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Technologies and Fuels for Decarbonising Maritime and Hinterland Freight Transport

Project „Deep Decarbonisation Pathways for Transport and Logistics Related to the Port of Rotterdam“ (PoR Transport)

Deliverable Work Package 1

Andreas Pastowski

Port of Rotterdam

Wuppertal Institut

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Project coordination:
Wuppertal Institute for Climate, Environment and Energy
Dorothea Schostok, Katharina Knoop, Prof. Dr. Stefan Lechtenböhmer
Döppersberg 19
42103 Wuppertal
dorothea.schostok@wupperinst.org, katharina.knoop@wupperinst.org,
stefan.lechtenboehmer@wupperinst.org

Authors:
Andreas Pastowski
In collaboration with Annika Tönjes

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Editor:
Wuppertal Institut für Klima, Umwelt, Energie gGmbH
Döppersberg 19
42103 Wuppertal
www.wupperinst.org

Contact:
Andreas Pastowski
Division Future Energy and Mobility Structures
andreas.pastowski@wupperinst.org
Tel. +49 202 2492-118
Fax +49 202 2492-108

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ASIF	Determinants of GHG emissions: Activity, structure, intensity, fuel
CNG	Compressed natural gas
CO_2	Carbon dioxide
DMFC	Direct methanol fuel cell
EEDI	Energy efficiency design index
EU	European Union
FT	Fischer-Tropsch process
GHG	Greenhouse gas
H_2	Hydrogen
HFO	Heavy fuel oil
IMO	International Maritime Organisation
LNG	Liquefied natural gas
MRV	Monitoring, reporting and verification
n.a.	Not available
NH_3	Ammonia
NO_X	Nitrogen oxides
P2F	Power to fuel
SEEMP	Ship energy efficiency management plan
SIR	System integration readiness
SO_X	Oxides of sulphur
TEU	Twenty-foot equivalent unit
TRL	Technology readiness level

1 Scope and methodology of maritime transport decarbonisation

1.1 The relevance of geographic scope

While maritime transport considered for this study refers to those ships calling at the Port of Rotterdam, it is clear that this is no match of maritime transport at the global scale. It refers to a specific fraction of maritime freight transport with vessels that technically and operationally comply with the existing environmental regulations under the umbrella of the International Maritime Organisation (IMO) as well as the European Union (EU), the Netherlands and the City and Port of Rotterdam. Currently, this is focused on regulations concerning emissions of air pollutants with conventional engine designs as well as quality of fuels used.

At the same time, Rotterdam is one of the bigger ports that attract larger vessels. Typical for the largest ships in operation, those are on average less old and more energy efficient. Vessel age is important not only because newer designs tend to be intrinsically more efficient but also because aging of vessels results in an increasing difference between technical design efficiency and diminishing factual efficiency caused by the decay of relevant technical components (ICCT 2013). For these reasons, it can be assumed that vessels calling at the Port of Rotterdam are on average less old, technically more advanced and subject to stricter monitoring and maintenance than at the global scale of maritime shipping. In principle, a complete stock taking of vessels calling at the Port of Rotterdam as compared to the global fleet would be possible but is beyond the scope of this study.

Thus it is unclear to which exact extent greenhouse gas (GHG) intensities of vessels calling at the Port of Rotterdam are below those on average at the global scale. Notwithstanding this, it needs to be kept in mind that this makes a difference that has an impact on existing baseline reductions of CO_2 emissions as well as the remaining future potential. Thus potentials for further reductions per individual strategy and of any combination of strategies considered for ships calling at the Port of Rotterdam may be somewhat lower than on average at the global scale of maritime shipping.

Beyond geographic scope, even more differentiation is required with regard to cruise ships with a relatively high willingness to pay of customers as opposed to vessels for freight transport where profit margins are slimmer. Thus cruise ships even though depicting very high energy intensities resulting from substantial facilities for accomodation and entertainment may to some extent be regarded as frontrunners in terms of technical progress some of which may trickle down to vessels for maritime freight transport and thus allow to decarbonise maritime shipping in general. However cruise ships are a special niche market of maritime passenger transport and not within the scope of this study.

1.2 Principle strategies for decarbonisation in maritime transport

In principle, following the ASIF approach, decarbonisation in the freight transport sector may rely on changes in demand for transport services (**A**ctivity), shares of modes of transport used (**S**tructure), energy intensity per mode used (**I**ntensity) and the use of decarbonised fuels or entire propulsion systems (**F**uel) (Schipper et al. 2000).

Demand for transport services is very relevant for decarbonisation but for the most part beyond the scope of this study. However it is clear that decarbonisation of whole economies will largely result in abolishing the use of fossil energy carriers which may have profound repercussions on related demand for maritime freight transport that has played a significant role since the industrial revolution. In a decarbonised world substantially less fossil energy carriers will be transported (Pastowski 2005). At the same time, some volume of carbon-neutral hydrocarbons will be produced based on renewable energy for trade and will hence need to be transported. Modal structure can be disregarded with maritime shipping as more energy efficient modes are simply unavailable and other modes (in particular air transport) can not reasonably be used for the bulk of intercontinental freight transport.

Technical and organisational changes are important categories for distinguishing potential strategies for the decarbonisation of energy use in maritime shipping. However some of them can not be considered in isolation. E.g. certain technologies may for the most part be important enabling factors for the implementation of new operational strategies (e.g. technologies that allow to systematically monitor energy use of vessels) or operational practices may need to be adapted following the implementation of new technologies (e.g. new propulsion designs).

Thus besides changes in demand for transport services resulting from decarbonisation, there are basically two pillars of strategies for maritime transport and likewise other transport modes:

- The first pillar is based on technical or operational innovation with existing ships and propulsion systems that result in an increase in energy efficiency and, consequently, a reduction of carbon emissions per ton-mile. It is clear that applying strategies for higher energy efficiency on their own will never result in a complete decarbonisation of maritime shipping (Loyd's Register 2016). At the same time, with these strategies the achievement of absolute reductions in CO_2 emissions from maritime shipping will heavily depend on the further growth of demand for transport services. The implementation of effciency measures often brings about reduced cost of transport services which may induce additional demand (rebound effect) that to some extent will counteract the initially envisaged absolute emission reduction.
- The second pillar of decarbonisation in maritime shipping rests with the implementation of decarbonised energy either with existing propulsion systems, hybrid or entirely new designs.

Deep decarbonisation of maritime freight transport requires a combination of both pillars: Starting with low hanging fruits, additional gains in efficiency may result in early reductions of emissions and cost that may enhance the pace of related innovation activity and the diffusion of new technology and operational practices.

As far as efficiency gains are not technically bound to conventional propulsion systems, those will also reduce the effort and cost required while switching to alternative fuels and propulsion systems. Decarbonised propulsion as the second pillar is a prerequisite for deep decarbonisation with future growth of maritime freight transport, regardless how much efficiency can be increased.

Thus the first pillar allows for early emission reductions while the second pillar will require more time owing to the fundamental changes required for the broad implementation of decarbonised fuels with regard to entirely new propulsion technology penetrating the fleet as well as the build-up of infrastructure required for the production and distribution of such fuels.

1.3 General scope of technologies and operational strategies for decarbonisation of maritime freight transport

In principle, there are plenty of technical and organisational strategies that might be deployed to decarbonise maritime freight transport. In order to shed some light on this and derive assumptions for quantitative scenarios for the Port of Rotterdam, the aim of this report was to provide illustrative figures for what currently seem to be the main strategies for decarbonisation of maritime freight transport.

It was not possible to undertake a complete review of existing studies that have reviewed existing estimates on the potential increases in energy efficiency or reductions in carbon emissions from all such strategies. Thus a few studies have been selected that cover the range of technical and operational solutions. Those have been combined with the results of a recent review of such studies (Bouman et al. 2017) in order to provide an impression of the orders of magnitude as well as the existing diversity of such estimates.

In the selection process of individual technical and operational strategies for this study those have been disregarded where potential efficiency gains have been estimated in the literature to be below 1 per cent. Thus the compilation of strategies in Annex 1 is not necessarily complete. This was primarily done for reasons of lucidity of the whole excercise and does not preclude future potentially more significant contributions from excluded strategies in particular resulting from break-through innovation activity. The result is a snapshot of currently available strategies and their likely contributions to increasing energy efficiency and reducing carbon emissions.

The main issues existing with the kind of studies and estimates reviewed are caused by the following factors that make it difficult to draw definitive quantitative results from them:

- Varying degrees of differentiation versus extent of aggregation and patterns of clustering of the various strategies;
- Different time horizons that – taking into account time required for the implementation of particular strategies – necessarily have an impact on their potential for decarbonisation;
- Studies that estimate the relative effect of strategies when applied to individual vessels or types of vessels versus those that try to quantify relative potentials looking at geographically varying and time-specific fleets with their respective levels of implementation already achieved;
- Operational strategies like slow steaming which will need to be politically adjusted (e.g. speed limits); and
- Operational strategies where the outcome is highly dependent on the difficult to predict further sectoral economic development and patterns of world trade (e.g. capacity utilisation at fleet levels).

Further to this, efficiency gains quoted for individual strategies may not be additive and generally there is a lack of data on vessel fleets regarding the current state of diffusion of technologies or operational practices. The mentioned review of studies concludes that the median values of efficiency gains of studies at the fleet level are 35% for 2020, 39% for 2030 and 73% for 2050. (Bouman et al. 2017)

However the current state of fleet penetration per individual strategy is far from well-known, which renders estimating aggregate efficiency and CO_2 reduction potentials of likely efficiency gains difficult. There are not many ships that are identical and the deployment of retrofits depends on operational characteristics of use (e.g. cargo type) and preferences of individual ship owners versus ship operators as well as the industry's business cycle and the price for heavy fuel oil (HFO).

A recent study that conducted a survey with selected ship owners and operators has shed some light on the extent of implementation of individual strategies for increasing energy efficiency with existing vessel fleets (Rehmatulla et al. 2017) . Generally, the study concludes that strategies for higher energy efficiency have been implemented to a smaller extent than assumed in the bulk of the literature. At the same time there is a clear mismatch between strategies that are expected to have a high effect on energy efficiency and carbon abatement and their low levels of implementation.

Opposed to the insufficient evidence on the level of implementation of strategies for increasing energy efficiency, the current implementation of decarbonised fuels used with conventional propulsion systems or entirely new propulsion systems is very scarce with current vessel fleets. Thus these cases can be neglected for purposes of assessing the related current state of achieved emission reductions.

In this study, nuclear reactors are not considered as alternative propulsion systems for the decarbonisation of maritime shipping. In principle, the technology is available as used with some military vessels and ice-breakers. However the particular risks and costs associated with the utilisation of this technology as well as potential proliferation of nuclear technology and materials mainly imply a shift from the risks of climate change to those of nuclear. Owing to the substantial damages that may arise from failure during operation of nuclear reactors and sites for disposing of longlived nuclear waste, it is difficult to determine whether such a shift may result in any net benefits.

Generally it can be stated that at the global scale there is plenty of renewable energy available based on hydro power, solar radiation, wind power, power from waves and ocean currents and geothermal energy. Hence in principle, there is no need to deploy strategies for decarbonisation that pose substantial risks with regard to other sustainability issues than climate change (e.g. irreversible loss of biodiversity, crowding out of food production through utilisation of biomass for fuels, radiation from nuclear reactors).

2 Assessment of strategies for transport decarbonisation

2.1 Assessment criteria: Technology readiness

Technology Readiness Levels (TRL) have been defined by NASA for space missions and those can be translated into TRL for technologies and operational practices used for maritime shipping as provided in the following Table.

Table 1 Description of TRLs for technologies applied with maritime vessels

TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or sea)
TRL 7	System prototype demonstration in a maritime environment
TRL 8	Actual system completed and “seaworthiness qualified” through test and demonstration (ground or sea)
TRL 9	Actual system “seaworthiness proven” through successful mission operations

Source: Adapted from Mankins (2004).

TRLs are generally high for technical efficiency strategies that regard hull, rudder and propeller designs as well as conventional propulsion and auxiliary power systems. The same goes for the use of alternative power with conventional propulsion systems which if at all only require limited technical adaptations applied to existing engines.

Operational strategies for increased energy efficiency are primarily based on modifications of the utilisation of existing technology. However some limited additional technologies that e.g. provide information on current energy use as well as meteorological and other conditions for the area a vessel is operating in might be important enabling factors for increasing operational efficiency. This particularly refers to sophisticated monitoring of energy consumption with regard to the technical state of the propulsion and auxiliary power systems as well as real-time monitoring of relevant variable conditions during the operation of vessels at sea like wind or ocean currents.

Major technical changes regarding propulsion systems and complementary fuelling and maintenance infrastructure for maritime vessels arise with the implementation of new decarbonised propulsion systems and fuels. In this case, the technology readiness of a propulsion technology on its own is an insufficient yardstick as compared to technologies for increasing energy efficiency that do not require any new complementary infrastructure (see section 2.3).

2.2 Assessment criteria: Diffusion of technology with new ships or retrofits

While implementation of new technologies for energy efficiency will to a substantial extent happen with newly-build ships, without retrofitting of existing ships the uptake of new technology may require a rather long time. Taking into account the economic lifetime of maritime vessels reaching 25 to 30 years in global operation, the ability of technical strategies to serve as retrofits is of utmost importance. However retrofits may lack economic efficiency with relatively old ships, given a short remaining life expectancy and hence limited efficiency gains and cost reductions that can be expected from such retrofits until the end of use.

Opposed to this, the age of individual ships is less important for the implementation of operational strategies for increased energy efficiency that can be applied with much less investment. Alternative propulsion systems are far less likely to serve as a retrofit as investment will typically be higher and the whole technical design of a ship can only be adapted with new capacity in order to achieve the best possible match with a particular new decarbonised propulsion technology.

2.3 Assessment criteria: System integration readiness

Technology Readiness Levels usually refer to single technologies and their state of development and applicability for real world use. However it is not seldom that single technologies require a suitable framework of complementary technologies, infrastructures and operational practices for successful real world implementation. Without such a complementary framework in place, some technologies may entirely fail, even though their individual TRLs may have achieved a very high level. Fuel-cell-electric cars are good examples of such technologies that heavily depend at least on a sufficient initial hydrogen production and distribution infrastructure (Sauser et al. 2010). This wider system context of some new technologies may be referred to as System Integration Readiness (SIR). Without sufficient SIR, a single technology will find very limited practical application even if its isolated TRL has reached a mature level.

SIR can be relevant with strategies for increased energy efficiency that are dependent on sufficient maintenance facilities at ports, staff development etc. With maritime transport, a sufficient level of SIR is of particular importance with new decarbonised fuels and entire propulsion systems. Maritime vessels often operate internationally over large distances. Thus at each port that they may be calling at it is of utmost importance that the provision of the respective decarbonised energy carrier as well as facilities for technical maintenance of the propulsion system are already in place.

Opposed to the broad availability of production and fueling infrastructure for HFO, other propulsion technologies entirely lack any such infrastructure. The only way to overcome such a situation is a stepwise approach that initially is focused on certain niches of application. Such niches may exist where ships permanently and exclusively operate on defined routes. This makes the provision of the respective fuel much easier for early application than it would be with a geographically dispersed implementation of fuel production and distribution combined with typically very limited numbers of ships initially demanding such fuels.

Thus in order to overcome an initially low level of SIR of new decarbonised propulsion systems, co-ordinated efforts are required to develop corridors of maritime shipping including major ports that allow for the early implementation of decarbonised propulsion systems without immediately having to deal with the multitude of potential destinations and relevant ports.

2.4 Assessment criteria: Efficiency improvement and carbon abatement

Abatement of carbon emissions is the prime objective of decarbonisation. However efficiency gains with energy use in maritime shipping may bring about more or less absolute carbon emissions depending on the carbon intensity of energy used. This means that energy intensity reductions with rather carbon intensive energy like HFO translate into high absolute reductions of CO_2 emissions. With lower carbon intensities of energy use like e.g. fuels based on CO_2 and renewable power (power to fuels), the absolute effect of efficiency gains on CO_2 emissions will be substantially smaller. At the same time, increased energy efficiency will require smaller volumes of decarbonised energy to be produced and distributed.

2.5 Assessment criteria: Selectivity regarding ship type and size or energy supply

Strategies for decarbonisation in the maritime shipping sector may not be equally useful with all ship types and sizes. E.g. sails can not easily be applied with container ships where the containers pile up on board and need to be easily accessible at container terminals.

Moreover decarbonised fuels and whole propulsion systems require different storage devices and main propulsion components that need to be located on a ship in a way that the loading capacity is not compromised and the weight distribution can be optimised.

This is particularly relevant with decarbonised energy carriers with substantially lower energy densities in terms of volume or weight. Battery-electric ships are a particularly critical example of this, as energy densities of existing battery technologies are such low that volume and weight of the energy required on board of large vessels in intercontinental traffic would substantially reduce the potential payload. Thus battery-electric concepts will only be relevant for short distance shipping as long as energy densities of batteries are not greatly increased over existing systems.

2.6 Assessment criteria: Interdependence with other strategies

Individual strategies for decarbonisation can more or less interact with other strategies in ways that might even turn them mutually exclusive. For instance, technical strategies may be effective with conventional but inappropriate with new propulsion systems. This is particularly true for strategies that allow to improve conventional main or auxiliary engine efficiency. The implementation of new propulsion systems render such strategies obsolete.

Moreover individual strategies for increased energy efficiency may target the same subsystem in a way that is exclusive or that the combined effect may not be significantly larger than that of each strategy on its own. An example of this are various hull coatings that are mutually exclusive.

A combination of propulsion systems may allow to achieve geographically diverse requirements in particular when one fuel can instantaneously be substituted for another during operation. However hybrid designs of whole propulsion systems may exacerbate issues regarding limited capacity available for payload.

2.7 Assessment criteria: Main risks and barriers

Many of the technical strategies for reducing specific fuel consumption and emissions from ships analysed here date back to earlier efforts of this kind which had resulted from the two major rises in crude oil prices in the mid senventies and early eighties of the last century (IMarEST 2011). This is partly due to the fact that numerous of the technologies used can be regarded as moving targets where designs have been gradually improved based on experience and laboratory studies as well as CAD and computer simulation.

However innovation in maritime shipping has always somewhat lagged behind in particular with new technologies and operational practices that might fatally fail under rough conditions at sea (DNV 2017). This is particularly evident with main and auxiliary engine, propeller and rudder technology which are critical elements under rough conditions when failure of those may result in shipwreck. Moreover with all technical and organisational strategies, major obstacles impeding implementation may arise from an insufficient track record and proof of seaworthiness combined with risk aversion on the part of ship owners and operators as well as insurance companies.

Beyond technical and economic causes for inertia, there is also an institutional one. Usually, the operator of a ship is not the owner which results in a principal agent and split incentive situation (ICCT 2011). For instance, the ship owner has to invest in order to let the benefits of increased efficiency be achieved by the charterer (Raucci et al. 2017). This will only work for ship owners, as far as operators are willing to pay proportionately higher rates. In particular during periods of vessel overcapacity and low HFO prices, this may not come true. There is very limited evidence that charterers are prefering more efficient vessels and willing to pay premium charter rates that might incentivise ordering more efficient vessel designs on the part of ship owners. (Prakash et al. 2016).

Last not least in a world of unconstrained carbon use in the shipping industry, volatility in crude oil and hence HFO prices might render investment in energy efficiency of vessels profitable or unprofitable (Faber et al. 2016). This depicts the high level of uncertainty whether such investment will turn out to be profitable within a reasonable period of time. However estimates suggest that growing fuel prices by roughly 40 per cent may result in an increase in cost-effectively abated carbon emissions by 25 per cent up to 2030 (DNV 2010).

2.8 Assessment criteria: Co-benefits

While existing risks and barriers of decarbonisation strategies might impede their successful application, there may also be relevant co-benefits that foster decarbonisation. One important co-benefit that can be achieved through decarbonising maritime shipping is reducing emissions of black carbon. Current internal combustion engine designs and fuels used in maritime shipping imply relatively high emissions of black carbon. The particular relevance for climate change results from the deposition of black carbon on snow, ice sheets and glaciers which reduces the albedo thus absorbing more solar radiation giving rise to a local temperature increase and speeding up of melting (Boggild, Goelles 2015). Maritime ships operating e.g. in the North Atlantic may already have an important share in the deposition of black carbon on ice sheets and glaciers in Greenland as well as the whole Arctic. As soon as a temporarily ice-free Northwest Passage will become a reality which might happen midcentury from ongoing climate change (Smith, Stephenson 2013), this will attract substantial traffic of cargo vessels and cruise ships taking advantage of this and result in a further increase in the deposition of black carbon in the Arctic.

Other substantial co-benefits of decarbonisation in maritime shipping are lower emissions of air pollutants at sea or in harbour areas that can be achieved through increased efficiency as well as fuel switching. Likewise such strategies may result in less noise from propulsion. Such co-benefits are particularly helpful for ports that are located close to human settlements where other sources of air pollutants or noise have already been substantially reduced and hence the relative contribution of operational activity at a port to overall emissions has greatly increased.

Another important issue is the level of toxicity and ecotoxicity at sea of energy carriers used for propulsion. This foremost refers to the current use of HFO and diesel fuel and spillage from normal operation at sea as well as from sinking of vessels. While some decarbonised energy carriers have a substantially smaller ecotoxicity footprint (e.g. methanol) others (e.g. ammonia) can be serious biological hazards (Thomas, Parks 2006).

2.9 Assessment criteria: Role of ports

Emissions of CO_2 from maritime shipping have been estimated to amount to on average 3.1 per cent of all global CO_2 and 2.8 per cent of all GHG emissions in the 2007 to 2012 period (IMO 2015). Most of those emissions occur in international waters and are not accounted for in national inventories of CO_2 emissions. The Kyoto Protocol has excluded international shipping and aviation from national inventories owing to difficulties involved with allocating such emissions to individual countries. Instead the IMO and its member countries are responsible for the reduction of CO_2 emissions from international maritime transport.

Thus at first glance ports seem to have a limited role the reduction of CO_2 emissions in the maritime transport sector. However operation of vessels in international waters is difficult to monitor and influence, while vessels calling at ports can be inspected and regulated.

Beyond the need to reduce CO_2 emissions of port-related operations, the development of ports can be restricted by a multitude of issues which directly or indirectly are associated with climate change. These are rises in the sea level, flooding and more frequent storm events which may heavily impact on port facilities that will need to be adapted to these effects of a changing climate (Messner et al. 2013). Other restrictions for port development result from emissions of air pollutants in port areas which are closely related to propulsion technologies and operational practices.

Thus technical and operational strategies for decarbonising maritime freight transport might to a large extent be influenced by ports. This may at the same time be helpful while dealing with the mentioned restrictions for port development. (UNCTAD 2015)

Ports can influence the decarbonisation of maritime shipping in various ways. Decarbonisation efforts may be focused on ports and the facilities that have a direct impact on the carbon intensity. This refers in particular to the provision of stationary logistics services at a port which includes loading and unloading, warehousing etc. Moreover ports can deliver decarbonised power to ships at berth. (Weenen et al. 2016)

Beyond this, ports can take an active role with regard to operation of maritime shipping outside the port area. It is clear that responsibility for CO_2 emissions from maritime shipping at sea does not rest with the ports that vessels are calling at. However, ports can work as incubators for the diffusion of innovative technologies and modes of operations at sea that allow to decarbonise maritime shipping. This refers to technologies and operational practices for increasing energy efficiency as well as the implementation of technologies that allow to switch to decarbonised fuels and entire propulsion systems.

It would be too difficult for ports to assesss the technical state of individual maritime vessels. Thus in order to foster the role of ports in the overall decarbonisation of maritime transport, regulations need to be implemented that allow ports to easily assess the energy efficiency and carbon intensity of vessels (see section 3.5).

Ports can also take a major role in shifting hinterland freight transport to more climate friendly modes which among other factors is dependent on sufficient transshipment facilities to inland navigation and rail transport. This may also bring about positive side-effects with regard to the number of trucks entering the port area and related traffic jams.

3 Structure and description of selected strategies for decarbonisation

3.1 Structure of strategies for decarbonisation through energy efficiency in maritime transport

Strategies for decarbonisation through energy efficiency refer to what can be done at the level of ship owners and operators as well as suppliers of ships or technical retrofits as well as complementary infrastructure and services. While these strategies can in principle be implemented by the above-mentioned stakeholders, under market conditions there may be insufficient incentives to do so to the extent necessary to achieve deep decarbonisation of maritime shipping.

Maritime vessels have depicted considerable improvements in energy efficiency during the 1980s. Efficiency then decreased after 1990, while recent years again brought about improvements. (Faber et al. 2016) Regarding the need to achieve deep decarbonisation, such varying developments in regard to vessel efficiency are not helpful. Thus a regulatory framework is required that is comprised of a combination of policy instruments that put sufficient incentives in place to foster the application of strategies for decarbonisation.

Strategies for decarbonising maritime freight transport by increasing energy efficiency can broadly be subdivided into technical and operational measures that allow to increase efficiency of energy use during operation of vessels at sea and ports. The tables in Annex 1 provide an overview of the most important of both strategies that may be applied. The following sections will not go into the details of all strategies mentioned in the tables. Instead, only a limited number of major strategies for increased energy efficiency are highlighted for illustrative purposes.

Strategies for technical efficiency can be further broken down into those that are independent of the kind of propulsion system used. Those refer to measures that are related to hull as well as rudder and propeller design.

Further technical strategies for increasing energy efficiency are closely related to conventional propulsion and auxiliary power systems and are focused on upgrading either through entirely new designs or retrofitting components of existing designs.

Another highly relevant technical strategy related to a ship's hull, propeller and rudder is automated underwater monitoring and maintenance. Sufficient maintenance has a substantial impact on whether the efficiencies of hull, propeller and rudder can be kept in tune with the specified design. Automated underwater monitoring and maintenance allows to perform this important strategy without dry-docking while calling at a port and without having to resort to monitoring and maintenance performed by divers. This offers substantial advantages regarding cost and time hence increasing the likelyhood that an optimal state of maintenance can be preserved.

3.2 Selected operational strategies for increased energy efficiency: Ship size

It is not entirely clear whether ship size is a technical strategy or an operational one. Of course building larger ships requires appropriate technology but ship size is also closely related to demand for transport services on a particular route and the size of a ship needs to be a good match. Consequently, deploying ever growing ships is not a general tendency but focused on those routes where the growth in volume and frequency of transport demand suggests to do so.

Generally, the historical success of maritime shipping is closely related to the growth of vessel sizes that has allowed to reduce cost per ton-mile exploiting typical economies of scale. Besides reduced capital and labour cost per unit, these cost reductions are closely related to energy use. The size of a ship and the length of its waterline are important determinants of its hydrodynamic resistance and energy use per ton-mile. Thus larger ships can cruise at higher speeds without running into prohibitively high energy cost or energy cost can be reduced while a certain cruise speed is maintained.

Depending on the type of goods transported and related ship types, optimisation through growing ship size has so far been focused more either on achieving higher cruise speeds or reductions of energy consumption. With on average higher capital intensity and lower densities of containerised goods, opting for higher cruise speeds with container vessels has been straightforward from an economic perspective. Opposed to this, increasing sizes of bulk carriers transporting relatively heavy goods with lower capital intensity was motivated more by trying to reduce energy cost per unit of goods transported.

There are ambiguities as to which extent ship size may contribute to the decarbonisation of single loops as opposed to whole logistics chains. With increasing vessel sizes the effects may not be exactly the same depending on whether looking at it from the perspective of an individual vessel on a given route or from a systems perspective. If a larger ship can be used to transport exactly the same volume of freight on a loop from one port to another which has previously been done with numerous smaller ships, a higher level of energy efficiency can be expected.

However deploying larger vessels is often based on the implementation of geographically bigger hub and spoke systems. This means that energy use for transshipment and a longer logistics chain deploying additional feeder vessels and transport modes used for hinterland transport may be relatively more important than just the loop between two ports. (Hassel et al. 2016)

In maritime shipping, hub and spoke systems usually involve using numerous smaller vessels as feeders and by that may on average increase transport distance. Another option is letting super large vessels call at several ports which compromises capacity utilisation between those ports. Another source for ambiguity is longer hinterland transport resulting from carrying goods on a larger vessel that can only call at geographically more concentrated ports.

The aforementioned means that the effect of increasing maximum ship sizes on energy efficiency is ambiguous. Beyond the factors mentioned, the effect on energy efficiency largely depends on whether higher energy efficiency is deployed to increase cruise speeds or to accommodate growing transport demand from larger geographic areas. However in a scenario where cruise speeds are reduced (see following section) larger ships might contribute to achieving higher energy efficiency.

3.3 Selected operational strategies for increased energy efficiency: Slow steaming

Given the substantial role of hydrodynamic drag of ships for energy efficiency, optimising vessel speed has always played an important role in shipping economics. In particular during the seventies and early eighties of the last century with relatively high HFO prices, vessel overcapacity and related low freight rates, slow steaming allowed to reduce fuel consumption and to increase economic efficiency (Michaelis 1997).

Conversely, when demand for vessel capacity is high as well as freight rates and while HFO prices are low there is an opposite economic incentive to increase vessel speeds in order to achieve more ton-miles and hence annual turnover per unit of capacity (Wan et al. 2018). Besides speeds of individual vessels depict a substantial variety some of which can not be explained by type of vessel or its energy efficiency (Prakash et al. 2016). There are various other detrimental or positive side-effects of slow steaming concerning shipping economics and supply chains which can not be discussed here in detail (see e.g. Mander 2017).

While depending on the quantity of speed reduction, slow steaming may allow to achieve substantial energy efficiency gains on a ton-mile basis. However the reduced productivity (annual ton-miles) of slow steaming ships will result in more ships in operation for a given demand for sea-borne freight transport to be performed within a certain period. Thus some portion of the reduced emissions per ship will be shifted to other vessels and there will be more vessels in operation. (McCollum et al. 2009, IMO 2015)

As mentioned, slow steaming is not exactly a new strategy. It has gained importance again resulting from the financial crisis in 2007 and the build-up of substantial global vessel overcapacity that still exists (IMO 2015). In order to let slow steaming permanently deliver significant contributions to decarbonisation, it would require to be introduced as a generalised measure instead of being temporarily applied by ship operators depending amongst other factors on global vessel capacity, the industry’s business cycle and the price for HFO. Thus without any legal obligations or permanent incentives that can counterbalance the effects of high demand for shipping services and low HFO prices, it is unlikely that slow steaming will be applied as a standard procedure (DNV 2017).

3.4 Selected operational strategies for increased energy efficiency: Optimising the utilisation of vessel capacity

In principle, utilisation of capacity is one of the most important organisational strategies for reducing energy use and carbon emissions per ton-mile. However this strategy is also a core area of already existing efforts to increase the economic efficiency of maritime freight transport. Thus there may be no low hanging fruits and still existing potential may require co-operation between competitors and, therefore, be difficult to achieve.

Moreover many goods require specialised vessels and trade in those goods is more or less a one-way street between exporting and importing countries. This primarily refers to bulk goods like crude oil, coal, iron ore, agricultural products etc. where there is no or much less trade in similar goods to the opposite direction, which results in specialised vessels running empty.

Even with container shipping it is well-known that there are more containerised goods to be transported e.g. from Asia to Europe than the other way round. In 2013, on the trade route North Asia-Europe roughly 9.2 million TEU were shipped West bound while just 4.5 million TEU were shipped East bound (World Shipping Council 2017). Thus as long as the spatial structure of world trade remains to be that unbalanced, it will be impossible to achieve a high on average utilisation of vessel capacity in maritime freight transport.

3.5 Insights regarding the implementation of new technologies and operational practices for increasing energy efficiency

In principle, technologies for increased energy efficiency of existing propulsion systems are relatively easy to implement with single ships, once the respective technology has become available for commercial application because no or only minor changes in complementary infrastructure are needed.

However in order to overcome barriers for implementation of such new technologies and operational practices, it may be required to initiate more international implementation projects with governments and partners from industry that allow to establish sufficient track records in terms of various ship types and actual operation at sea.

The intense business cycle in the maritime shipping industry and volatility of fuel prices (HFO) pose substantial economic risks for investment in energy efficiency, regardless whether with new capacity or retrofits. Dynamic technical energy effciency standards for ships may help overcome inertia resulting from such economic instability as far as these can only be met through the implementation of additional efficiency measures.

Thus efficiency standards may play a vital role in the diffusion of strategies for increasing energy efficiency in that they create a regulatory framework that promotes the diffusion of new technology and operational practices independent of highly variable incentives caused by the substantial volatility in the industry's business cycle and HFO prices (DNV 2010, Faber et al. 2016).

In this regard, it is helpful that the IMO has introduced the Energy Efficiency Design Index (EEDI) as well as the Ship Energy Efficiency Management Plan (SEEMP) in 2011. Complementary to this, the European Union is implementing the Monitoring, Reporting and Verification Directive (MRV) which obliges shipyards, owners and operators to review the technical state of ships. In principle, this opens up an easy assessment of individual vessels regarding their energy efficiency by stakeholders like shippers or ports that would otherwise hardly be possible. (Johansson et al. 2017)

However the EEDI only covers new ships with dynamic minimum efficiency standards according to vessel type and size. Taking into account an average age of 25 years for maritime vessels it will require quite bit of time to achieve any substantial effect of the EEDI at the fleet level (Smith et al. 2016a, International Transport Forum 2018). Moreover, using the IMO EEDI database, a recent study has cast doubt as to whether the EEDI standards for 2025 are strict enough based on findings that many ships recently built already comply with them (T&E 2017).

In principle and similar to maritime shipping, there is a bulk of technical and operational strategies that may be used to increase the energy efficiency of transport modes that are used for hinterland freight transport, starting from ports to the destinations of goods for further manufacturing and, eventually, final consumption. Modes of transport primarily used for this are inland navigation, railways, and road freight transport. Air transport is of minor importance for hinterland transport originating from ports but contributes to the extent of fossil fuel use resulting from total transport activity in Europe most of which is imported using maritime vessels. The multitudes of strategies for enhanced energy efficiency that may be deployed by each mode of hinterland freight transport is beyond what can reasonably be influenced by ports and thus an in-depth analysis beyond the scope of this study.

4 Energy carriers and propulsion technologies for transport decarbonisation

4.1 Energy carriers and propulsion technologies for decarbonising maritime and hinterland freight transport

Beyond energy efficiency, alternative propulsion systems used with complementary energy carriers are prime technical strategies for decarbonising all modes of freight transport. There is an entire portfolio of options available or under development that may play a role in the decarbonisation of the various modes of freight transport using more or less decarbonised energy carriers. The most important aspect of such energy carriers is to which extent they can be regarded as decarbonised and what consequences of their use have to be faced in terms of the achievement of other sustainability criteria.

It is clear that all modes of freight transport have specific technical and operational properties that may be more or less conducive to using particular energy carriers. E.g. direct use of electricity via overhead wires is well-established with railways but will pose substantial issues with other modes.

With regard to this, by far most important are the volumetric and gravimetric energy densities of energy carriers that have an impact on the size of on-board storage required for typical operation and hence the payload that can be transported. Next to this, using decarbonised energy carriers requires appropriate propulsion technologies that may be more or less suitable to the operating conditions of the respective mode.

Moreover, using particular energy carriers requires sufficient production capacity and supply infrastructure to be in place. Given the required contributions to decarbonisation can be achieved, the cost of the production of energy carriers and their distribution as well as those associated with the implementation of the respective propulsion technology will be decisive. However, there are still uncertainties as to what options will be most cost-effective under which conditions.

From today’s perspective the portfolio of principally available options for decarbonising transport energy use is at least comprised of:

- Compressed or liquefied natural gas as a fuel (LNG, CNG) for internal combustion engines;
- Biogas as a fuel with internal combustion engines;
- Biodiesel or -ethanol as fuels with internal combustion engines;
- Direct electricity use from renewable production with electric propulsion systems;
- Indirect electricity use from renewable production with storage in batteries;
- Indirect electricity use from renewable production with hydrogen and fuel cells;
- Indirect electricity use from renewable production with CO_2-reuse for Power-to-fuels and internal combustion engines; and
- Indirect electricity use from renewable production with hydrogen or CO_2-reusing methanol and fuel cells.

Generally, the mentioned scope of options is already larger than appropriate to be implemented given that each fuel requires its own production system and distribution infrastructure where economies of scale can be expected to be significant determinants of cost effectiveness. This means that implementing a limited number of decarbonised energy carriers for the operation of each mode of transport is to be preferred over a large diversity of options.

Moreover, once any such system has been implemented it may be difficult to be phased out again in order to switch to other energy carriers that provide lower carbon intensities needed for the achievement of the total extent of decarbonisation but that may require more time to be introduced. This is most relevant for natural gas that if at all (methane leakages) can only deliver limited contributions to decarbonisation and that will eventually need to be phased out again.

Similarly - depending on feedstock and technology used - biofuels may even be counterproductive (biodiesel from palm oil Gärtner et al. 2007) for decarbonisation and result in unwanted side-effects in terms of crowding out of land use for nutritional purposes as well as losses in biodiversity. Thus as long as no sustainably produced volumes of biofuels are available based on new production technologies and feedstocks, biofuels need to be phased out for more sustainable options.

Ultimately, the selection of decarbonisation options for each mode of transport needs to strike a balance with regard to:

- Potential relative and absolute contribution to decarbonisation as compared to conventional fuels;
- Compatibility with other sustainability criteria (air pollution, land use, biodiversity);
- Suitability regarding the operating conditions of individual transport modes (e.g. rough conditions at sea in maritime transport, energy densities and resulting necessary on-board storage facilities as well as logistics required for delivery);
- Flexibility of use with conventional (internal combustion engine) and – at a later stage – more advanced propulsion technologies (fuel cells);
- Ability to serve as a blend to conventional fuels thus working as a stepping stone on the way to more advanced decarbonisation options; and
- Time required for implementation.

From an energy efficiency perspective, direct electricity use from renewable production can be expected to deliver the highest contributions to decarbonisation as compared to all other options resulting from the high efficiency involved with a limited number of conversion processes. However, overhead wires are well-established with railways but not at all with other modes. Thus with road freight direct electricity use may be taken into consideration while with other transport modes it can be ruled out.

In particular with maritime transport, inland navigation, and aviation, direct use of renewable electricity is simply no option except for the limited use of photovoltaics or wind on board of vehicles. Moreover direct electricity use with transport operations comes with the disadvantage of creating additional demand for electricity also at times when electricity based on renewable production is in short supply. Opposed to this, producing transport energy based on renewable power that can easily be stored at times and places with abundant production and then transported to the place of use offers the advantage to make contributions to the stabilisation of an overall energy system that is based on renewable energy.

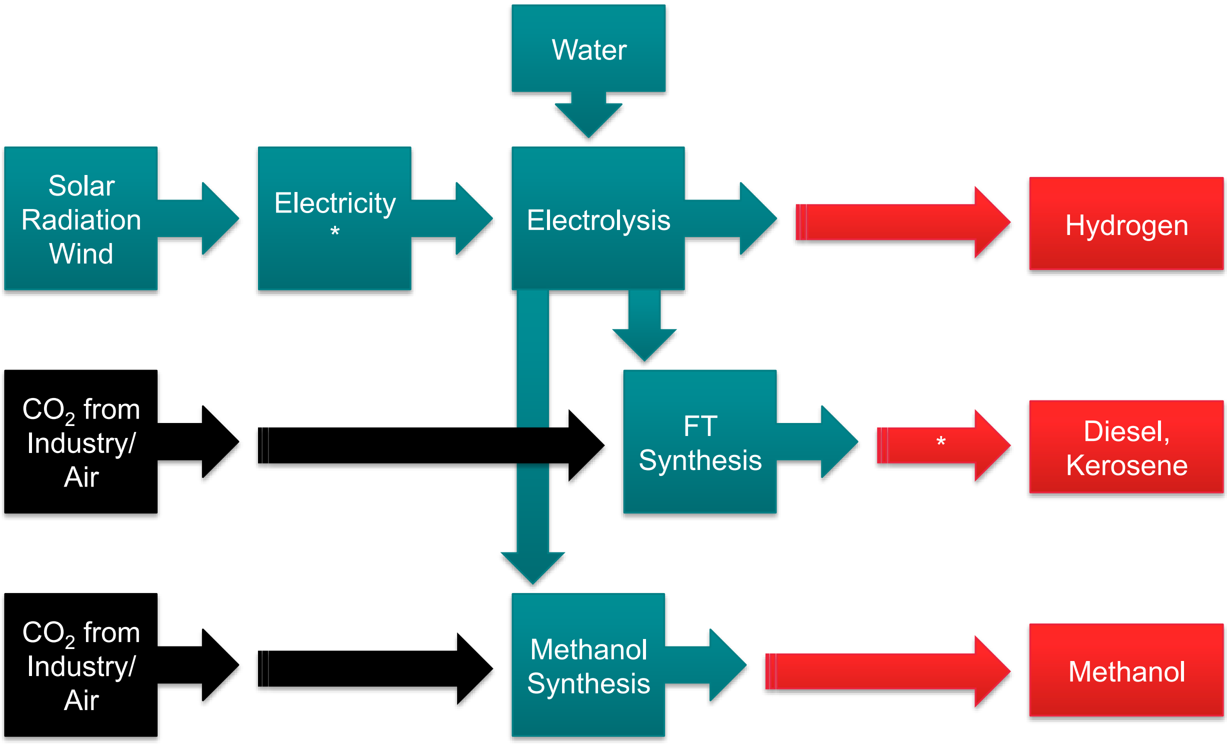

Figure 1 **Hydrogen from renewable electricity and fuels derived from it reusing CO_2**

** The extent of decarbonisation depends on the use of electricity from renewable sources like solar radiation or wind during the generation of hydrogen and with further downstream processes.*

Source: WI

Besides producing energy carriers like diesel or methanol based on renewable power can at least partly be outsourced to regions of the world where e.g. solar radiation or wind are more intense as well as constant. This allows to deploy lower production cost resulting from the higher capital productivity involved with the more intensive utilisation of production facilities.

Another P2F option that does not even require any carbon is ammonia that can be drawn from renewably produced hydrogen and nitrogen from the atmosphere. However ammonia can not be used as a blend with conventional fuels and infrastructure available for fuels will not seamlessly work with it. Besides it needs to be stored pressurised and is more hazardous with regard to ecosystems and human health than e.g. methanol.

For the reasons mentioned, converting renewable power into hydrogen that may further be processed with CO_2 from industry or ultimately the atmosphere into liquid fuels like Fischer-Tropsch diesel or methanol is an option that may offer substantial advantages in the short and medium term.

While direct use of hydrogen with fuel cells is not at all a mature technology with any mode of transport except for some military submarines, hydrogen used for Fischer-Tropsch diesel synthesis or methanol synthesis with CO_2 can be converted into liquid fuels that may be used with existing or slightly modified internal combustion engines. Moreover, these fuels can easily be transported and stored or blended with conventional fuels. At the same time, the hydrogen as well as the methanol path open up the option to electrify propulsion systems at a later stage when hydrogen fuel cells or direct methanol fuel cells might have matured and have become cost effective as compared to internal combustion engines.

An option that is still relatively high on the agenda and that is increasingly being used with big container vessels or cruise ships is natural gas as LNG which has been fostered by stricter regulations of NO_X and SO_X emissions and diminishing prices for natural gas from fracking in North America (DNV 2010, Wärtsilä 2017). The propulsion technology is available with many modes of transport and, for the most part, large scale distribution infrastructure is readily in place. However the lower energy density even of LNG reduces the payload capacity of vessels used for freight transport (RAE 2013) and the CO_2 reduction potential of roughly 20 per cent over conventional fuels is too limited taking into account the very high overall emission reductions required for decarbonisation in the long run.

At the same time, methane leakages can pose substantial issues from this particularly potent GHG counteracting any effective reductions in GHG emissions (Bouman et al. 2017). Downstream methane leakages have to be expected to a higher extent with transport operations than with stationary use. With all modes of transport accidents happen and and in particular conditions of operation at sea (e.g. vibrations, corrosion from sea water etc.) are generally more conducive to leaking from on-board facilities.

Preventing leakages requires delicate technical concepts and strict maintenance and control with the application of methane as a transport fuel. A focus of application may be LNG tankers, where technical standards are well above average and the inevitable boil-off from the large tanks may be used for propulsion.

While fossil methane can be substituted using methane based on biomass or from power to gas processes, the leakage issue might effectively preclude using methane as an energy carrier for transport purposes in a decarbonised world. As a consequence, the fossil natural gas path can only be an interim solution and methane will need to be phased out in the long run.

4.2 Assessment of energy carriers and propulsion technologies by mode of freight transport

Energy use of the various modes of freight transport may in two distinct ways be relevant for port operation:

- Firstly, a port works as a hub between maritime freight transport and hinterland transport via inland navigation, rail and road freight transport. A port thus needs to supply the energy used by all modes of transport relevant for port operation to allow for their seamless integration.
- Secondly, transport energy use and that of other sectors may have a strong impact on goods transported to and from ports as well as related transshipments.

Both freight transport and transport energy use are very relevant for the Port of Rotterdam and will need to adapt to the transitioning to a decarbonised transport system and overall economy. Switching of transport modes from fossil fuels to decarbonised energy may depict certain similarities. However, each mode of transport requires tailored solutions based on its physical and technical characteristics as well as its specifics of operation. Thus it makes sense to qualitatively assess options for decarbonised energy use by mode of transport which is here focused on freight transport but similarly applies to passenger transportation.

In maritime shipping, the most promising medium-term options for decarbonising energy use rest with the application of the P2F options Fischer-Tropsch diesel or methanol involving hydrogen from renewable electricity and reuse of CO_2 from industrial sources or the atmosphere. Both can be implemented with existing conventional drivetrains and distribution infrastructures except for plants for producing these fuels.

At a later stage, methanol might be combined with direct methanol fuel cells (DMFC) allowing to electrify propulsion. Hydrogen might also play a role, once fuel cells are cost effective. However hydrogen requires more sophisticated transportation and storage and needs to be handled with more care in order to rule out fatal accidents resulting from leakages and combustible mixtures with air.

Table 2 Decarbonised energy for maritime shipping

	Current Use	CO_2 Reduction	TRL	SIR	Trans-formation	Time Horizon	Co-benefits	Risks
HFO	dominant	fossil	high	high	impossible	n. a.	-	outdated
Diesel	minor	fossil	high	high	impossible	n. a.	-	outdated
Sustaina-ble Bio-diesel	no	varies by input	high	high	sustaina-ble input ?	b. medium ?	-	table/tank
P2F/CO_2 Diesel	no	very high *	limited	high	possible	u. medium	air pollution	-
LNG	niche	limited/ fossil	high	medium	sustaina-ble bio-methane	b. medium ?	air pollution	outdated, leakages
Sustaina-ble Bio-methane	no	varies by input	high	medium	sustaina-ble input ?	b. medium ?	air pollution	table/tank, leakages
P2F/CO_2 Methanol	no	very high *	medi-um	medium	possible	u. medium	air pollution	-
Ammonia	no	very high *	limited	limited	possible	b. medium	air pollution	toxicity
P2F Hy-drogen FC	niche	very high *	limited	limited	possible	b. medium	air pollution	-

*Explanatory notes: TRL - Technology Readiness, SIR - System Integration Readiness, u. medium: full implementation until medium time horizon, b. medium: full implementation beyond medium time horizon. * depending on use of renewable electricity. Source: WI*

With inland navigation, options for decarbonising energy use are similar to those available for maritime shipping. An exception is that inland navigation is not subject to the corrosive force of sea water and rough conditions at sea which might turn methane into a relatively lower risk and suitable option, in particular when it is not derived from fossil sources.

Battery electric drives are imaginable at least as a niche application for short distance inland shipping while broader use of batteries as energy storage systems in the shipping sectors will require revolutionary advances in energy densities of batteries.

Table 3 Decarbonised energy for inland navigation

	Current Use	CO_2 Reduction	TRL	SIR	Trans-formation	Time Horizon	Co-benefits	Risks
Diesel	domi-nant	fossil	high	high	impossible	n. a.	-	outdated
Sustainable Biodiesel	no	varies by input	high	high	sustaina-ble input ?	b. medium ?	-	table/tank
P2F/CO_2 Diesel	no	very high *	limited	high	possible	u. medium	air pollution	-
LNG	no	limited/ fossil	high	medium	sustaina-ble bio-methane	b. medium ?	air pollution	outdated, leakages
Sustainable Biomethane	no	varies by input	high	medium	sustaina-ble input ?	b. medium ?	air pollution	table/tank, leakages
P2F/CO_2 Methanol	no	very high *	medium	medium	possible	u. medium	air pollution	-
Ammonia	no	very high *	limited	limited	possible	b. medium	air pollution	toxicity
P2F Hydro-gen FC	no	very high *	limited	limited	possible	u. medium	air pollution	-
Battery-electric	no	very high *	limited	limited	short distance niche	b. medium	air pollution	-

*Explanatory notes: TRL - Technology Readiness, SIR - System Integration Readiness, u. medium: full implementation until medium time horizon, b. medium: full implementation beyond medium time horizon. * depending on use of renewable electricity. Source: WI.*

While road vehicles do not operate globally but within geographically more limited continental areas, more diversity regarding energy carriers used in different regions is imaginable than with maritime shipping or aviation which to a large extent operate globally. An option currently under discussion in Sweden and Germany is direct electricity use with lorries on motorways following the build-up of overhead wires and the utilisation of vehicles that combine a conventional drive train with an electric one and two current collectors.

However this option faces several challenges. The implementation path towards motorways with overhead wires lacks at least the visibility of how the necessary investment into such an infrastructure may be financed taking into account a long-lasting build-up period and initially very low spatial coverage of the motorway network and limited turnover from its use. At the same time, it is unclear whether logistics service providers will invest into more costly hybrid vehicles, given initially very low spatial coverage of the electrified motorway network. Moreover, such a system is difficult to operate in the Netherlands or Germany alone as important European transit countries but would require an EU-wide approach.

With road freight there are strong arguments in favour of power-to-fuel energy carriers that can initially be blended with conventional fuels and that may use the existing supply infrastructure. Methanol (and ethanol) is clean-burning and has been demonstrated to work with stationary internal combustion engines. Owing to the wide-spread use as a chemical feedstock, distribution infrastructure largely exists and can be adapted to the needs of bunkering ships at lower cost than an equivalent LNG infrastrucure. (Ellis, Tanneberger 2015) At the same time, the methanol path might be used to electrify drive trains at a later stage, once DMFCs have become cost effective.

Table 4 Decarbonised energy for road freight

	Current Use	CO_2 Reduction	TRL	SIR	Trans-formation	Time Horizon	Co-benefits	Risks
Diesel	domi-nant	fossil	high	high	impossible	n. a.	-	outdated
Sustaina-ble Bio-diesel	blending	varies by input	high	high	sustaina-ble input ?	b. medium ?	-	table/tank
P2F/CO_2 Diesel	no	very high *	limited	high	possible	u. medium	air pollution	-
LNG	niche	limited/ fossil	high	medium	sustaina-ble bio-methane	b. medium ?	air pollution	outdated, leakages
Sustaina-ble Bio-methane	no	varies by input	high	medium	sustaina-ble input ?	b. medium ?	air pollution	table/tank, leakages
P2F/CO_2 Methanol	no	very high *	medium	limited	possible	u. medium	air pollution	-
Ammonia	no	very high *	limited	limited	possible	b. medium	air pollution	toxicity
P2F Hy-drogen FC	military niche	very high *	limited	limited	possible	b. medium	air pollution	-
Direct Electric	no	very high *	medium	limited	highway niche?	b. medium	air pollution	investment
Battery-electric	niche	very high *	High/ medium	limited	last mile niche	u. medium	air pollution	-

*Explanatory notes: TRL - Technology Readiness, SIR - System Integration Readiness, u. medium: full implementation until medium time horizon, b. medium: full implementation beyond medium time horizon. * depending on use of renewable electricity. Source: WI.*

Moreover hydrogen or batteries are options for the electrification of drive trains for road transport in particular with vehicles covering the last mile of delivery in urban areas. Conventional delivery vehicle manufacturers did not respond to evolving market demand. Thus in 2014, logistics service provider Deutsche Post DHL has acquired a vehicle manufacturing start-up (StreetScooter). The objectives were to speed up the process of switching to electric drive-trains with its delivery vehicle fleet and even to sell such vehicles (Weiss, Brautlecht 2017). Having successfully started with smaller sized delivery vehicles, the company has teamed up with Ford Motor for producing larger delivery vehicles and even for looking into heavy duty vehicles with hydrogen fuel cell-electric drives.

The transformation necessary for decarbonising rail transport with direct electricity use is largely about upstream emissions and shifting to carbon-neutral production in the electric utility sector. An exception are railway tracks where the low frequency of trains will not justify the investment in overhead wires. As another exemption, shunting locomotives operate at locations where transshipment activity precludes electric wires over the track. For these niches of rail transport, either diesel propulsion may persist with diesel provided from carbon-neutral P2F production or a switch to already existing battery-electric or hydrogen fuel cell-electric propulsion (Adolf et al. 2017) is possible.

Table 5 Decarbonised energy for rail freight

	Current Use	CO_2 Reduction	TRL	SIR	Trans-formation	Time Horizon	Co-benefits	Risks
Direct Electric	dominant	very high *	high	high	grid electricity	u. medium	air pollution	-
Diesel	niche	fossil	high	high	impossible	n. a.	-	outdated
P2F/CO_2 Diesel	no	very high *	limited	high	possible	u. medium	air pollution	-
P2F/CO_2 Methanol	no	very high *	limited	medium	possible	u. medium	air pollution	-
Ammonia	no	very high *	limited	limited	possible	b. medium	air pollution	toxicity
P2F Hydro-gen FC	niche	very high *	limited	limited	possible	b. medium	air pollution	-
Battery-electric	niche	very high *	medium	medium	shunting niche	u. medium	air pollution	-

*Explanatory notes: TRL - Technology Readiness, SIR - System Integration Readiness, u. medium: full implementation until medium time horizon, b. medium: full implementation beyond medium time horizon. * depending on use of renewable electricity. Source: WI.*

With aviation the options at hand for decarbonising energy use are most limited. While kerosene produced from sustainable biomass or P2F might be implemented as a drop-in solution using existing turbines and supply infrastructure, electrification via hydrogen will require substantial changes in many components of the overall aviation system. Such a transformation might take more time than available until 2050.

Table 6 Decarbonised energy for air freight

	Current Use	CO_2 Reduction	TRL	SIR	Trans-formation	Time Horizon	Co-benefits	Risks
Kerosene	dominant	fossil	high	high	impossible	n.a.	-	outdated
Sustaina-ble Bioker-osene	no	variable/ input	limited	medium	sustaina-ble input	b. medium ?	-	table/ tank
P2F/CO_2 Kerosene	no	very high *	medium	medium	possible	u. medium	air pollution	-
P2F Hy-drogen FC	no	very high *	limited	limited	possible	b. medium	air pollution	-

*Explanatory notes: TRL - Technology Readiness, SIR - System Integration Readiness, u. medium: full implementation until medium time horizon, b. medium: full implementation beyond medium time horizon. * depending on use of renewable electricity. Source: WI.*

4.3 Insights obtained from the fuel switch analysis

Alternative fuels and propulsion systems require co-ordinated efforts where technology readiness of individual components like propulsion technology or fuel production and distribution on their own are necessary but not sufficient preconditions of application and geographically widespread operation. This refers to the System Integration Readiness (SIR) of options mentioned in section 2.3 that goes beyond TRL for individual system components.

In the long run, those technologies and fuels are of particular interest that allow to switch from carbon-intensive propulsion systems to decarbonised propulsion systems in a way that the overall envisaged emission reduction for GHG can be met up to 2050.

With the exception of rail transport, that predominantly uses direct electricity for traction, maritime shipping and all other modes for hinterland transport currently use basically the same or very similar fuels based on crude oil. Options principally available as low carbon fuels and predominantely discussed in existing studies are natural gas and fuels based on biomass. The Dutch government has committed itself to increasing the use of LNG and sustainable biofuels with inland navigation and short-sea shipping (SER 2014).

The advantages of LNG and biofuels are that they do already exist and their system integration appears to be much easier than for certain other decarbonised energy carriers. For instance hydrogen based on renewable power largely lacks production facilities, can not easily be transported and distributed using existing facilities and requires new propulsion technologies and hence at least retrofitted or entirely new vehicles.

For inland navigation and aviation, where direct electricity use can be disregarded, the options remaining will be liquid fuels based on sustainably produced biomass or renewable power and CO_2 (PtF). For aviation, the energy density required is very high in order to keep volume of fuel carried on long distance flights manageable and hence payload at a sufficient level. Thus options for aviation are kerosene based on either biomass or renewable power and CO_2. Another option may be hydrogen that will need to be liquefied to keep the volume stored on board of aircraft limited.

Generally, fossil fuels (crude oil, coal and natural gas) have been very important goods transported in the maritime transport sector both in terms of tons carried and ton-miles performed. While decarbonisation will advance with all transport modes, energy carriers used will transition from fossil fuels to decarbonised energy. Both types of energy carriers can to some extent be supplied locally and hence will to a varying extent need to be imported and transported by maritime shipping and the modes required for hinterland transport (Pastowski 2005, Sharmina et al. 2017).

Beyond the transport sector, decarbonisation will result in much less fossil fuels and more decarbonised energy carriers to be transported: Coal use will have to be abolished, while crude oil and petroleum products will have to shrink substantially. Natural gas will to a far lesser extent be influenced by decarbonisation of the transport sector than by changes in stationary use.

Biomass has become a focus area of strategies to decarbonise energy use in many sectors. So far, production capacity remains to be bound to available arable land also required for other uses like food production. Moreover it remains to be based on energy intensive inputs which may result in mediocre reductions of CO_2 emissions. Other biomass options under discussion like algae are still in their infancy laboratory stage. So-called second or third-generation biomass-based fuels will need to be assessed in terms of their real-world energy input and technical installation requirements, once they have reached a relevant development stage.

Thus the share of fuels based on biomass might grow provided the issues with upstream emissions can be resolved and related land-use can be focused on areas not required for food production or the preservation of biodiversity. However this is unclear from today's perspective.

Instead of fuels from limited biomass, those that are based on renewable electricity and CO_2 (P2F) might grow substantially. Some portion of these fuels will need to be imported as far as they can not cost-effectively be produced in Europe. Besides availability of renewable power, CO_2 from other industrial sources will be required which might pose issues in an advancing decarbonisation process. Ultimately, CO_2 will need to be extracted from the atmosphere or other natural sources (geo-thermal) to allow for sufficient supplies for P2F. Issues with the availability of CO_2 might be another reason to opt for hydrogen that can operate without any carbon input but still lacks the availability of cost-effective fuel cells.

There are still substantial uncertainties regarding the potentials of the various fuel options discussed from a technical feasibility perspective and also taking into account evolving demand from other sectors.

5 Summary

Even though maritime shipping offers the highest energy efficiency of all modes of transport, there is still substantial technical and operational potential. However, existing estimates of further potentials of individual strategies vary greatly.

This can be interpreted as indication that evidence on the state of the world's merchant fleet of maritime vessels concerning the implementation of strategies for energy efficiency is still limited. In order to resolve this, the implementation of monitoring and control regulations is underway and will provide a clearer picture and work as an incentive that will enhance the uptake of technical and operational innovation.

Summing up the aforementioned regarding decarbonised fuels, there are sufficient options for decarbonisation of all transport modes up to 2050 even though – in particular for aviation – the number of viable options is much more limited for some modes of transport. With electrified rail freight, decarbonisation will simply proceed hand in hand with the decarbonisation of the electric utility sector.

While not all options can usefully be implemented simultaneously, the main challenge is about identifying a limited set of optimal decarbonised fuels per mode of transport. Decarbonised fuels need to be a good match regarding the operational characteristics of the respective mode of transport.

Moreover, decarbonised fuels that can be used as a blend to conventional fuels with existing internal combustion engines and related infrastructure offer substantial advantages in that they can serve as stepping stones into a future where entirely new propulsion systems will be required. Even more so, fuels that can be used both with internal combustion engines and fuel-cell electric drives will foster the overall transformation of transport energy use to decarbonisation. The latter is particularly true for methanol, that combines a relatively high energy density at normal conditions regarding temperature and pressure with a toxicity footprint that is not only better than that of conventional fuels but also than that of some of the other candidate fuels for decarbonisation (e.g. FT diesel, ammonia).

Natural gas (as CNG or LNG) has the advantage of a relatively wide-spread distribution infrastructure and that internal combustion engines can be adapted with limited effort. However even if upstream and downstream methane leakages can be kept to a minimum, the potential reduction in CO_2 emissions from the use of natural gas over other conventional fuels is rather limited as compared to the overall ambition level.

Therefore it is questionable whether substantial efforts for the utilisation of natural gas are very helpful to make the ultimate very ambitious reduction in CO_2 emissions become real. In particular to the extent that downstream emissions of methane need to be expected resulting from technical malfunctioning of components during normal transport operation or accidents, substantial contributions from natural gas to protecting the global climate as the ultimate end of decarbonisation in the transport sector are questionable.

Generally, options for decarbonisation of transport energy use based on biomass will depend on whether issues with energy intensive inputs and land use can be resolved which is far from clear from today's perspective. Thus bio-methane will for the most of it depend on the same limited biomass feedstocks and ultimately arable land as liquid biofuels.

Power-to-fuels that utilise CO_2 like Fischer-Tropsch diesel or methanol might be long-term solutions as far as they are based on renewable electricity and as long as sufficient CO_2 emissions from other sources are available or, ultimately, CO_2 is directly used from the atmosphere. Methanol is not limited to use with internal combustion engines but can further proceed to electric drives, once the direct methanol fuel cell technology has matured.

Ammonia offers the advantage of being an entirely carbon-free technology but can not serve as a blend and has an unsustainable environmental footprint for humans and ecosystems if spillage occurs. So far Ammonia has primarily been considered for use with power stations by cracking the NH_3 into H_2 and nitrogen prior to combustion of the H_2 in a gas turbine. (ISPT et al. 2017)

Hydrogen is another option that is independent of available sources for CO_2 but is relatively complicated to store, transport and distribute and still lacks more afordable and mature fuell cell technology. However except for aviation, where on-board storage is particularly tricky, hydrogen fuel cell electric propulsion systems could in the long run be used with all modes of freight transport.

All Power-to-Fuel (P2F) options are as much dependent on the availability of sufficient renewable electricity supplies as electricity directly used for decarbonising rail freight or any other mode. However it appears unlikely that all renewable power and CO_2 inputs required for P2F can be made available in Europe on its own. Therefore most likely certain fractions of P2F energy and hydrogen will need to be imported. This allows to deploy lower production cost in regions of the world where solar radiation is more intense or where there is more constant wind available.

Thus some of the options for decarbonisation considered here do already or in future will serve as stepping stones into a decarbonised future of transport energy use. Others however, are most likely interim solutions (methane, biofuels) or will require more time for the further development of technical components and build-up of related infrastructure for production and distribution (hydrogen).

Maritime shipping, inland navigation, road freight and aviation basically have to transition from a limited diversity of fuels based on crude oil to carbon neutral electricity and fuels derived from it (P2F). Opposed to railways, direct electricity use is currently only considered for lorries on highways which is difficult with regard to the necessary investment in wiring and the required hybrid vehicle drives. For the other transport modes considered it can be disregarded.

Battery-electric drives may become a niche in inland shipping and harbour activity where the weight and bulk of batteries can be kept relatively small owing to short distance operation. However, this niche and its impact on overall emissions from maritime shipping and inland navigation will be of minor importance. From today's perspective, it would require substantial advances in battery technology to turn it into a viable option for any long distance transport.

6 Annex 1: Assessment of strategies for decarbonising maritime shipping

Grouped Strategies	Individual Strategies	Ship Technology Readiness Level	Ret rofit	System Integration Readiness	Efficiency Improvement (EI)/ Carbon Abatement (CA)	Selectivity	Interdependencies	Risks/ Barriers	Co-benefits	Role of Ports
Energy Efficiency: Hull Design	Hull Form	TRL9	No	Installation and maintenance	EI 3% (Michaelis 1997) CA 2-30% (Bouman et al. 2017)	Variable with ship type	Slow steaming will reduce effect	Split incentives/ HFO price	Less air pollution	Statutory overall efficiency obligations
	Light weight design		No	Installation and maintenance	CA 0.1-22% (Bouman et al. 2017)	Variable with ship type	Slow steaming will reduce effect	Split incentives/ HFO price	Less air pollution	Statutory overall efficiency obligations
	Bulbous Bow Reshaping	TRL9	Yes	Installation and maintenance	EI up to 20%	Basically unlimited	May foster effect of slow steaming	Split incentives/ HFO price	Less air pollution	Statutory overall efficiency obligations
	Air Lubrication	TRL9 (Rehmatulla et al. 2017)	Yes	Installation and maintenance	3% (Smith et al. 2016b) 5-15% (ICCT 2011) CA 1-15% (Bouman et al. 2017)	Tankers/ dry bulk (10-15%) container (5-9%)	May rule out certain hull coatings	Split incentives/ HFO price	Less air pollution	Statutory overall efficiency obligations
	Silicone Hull Coating		Yes	Installation and maintenance	EI <1% (Smith et al. 2016b)	Basically unlimited	May rule out other hull coatings	Split incentives/ HFO price	Less air pollution	Statutory overall efficiency obligations
	Polymer Hull Coating		Yes	Installation and maintenance	EI <2% (Smith et al. 2016b)	Basically unlimited	May rule out other hull coatings	Split incentives/ HFO price	Less air pollution	Statutory overall efficiency obligations
	Future Hull coating		No	Installation and maintenance	EI 10% (Smith et al. 2016b)	Basically unlimited	May rule out other hull coatings	Split incentives/ HFO price	Less air pollution	Statutory overall efficiency obligations

Grouped Strategies	Individual Strategies	Ship Technology Readiness Level	Ret rofit	System Integration Readiness	Efficiency Improvement (EI)/ Carbon Abatement (CA)	Selectivity	Interdependencies	Risks/ Barriers	Co-benefits	Role of Ports
Energy Efficiency: Rudder and Propeller Design	Rudder Bulb		Yes	Installation and maintenance	EI 2% (Smith et al. 2016b) 5% (IMO 2009)	High speed vessels (IMO 2009)		Split incentives/ HFO price	Less air pollution	Statutory overall efficiency obligations
	Pre-swirl Stator Duct	TRL9 (Rehmatulla et al. 2017)	Yes	Installation and maintenance	EI 0-6% (Smith et al. 2016b)		Rules out Contra Rotating Propeller and Vane Wheel (Smith et al. 2016b)	Split incentives/ HFO price	Less air pollution	Statutory overall efficiency obligations
	Vane Wheel		Yes	Installation and maintenance	EI 3% (Smith et al. 2016b) 10% (IMO 2009)		Rules out Contra Rotating Propeller (Smith et al. 2016b)	Split incentives/ HFO price	Less air pollution	Statutory overall efficiency obligations
	Contra Rotating Propeller	TRL9 (Rehmatulla et al. 2017)	Yes	Installation and maintenance	EI 8-15% (Smith et al. 2016b) 3-6% (IMO 2009)	particularly beneficial with Ro-Ro/ container vessels (IMO 2009)	Rules out Vane Wheel (Smith et al. 2016b)	Split incentives/ HFO price	Less air pollution	Statutory overall efficiency obligations
	Stern Wedges		Yes	Installation and maintenance	EI 3-7% (Smith et al. 2016b)			Split incentives/ HFO price	Less air pollution	Statutory overall efficiency obligations
	End Plated Propeller		Yes	Installation and maintenance	EI 2-8% (Smith et al. 2016b)			Split incentives/ HFO price	Less air pollution	Statutory overall efficiency obligations

Grouped Strategies	Individual Strategies	Ship Technology Readiness Level	Retrofit	System Integration Readiness	Efficiency Improve-ment (EI)/ Carbon Abatement (CA)	Selectivity	Interdependencies	Risks/ Barriers	Co-benefits	Role of Ports
Energy Efficiency: Autonomous Underwater Monitoring and Maintenance	Hull Cleaning	TRL9 (Krikke 2015)	Yes	Service availability	EI 5% (Krikke 2015) 1-10% (IMarEST 2011) depends on prior state	Basically unlimited, no variability by ship type and weight		HFO Price	Less air pollution/ less dry-docking	Promotion of service supply
	Propeller Polishing	TRL9 (Krikke 2015)	Yes	Service availability	EI 5% (Krikke 2015) 2.5-8% (IMarEST 2011) depends on prior state	Basically unlimited, no variability by ship type and weight		HFO price	Less air pollution/ less dry-docking	Promotion of service supply
	Rudder Blade Repair	TRL9	Yes	Service availability	EI depends on prior state	Basically unlimited		HFO price	Less air pollution/ less dry-docking	Promotion of service supply

Grouped Strategies	Individual Stratgies	Ship Tech-nology Readiness Level	Ret rofit	System Integration Readiness	Efficiency Improve-ment (EI)/ Carbon Abatement (CA)	Selectivity	Interdepend-encies	Risks/ Barriers	Co-benefits	Role of Ports
Energy Efficiency: Conven-tional Pro-pulsion and Auxil-iary Power System Upgrading	Heat Re-covery: Rankine Cycle	TRL9 (Rehmatulla et al.)	Yes	Installation and maintenance	EI 3-4% (Smith et al. 2016b)	Basically unlim-ited	Mutually exclu-sive with other heat recovery/ obsolete with decarbonised propulsion	Split incen-tives/ HFO price	Less air pollution	Statutory overall effi-ciency obliga-tions
	Heat Re-covery: Organic Rankine Cycle	TRL9 (IMO 2009)	Yes	Installation and maintenance	EI 2-4% (Smith et al. 2016b)	Basically unlim-ited	Mutually exclu-sive with other heat recovery/ obsolete with decarbonised propulsion	Split incen-tives/ HFO price	Less air pollution	Statutory overall effi-ciency obliga-tions
	Turbo-compound-ing		Yes	Installation and maintenance	EI 2-4% (Smith et al. 2016b)	Basically unlim-ited	Obsolete with decarbonised propulsion	Split incen-tives/ HFO price	Less air pollution	Statutory overall effi-ciency obliga-tions
	Turbo-compound-ing Parallel		Yes	Installation and maintenance	EI 2-3% (Smith et al. 2016b)	Basically unlim-ited	Obsolete with decarbonised propulsion	Split incen-tives/ HFO price	Less air pollution	Statutory overall effi-ciency obliga-tions
	Diesel-electric Machinery	TRL9 (Krikke 2015)	Yes	Installation and maintenance	EI 5-8% (Krikke 2015) CA 2-45% (Bouman et al. 2017)	Basically unlim-ited	Obsolete with decarbonised propulsion	Split incen-tives/ HFO price	Less air pollution	Statutory overall effi-ciency obliga-tions

Grouped Strategies	Individual Strategies	Ship Technology Readiness Level	Retrofit	System Integration Readiness	Efficiency Improvement (EI)/ Carbon Abatement (CA)	Selectivity	Interdependencies	Risks/ Barriers	Co-benefits	Role of Ports
Energy Efficiency: Operational Strategies	Increasing Ship Size	TRL9	Yes	Complementary port infrastructure	CA 4-83% (Bouman et al. 2017)	Depends on freight volume and frequency		Feeder traffic and more calls	Less air pollution	Enabling role of port facilities
	Slow Steaming	TRL9	Yes	Complementary technology/ qualification	EI ranging from 15-19%/ 36-39% (ICCT 2011, IMarEST 2011) to 45% (Gilbert et al. 2014)	Basically unlimited, very low variability by ship type	Slot management and port efficiency	Demand/ HFO price/ capital cost/ off-design operation	Less air pollution	Port efficiency/slot management
	Port Efficiency	TRL9 (Krikke 2015)	Yes	Complementary technology/ staff qualification	EI 5% (Krikke 2015)	Basically unlimited, no variability by ship type and weight	Slow steaming		Less air pollution	Un-/loading efficiency
	Capacity Utilisation	TRL9	Yes	High	CA 5-50% (Bouman et al. 2017)	Spatial and ship type		Spatially unpaired demand	Port efficiency	
	Hinterland modal shift	TRL9	Yes	Network capacity		RoRo, bulk, container		Limited network capacity	Less congestion in port area	Transhipment facilities and networks
	Voyage Optimisation	TRL9 (Krikke 2015)	Yes	Complementary technology/ qualification	EI 4% (Krikke 2015) 0.6-7% (IMarEST 2011) CA 0.1-48% (Bouman et al. 2017)	Basically unlimited, no variability by ship type and weight	Slot management and port efficiency		Less air pollution	Real-time slot management
	Crew Training and Awareness	TRL9 (Krikke 2015)	Yes	Complementary technology/ qualification	EI 5% (Krikke 2015)	Basically unlimited	May foster gains from other operational strategies		Less air pollution	Provision of training courses
	Dynamic Maintenance Planning	TRL9 (Krikke 2015)	Yes	Complementary technology/ qualification	EI 5% hull/ 5% propeller (Krikke 2015)	Basically unlimited			Proportionately less air pollution	Provision of training courses
	Trim Optimisation	TRL9 (Krikke 2015)	Yes	Complementary technology/ qualification	EI 5% (Krikke 2015)	Basically unlimited			Less air pollution	Provision of training courses
	Engine Condition Monitoring	TRL9 (Krikke 2015)	Yes	Complementary technology/ qualification	EI 4% (Krikke 2015)	Basically unlimited			Less air pollution	Provision of training courses
	Monitoring Energy Use	TRL9 (Krikke 2015)	Yes	Complementary technology/ qualification	EI 3% (Krikke 2015)	Basically unlimited			Less air pollution	Provision of training courses

Grouped Strategies	Individual Strategies	Ship Technology Readiness Level	Retrofit	System Integration Readiness	Efficiency Improvement (EI)/ Carbon Abatement (CA)	Selectivity	Interdependencies	Risks/ Barriers	Co-benefits	Role of Ports
Fuel Switching: Conventional Propulsion Decarbonised Fuel	Liquefied Natural Gas (LNG)	TRL9 (Krikke 2015) (IMO 2016a)	Yes	Complementary technology/ distribution infrastructure/ staff qualification	CA 4% (Krikke 2015) 20% (IMO 2016a) 5-30% (Bouman et al. 2017)	Basically unlimited, straightforward with boil-off on LNG carriers	May rule out other propulsion systems unless hybrid design	Methane leakages/ lock-in with ICE/ fuel bunker network/ HFO price	Less air pollution	Statutory GHG limits/ provision of fuelling infrastructure
	Biodiesel	TRL 9	Yes	Complementary technology	CA 30-90% less direct GHG (IPCC 2014) 25-84% (Bouman et al. 2017)	Basically unlimited limited biomass supply	May rule out other propulsion systems unless hybrid design	Land use change/ seawater ecotoxicity/ lock-in with ICE/ HFO price	Less air pollution	Statutory GHG limits/ provision of fuelling infrastructure
	P2F FT-Diesel	TRL9	Yes	Complementary technology	CA	Basically unlimited renewable electricity supply	May rule out other propulsion systems unless hybrid design	Seawater ecotoxicity/ lock-in effect with ICE/ HFO price	Less air pollution	Statutory GHG limits/ provision of fuelling infrastructure
	P2H_2 Ammonia		Unclear	Complementary technology/ distribution infrastructure/ staff qualification		Basically unlimited renewable electricity/ H_2 supply	May rule out other propulsion systems unless hybrid design	Toxicity/ seawater ecotoxicity/ lock-in effect with ICE/ HFO price		Statutory GHG limits/ provision of fuelling infrastructure
	Biomass Methanol		Yes	Complementary technology/ distribution infrastructure/ staff qualification	CA	Basically unlimited limited biomass supply	May rule out other propulsion systems unless hybrid design	Land use change/ lock-in with ICE/ fuel bunker network/ HFO price	Less air pollution	Statutory GHG limits/ provision of fuelling infrastructure
	P2F Methanol	TRL9 (IMO 2016b)	Yes	Complementary technology/ distribution infrastructure/ staff qualification	CA significant GHG reductions if produced from biomass with clean energy (IMO 2016b)	Basically unlimited renewable electricity supply	May rule out other propulsion systems unless hybrid design	Lock-in with ICE/ fuel bunker network/ HFO price	Less air pollution	Statutory GHG limits/ provision of fuelling infrastructure

Grouped Strategies	Individual Strategies	Ship Technology Readiness Level	Retrofit	System Integration Readiness	Efficiency Improvement (EI)/ Carbon Abatement (CA)	Selectivity	Interdependencies	Risks/ Barriers	Co-benefits	Role of Ports
Fuel Switching: Decarbonised Propulsion Systems	P2F Methanol/ Direct Methanol Fuel Cell-electric	Premature stage of DMFC	Unlikely	Complementary technology/ distribution infrastructure/ staff qualification	CA 100% direct	Basically unlimited renewable electricity supply	May rule out other propulsion systems unless hybrid design/ may turn technical efficiency for conventional propulsion obsolete	Upstream emissions/ fuel bunker network/ HFO price	No direct air pollution	Statutory GHG limits/ provision of fueling infrastructure
	P2H_2/Fuel Cell-electric	Limited military use TRL5-6 (Adolf et al. 2017)	Unlikely	Complementary technology/ distribution infrastructure/ staff qualification	CA 100% direct (Gilbert et al. 2014) 2-20% (Bouman et al. 2017)	Basically unlimited renewable electricity supply	May rule out other propulsion systems unless hybrid design/ may turn technical efficiency for conventional propulsion obsolete	Upstream emissions/ fuel bunker network/ HFO price	No direct air pollution	Statutory GHG limits/ provision of fueling infrastructure
	Sails (Wind Power)	Untested in commercial use (Gilbert et al. 2014)	Yes	Complementary staff qualification	CA 10-50% (Smith et al. 2016b)	Not applicable with container vessels and dry bulkers	Dependent on other propulsion system	Limited space onboard for sails, HFO price	Proportionately less air pollution	Statutory GHG limits
	Kites (Wind Power)	Limited commercial use (Gilbert et al. 2014)	Yes	Complementary staff qualification	CA 5% (Smith et al. 2016b) 2-20% (ICCT 2011)	Over 30m vessel length/ speed restricted at 16 knots (Gilbert et al. 2014)	Dependent on other propulsion system	Operation may be difficult with kites, HFO price	Proportionately less air pollution	Statutory GHG limits
	Flettner Rotors (Wind Power)	Limited commercial use (Gilbert et al. 2014)	Yes	Complementary staff qualification	CA 10-30% (Smith et al. 2016b) 3,5-12% (ICCT 2011)	Up to 60,000 dwt (Gilbert et al. 2014) not applicable with container vessels and dry bulkers	Dependent on other propulsion system	Limited space onboard for rotors, HFO price	Proportionately less air pollution	Statutory GHG limits

Grouped Strategies	Individual Strategies	Ship Technology Readiness Level	Retrofit	System Integration Readiness	Efficiency Improvement (EI)/ Carbon Abatement (CA)	Selectivity	Interdependencies	Risks/ Barriers	Co-benefits	Role of Ports
Fuel Switching: Decarbonised Power at Berth	Cold Ironing with Grid Electricity	TRL9 (Krikke 2015)	Yes	Complementary staff qualification	CA depends on grid electricity 3-10% (Bouman et al. 2017)	Basically unlimited	Obsolete with on-board decarbonised power		Less air pollution at ports	Provision of grid infrastructure
	Cold Ironing with Renewable Power	TRL9 (Krikke 2015)	Yes	Complementary technology/ staff qualification	CA up to 100%	Basically unlimited	Obsolete with on-board decarbonised power		Less air pollution at ports	Provision of grid infrastructure

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