might require a lot of procedures and permits in order to be certified at a bunker station. This can make it very expensive in practice.

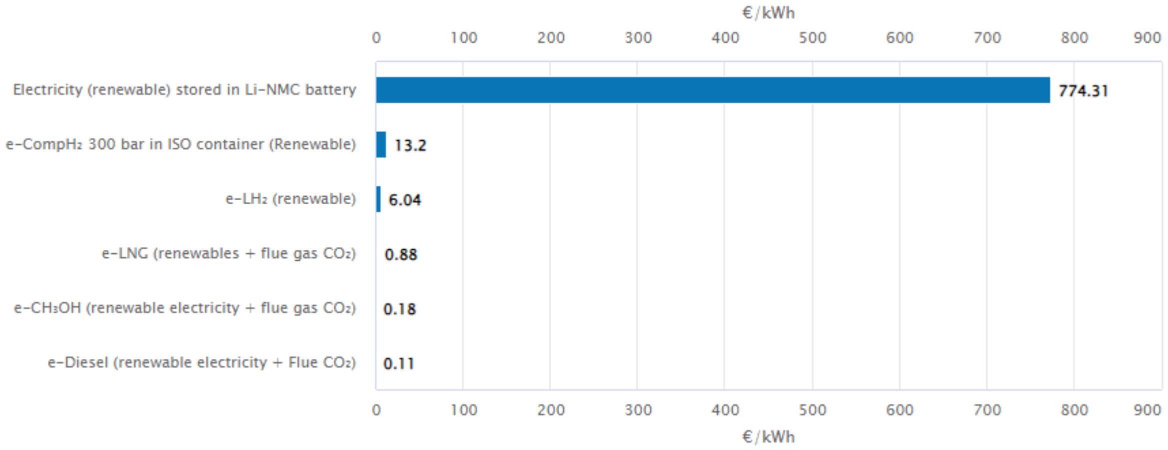

Figure 16 Capex (capital expenditure) for energy carrier storage on-board [19]

Other aspects to consider when selecting energy carriers are toxicity and safety. Whilst all technical solutions require class approval, complemented by hazard identification (HAZID) studies where necessary, which will reduce the risk that failures lead to a hazardous situation. Nevertheless, it is important to consider what unexpected situations can lead to. When considering a leakage of the fuel tanks, the exact effects are difficult to quantify. Methanol will dissolve, liquid hydrogen quickly turns to gas-phase. But diesel oil (also bio-based) will remain for a long time and requires intensive cleaning. When it comes to vapours and the toxicity of them to humans, methanol is a concern as it is toxic. The other technologies are relatively harmless from this point of view, though Li-NMC batteries can also emit toxic gases when a thermal runaway occurs. Table 6 gives qualitative summary of the toxicity per energy carrier.

6 | Overview of energy carrier toxicity to aquaculture and vapours to humans [20]

ENERGY CARRIER	SCORE FOR AQUACULTURE	SCORE FOR VAPOURS
Methanol	++	-
Methane	-	+
Batteries (Li-NMC)	+/-	+/-
Diesel	- -	+
Hydrogen	+	+

From this qualitative comparison, hydrogen appears to be the best option and possibly also electricity directly stored in batteries on the vessel.

Lastly fire safety is considered. As mentioned in the previous paragraph, by means of class approval and HAZID studies the risk of fire should be mitigated, which will require mitigation measures to be put in place. Simply said, fuels with a higher risk of fire/explosion will require more mitigation. Thus, the fire safety can also be considered in terms of mitigation level needed. When we try to compare the energy carriers under consideration it can be said that compressed hydrogen has the "worst papers": it requires little effort to ignite. An advantage however is that any leakage of hydrogen quickly rises into the atmosphere. Which is why compressed hydrogen should be installed on open-deck. The high-pressure storage can be more likely to result in explosions, when a fire occurs. Liquid hydrogen is less dangerous from this perspective because it is cryogenic, and there is low pressure. Methane has a higher flashpoint and does not rise like hydrogen because it is much heavier. The first risk is still considerable. Batteries (Li-NMC) also require a complex control system to check the state. There are also other chemistries which have a higher intrinsic safety. Methanol is also a low flashpoint fuel, and requires mitigations to fire hazards, but the fact that it is a liquid under normal conditions helps. Diesel (or other drop-in fuels) require the least amount of mitigation.

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7 | Overview of intrinsic fire safety [20]

ENERGY CARRIER	INTRINSIC FIRE SAFETY
Hydrogen compressed	---
Methane/CNG	--
Hydrogen liquid	--
Methane/LNG	--
Batteries (Li-NMC)	-
Methanol	+
Diesel/HVO/FAME	++

3.2.3 Description of the energy carriers

This section will describe the various energy carriers in more detail.

3.2.3.1 Drop-In Fuels: e-Diesel and HVO

A diesel engine is the workhorse of almost every commercial vessel nowadays and will be in the mid-term future as it offers high performance over a long period of time. To reduce dependence on fossil fuels and mitigate climate change by releasing greenhouse gases, sustainable alternatives are gaining attention. Drop-in fuels are interchangeable substitutes for conventional fossil hydrocarbons (gasoline, jet fuel, and diesel), meaning they do not require significant adaptation of the engine or the fuel system. Referring to Figure 9, Drop-in fuels are basically Diesels made from the Biomass or Renewable resources (E-diesel).

Usually, they are standardised as paraffinic fuels according to EN 15940 and can be used “as is” in currently available engines either in pure form and/or blended in any ratio with conventional fuels. However, lubricants and some engine control parameters might need to be changed in coordination with the engine manufacturer to improve efficiency and/or environmental performance. For IWT the engines have to to be certified under the NRMM directive. This includes, that the fuel has to be specified in the manufacturer’s fuel directive and the type approval for each engine series according to the recent emission standards. Since the type approval process is elaborate with extensive hours on the test bench and costly compared to the small market, standardization and the future usage and availability of blends or pure drop-in fuels have to be coordinated far in advance. The guidelines related to this topic published by the European Association of Internal Combustion Engine Manufacturers can be surveyed online (EUROMOT 2020) and are subject to continuous further development. For coastal vessels running under IMO regulation the situation is much easier.

Among the drop-in fuels that are considered important for inland navigation are Gas To Liquid (GTL) and Hydrotreated Vegetable Oil (HVO). GTL is produced with the Fischer-Tropsch synthesis, a process generally called X-To-Liquid (XTL) that was developed by Franz Fischer and Hans Tropsch in 1925. The “X” is a variable and is replaced by an abbreviation of the original energy carrier, e.g. “G” for gas. Within this process various liquid synthetic fuels such as GTL, lubricating oils and other paraffinic products for the chemical industry can be obtained from natural gas, other gasified fossil fuels or biomass. HVO is a mixture of straight-chain and branched paraffins, the simplest form of hydrocarbon molecules under the

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aspect of clean and complete combustion. Typical carbon numbers[2] are C15…C18. In addition to paraffins, fossil diesel fuels contain also significant amounts of aromatics and naphthenes. Aromatics impair a clean combustion. HVO, on the contrary, does not contain aromatics, and its composition is similar to that of GTL and BTL diesel fuels, produced by the Fischer-Tropsch synthesis from natural gas and gasified biomass. HVO should not be mistaken with the classical biodiesel, which is a chemically fatty acid methyl ester (FAME) and could cause trouble in long-term storage and being used as a fuel substitute in conventional engines. Today this is the most commonly used biofuel, as the EN590 diesel contains a 7% blend with fossil diesel (B7). Increasing the blends of FAME is a greater challenge than for HVO and not covered by usual test fuels. Nevertheless, FAME and higher blends with fossil fuel (e.g. B20) are increasingly considered as an option for the shipping sector due to the lacking competition with aviation and currently being deployed on a few inland ships.

Future XTL diesels, could be so called e-Diesel when based on hydrogen made from renewable electricity and carbon capture. The most important downside of e-Diesel is that it requires a lot of energy for the synthesis as seen in Figure 13. [1] In fact, it is the less efficient path of today's options, with less than half of the in/out efficiency compared to the direct use of electricity. Also, environmental impacts in case of leakages are higher than for other (renewable) energy carriers.

3.2.3.2 Methane (LNG or CNG): e-LNG/CNG or bio-LNG/CNG

Methane (CH_4) is an odourless, colourless, non-toxic and non-corrosive gas with a flammability range of 5 ÷ 15% of fuel-air mixture. It is the main component (>90%) of fossil natural gas with the rest mostly ethane, propane, butane and nitrogen. If gaseous and compressed it is called CNG, in its liquefied state LNG for Liquefied Natural Gas. Besides usage as a fuel in combustion engines it can also be used as a hydrogen carrier for fuel cells in combination with a reformer or directly in Solid Oxide Fuel Cells (due to the low TRL not covered here). LNG shall not be mistaken for LPG (Liquefied Petroleum Gas, mainly consisting of propane and butane). Due to its lowest possible carbon content of all hydrocarbons, methane has a potential to reduce CO_2 emissions when used as a fuel (in the range of 10% to 20% compared to diesel, if engines are optimised for the use of natural gas). Nevertheless, since methane gas is itself a very climate-impacting gas, leakages are way more critical. Thus, methane slip must be kept under control when CNG or LNG are produced, distributed and used as fuel in order to maintain the advantage of low emissions from combustion; and to ensure reductions in greenhouse gas (GHG) emissions while using LNG. The 20-year Global Warming Potential (GWP20) of methane is as high as 84 times the GWP of CO_2. Due to the chemical persistence of methane the GWP for a period of 100 years is lower. However, the emission of 1 kg of methane still would heat up the earth by the same amount as 28 kg of carbon dioxide in a period of 100 years (GWP100).

LNG is produced by cooling down natural or synthetic gas to minus 162 °C, thus converting it to liquid state for ease of storage and transport. Remaining CO2 has to be removed completely before. To be renewable, methane could also be produced as a power-to-X fuel with renewable electricity or by using biologic substrates. Renewable methane can be blended with natural gas and used directly as a renewable substitution. When the methane is produced from biomass or based on electric power it should not be called "natural gas". Therefore, bio-LNG is a misnomer and the term Liquefied Methane Gas (LMG) should be used instead. In case LNG is spilt, it evaporates, forming visible "clouds". Portions of the cloud could be flammable or explosive under certain conditions.

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[2] The carbon number is the number of carbon atoms in each molecule of hydrocarbons.

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Methane is considered a low flash point fuel which imposes certain mitigations for on-board storage. A fuel-air mixture of about 10% methane in air (the middle of the 5 ÷ 15% flammability limit mentioned above) and at atmospheric pressure might be ignited if it does encounter an ignition source (a flame or spark or a heat source with 540 °C or more). Otherwise, the vapour will generally dissipate into the atmosphere. LNG contributes to a significant reduction of sulphur oxides emissions (SO_X) in seagoing applications, nitrogen oxides emissions (NO_X), particulate matters (PM) and carbon dioxide emissions (CO_2) from vessel engine exhaust emissions in comparison to diesel fuels. In comparison to diesel CO_2 emissions are reduced by 10 to 20%-. When the methane slip is included, the GWP or CO_2 equivalent is about 5% lower with the current technology used in inland waterway transport [21] (4-stroke high speed engines). In the future further reductions of methane-slip can be expected. Pollutants are also reduced by using methane. Particulate matter is reduced by nearly 100%, NO_X emissions have a large bandwidth but are sometimes reported to be lowered by up to 90% and even more. However, these differences are already substantially reduced by contemporary emission legislation and exhaust gas aftertreatment which is currently required for newbuilt vessels and required for engine replacement in existing vessels. The reduction of SO_X known from the maritime sector only plays a minor role in inland-waterway shipping due to the use of very low sulphur fuels since 2011.

3.2.3.3 Methanol

Methanol is the simplest member of the group of alcohols with the molecular formula CH_3OH making it rich in hydrogen with only a single carbon atom. It is a clear colourless liquid with a density of 0.79 kg/l. It is today mainly produced from fossil sources (natural gas), but can also be produced regeneratively. There are various ways to produce renewable methanol. One is to capture CO_2 from geothermal power generation which is then reacted together with renewable hydrogen (produced via electrolysis) into renewable methanol. Other methods are to convert biogas from fermentation or gasification of sustainable biomass into bio-methanol as well as producing it from solid waste feedstocks. It is also produced as a by-product of the kraft pulping process in paper production. Methanol can be used in adapted combustion engines or as a hydrogen carrier for fuel cells. Reforming at 300 °C produces H_2-rich reformate gas. When used with a Proton Exchange Membrane Fuel Cell (PEM FC), a fine purification is necessary. Reforming reduces the overall system efficiency of a FC system. Methanol is toxic when inhaled, but when leaked into water it quickly biodegrades. Due to the liquid property of methanol (it remains liquid up to a temperature of 60 °C at ambient pressure), the advantage of methanol is that it does not require pressurised or cryogenic storage tanks. And with that it also has a relatively high energy density. Due to the corrosiveness, materials for piping and tanks need to be selected carefully and components of engines to be retrofitted have to be considered. Stainless steel or appropriate coatings (Zinc) are proven solutions. The release of methanol on-board requires a careful safety assessment, as it is not only toxic, but also a low flash point fuel. In addition, the oxidation of methanol can produce methanal (CH2O, also known as formaldehyde) which is not only toxic but also cancerogenic and able to denaturise proteins. This needs to be considered carefully in the control of combustion processes and potential after-treatment systems.

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3.2.3.4 Hydrogen

Hydrogen (H_2) is gaseous under normal conditions (15°C and 1 bar) with a density of 0.08409 kg/m^3. Hydrogen is the most commonly known chemical element and can be transported as compressed gas liquified at -253°C or in a derivative like ammonia for longer distances. Generally, gases can be liquefied at high pressures or low temperatures. Hydrogen cannot be liquefied at all above –240 °C no matter how high the pressure is. Usually, liquid H_2 is stored at ambient pressure below –254 °C, about 90 °C below the temperature of LNG. Liquefaction of hydrogen is an energy demanding process, requiring about one third of the stored energy content. Pressurization up to 800 bar requires less energy (in the range of 10%) and is more common today even though the volumetric energy density is lower (Figure 11). Currently, there is much active research on how this process can be made as energy-efficient and climate-neutral as possible. Globally, the current production of hydrogen is linked to significant GHG emissions. About 75% of the global hydrogen production is based on natural gas and almost all the rest from coal. A very small share of dedicated hydrogen production globally comes from water electrolysis today. To differentiate between hydrogen generation technologies and their sustainability a colour scheme is used. Hydrogen is called grey when it is produced based on natural gas or coal, green when water electrolysis with renewable electricity is used. Between grey or black and green additional colours have been introduced. Blue hydrogen stems from steam reforming in combination with carbon capture and storage, pink hydrogen is based on nuclear energy, and there are even more less frequently used hydrogen production paths and colours. When hydrogen is used in the PEM FC, attention must be paid to hydrogen purity, which is an advantage of hydrogen from electrolysis. In principle, any hydrogen contamination can impair the performance and service life of the membrane electrode assembly. The required purity is particularly difficult to achieve during the reforming process from natural gas or methanol. The hydrogen purity should be above 99.99 vol.% for PEM FC usage. Internal combustion engines running on H_2 can also considered and for internal combustion engines the purity of H_2 is less of an issue which thus gives less restrictions.

3.2.3.5 Electricity

Electricity is an energy carrier which can be stored in batteries or in supercapacitors on-board of vessels. Section 3.3.5 provides more details on the different type of batteries and their characteristics.

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3.3 Energy Converters

3.3.1 Marinisation of engines

In the inland waterway transport, a much-discussed topic is the loss of type approval after marinisation. For Euro VI and NRE engines, it is the responsibility of the technical services to determine whether a modification leads to a loss of type approval. It is therefore very important that the marinisation company works closely with the technical services and the original equipment manufacturer (OEM).

Another issue that must be considered when installing a road engine in a vessel is the emergency running mode of the road engine. According to ES-TRIN, this mode is not permitted for vessels. It must therefore be clarified with the manufacturer beforehand whether the emergency running mode can be switched off or whether the engine has a fire-truck mode, which also does not allow a reduction in performance in the event of a malfunction. Other adjustments, which need to be performed, are described below:

Modifications of the electrical system include motor control, throttle control, monitoring system. In some cases, the software of the engine control unit (ECU) must also be adapted. In contrast to the torque request in truck operation, a speed request is required in on-board operation. The injection lines are replaced with a double-walled design to prevent fuel from a leak spraying on the hot engine surface. A suitable gearbox is required in direct drives to match the propeller and engine characteristics. If the engine power is not sufficient for direct drive, a diesel-electric system is a suitable option. Both Euro VI and NRE engines include an exhaust gas after treatment system to reduce PM and NO_x according to the emission limits. For all these Euro VI and NRE engines the DPF and SCR systems are provided by the engine manufacturer. The systems are mostly of small size; nevertheless, they must be fitted in the engine room. The Euro VI or NRE engine needs to be connected to the water cooling system on board. Also, the connection of the charge air cooler with the water cooling circuit is necessary.

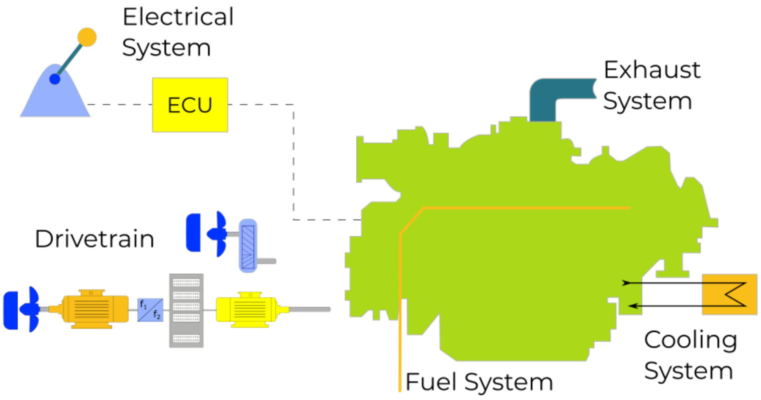

Figure 17 Components of an ICE that need to marinised

Besides dedicated marine engines in IWT also Euro VI truck engines and NRE can be employed for direct propulsion or for a diesel-electric concept. Before they are used, however, some changes (referred to as marinisation) must be made, which are also described below.

Emission limits for inland waterway transport

According to Directive (EU) 2016/1628 category NRE engines are all engines suited to move, or to be moved, by road or otherwise, that not explicitly excluded or included in any other category. These engines with a reference power of less than 560 kW may be used in place of Stage V motors of categories IWP and IWA. NRE engines have Stage V emission limits slightly differing from the limits for

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IWP/IWA engines (identical or more stringent). The table below compares the relevant limits. The NRE engine has a much better performance for NO_x emissions. It can be seen that the regular IWA/IWP engine in the category $130 \le P < 300$ has quite lenient requirements with respect to particulate matter emissions which may lead to the situation that these engines do not necessarily have a DPF system. However, it has to be noted that this comparison is not completely fair since the different engine categories are linked to differing test cycles (ISO 8178). The test cycles define the operating points in terms of engine speed and torque together with weighting factors. For example, class IWP-v-4 is approved according to test cycle E3 while NRE engines are tested according to C1.

8 | Relevant Stage V emission limits

Emission stage	**Sub-category**	**Power range**	**Ignition type**	**CO**	**HC**	**NO_x**	**PM**	**PN**	**A**
		kW		g/kWh	g/kWh	g/kWh	g/kWh	#/kWh	
Stage V	NRE-v-6 NRE-c-6	$130 \le P \le 560$	all	3.50	0.19	0.40	0.015	1×10^{12}	1.10
Stage V	IWP-v-3 IWP-c-3	$130 \le P < 300$	all	3.50	1.00	2.10	0.100		6.00
Stage V	IWP-v-4 IWP-c-4	$P \ge 300$	all	3.50	0.19	1.80	0.015	1×10^{12}	6.00

The Euro VI heavy duty emission standards were introduced by Regulation No 595/2009/EC. The emission limits, which are stricter than the Stage V IWA/IWP values, are meant for the World Harmonized Stationary Cycle (WHSC) and the World Harmonized Transient Cycle (WHTC). Again, the comparability of the emission limits is limited by the differing test cycles. The emission limits of Euro VI are close when comparing to the limits for Stage V NRE engines with a similar power rating ($130 \le P \le 560$) of truck engines.

9 | World Harmonized Stationary Cycle (WHSC) and World Harmonized Transient Cycle (WHTC)

	CO	NMHC	CH_4	NO_x	PM	PN
	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	
WHSC	1.50	0.13	-	0.40	0.01	8.0×10^{11}
WHTC	4.00	0.16	0.50	0.46	0.01	6.0×10^{11}

To reach the emission limits listed above all engines need to be equipped with an exhaust gas after treatment system. All engines are already equipped with these systems by the manufacturers.

On board vessels, safety is always of paramount importance. Therefore, although automatic control is the general rule, an exception shall remain for emergency cases where overriding of the system is needed to reduce imminent danger.”

The specific engine test cycles and their weighting factors for B-type (11 mode) test cycles are given in the table below. The following test cycles and weighting factors should be applied for verification of compliance of marine diesel engines, to determine compliance with the emission limits.

10 | Weighting Factors of B-Type ISO 8178 Test Cycles [22]

Mode number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Torque, %	**100**	**75**	**50**	**25**	**10**	**100**	**75**	**50**	**25**	**10**	**0**
Speed	Rated speed					Intermediate speed					Low idle
Type C1	0.15	0.15	0.15	-	0.1	0.1	0.1	0.1	-	-	0.15
Constant speed											
Type D2	0.05	0.25	0.3	0.3	0.1	-	-	-	-	-	-
Marine application											
Type E1	0.08	0.11	-	-	-	-	0.19	0.32	-	-	0.3
Type E2	0.2	0.5	0.15	0.15	-	-	-	-	-	-	-
Marine application propeller law											
Mode #	**1**		**2**		**3**		**4**		**5**		
Type E3											
Power, %	100		75		50		25		-		
Speed, %	100		91		80		63		-		
Weighting	0.2		0.5		0.15		0.15		-		
Notes: Engine torque is expressed in percent of the maximum available torque at a given engine speed Rated speed is the speed at which the manufacturer specifies the rated engine power Intermediate speed is the speed corresponding to the peak engine torque.											

The modes for testing marine auxiliary engines are [23]:

Cycle C1 is for "Compression-ignition engine powered non-road machinery and industrial equipment" with variable-speed and variable-load auxiliary engines like mobile cranes, pumps and other cargo handling equipment, compressors, etc.

Cycle D2 is used for constant-speed auxiliary engines like generator sets that are not used for propulsion, gas compressors, welding sets, etc.

The modes for testing marine propulsion engines are:

Cycle E1 is for compression ignition engines for propulsion of craft less than 24 m in length except tug boats and push boats.

Cycle E2 is for constant-speed heavy duty engines for propulsion of ships of any length including diesel-electric drive and variable-pitch propeller applications.

Cycle E3 is for propeller-law heavy-duty engines for propulsion of ships of any length.

Emission limits for coastal vessels

Certification of combustion engines for maritime vessels sailing under IMO regulation is different compared to inland vessels for which the engines are certified under the rules of the European Commission by means of the NRMM directive and CESNI requirements. The emission regulations for seagoing vessels focus on sulphur limits in the fuel, and on NO_X limits, which directly relates to the engine. In contrast to inland vessels, no attention is paid in the emission limits to particulate matter emissions.

The IMO NO_X limits are given in Table 11, where it must be noted that Tier III limits only apply in ECAs (Emission Control Areas). The ECAs in Europe are shown in Figure 18. Unlike in inland waterway transport, it can be possible to fit a vessel with an exhaust gas after treatment system. Depending on the type of engine, MARPOL Annex VI specifies the different test cycles. When comparing Table 8 and 11 it is not only clear that fewer pollutants are addressed, but also that the quantities are much lower for inland waterway transport (NO_X Stage V: 0.4-2.1 g/kWh, NO_X Tier III: 2-3.4 g/kWh).

11 | IMO NOx limits

Tier	Vessel construction date on or after	Total weighted cycle emission limit (g/kWh) n = engine's rated speed (rpm)		
		n < 130	n = 130 - 1999	n ≥ 2000
I	1 January 2000	17.0	45·n(-0.2) e.g., 720 rpm – 12.1	9.8
II	1 January 2011	14.4	44·n(-0.23) e.g., 720 rpm – 9.7	7.7
III	1 January 2016	3.4	9·n(-0.2) e.g., 720 rpm – 2.4	2.0

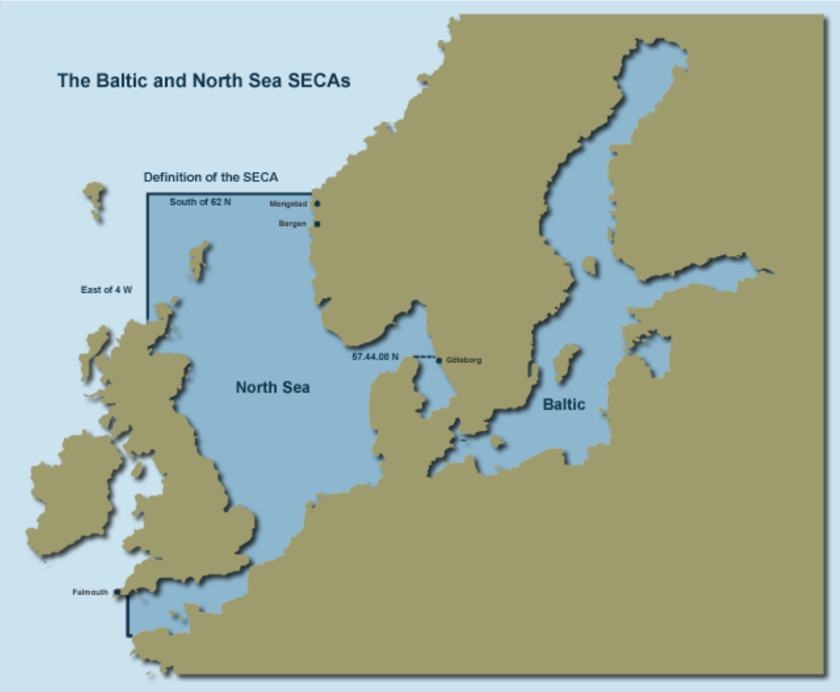

Figure 18 Emission control areas in Europe: North Sea and Baltic Sea.

In order to provide higher standards for emissions, some classification standards also offer ULEV notations (Ultra Low Emission Vessel). This means that a seagoing vessel will basically follow the Stage V emission levels [24].

3.3.2 Engines for Methanol and Hydrogen

Currently, the introduction of methanol and hydrogen internal combustion engines for the inland waterway sector faces one major barrier: so far, methanol and hydrogen have not yet been included as reference fuels in the NRMM directive and cannot be EU type-approved accordingly. This means for the OEM that it is not allowed to bring these engines on the market. Only temporary (up to 24 months with a maximum extension of 24 additional months) and/or national permits for field testing are possible according to Article 34 or 35 of directive (EU) 2016/1628. Another barrier is, that the ownership of the engine shall remain with the manufacturer according to the commission delegated regulation (EU) 2017/654. This is usually not accepted by shipping companies and their customers for expensive (cargo) ships aiming at long-term charters.

When methanol is used as fuel for an internal combustion engine, several design challenges are to be met. First of all, methanol is a low flashpoint fuel with the flashpoint at 11 °C. This means that the regulations for the use of low flashpoint fuels on board vessels must also be complied with. In addition, the methanol flame is virtually invisible in daylight. This can pose a safety risk for the crew and special sensors would also have to be used for detection; for example, infrared cameras or temperature measurement would be suitable. One advantage of burning methanol is that the flame temperature is significantly lower than that of diesel and water can be used very well as an extinguishing agent. In contrast to diesel, methanol is significantly more corrosive and the lubricating effect of alcohol is also significantly poorer than that of diesel. The metals and rubbers that come into contact with methanol must therefore be selected very carefully. This also applies to spare parts in later use. The following engine concepts are relevant for the use of methanol as fuel in marine applications.

- Dual fuel high pressure direct injection (DF-HPDI) as 2-stroke and as 4-stroke
- Dual fuel port injection (DF-PI)
- Port injection spark ignited (SI)
- Compression ignited, with ignition improver (CI)

3.3.2.1 Dual fuel high pressure direct injection (DF-HPDI)

The typical heavy duty high performance marine engines are operating according to the diesel cycle. The large engines have today an efficiency of > 50%. They are either two-stroke slow speed engines or four-stroke medium or high-speed engines. One available concept to use pure methanol as fuel in both two- and four-stroke engines is the dual fuel high pressure direct injection (DF-HPDI) concept. The concept relies on direct injection of methanol to the cylinder much like the ordinary diesel cycle. In order to guarantee proper ignition a small burst of pilot diesel fuel is injected momentarily before the methanol is injected. This first burst of pilot fuel ignites and raises the temperature in the cylinder before the injection of methanol follows. The fuel injectors can be designed in different ways. Either by using separate injectors for methanol and diesel or by use of an injector capable of distributing both types of fuel separate of each other in the same unit. A large marine two-stroke engine has only one exhaust valve in the centre which leaves space for several fuel injection valves. On the MAN 2-stroke 50 cm bore engines there are two fuel oil injection valves and two methanol fuel injection valves. The MAN B&W methanol engine was official tested first time on November 3, 2013 [25].

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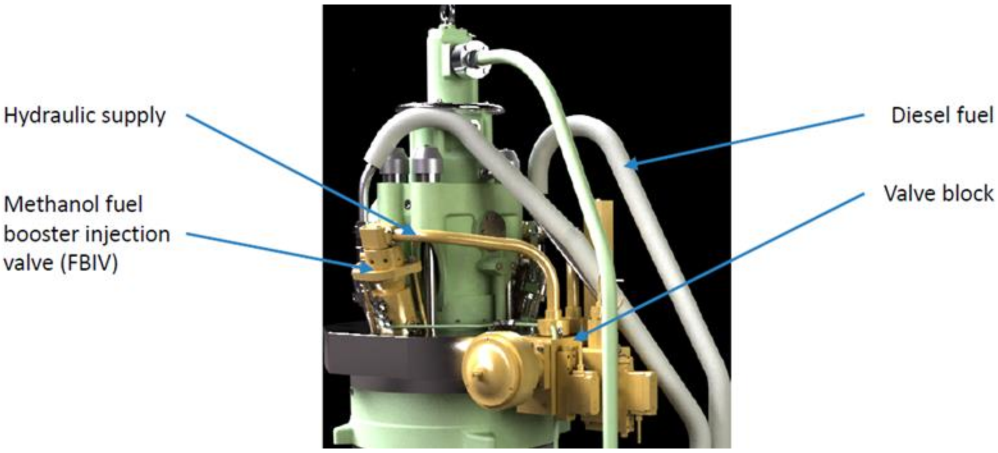
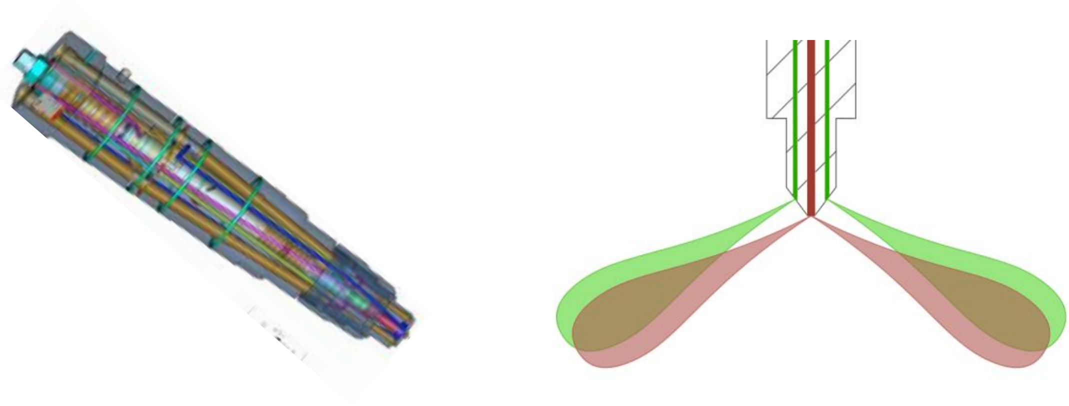


Figure 19 A cylinder head on a MAN two-stroke methanol engine

A four-stroke engine has both inlet and exhaust valves in the cylinder head, typically two of each. The fuel injection valve is placed in the centre and there is normally no space available to fit another fuel injection valve. Wärtsilä together with Woodward L'Orange has developed a fuel injection valve where both the (diesel) oil fuel and the methanol are injected by the same unit, see Figure 20.

Wärtsilä originally used the dual fuel injection valve for a gas-diesel application and the injector was adopted for methanol-diesel operation for a Wärtsilä Vasa 32 engine for the first time in the SPIRETH project and then used for the 8ZAL40S engines in the methanol conversion of the Stena Germanica. The High Pressure Dual Fuel Injector, shown in Figure 20, can deliver approx. 1MW per cylinder (injector) and can be fitted in engines with a cylinder diameter of 320 mm and larger. A smaller injector is being developed that will fit engines with a cylinder diameter of 170 mm.

Cummins-Westport has a similar gas-diesel injector for smaller application. It should be possible to adopt the Cummins-Westport injector also to methanol-diesel operation. The capacity of the injector is approx. 100 kW per cylinder (injector).



Source: Wärtsilä

Figure 20 Principle of fuel injector capable of distributing two separate fuels individually.

The injection mechanism can be controlled in several different ways, either by hydraulic pressure (oil), solenoid or a piezoelectric controller. The illustration below shows the operation of a 4-stroke dual fuel high pressure direct injection methanol engine.

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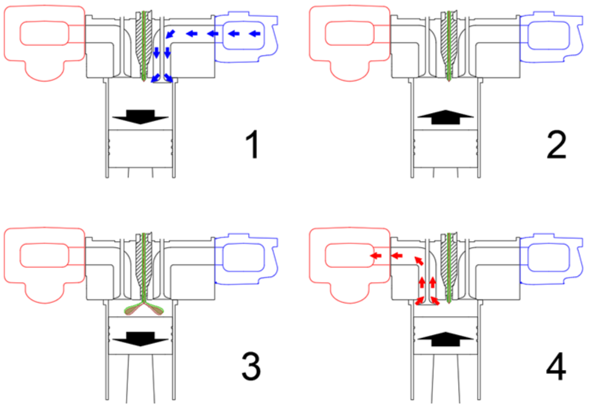

1. The piston moves down, and air enters the cylinder.
2. The piston moves up and compresses the air, temperature and pressure are increased.
3. Close to TDC the fuel is injected, the diesel pilot fuel a fraction before the methanol, The piston is then pushed down by the expansion of the hot gases.
4. The emission gases are pushed out through the exhaust valve.

Figure 21 The combustion principles of a 4-stroke diesel engine with combined methanol and diesel pilot injector

Emissions of particles are heavily reduced and limited to the pilot diesel. NO_X emissions are on IMO Tier III levels without exhaust gas aftertreatment. The fraction of unburnt fuel and thereby formaldehyde emission are very low.

As methanol is injected to the ongoing combustion at TDC the cylinder liner and air channels are not exposed to methanol. Likewise blow-by gases should not contain methanol that could increase decomposition of lubricating oil in the crank case. Modifications to the engine should be limited to the fuel injection system with full flexibility to operate on conventional diesel fuel with no loss of performance.

3.3.2.2 Dual fuel port injection (DF-PI)

All major marine engine suppliers have dual fuel engines where methane gas (LNG) can replace a significant part of the HFO or MGO. The same concept can be used for methanol by replacing the gas valve with a methanol injector. This methanol injector is placed upstream of the inlet valve.

On diesel mode, the engine runs as normal diesel. When switch to methanol mode, the engine runs on Otto cycle. The main fuel is injected from the methanol injector and into the combustion chamber with intake air, and a burst of pilot fuel initiates the combustion at top dead centre (TDC).

Dual fuel engines normally operate on lean mixtures in methanol mode as the pilot fuel is sufficient to ensure combustion. This allows for higher compression ratio and thus higher efficiency.

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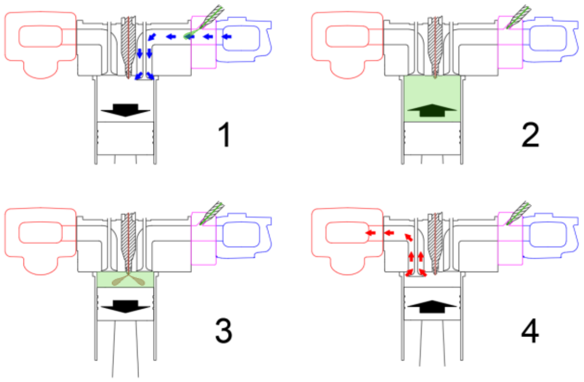

Figure 22 The combustion principles of a 4-stroke port injected engine with diesel pilot ignition

1. The piston moves down; methanol injects from the port with inlet air.
2. The piston moves up and compresses the air-methanol mixture, temperature and pressure are increased.
3. Close to TDC the diesel is injected as pilot fuel and ignites the compressed methanol air mix in the cylinder. The piston is then pushed down by the expansion of the hot gases.
4. The emission gases are pushed out through the exhaust valve.

3.3.2.3 Port injection spark ignited (SI)

The spark ignition (SI) concept is similar to the port injection dual fuel concept, but uses spark plugs to replace the function of diesel injectors. The advantage with the spark plug is that no other fuel is needed to initiate the combustion, but it also limits the flexibility as dual fuel operation is not supported. The ignition power of a spark plug is also much lower than the ignition power from pilot fuel. This limits the size of engines where an open spark plug can be used for ignition of combustion. For larger engines, the spark plug is placed in a pre-chamber where a small part of the fuel mix is ignited. This ignited fuel mix generates a jet that ignites the rest of the fuel. Compared to a dual fuel engine the compression ratio is lower to prevent knocking. Combustion temperatures are kept low with a lean fuel/air mixture and emissions are comparatively low.

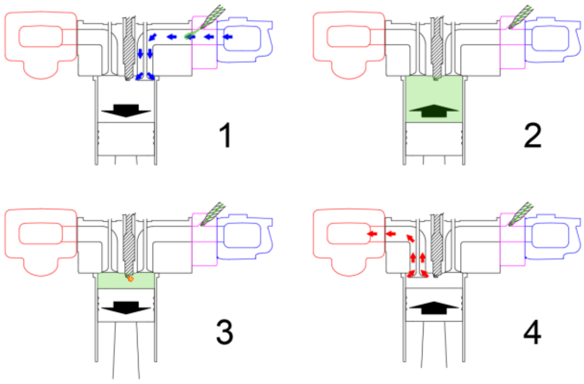

Figure 23 The combustion principles of a 4-stroke engine with port injection and spark ignition

1. The piston moves down, methanol injects from the port with inlet air.
2. The piston moves up and compresses the air-methanol mixture, temperature and pressure are increased.
3. Close to TDC the spark plug ignites methanol. The piston is then pushed down by the expansion of the hot gases.
4. The emission gases are pushed out through the exhaust valve.

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3.3.2.4 Compression ignited, with ignition improver (CI)

The low cetane number and high octane number of pure methanol makes it more suitable for spark ignited Otto combustion. However, by adding an ignition improver the characteristic of methanol is changed so it can be used as single fuel in a compression ignited engine. Scania developed this concept for ethanol in the 1980s and have used it extensively for busses and trucks were. Ethanol and methanol have similar combustion characteristics and the concept has now been adopted for marine and industrial compression ignited methanol engines.

The concept is based on the modification of Scania marine and industrial engines by using original Scania components from their ethanol (ED95) bus and truck engines.

Today Enmar Engines are selling compression ignited methanol engines that uses MD97 fuel. The fuel contains methanol and 3% Beraid ignition improver as well as a small fraction of lubricant. The engines are based on the Scania marine engines with several modifications, including alcohol fuel injectors and higher compression positions. With the ignition improver, the engine can run on diesel cycle with methanol and provides similar performance as a diesel engine with high efficiency and fulfils IMO Tier III NOx emission levels without after treatment system.

Figure 24 Compression ignited methanol (MD97) engine 16LV8 415 kW at 2100 rpm, available from Enmar Engines AB

Within SYNERGETICS the two options Compression ignited, with ignition improver (CI) and the Dual fuel port injection (DF-PI) will be compared.

3.3.2.5 Hydrogen in combustion engines

Not only can hydrogen be used as fuel for a fuel cell but also for the classic internal combustion engine (ICE). Lately manufacturers have started the development of commercially available engines. In contrast to the fuel cell or the battery, no rare-earth metals are needed to produce the combustion engine.

An internal combustion engine burning hydrogen can work on the Diesel- or the Otto cycle. The engine developed by CMB.TECH is described in Figure 25.

Being carbon-free, makes the hydrogen operation of the combustion engine at least theoretically CO_2, CO and hydrocarbon-free. In real operation, however, traces of hydrocarbons in the exhaust gas can be detected due to lubricating oil in the combustion chamber. The local emission of nitrogen oxides, though, must be considered [26]. The formation of nitrogen oxides in combustion can, for example, be greatly reduced by appropriate regulation. The remaining nitrogen oxides in the exhaust gas are then retained by a catalyst (SCR) [26].

In [1] the theory of combustion of hydrogen is described as: The wide ignition limits of hydrogen allow quality control over the entire operating range of the engine. In contrast to conventional fuels, hydrogen can theoretically be burned homogeneously up to an air ratio of $\lambda = 10$. As with conventional fuels, the required ignition energy increases with the air ratio. To ignite a stoichiometric hydrogen-air mixture,

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only one tenth of the energy required to ignite a gasoline-air mixture is needed. In contrast, the self-ignition temperature of hydrogen is significantly higher than that of conventional liquid fuels. Although this can bring advantages in terms of knocking behaviour in the case of premixed combustion, it requires very high compression ratios or other measures to increase the charge temperature in the case of the self-igniting hydrogen engine.

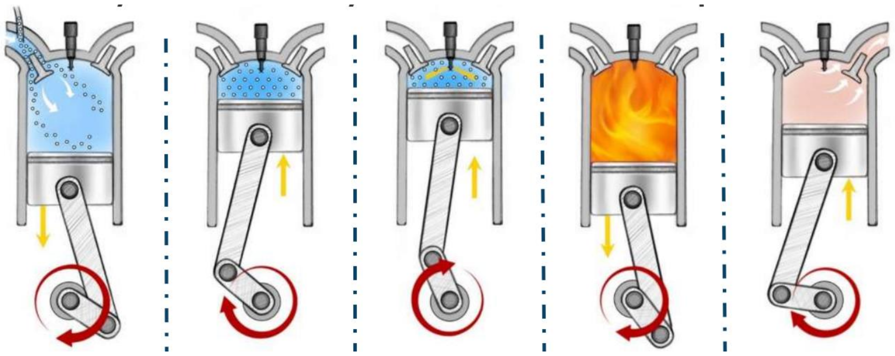

Figure 25 Hydrogen-Diesel co-combustion in a Diesel-engine [27]

1. Hydrogen is injected in the aspirated air during the intake stroke.
2. During the compression stroke hydrogen mixes into a homogeneous mix.
3. A small amount of diesel pilot fuel is injected into the combustion chamber just before top dead centre.
4. Diesel auto-ignites due to the high temperature and pressure and co-combusts with all the hydrogen, forcing the piston down during the power stroke.
5. The cylinder is cleaned during the exhaust stroke. Due to the hydrogen co-combustion the NO_X and CO_2 emissions have strongly reduced in the exhaust gases.

Figure 26 Hydrogen Mono-fuel engine with spark ignition. Here, nearly zero-emission is possible. A high lambda value is required for low NO_X emissions and high efficiency. Mono-fuel engines tend to be larger than dual-fuel engines due to reduced power output [27]. Red resembles oxygen, blue hydrogen and orange the emerging NO_X.

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The joint-venture BeHydro [28] of the engine manufacturer Anglo Belgian Corporation (ABC) and CMB (Compagnie Maritime Belge), a diversified shipping and logistics group has launched a monofuel hydrogen engine in May 2022 [29]. According to the project "the innovative 100% hydrogen engine range has been developed for heavy duty applications and has a power range from 1 MW to 2.6 MW. These hydrogen engines are available in 6- and 8-cylinder in-line engines and 12- and 16-cylinder V-engines. As a main drive or in combination with an alternator, they are a reliable and 100% environmentally friendly source of energy for ships, drilling rigs or other marine applications. They are also ideally suited for driving locomotives." [29].

3.3.3 Electric Drives

Today the large majority of inland and coastal vessels is equipped with internal combustion engines, the so-called diesel-direct propulsion. The engine torque most commonly is transmitted to the propeller via a gearbox or directly for slow-speed engines which can be reversed. These systems are technically mature, durable and cost-effective. Direct propulsion is also efficient for seagoing vessels travelling long distances with a largely constant operating point. Even if combustion engines with alternative fuels can be integrated analogue, x-electric drives are increasingly being used in inland and coastal shipping though the additional energy conversion brings additional losses. On the one hand, this is due to the complex operating profiles with very different power requirements, for example when sailing up and down rivers with fluctuation water depths. On the other hand, not all fuels and combustion processes are suitable for meeting the characteristics of the propeller in terms of rpm-dependent torque. In addition, an appropriately designed x-electric drive system can be adapted more flexibly to future developments in clean drives.

For the deployment of electric drives on board, products from numerous manufacturers are available in the required power range of 500 kW – 1200 kW. If the individual technical requirements and boundary conditions of a ship cannot be covered by the manufacturer's portfolio, many manufacturers offer the option of having a customised drive built. In principle, DC motors or three-phase synchronous motors can be considered. The differences, advantages and disadvantages of the various motors are explained below.

3.3.3.1 DC motors

Fuel cells and batteries provide their energy as direct current. This means that the type of mains does not have to be changed to supply the motor. Every form of energy conversion (e.g. from AC to DC) is subject to losses. Avoiding additional conversions increases the overall efficiency of the drive. In addition, DC motors offer a very high torque in the starting phase and can cover a wide speed range. The choice of machine, in terms of torque and speed, can be matched to the propeller shaft either as a direct drive or for use with a gearbox. In both cases, there is no need to provide a reversing gearbox, as the direction of rotation of the machines can be changed electrically and without delay.

DC machines essentially consist of a rotor and a stator, both of which must be supplied with power. As the rotor rotates, the transmission can only be realised with slip rings. These are subject to minimal wear during operation. As a result, DC motors are not maintenance-free and incur some costs over their service life. However, these machines are made of ordinary metals such as copper and steel. It is therefore possible to completely recycle such a motor at the end of its service life.

In DC motors, there are various ways of interconnecting the excitation windings of the stator and the armature windings of the rotor. This allows different machine characteristics to be achieved. Only separately excited DC machines are suitable for the main drive on board inland waterway vessels. The excitation windings and armature windings are fed by two different control circuits. Both are based on pulse width modulation of the mains voltage. This separation means that the machine can be optimised

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for the applied load. As a result, a high degree of efficiency can be achieved over the entire operating range of the machine.

3.3.3.2 Three-phase synchronous motor

Like DC motors, synchronous motors are available in different speed and torque ranges. They can also change their direction of rotation without delay and can be connected to the propeller shaft either directly without a gearbox or via a gearbox. The characteristics required in marine applications can be provided most efficiently by permanently excited synchronous motors. These high-pole motors with a good torque-to-mass ratio are often referred to as torque motors.

They are characterised by a constant torque curve over the entire speed range. The speed is varied and the machine characteristic curve is adapted to the load characteristic curve only by supplying the excitation windings. No complex tuning of various resistors and the magnetic flux is necessary here, as is the case with DC machines. The excitation windings are supplied with alternating current. The motor speed is directly proportional to the frequency of the excitation voltage. The torque is adjusted via the current through the excitation windings, which in turn is approximately proportional to the level of the supply voltage. A frequency converter is usually used to convert the energy from the mains into a frequency and voltage-variable network for a synchronous motor. When the rated speed of the machine is reached, the torque decreases because the power remains constant.

A DC machine is recommended for ships characterised by frequent speed changes and partial load ranges. For ships where a highly efficient drive is paramount, the synchronous machine is the first choice. For the control of motors, a distinction is essentially only made between direct current and three-phase machines. Pulse width modulation is normally used to control DC motors. A frequency converter is generally used to control three-phase machines.

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3.3.4 Fuel Cells

The principle of the fuel cell was invented in 1838, however the first commercial use of fuel cells came more than a century later in NASA space programs to generate power for satellites and space capsules. Since then, the improvement of the fuel cell began and nowadays they are used in many other applications, e.g., for primary and backup power for commercial, industrial and residential buildings and in remote or inaccessible areas. The second most important application for fuel cells is as a power source for vehicles of all kinds.

With fuel cells local emission-free power generation is possible. The comparison of a fuel cell with a conventional internal combustion engine shows that no mechanical stress on components takes place because no fuel is burned. However, the durability/lifetime of a fuel cell is much smaller compared to internal combustion engine. The sector calculates with 30,000 running hours for fuel cells and 200,000 hours for a combustion engine. This adds to further increase of the difference in the total cost of ownership during the lifetime of a vessel and thus this is a big disadvantage for the fuel cell compared to the internal combustion engine. Another disadvantage is the dependency on the purity of the fuel which is less critical with H_2 ICE for example.

3.3.4.1 Fuel cell types

The following diagram shows the basic conversion process in a fuel cell using the example of hydrogen as a fuel.

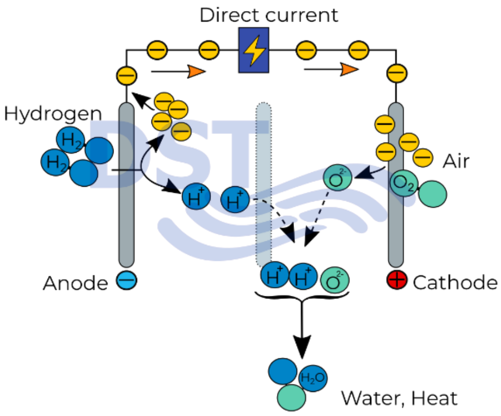

Figure 27 Basic working principle of a fuel cell

All fuel cells consist of two electrodes - the anode and the cathode. These are separated by an electrolyte with an ion-permeable membrane. After the fuel has been supplied to the anode, it is divided into electrons and protons. The free electrons flow into an outer circuit between the anode and cathode to be used as an electric current. The protons spread through the electrolyte to the cathode. At the cathode, the oxygen from the air combines with the electrons from the outer circuit and protons from the electrolyte. This results in water and heat. All fuel cell types are based on the reaction of a fuel with oxygen. The electrochemical reaction generates basically electricity, heat and water. From the fuel cell, the electricity is provided as direct current (DC). If alternating current (AC) is required for further use, DC from the fuel cell is routed to an inverter is converted there to AC.

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Figure 28 the basic structure of an SOFC, a fuel cell being capable of directly using ammonia or methanol rather than hydrogen as fuel. This consists of a solid electrolyte (usually a ceramic), which is arranged between an anode and a cathode. The fuel is fed to the anode and the oxidising agent, usually air, to the cathode. The electrodes are solid, porous structures that allow the fuel and air to diffuse into the electrolyte, while the products of the electrochemical reaction on the anode side diffuse away from the electrolyte. The electrolyte conducts the oxygen ions, which are produced during the electrochemical reduction of molecular oxygen, from the cathode side to the anode side of the SOFC. The fuel diffuses through the anode to the anode-electrolyte interface. Here it reacts catalytically with the oxygen ions, releasing electrons which are transported through an external circuit and generate electricity. The individual cells are electrically connected in series with a metallic connection to increase voltage and power and can be stacked to achieve an optimum stack size. Several stacks can be arranged in a cabinet to form an SOFC module.

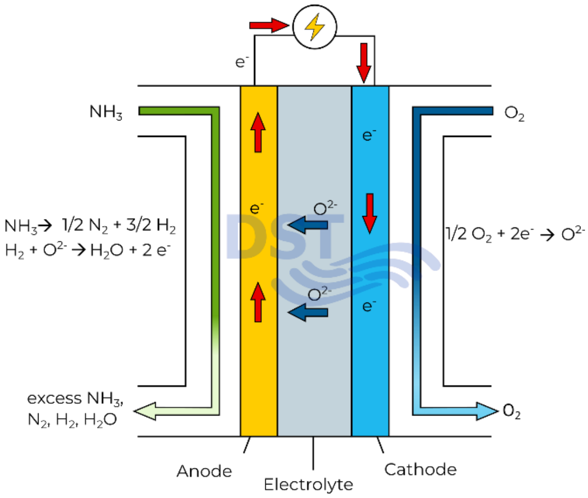

Figure 28 Ammonia solid oxide fuel cell. The electrolyte is a solid membrane. To transport the oxygen ions as efficiently as possible, an operating temperature of 500 to 1000 °C is required.

Basically, fuel cells are classified according to their operating temperature and the type of electrolyte used in the fuel cell. The following fuel cells are particularly interesting for inland waterway vessels:

Low temperature proton exchange membrane fuel cell (LT-PEMFC)	High temperature proton exchange membrane fuel cell (HT-PEMFC)	Solid oxide fuel cell (SOFC)
PEMFC uses a water-based polymer membrane as electrolyte, H_2 as fuel and O_2 as oxidant. The operating temperature is < 100 °C. Due to the low temperature, only pure hydrogen can be used in PEMFC. The byproducts besides electricity are water and heat. The fuel cell can be started cold without pre-heating to the operating temperature.	The operating temperature can reach up to 200 °C and mineral acid electrolyte instead of a water based one is used. Before starting, the HT-PEMFC must first be brought to operating temperature.	The SOFC contains a solid electrolyte. From an operating temperature of approx. 650 °C up to 1000 °C, the so-called oxide ceramic conducts the hydrogen ions through it. An internal reforming of natural gas, methanol or ammonia to hydrogen takes place in the SOFC itself.

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3.3.4.2 Technical concept

An electric motor drives the propeller with constant rpm at any load case. Its advantage is a nearly constant efficiency at all load cases. Depending on the selected electric motor a gear box can be omitted. The frequency converter supplies the electric motor with a frequency and voltage amplitude variable AC voltage. The converter can be supplied by any AC or DC on board energy grid. The rotational speed of the electric motor is con-trolled by varying the output frequency. The main switch board distributes the energy from all sources to all loads. The loads are frequency converters at the propulsion system. The fuel cell provides the base load. The fuel is stored in the tank. Peak loads are absorbed by the battery which can be charged either by the fuel cell or via shore power.

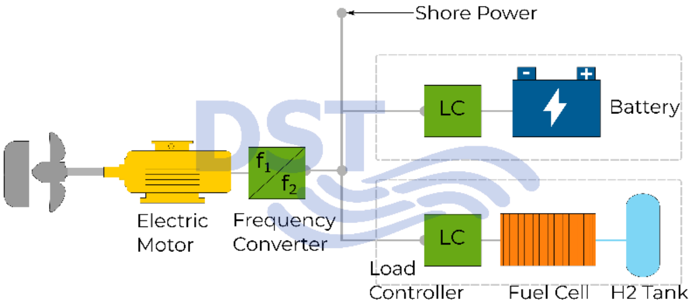

Figure 29 Fuel cell drive train

3.3.4.3 Benefits and downsides

The main advantage of a fuel cell is obviously its emission-free operation, provided that the fuel was also produced in an emission-neutral way. This is nowadays still a great challenge.

At full load and at some partial load states a fuel cell provides high efficiency. Because of the modular design, the stack size is customizable for the individual vessel. Manufacturers also state that the maintenance effort is extremely low. Also, the increased comfort due to low noise and no vibrations is favourable.

The EMSA study from 2017 [30] clearly shows that since the early 2000s there have been and continue to be new initiatives aimed at finally establishing the fuel cell as a propulsion system for ships of all sizes. There have also been some setbacks during this time, such as the loss of the fuel supply for the Alsterwasser.

In the recent past, many new exemptions have been granted for retrofit inland vessels that are to be equipped with a PEMFC system. They are addressed in the WP 2.1 database. In addition, the first projects for the maritime use of ammonia SOFCs have been launched. In 2020 it was announced that the offshore supply vessel VIKING ENERGY will be equipped with a 2 MW SOFC in 2024 [31]. The conversion is being carried out as part of the ShipFC project [32].

However, the disadvantages of fuel cells cannot be disregarded. Fuel cell systems are still the technologies with not only the highest investment cost, but also with the highest fuel costs, if pure hydrogen is needed, the shortest lifetime and are very sensitive to the purity of the fuel. Therefore, it is still hard if not impossible to find a business case, comparable to a standard Diesel engine, but also to other technologies involving combustion engines with alternative fuels or pure battery electric solutions. Moreover, due to still comparably low experience in field testing, it is not yet fully clear what the maintenance effort and costs will be. Replacing the membranes, for example, is again associated with high investments.

In conclusion, it can be said that fuel cells have potential, but their application is still overshadowed by the problems and high costs associated with the widespread use of a technology in a new field.

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3.3.5 Batteries

Literally, the general term battery refers to a set of equipment or machines or other devices cooperating in the same function. However, in common usage, battery is a device that converts chemical energy into electricity using electrochemical reactions. Batteries provide the possibility to store electrical energy and make it available on the move. They are used in many applications with differing requirements. Thus, there is a wide range of battery types, including lead–acid, nickel–based, lithium-ion, sodium–sulphur, redox flow batteries and others. These vary in power density, capacity, cycle lifetime, efficiency, the number of charging/discharging cycles they can perform, capital costs, charging time, reliability, and safety.

Following, a brief account is made of the battery-powered vessels development in history and a focus is made on the two main type of battery in use today: lead-acid batteries and lithium-ion batteries.

Battery-powered vessels in history

The history of battery-powered ships predates the development of diesel-powered ships. Battery-powered ships were among the earliest attempts at electrically driven vessels, and their development dates back to the 19th century. Moritz Hermann demonstrated the first known electrically powered boat in the late 1830s. The electric motor installed experimentally on small boats was powered by a battery consisting of 69 Grove cells, which enabled a speed of about 4 km/h. Due to numerous imperfections, the invention was soon forgotten [33] [34]. It took until the year 1885 to see the first successful electric-powered ship, Elektra. It was a passenger ferry with a capacity of 30 people, built by the German Siemens & Halske. It measured 11 meters in length by 2 meters in width and was powered by a 4.5 kW motor supplied by batteries [34]. Electric propulsion technology also found applications in early submarine development. One notable example is the French Navy's Gymnote, a fully electric submarine designed by Henri Dupuy de Lôme and Gustave Zédé. The Gymnote was launched in 1888 and was one of the first to successfully navigate using electric propulsion, reaching a speed of about 7 knots [33]. By 1900, France, the United States, and Britain were exploring the submarine concept, based on the internal combustion engine for surface operation and batteries for use when submerged.

During the late 19th and early 20th centuries, electric propulsion gained popularity in various types of vessels, especially smaller craft such as ferries, pleasure boats, and submarines. Electric-powered ships had advantages such as quiet operation, low emissions, and the ability to provide precise control over the propellers, making them well-suited for certain applications. Despite these early achievements, battery-powered ships faced significant challenges that limited their adoption:

- **Limited Range**: batteries of that era had limited energy storage capacity, restricting the range of battery-powered vessels;
- **Steam Engines**: steam engines were the dominant form of propulsion during the 19th century, and their reliability and power made them preferable for most maritime activities;
- **Diesel Engines**: towards the end of the 19th century, diesel engines emerged as a promising alternative to steam engines, and their development was accelerated by their superior efficiency and fuel economy.

The widespread adoption of diesel-powered ships began to gain momentum in the early 20th century. As diesel engines became more reliable, they eventually surpassed both steam and battery-powered ships in terms of range, power, and practicality for oceanic voyages. Diesel-powered ships offered more extended operational range, reduced fuel consumption, and the ability to carry larger cargoes, making them the preferred choice for long-haul sea transport. However, as environmental concerns and advancements in battery technology continue to progress, there has been renewed interest in batteries for ships, especially for short-distance operations and in areas where emissions regulations are stringent. The MV Ampere car ferry, unveiled in 2015, is credited with ushering in the era of all-electric ships. Modern battery-powered ships, often referred to as electric or hybrid-electric vessels, represent a promising direction in the pursuit of more sustainable maritime transportation.

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3.3.5.1 Lead-acid battery

Lead-acid battery was invented in 1859 by Gaston Plante, and has been widely used throughout the world in automotive industry, stationary applications, large-scale energy storage, storage of electricity produced by renewable energy sources and for back-up power supplies. Its success is due not so much to its capabilities but to the very low cost of the materials it is made of, mainly lead and sulphuric acid.

These batteries consist of a plastic casing containing positive and negative plates, separated by porous material (such as rubber, glass, cellulose, or PVC) and immersed in an electrolyte solution of sulphuric acid (H_2SO_4), which does not play the role of a medium for ionic transport, but acts as an active material. The positive electrode of lead-acid batteries consists of lead dioxide (PbO_2), while the negative electrode consists of pure lead (Pb). The chemistry of lead-acid batteries has remained unchanged since their invention, with only limited adjustments made to enhance their efficiency and performance.

In lead-acid batteries the whole battery reaction is written as:

$$\mathrm{Pb} + \mathrm{PbO_2} + 2\mathrm{H_2SO_4} \rightleftharpoons 2\mathrm{PbSO_4} + 2\mathrm{H_2O}$$

in which the discharging occurs reading the chemical formula from the left to the right. In the course of discharge, both electrodes undergo a transformation into lead sulfate, which is reversed during the charging phase.

In an ideal situation, during full charge, all lead sulfates would revert to their original materials. In practice, during the charging process, some of the lead sulfates remain unchanged and do not undergo conversion, creating a passive layer on the electrode surface. This phenomenon, called passivation process, is repeated in each cycle until the cell becomes unusable.

Advantages and disadvantages

Lead-acid batteries are valued for their cost-effectiveness, reliability, and ability to deliver high currents but have limitations in terms of energy density, cycle life, and environmental concerns. Their application is best suited for situations where these advantages outweigh their disadvantages, such as in backup power systems, automotive starting batteries, and stationary power sources.

Advantages:

1. **Low Cost:** lead-acid batteries are relatively inexpensive to manufacture, making them cost-effective for a wide range of applications;
2. **Reliability:** they are a well-established and reliable technology. Their behaviour and performance characteristics are well-understood;
3. **High Discharge Current:** lead-acid batteries can deliver high peak currents, making them suitable for applications where a sudden surge of power is required, such as starting internal combustion engines in vehicles;
4. **Low Self-Discharge Rate:** these batteries have a low self-discharge rate, meaning they can hold their charge for extended periods, making them suitable for standby and backup power applications;
5. **Recyclability:** lead-acid batteries are highly recyclable. Most of their components, including lead and sulphuric acid, can be recovered, and reused in the production of new batteries, contributing to environmental sustainability;
6. **Availability:** they are readily available in various sizes and configurations, ranging from small capacities to large industrial batteries, which adds to their versatility.

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Disadvantages:

1. **Low Energy Density:** lead-acid batteries have a relatively low energy density, meaning they store and deliver less energy per unit of weight and volume compared to some other battery types, as shown in 12;
2. **Limited Full Discharge Cycles:** lead-acid batteries are limited in the number of full discharge cycles they can withstand, typically ranging from 50 to 500 cycles;
3. **Storage Limitations:** they should not be stored in a fully discharged state, and their cell voltage should not drop below a certain cutoff value to prevent plate sulfation and battery damage;
4. **Sulfation:** lead-acid batteries are prone to sulfation, a process in which lead sulfate accumulates on the electrode plates, reducing the active surface area and leading to irreversible damage over time;
5. **Environmental Concerns:** lead-acid batteries pose environmental concerns due to the toxic nature of lead and the corrosive properties of the sulphuric acid electrolyte.

12 | Approximate energy densities of conventional energy storage systems (batteries) and energy carriers

Material	**Gravimetric energy density [MJ/kg]**	**Volumetric energy density [MJ/L]**
Hydrogen (liquid)	120 (LHV)	8.5 (LHV)
Hydrogen (700 bar, 25 °C)	120 (LHV)	4.5 (LHV)
Diesel	45.6	38.6
Methanol	19.7	15.6
Ammonia (liquid)	18.6	11.5
Li-ion battery	0.36 ÷ 0.875	0.9 ÷ 2.63
Alkaline battery	0.48	1.3
Lead-acid battery	0.17	0.56

Established recycling ecosystem

As stated before, one of the benefits of lead–acid batteries is its recycling capability. Most of the components (above 95%, according to [35]) of a lead-acid battery can be reused through recycling. The process involves collecting and transporting the consumed batteries to a dedicated recycling plant. Here, the separation of the various constituent parts of the batteries takes place, followed by the melting and refining of the lead-based components. The plastic parts undergo a washing process, followed by their shredding or melting to create new products. In addition, the sulphuric acid electrolyte may undergo a purification or treatment process before being safely disposed of or reused. Eventually, the waste is disposed [35], [36], [37]. Thanks to its ease of recycling, in the EU and USA, more than 99% of lead-based batteries are collected and recycled in a closed loop system [38].

Despite this benefit, the contact between humans and the environment with lead is mainly through the treatment of lead batteries. Gases and wastes that include lead, if dispersed in the environment, besides posing a threat to human health, can infiltrate soil and water resources, causing their poisoning.

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3.3.5.2 Lithium-ion battery

There are different types of rechargeable batteries that use lithium as a component, but they vary in terms of their chemistry, electrolyte, design, and applications.

The term "lithium batteries" is frequently misinterpreted or inaccurately used when referring to the more specific term "lithium-ion batteries". To prevent any potential confusion, it is advisable to begin by providing clear definitions and subsequently concentrate on the topic of lithium-ion batteries.

According to [39], there are four variety of lithium batteries: lithium metal, lithium–ion, lithium polymer, and solid–state electrolyte lithium battery. **Lithium metal** batteries use pure lithium metal for the anode as the source of the lithium ions during charging and discharging and various lithium compounds for the cathode. They are known for their high theoretical energy density but face safety concerns. **Lithium-ion** batteries have a graphite anode, various lithium compounds for the cathode and non-aqueous liquid electrolyte. They are generally considered safer than lithium metal batteries because of their use of graphite anodes, which are less prone to dendrite formation. **Lithium polymer** batteries are characterised by solid or gel polymer electrolytes, which provide flexibility and form factor versatility, making them suitable for applications where customised shapes and space constraints are important. **Solid-state lithium** batteries are an emerging technology promising improved safety, energy density and longer cycle lives by employing a solid-state electrolyte.

What is a lithium-ion battery?

Lithium-ion batteries were first developed in the 1970s and became commercially available in the early 1990s by Sony. Lithium-ion batteries (LIB) have become a ubiquitous energy storage solution, widely used in various applications such as portable electronics, electric vehicles, and renewable energy systems.

Lithium-ion batteries operate on the principle of lithium-ion intercalation (or insertion), which is the process of moving lithium ions between the positive (cathode) and negative (anode) electrodes of the battery during charging and discharging. During discharging, the lithium-ions move from the anode to the cathode, while the electrochemical reaction causes electrons to flow from the anode to the cathode in an external circuit. During charging, the lithium-ions move from the cathode to the anode, while an external electrical power source applies a voltage that forces a charging current to flow from the cathode to the anode.

A single cell of these batteries has a nominal voltage around 3.6 volts, though this may vary based on the specific battery chemistry and design. It is composed of several key components: a carbonaceous material, typically graphite, as the negative electrode; a positive electrode comprising a lithium-containing metal oxide compound, such as $LiFePO4$; a non-aqueous electrolyte designed to ensure high conductivity of the lithium-ions and a wide range of electrochemical stability; and a separator that prevent short circuits while allowing the passage of lithium-ions. The high cell voltage limits the electrolytes to non-aqueous electrolytes, as aqueous electrolytes dissociate at such a high voltage.

Although these kinds of batteries offer excellent performance, it is crucial to recognise their delicate nature, which requires the use of dedicated protection. Protection circuits, often integrated into the battery management system (BMS), monitor and regulate battery voltage, temperature and current during charging and discharging. They help prevent overcharging and overdischarging, which can cause irreversible damage or even safety accidents, making the batteries suitable for various applications.

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Electrode chemistry

Lithium-based batteries are categorized according to their cathode (an abbreviation name is used to ease the recollection). Here, according to [35] and [40], a brief account is made of the most well-known lithium batteries and radar charts are reported to represent the *specific energy* (or gravimetric energy density), the *specific power* (or the ability to deliver high current), *safety*, *performance* (at hot and cold temperatures), *life span* (reflecting calendar life and cycle life[3]) and *cost*.

Different cathode materials offer trade-offs in terms of specific energy, safety, lifespan, etc., making them suitable for different applications. According to [39], some batteries excel in one characteristic (e.g. safety), while others perform better in other characteristics (e.g. specific power). Since none can claim absolute perfection in all parameters, we have to resort to different chemistries to meet different requirements.

Lithium-Cobalt Oxide ($LiCoO_2$) – LCO

The battery consists of a cobalt oxide cathode and a graphite carbon anode. It is the most widely used cathode material for all mobile devices, such as telephones and laptops. It boasts a high specific energy, but suffers from a relatively short lifetime, low thermal stability, limited specific power, high cost of cobalt and concerns over cobalt availability and safety. For thermal reasons, the cells must be charged at low currents (< 1C), which makes them unsuitable for fast charging.

The importance of the $LiCoO_2$ battery is slowly declining in favour of materials with better performance, lower cost and fewer concerns about raw material availability.

Figure 30 depicts the radar chart for the LCO battery.

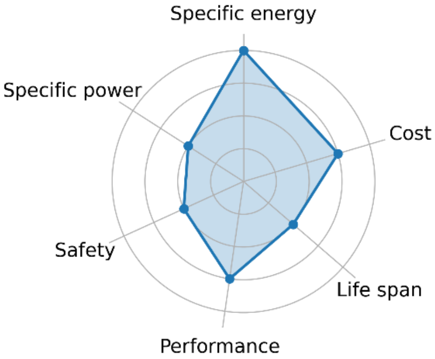

Figure 30 Average characteristics of LCO batteries

Lithium Iron Phosphate ($LiFePO_4$) – LFP

Thanks to the inherent stability of phosphate, these batteries have exceptionally long cycle lives. Furthermore, they boast a good thermal resistance, can provide very high power and are more tolerant to overcharge and overdischarge conditions, proving superior safety over other types. On the other hand, they suffer higher self-discharge than other lithium-ion batteries, which can cause balancing issues with aging and have reduced energy density, as shown in Figure 31.

Thanks to the ability to deliver high current LFP batteries are often used to replace the lead acid starter batteries.

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[3] Calendar aging is the decrease in capacity and power over time; cycle aging is the decrease in capacity and power due to the use of the battery.

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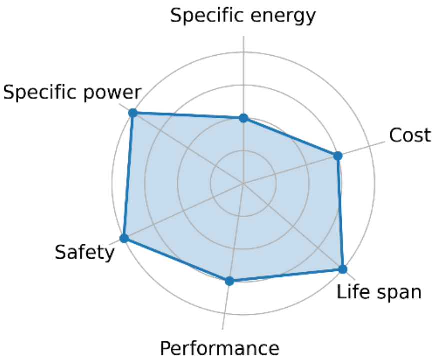

Figure 31 Average characteristics of LFP batteries

Lithium-Manganese Oxide ($LiMn_2O_4$) - LMO

The battery consists of a lithium manganese oxide cathode. Its layered open structure improves ion flow on the electrode by lowering the internal resistance. It boasts a high specific power, but at least 20% lower specific energy compared with LCO [39], high thermal stability (which ensures high current rates, so fast charging), enhanced safety and lower cost, but the life span is limited.

Figure 32 depicts the radar chart for the LMO battery.

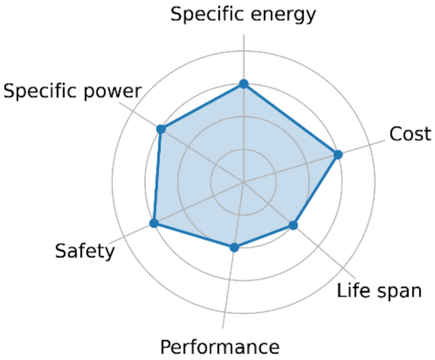

Figure 32 Average characteristics of LMO batteries

Lithium Titanate ($Li_4Ti_5O_{12}$) – LTO

Unlike other battery types, LTO cells are named after the replacement of the graphite in the negative electrode with Li-titanate ($Li_4Ti_5O_{12}$). The positive electrode is similar to that of LMO, LFP or NMC batteries. These batteries can be fast charged and, thanks to the high specific power, they can deliver a high discharge current of 10C. Furthermore, the LTO provides superior safety, excels in terms of cycle life, performs well at low temperatures and is thermally stable at high temperatures. However, it is important to note that LTO batteries are relatively expensive and their specific energy is not very high.

Figure 33 shows a radar chart of the LTO, illustrating its characteristics.

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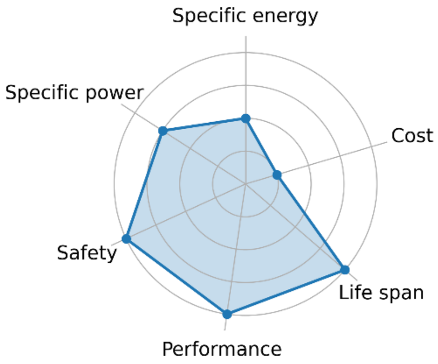

Figure 33 Average characteristics of LTO batteries

Lithium-Nickel-Manganese-Cobalt Oxide ($LiNiMnCoO_2$) - NMC

This type of battery uses the nickel-manganese combination to enhance the strengths of each element: nickel has high specific energy but low stability, manganese has a layered open structure which improves ion flow on the electrode by lowering the internal resistance and cobalt stabilizes nickel. The cathode combination is usually one-third nickel, one-third manganese, and one-third cobalt and it makes the cell to be less expensive than LCO or LMO. Since cobalt is expensive and its availability limited, battery manufacturers are reducing the cobalt content in favour of the cheaper nickel with some compromise in performance.

The presence of nickel in these batteries increases the specific energy compared to LMO, as shown in Figure 34.

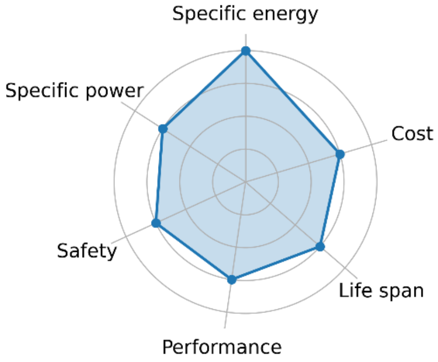

Figure 34 Average characteristics of NMC batteries

Lithium-Nickel-Cobalt-Aluminium Oxide ($LiNiCoAlO_2$) - NCA

These batteries share the same characteristics as NMC batteries, boasting attributes such as high specific power, high specific energy, and a long service life. However, they present cost and safety issues, as illustrated in Figure 35, which summarises their characteristics.

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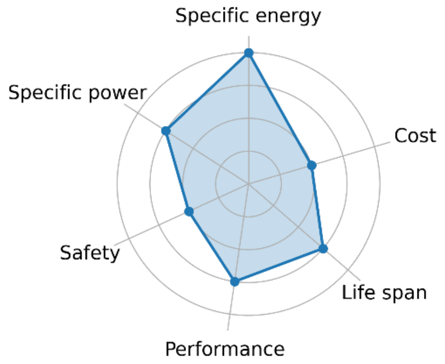

Figure 35 Average characteristics of NCA batteries

Summary of cell characteristics

According to [35], [40], [34] compares the main characteristics of the previously mentioned cell chemistries. It is not possible to rank the best and the worst. According to requirements, NCAs stand out for their specific energy, NMCs for its balanced characteristics, LFPs and LMOs for their high specific power, thermal stability and safety, and LTO for their long life and excellent performance at low temperatures.

13 | Summary of the main characteristics of lithium cells

Characteristics	**LCO**	**LFP**	**LMO**	**LTO**	**NCA**	**NMC**
Nominal voltage [V]	3.6	3.2	3.7	2.4	3.6	3.6
Operating range [V]	3.0 ÷ 4.2	2.5 ÷ 3.65	3.0 ÷ 4.2	1.8 ÷ 2.85	3.0 ÷ 4.2	3.0 ÷ 4.2
Specific energy [Wh/kg]	150 ÷ 200	90 ÷ 120	100 ÷ 150	50 ÷ 80	200 ÷ 260	150 ÷ 220
Charge [C-rate]	0.7 ÷ 1C	1C	0.7 ÷ 1C (3C max)	1C (5C max)	0.7C	0.7 ÷ 1C
Discharge [C-rate]	1C	1C (25C*)	1C (10C*)	10C	1C	1C (2C*)
Cycle life	500 ÷ 1000	2000+	300 ÷ 700	3000 ÷ 7000	500	1000 ÷ 2000
Thermal runaway [°C]	150	270	250	Very safe	150	210
Cost [€/kWh]	NA	~ 550	NA	~ 950	~ 330	~ 400

** experienced by some cells*

Terminology

There are several battery-related terms that are recurrently used. To prevent any potential confusion, this report clarify these terms as follows, in accordance with references [41]:

- State of Charge (SOC): SOC represents the battery's available energy as a percentage of its full capacity.
- Depth of Discharge (DOD): DOD measures the percentage of energy discharged in a single cycle. For example, a DOD of 60% can refer to a discharge from 100% SOC to 40% SOC, but it can also refer to a discharge from 60% SOC to 0% SOC. To describe the range of SOC levels within which a discharge occurs, the term "average SOC" (μSOC) is used.
- Full Equivalent Cycles (FEC): FEC denotes the number of cycles completed by a battery and is defined as cycles at 100% DOD.
- State of Health (SOH): SOH quantifies a battery's health by indicating the percentage of its initial capacity that remains available after aging.

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- End of Life (EOL): EOL indicates the predetermined point of SOH at which the battery is considered unable to power the application, typically set at 80%.
- C-rates: C-rates measure the rate at which a battery is charged or discharged relative to its capacity. A 1C rate corresponds to a full charge or discharge in one hour, while a 0.5C rate takes two hours, and so on. It is often used to describe the charging and discharging current in relation to the battery's nominal capacity (C). Here is how the C-rate is calculated:

C-rate (C) = Current (in amperes, A) / Capacity (in ampere-hours, Ah)

Cell packaging

The choice of packaging depends on the application's requirements for energy density, shape, and size. There are four primary cell designs: cylindrical, button, prismatic, and pouch cells. However, button cells, also known as coin cells, are not suitable for large battery systems due to their compact size and the absence of integrated safety systems.

Cylindrical cells have a tubular or cylindrical shape. They are known for their relatively high energy density, good load handling capabilities, consistent voltage output throughout most of their discharge cycle and are easy and cheap to produce. They generally have favourable cycle and calendar life characteristics, are easily cooled, and offer relatively high levels of safety with built-in protection circuits to prevent overcharging, over-discharging, short-circuiting, and pressure build-up thanks to a pressure relief mechanism in case of failure. However, a disadvantage is their lower packing density, which results in a lower overall energy density when used in a battery system compared to a single cell. Typical applications for cylindrical cells are flashlights, portable electronics, power tools, medical instruments, laptops and electric bicycles [41], [42].

Button cells (also known as coin cells) are small and inexpensive to build, but are not suitable for use in large battery systems. The drawbacks of button cells are the swelling if charged too quickly and the absence of safety vents [42].

Prismatic cells have a flat, rectangular or square shape (i.e., higher packing density) which makes them suitable for efficient packing in battery packs and applications with space constraints. However, they are more challenging and costly to manufacture, tend to have a lower cycle life, and can be challenging to cool evenly. These cells are found in mobile phones, tablets and, the large formats of them, in hybrid and electric vehicles [41], [42].

Pouch cells are characterized by their thin, flat, flexible design, which allows for efficient packaging (up to 90-95%) and versatile use in various applications and for their lightweight and cost-effective nature due to the absence of a metal casing. Nevertheless, pouch cells are sensitive to high humidity and elevated temperatures, which poses challenges in implementing safety features for them, and they tend to swell [42].

Charging protocol

Lithium-ion batteries are charged through a controlled voltage or current process. As illustrated in Figure 36, charging typically involves two phases: the constant current phase, where the battery is charged at a steady rate, followed by the constant voltage phase, where the voltage is kept constant while the current gradually decreases.

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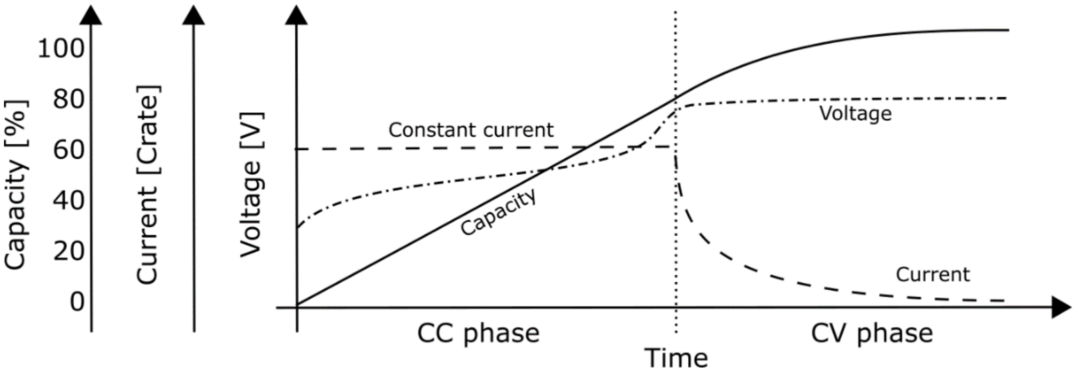

Figure 36 Charging protocol of lithium-ion batteries

In accordance with reference [39], let us break it down.

Constant Current (CC) Phase: During this phase, the lithium-ion battery is charged at a steady and controlled current level. The charging current is typically set at a specific rate, often represented as "C," which is a multiple of the battery's capacity. While the current is held constant, the voltage across the battery gradually increases. The voltage starts at a relatively low level and increases as the battery charges. The goal is to reach a specific voltage range, often between 4.1 V and 4.2 V for most lithium-ion batteries, before transitioning to the next phase. During the CC phase, the battery's capacity gradually increases. However, this phase typically charges the battery to around 70-80% of its full capacity. It is a relatively fast charging phase and is designed to get the battery to a high charge level quickly. The charger or charging controller monitors the battery's voltage and adjusts the current to maintain a constant rate. Once the voltage reaches the desired upper limit (e.g., 4.1-4.2 V), the charger switches to the next phase, the Constant Voltage (CV) Phase.

Constant Voltage (CV) Phase: Once the battery's voltage reaches a predefined level, the charger switches to the constant voltage phase. In this phase, the voltage across the battery terminals is kept constant, and the charging current gradually decreases. This voltage level is typically set at or slightly below the upper voltage limit specified for the battery, which is usually in the range of 4.1 V to 4.2 V for most lithium-ion batteries. As the battery continues to charge in the CV phase, the charging current gradually decreases. The primary purpose of the CV phase is to "top off" the battery, ensuring it reaches its full capacity without overcharging. This phase allows the battery to absorb the last bits of energy while preventing the voltage from exceeding the upper limit, which could lead to safety risks and damage. The CV phase continues until the charging current decreases to a predefined low threshold, often around 3% of the initial constant current used in the CC phase. This drop in current signals that the battery is almost fully charged, and the charging process is nearly complete.

If the maximum voltage limit is exceeded during charging, the rate at which lithium-ions move to the negative electrode (anode) becomes faster than the rate of intercalation. In such situations there is a risk of metal depositing, leading to the formation of dangerous lithium metal crystals, often referred to as dendrites. These dendrites can extend from the negative electrode (anode) towards the positive electrode, potentially puncturing the separator, causing a short circuit, and even generating heat or starting a fire [39].

Battery aging

Batteries play a crucial role in powering various devices, vehicles, and vessels. However, prolonged use leads to the inevitable aging of batteries, characterized by a decline in either capacity or power. This aging process stems from the natural wear and tear experienced by the battery's internal components, including the loss of free lithium, material deterioration, electrode disintegration and surface layer formation (the electrolyte material reacts with the electrode, forming a layer on the surface of the electrode, also known as SEI – solid electrolyte interface). The rate of battery aging is highly reliant on the specific chemistry, structure of the battery cell in use, usage, and environmental conditions.

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Battery aging can be categorized into two distinct types: calendar aging and cycle aging. Calendar aging occurs continuously throughout the battery's life, even when it is not actively in use. It depends on factors like state of charge (SOC) and temperature (T) and is quantified over time (t). In contrast, cycle aging takes place whenever the battery is subjected to charge or discharge cycles. Cycle aging is primarily influenced by parameters such as depth of discharge (DOD), average state of charge (µSOC), and the C-rates for charging and discharging. Furthermore, humidity and pressure within the battery space can influence battery ageing, as well as overcharging or over-discharging and unbalanced state of charge between cells in the same system [41].

In what follows, according to [41], a brief account is made of the aging due to temperature, state of charge, C-rates and depth of discharge. Humidity and pressure levels in the environment where batteries are stored can be controlled by air conditioning systems, while overcharging, overdischarging and unbalance states of charge can be monitored by the battery management systems (BMS).

Aging due to temperature

Battery aging due to temperature is a critical factor that significantly impacts the performance and longevity of batteries. The relationship between temperature and battery aging is complex, and understanding it is essential for optimizing battery operation and extending its useful life.

High Temperatures: high temperatures can accelerate the aging process of batteries. When a battery is exposed to elevated temperatures, it experiences several detrimental effects, such as the accelerated decomposition of the battery's electrolyte. This leads to the faster depletion of the active lithium in the battery and the rapid growth of the solid electrolyte interface (SEI). High temperatures typically reduce impedance, resulting in improved power output from the battery, which can be beneficial in certain applications. However, the downside is that increased power output at high temperatures often comes at the expense of accelerated aging, thus a decline in battery capacity over time.

Low Temperatures: when a battery is exposed to cold conditions, there is a risk of lithium plating occurring on the anode. This can lead to the depletion of the available lithium in the battery, reducing its capacity and overall performance. Additionally, low temperatures increase impedance, causing an immediate and often reversible decrease in power output. For long-term storage, keeping batteries at lower temperatures is generally advisable, as it can slow down the continuous aging processes. However, during cycling, maintaining the battery at an optimal operating temperature is essential. The specific optimal temperature can vary depending on the battery's chemistry, design, and intended application.

Aging due to state of charge

Battery aging due to the state of charge (SOC) is an aspect that influences the performance and lifespan of batteries. The SOC of a battery determines the voltage at which it operates. High SOC means the battery is closer to its fully charged state, and low SOC indicates a lower charge level. These different SOC levels result in varying electrode potentials, which, in turn, affect the occurrence of side reactions between the electrode materials and the electrolyte. In particular, a high SOC places the graphite electrode at a low potential, which falls outside the electrochemical stability window of the electrolyte. Consequently, this condition leads to the degradation of the electrolyte material and the growth of the SEI on the electrodes. In addition, SOC has a direct impact on the battery's internal resistance, with higher values observed at both high and low SOC levels. High internal resistance contributes to higher temperatures during cycling, thus accelerating the ageing process.

To mitigate ageing, during storage, it is advisable to maintain a low SOC level. To mitigate ageing, during cycling, it is recommended to operate the battery in a range of 20% to 70% SOC due to the associated low internal resistance, although these optimum values may vary depending on the specific chemistry and design of the battery.

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Aging due to C-rates

Rapid charging at high C-rates accelerates the growth of SEI and the loss of lithium due to the formation of lithium plating on the anode. Furthermore, when a high C-rate occurs in a high state of charge, it can lead to disintegration of the anode material, aggravating battery deterioration. Subjecting a battery to rapid charging and discharging at high C-rates leads to an increase in the internal resistance, thus in temperature and, therefore, accelerated aging.

Aging due to depth of discharge

The depth of discharge has a significant influence on the number of cycles a battery can undergo. Deeper discharges result in a shorter cycle life, while shallower discharges can prolong it considerably. However, designing a battery for shallower discharges could lead to an oversized and more expensive battery than a smaller system that requires earlier maintenance but allows more space on board.

A significant depth of discharge (DOD) leads to significant volumetric shifts in the electrode material. These volumetric displacements accelerate various ageing mechanisms such as the disintegration of the electrode material, caused by the mechanical stresses induced by these displacements; the destruction of the SEI layer, which exposes the electrode material to the electrolyte, favouring further side reactions between the two; and the increased loss of free lithium due to high DOD, i.e., higher battery utilisation.

3.3.5.3 Battery management system

Battery management systems (BMS) are essential for monitoring and controlling individual cell voltages, temperatures, and states of charge/discharge. BMS helps optimize battery performance, life, and ensure safety.

According to [43], the lithium-ion battery management system (BMS) accomplishes several functions:

- **Over-voltage Protection**: the system protects cells that exceed the upper voltage limit by interrupting the charging current. If the maximum voltage limit is exceeded during charging, there is a risk of metal depositing, leading to the formation of dangerous dendrites. These dendrites can extend from the anode towards the cathode, potentially puncturing the separator, causing a short circuit, and even generating heat or starting a fire. Overvoltage protection also helps maintain the long-term health and lifespan of the battery. Continuous overvoltage can lead to cell degradation and reduced capacity;
- **Under-Voltage Protection**: it ensures that no cell's voltage drops below a designated threshold by stopping the discharging current. Undervoltage protection is essential to prevent deep discharge, which can harm the battery and result in capacity loss, safety issues, and, in extreme cases, irreversible cell damage;
- **Over-Temperature Protection**: the BMS prevents any cell from exceeding a specified temperature limit by directly ceasing the battery current or initiating cooling mechanisms. Overheating can have detrimental effects on cell health and life. Prolonged exposure to high temperatures can cause cell degradation, reduce capacity, and shorten the battery's overall lifespan;
- **Current Regulation**: the BMS monitors and regulates the charging and discharging current, adapting it based on the cell's voltage and temperature;
- **Balancing**: the system ensures all individual cells within a battery pack maintain the same state of charge (SOC) and voltage. Balancing prevents overcharging of cells with higher voltage and overdischarging of cells with lower voltage. Differences in cell voltages can lead to capacity mismatches, reduced overall capacity, and potentially unsafe conditions.

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Safety

Battery safety is of paramount importance in various applications, as batteries have become integral components in our daily lives, powering everything from mobile devices to electric vehicles and renewable energy storage systems. Understanding the safety aspects of batteries, including their main failures and the specific issue of thermal runaway, is crucial to ensure the protection of both people and the environment.

The main battery failures include:

- **Short Circuits:** internal or external short circuits can cause a rapid discharge of energy within the battery, generating heat and potentially leading to thermal runaway;
- **Overheating:** overcharging, excessive discharging, or exposure to high temperatures can cause a battery to overheat, which can lead to reduced performance and safety risks;
- **Physical Damage:** physical damage to the battery can puncture the casing or damage internal components, potentially causing a short circuit or leakage of battery electrolytes.

In the event that batteries explode, these materials have the potential to inflict damage on the surrounding environment. Some of these compounds possess toxic properties and pose a danger to human life. Among the well-documented failure modes in batteries is the occurrence of *thermal runaway*. Thermal runaway is a particularly hazardous failure mode in batteries. It occurs when a battery's temperature rises uncontrollably due to an imbalance between heat generation and dissipation. This can lead to a catastrophic chain of events with the potential for severe consequences. As the temperature rises, more heat is generated through the electrochemical reactions and Joule heating. Elevated temperatures can cause the battery's components to break down. In severe cases the internal pressure and heat can result in an explosion due to the high explosivity of lithium.

To ensure battery safety and prevent thermal runaway, various measures are taken:

1. **Battery Management Systems (BMS):** essential for monitoring individual cell voltages, temperatures, and states of charge/discharge and to ensure it operates within safe limits;
2. **Thermal Management:** effective cooling systems help regulate battery temperature;
3. **Safety Features:** batteries could feature thermal fuses and pressure relief mechanisms to prevent failures;
4. **Quality Control:** high-quality materials and rigorous manufacturing processes help minimize internal defects and failures;
5. **Proper Usage:** following the recommended charge and discharge profiles and avoiding overcharging or fast charging are essential for battery safety.

Expected developments

Promising battery technologies of the future include solid-state lithium-ion, lithium-sulphur and lithium-air batteries. Solid-state lithium-ion batteries are gaining attention for their potential to offer higher energy density, fast charging and increased safety by using solid electrolytes instead of liquid ones, reducing the risk of leakage and thermal issues [35]. Lithium-sulphur batteries (Li-S) boast a high specific energy of 550 Wh/kg and are thermally stable at low temperatures offering recharging even at -60 °C. Furthermore, sulphur is widely available. The weaknesses are the limited cycle life, about 40–50 charges/discharges, due to sulphur loss during cycling and poor stability at high temperatures [40]. Lithium-air batteries have the highest theoretical specific energy of all battery systems, exceeding 5000 Wh/kg [39]. These batteries do not store cathode material inside the battery, resulting in a lighter and more compact cathode. In fact, the battery uses a catalytic air cathode that supplies oxygen. The main drawback is represented by the short cycle life [39].

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Future developments in the field of batteries aim to solve several key challenges, including charging speed, durability, performance, safety, sustainability, and regulations. Researchers and manufacturers are dedicated to improving the energy density of lithium-ion batteries, mainly by creating materials with higher capacity and optimising electrode structures to store more energy in the same space or weight. Efforts are also focused on achieving faster charging capacities. Extending the life of lithium-ion batteries is another important goal. This involves the development of more robust electrode materials and better control of charging and discharging processes to reduce wear over time. The priority of safety remains paramount: advanced thermal management systems, smart battery management and better materials have been developed to reduce the risks associated with overheating and fires. In addition, the reuse of lithium-ion batteries for secondary applications, such as residential energy storage or electric vehicle charging stations, is becoming more widespread. This approach extends the life of batteries beyond their initial use, minimising waste. Environmental sustainability is another focus, with manufacturers actively pursuing eco-friendly battery chemistry. In addition, the expansion of lithium-ion battery recycling programmes aims to mitigate the environmental impact associated with battery disposal. With the continued proliferation of lithium-ion batteries in various applications, it is logical to expect regulations and standards to evolve. These changes are essential to ensure the safety and environmental responsibility of lithium-ion batteries as their use becomes more widespread.

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4. Hydrodynamic Improvements

The hydrodynamics of seagoing (coastal) ships are well understood, documented in literature and addressed by several finished and ongoing European research projects in dedicated calls. Resistance and power demand as well as the impact of various form parameters or energy-saving devices (ESDs) can be estimated with statistical or empirical models or formulae. Therefore, this chapter focuses on inland ships and their specific boundary conditions first. Afterwards, ESDs for seagoing ships are discussed together with their applicability for inland shipping.

Despite the inherently high energy-efficiency of transport on inland waterways and the related low fuel costs per passenger- or tonne-kilometre, there is a strong motivation to maximise profitability. The aim here is to achieve an optimum combination of low investment and operating costs and the highest possible profits. As profits are directly linked to transport performance, cargo holds should be as large as possible and often correspond to the dimensions of a certain number of containers. The main dimensions of the ships are usually limited by lock sizes or regulations on certain waterways. This leads to long parallel midship sections and short fore and aft ship geometries. It is also important to avoid downtimes due to low water periods. The ships should be able to continue sailing economically and safely even with a very shallow draught. Hekkenberg [44] provides a good overview of the most important factors that determine the economic efficiency of inland vessels and inland navigation.

In order to fulfil these requirements, ship designs have emerged that include short aft hulls, highly loaded ducted propellers and devices such as propeller tunnels to prevent ventilation at shallow draughts. The hydrodynamics of these full hull forms with large block coefficients is challenging and strongly influenced by the available under-keel clearance. As a consequence, many vessels leave significant room for improvement of their power demand and energy efficiency under realistic operating conditions. Increasing energy costs with conventional fuels and even more with alternative low- or zero-emission technologies result in a higher priority of hydrodynamic optimisation. Slightly increased manufacturing costs and even reduced cargo capacity are more likely to be tolerated in the future compared to the last decades where the majority of the fleet was built.

Some ships are analysed with the help of CFD calculations and model tests, which makes it possible to improve unfavourable ship lines before the ships are built. However, these investigations are limited to individual newbuildings. The aft-ship replacement, which is researched within SYNERGETICS, allows significant hydrodynamic improvements for the existing fleet. Other options, also explained in the following, can be retrofitted with less effort.

The historical development of ship dimensions goes hand in hand with the dimensions of natural waterways (mainly water depth and width) and their development in canals and locks. Today, there is a very heterogeneous fleet of inland waterway vessels whose dimensions are based in particular on the standardised classification of European waterways (see Table 3). The durability of the ships also means that older, smaller ships - some of which are over 100 years old - are still in operation today. In many cases, modifications have been made to these ships, in particular extensions in length and the recombination of aft ships and cargo sections. Even widening has proved to be economical for some ships.

In the following it is assumed that dimensions of the cargo holds will not be altered, as well as the required ship speed will not be lowered (which would obviously reduce the energy demand directly). Against this background, hydrodynamic improvements will be discussed. Note, that specific features and devices will be presented that help to increase the hydrodynamic efficiency of the vessels, but emphasis is given to the fact that the basis for a hydrodynamically optimised vessel is a good ship design. This comprises the design of the hull, the propulsion system, the appendages and other elements.

Furthermore, ship design always means system design. Many aspects like ship operation, environmental conditions, resistance, propulsion and the main engine, besides others, interact. While it is useful to optimise individual elements, and while it is also required and the established procedure to break the global optimisation task down into subtasks, it is always necessary to keep the overall system and the

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interaction of the individual components in mind. Only the total system view will eventually lead to maximum savings. For example, if a ship is (hydrodynamically) optimised for a certain design speed, which is often the case, but later operated at different, usually lower, velocities or on other types of waterways with other prevailing water depths and widths, the system will never fully benefit from the design speed optimisation.

It is a matter of fact that the existing fleet is very inhomogeneous due to different applications/tasks, different shipping routes/water ways, different types of ownerships and so on, and this will not substantially change in the future. However, all existing and future inland vessels are of course exposed to the same physical principles. This means that the ship resistance largely determines the required power. Thus, all ships, independent of type, size, transport task or even their energy system will directly benefit from a reduced ship resistance. Primarily, less power and hence less energy are required to drive the vessel. Secondary or indirect effect is, that reduced power demand will lead to smaller engine sizes, hence less engine weight, as well as smaller drive trains and smaller energy storages.

However, the resistance of inland waterway vessels, in contrast to seagoing vessels, can be much less influenced by specific measures. The resistance in shallow water operation is only to a little extend dependent on variations of the hull geometry, but widely dominated by the shallow water effects. Therefore, the focus on the minimisation of ship resistance is less relevant than for sea-going ships. The complex interaction of hull, propulsor and waterway can have a huge impact on the power demand as shown in Figure 37 below. Here four different but representative designs of large Rhine ships (110 m by 11.4 m) are compared at a draught of 2.8 m at a moderate shallow water depth of 3.5 m. All of them have similar cargo capacity and investment costs. The only differences are the shape of the aftship and the number of propellers (one or two) and their diameter (1.6 m for twin-screw and 1.76 for single-screw designs). In the plot on the left-hand side, only marginal differences in the effective power, based on resistance tests in model scale, can be observed. On the right-hand side, the delivered power predicted from model self-propulsion tests in DST's shallow water basin is plotted. Only, with propulsion a massive difference in power demand up to a factor two between the best and the worst design can be observed. Relative differences at larger water depths are much smaller and close to those for resistance/effective power in the deep-water case.

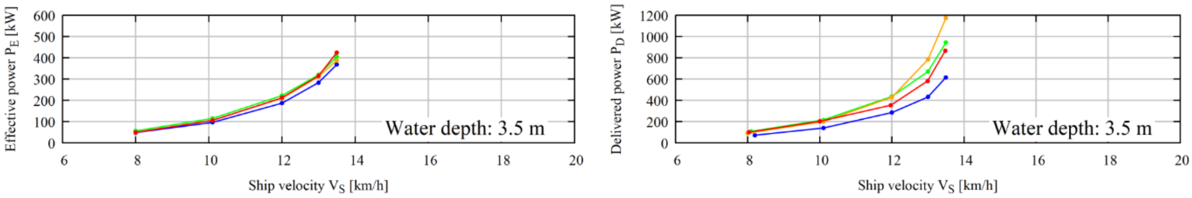

Figure 37 Effective (left) and delivered (right) power for four different aftship designs

Another relevant difference between seagoing and inland water vessels with respect to hydrodynamics are the absence of added resistance due to motion in waves. Furthermore, several hydrodynamic improvements / energy-saving devices that work efficiently on seagoing vessels do not work (or very much less) for inland water vessels. This is mainly due to the limited water depth / keel clearance and the consequential substantially different flow conditions for the propellers. Also wind-assisted propulsion, addressed by other Horizon Europe projects, is no option in inland shipping.

The hydrodynamic effects and measures that are considered relevant for inland vessels are described in the following. The frictional resistance of the hull is largely influenced by its surface roughness. This is generally determined by the average roughness of the hull coating. The roughness can increase due to bio fouling, especially in regions with higher water temperatures. Special coatings, like silicone-based coatings, reduce the friction resistance of the hull. Additionally, regular cleaning of the hull can be beneficial.

Air lubrication currently is not considered viable for inland waterway vessels. The effectiveness of such systems is questionable in restricted waters. Also, the investment and operational costs (CAPEX for compressors and hull penetrations; OPEX for operation of compressors) are considered prohibitive. Some systems increase the draught of the vessel or decrease the cargo capacity at a given draught.

Well-designed ship lines are the crucial basis for minimised wave-making resistance (not to confuse with added resistance in waves). While there is generally more freedom of design for new designs and newbuildings, an analysis of the ship lines of existing vessels is also valuable and can lead to an improvement. No extensive fairing will be carried out for existing vessels, of course, but an investigation of the existing hull shape may detect local obstacles that are easy to eliminate and/or modify, or may even lead to the insight that a replacement of a part of the ship hull might be worthwhile (up to the replacement of an entire aftship). For typical close-to-box-shaped inland water vessels, there is usually only little room for the optimisation of the wave resistance, as bow and aftship cannot be designed more slender in order to maintain the maximum box shaped cargo holds. However, in some cases even smaller modifications like a slight shift of the forward shoulders or optimisation of the aftship lines can improve the wave resistance. For the design of the aftship lines, another crucial aspect is the layout of the curvature. Too tight radii of curvature have to be avoided in order to prevent flow separation due to large flow velocity gradients. If flow separation occurs, the residual resistance of the bare hull increases substantially and the hull-propulsor interaction can result in an additional increase in power demand.

However, the most significant aspect of aft ship lines modification is the optimisation of the propulsion conditions. Appendages inhere a disproportionately negative impact on the ship resistance. Bulky or poorly aligned appendages have to be avoided in new designs and eliminated/replaced on existing vessels. Note, that especially for inland water vessels, “appendages” might also be structural parts that serve a purpose which is not related to the propulsion or hydrodynamic performance of the vessel, but to the transport task (e.g. push brackets) or loading/unloading procedures. They might be just “accidentally” submerged under transit conditions due to the wave patterns. The rudder has a significant influence on the resistance, more precisely mainly the operation of the rudder. This is discussed further below under operational aspects.

The aerodynamic resistance can also be subject to optimisation since it also contributes to the total resistance of the vessel and hence to the power demand. The layout of the deck house, deck equipment etc. can be optimised in order to reduce the added resistance due to wind. Furthermore, the wind can lead to a drift angle of the vessel which also leads to a larger resistance.

The second crucial measure that determines the power requirement of a ship, next to the resistance, is the efficiency of the propulsion. Due to the limited options to reduce the resistance for shallow water navigation, the propulsion is even more important and dominant. This regards the optimisation of the operating conditions of the propeller, largely determined by the inflow conditions into the propeller plane. Again, the basis for an efficient propulsion is a proper design, not only with respect to the propeller itself, but also to the aftship lines and appendages. Fixed pitch propellers are designed to be operated in their optimum efficiency point. Accordingly, it is advisable to change the propeller if the vessel shall be operated at a lower speed, hence lower rpm of the engine.

An important type of loss is the rotational energy lost in the propeller slipstream. There are a number of devices that have been developed, mainly for sea-going ships, to reduce the rotational losses and to recover some of this energy. These devices can be divided into two categories: Those that work upstream of the propeller, and those installed downstream of the propeller. Examples for upstream devices are pre-swirl fins, pre-swirl stator blades, Mewis ducts and even asymmetric aftbodies. For the post-swirl devices, it has to be noted, that already the bare rudder(s) behind the propeller can recover some of the rotational energy. Hence, rudders have always to be taken into account when the effects of other energy saving devices are investigated. Other downstream elements are for example the Grim vane wheel, positioned directly behind the propeller generating additional thrust, as well as stator fins or rudder thrust fins, both mounted on the rudder. It has to be considered that since the purpose of all

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these devices is the reduction of the same type of loss, only a one single item should be taken into account. Benefits are not cumulative.

For the reduction of tip vortex losses, tip fins similar to aircraft winglets, can be applied. Hub vortex losses can be reduced by propeller boss cap fins (PBCF) or hub vortex vanes (HVV), like a small vane propeller fixed to the tip of a conical boss cap. Also, costa bulbs that are mounted at the leading edge of the rudder blade are an established device for seagoing ships.

Propellers operate in an inhomogeneous wake behind the ship. Therefore, pressure fluctuations on the propeller are induced. The propeller design aims to limit these fluctuations and the respective vibrations. The more homogeneous the wake is, the better, i.e. the more efficient, the propeller design can be chosen. Devices that support the equalisation of the wake have been proposed like Schneekluth nozzles or wake equalizing ducts (WED) or vortex generators. Shallow water effects strongly alter the wake field so that the propeller operates under more complex conditions, see below.

As far as deep-water operation is considered, all these measures and devices have certain benefits and therefore most of them have also reached market readiness for seagoing vessels and have proven their advantages there. However, for inland water vessels operating in shallow water – the still water draft of the vessel is in many cases even less than the propeller diameter – the operational conditions of the propeller get very challenging. This is due to blockage effects, the inhomogeneity of the inflow and due to air entrainment into the inflow to the propeller (i.e. ventilation).

In general, a propeller is more efficient with increasing diameter. While the propeller diameter is limited by the draft for all conventional ships, the limit is even more critical for inland vessels operated in shallow water. Inland vessels are designed with a low draft and propeller ventilation can result in a loss of thrust. The smaller the underkeel clearance is, the more the flow between the riverbed and the hull is blocked, so that the water needs to be drawn in from the sides into the propeller plane. As a result of the limited propeller diameter, which increases the thrust loading, and the changing propeller inflow, most inland waterway vessels benefit from ducted propellers. The ducts protect the propellers and deliver additional thrust.

In order to hinder ventilation, the aftbodies often feature a more or less pronounced tunnel shape. The drawback of these means is an increased power demand. A practical, yet expensive solution are flex tunnels that can be deployed if necessary to avoid ventilation and can be folded into the hull for conditions without risk of ventilation.

As a consequence of the effects depicted before, the design of the aftship of inland waterway vessels running at variable water depths has a crucial influence on the power requirement. Moreover, it has to be noted that the design of an inland waterway vessel must be conducted on an individual basis, taking the specific boundary conditions into account.

Finally, several operational aspects directly or indirectly interfere with or influence the hydrodynamic performance of the vessel. During constant forward motion, the movement of the rudder(s) is the main operational influence. Less rudder motion is beneficial for the hydrodynamic performance as the propeller stream remains unaffected and less drag is induced. Thus, a smooth navigation mode and a well parametrised rate of turn controller are beneficial for fuel savings. There are electronic support systems like track-controllers that help to reduce the required rudder operation.

A similar case is the intelligent choice of the path along a river, with respect to local water depth, local currents and encountering ships. Also, in this respect both a prescient operation mode, often based upon experience of the crew, and state-of-the-art navigational electronics / routing systems can help to choose a fuel-efficient route selection.

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5. Conclusions

This deliverable D1.1 was compiled within Task 1.2 of SYNERGETICS WP1 to serve as a reference book for the state of play of technologies suitable for retrofitting of inland and coastal ships. Upcoming deliverables and tools will build on the content and provide updated or more detailed information for individual parts. The report starts with an overview of the considered fleets and their boundary conditions and requirements for greening measures. The concept and exemplary contents of the Sustainable Power Portal, that was developed within the working group Sustainable Alternative Power for Ships (SAPS) of the European Sustainable Shipping Forum (ESSF), is presented, as the SYNERGETICS Catalogue of retrofitting measures will use it as a starting point.

Afterwards, technical solutions are presented including developments in other sectors. Section 3.2 deals with the energy carriers and 3.3 with the corresponding energy converters. Last but not least chapter 4 summarises the relevance of hydrodynamic improvements on energy efficiency and overall emissions.

Even though this report is a neutral compilation of information, it confirms why shipping is categorised as a hard-to-abate sector. Advantageous boundary conditions that have favoured or are expected to favour the rapid spread of low-emission technologies, at least in some other sectors, are hardly to be expected in the shipping industry. These include, for example, kinetic energy recovery when braking road and rail vehicles, the relatively simple provision of overhead lines on tracks and special cases such as "perpetual motion electric trucks". Factors such as the pressure to comply with clean air plans are also unlikely to be a driving force in the shipping industry. In contrast, the greater pressure in other applications partially leads to those sectors being favoured in the competition for energy carriers, that are only available to a limited extent, even in the medium term. The high costs related with sustainable energy carriers, their storage and conversion technologies form an additional barrier for the market uptake. Since inland and coastal shipping as a sector is not a development driver in the true sense of the word, it can be more efficient to adapt technologies with already relatively high TRL and market-availability to the requirements on board, i.e. to carry out marinisation.

In addition to the introduction of new propulsion systems, the continuous increase in energy efficiency by means of hydrodynamics is an important measure next to other approaches to increase efficiency (e.g. logistic optimisation, trip planning). Thus, all ships, independent of type, size, transport task or even their energy system will directly benefit from a reduced ship resistance. Primarily, less power and hence less energy are required to drive the vessel. While labelling of the energy efficiency is already mandatory for large seagoing ships, such indicators are still being developed for inland navigation. Secondary or indirect effect is, that reduced power demand will lead to smaller engine sizes, hence less engine weight, as well as smaller drive trains and smaller energy storages. All in all, the time for greening shipping is more favourable than in the decades before. However, in freight transport in particular, no technology is yet within striking distance of conventional drives in economic terms. High costs, technical and regulatory hurdles and disadvantages in ship operation stand in the way of commercial viability. Holistic strategies comprising technology development, increased awareness, incentive schemes and regulations must be developed and rolled out in order to achieve rapid decarbonisation. The required synergy effects are the core topic of the SYNERGETICS project.

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