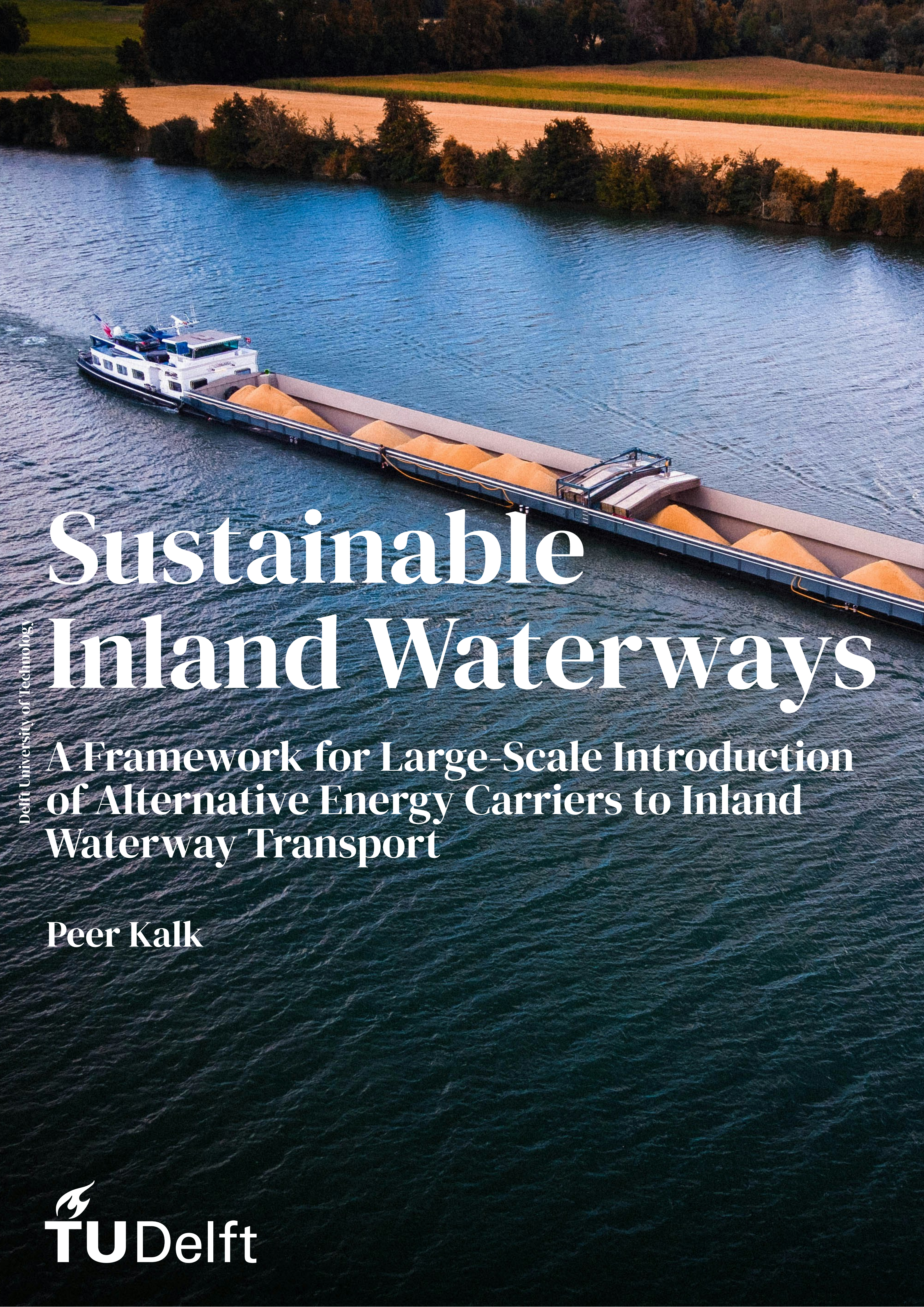

Delft University of Technology

# Sustainable Inland Waterways

## A Framework for Large-Scale Introduction of Alternative Energy Carriers to Inland Waterway Transport

Peer Kalk

TU Delft

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by


## Peer Kalk


To obtain the degree of Master of Science
at the Delft University of Technology


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# Preface

*Climate change has always been a challenge which has interested me. It was only about a decade ago that I learned that there is technology available which is ready to power the transition. When I saw that Tesla produced battery-powered cars, it showed me that it is actually possible to battle global warming with current technology. From that moment on, I have been captured in the electrification. It is one of the reasons why I started studying Electrical Engineering.*

*During my bachelor degree I learned a lot about the technological complexities of the energy transition, but I could not always see the bigger picture yet. So, afterwards, I joined the Hydro Motion Team for a year, where we built a hydrogen-powered boat together with a team of 25 students. It allowed me to see first-hand that batteries are not the only solution to power electrification. During this year, I had a combined role of managing a department and engineering and this made me realize that this combination excited me. For that reason, I started studying the master degree Management of Technology.*

*Since the moment when I learned there was an answer to climate change and I could be a part of it, I have tried to learn as much as I could to put myself in a position where I could also make a change. Now I am writing a thesis on how alternative energy carriers should be implemented in inland waterway transport. The first goal has been achieved. The first of many. The next goal is to actually make a change.*

*I would like to thank my supervising committee, Aad Correljé and Eugen Popa, for aiding me throughout the writing of this research. Personally, with little background in social research, your support has helped me to make this research into something I had hoped to do when I initially set off. At moments where I needed a push, as well as at moments where I thought I had it all sorted out, you have always given me constructive feedback.*

*I also owe a special thank you to everyone who took the time for an interview with me. Without you and your insights I would not have been able to get the results I got out of this research. I also hope you all succeed in expanding the implementation of the alternative energy carriers you are involved with. I believe there is a very exciting future ahead for many new technologies.*

*Also, I would like to express my gratitude to my family, especially my parents and my sister, and my friends; from Hydro Motion, from Broach, and from my studies. Throughout the writing of this thesis, but also before, the days and sometimes weeks of work could be long, but there was also a place with every one of you to take time and also enjoy life outside of my studies.*

*Peer Kalk*
*Delft, July 2024*

# Executive Summary

Inland waterway transport (IWT) is an integral part of today's society. Similar to other transport sectors, however, it has to transition away from fossil fuels. Regulations are tightening, but barges have a largely varying operational profile, making it difficult to find one suitable alternative to contemporary diesel. There are many alternatives available, yet none of them can fully replace diesel in the short term without impeding the sector too much. It seems that a mix of alternative energy carriers (AECs) is needed throughout the transition. Hardly any of the alternative energy carriers are being applied in IWT and when they are, it is typically still on a very small scale. This leaves the question why this is the case. This research is aimed at finding the determinants for the large-scale introduction of AECs to IWT.

Energy carriers in IWT can be seen as a system around a technology. To analyze their shortcomings for large-scale introduction to the sector, it is important to understand the necessities for the large-scale introduction of such a system in the first place. The framework from Ortt and Kamp (2022) for technological innovation systems (TIS) characterizes exactly this. Therefore, to analyze the determinants for the large-scale introduction of AECs to IWT, this framework is used. This framework consists of seven building blocks. These are *product performance & quality*, *product price*, *production system*, *complementary products and services*, *network formation*, *customers*, and *innovation-specific institutions*. These seven building blocks split up the aspects of large-scale introduction into smaller parts which are analyzed individually.

To gather data on why AECs are not being applied in IWT currently, seven different AECs are analyzed. These energy carriers all have a potential to be implemented on a larger scale in the sector. They are *diesel*, *LNG*, *hydrogen*, *methanol*, *ammonia*, *batteries*, and *flow batteries*. The data is gathered by interviewing experts in IWT who have experience with AECs. A total of eight interviews were conducted with ten interviewees in total. These experts vary in their position in the sector. Types of actors and stakeholders who have been interviewed were representatives for a *barge owner*, *shipyard*, *energy carrier supplier*, *component supplier*, *classification society*, *terminal*, and a *researcher*. The results from the interviewees have been coded using *ATLAS.ti*. The first step was to code all observations in interviews to a corresponding building block from the TIS framework. Once all the observations had been split up into building blocks, the building blocks could be analyzed individually. At this point, the determinants could be extracted from the observations per building block. This has resulted in a total of 23 determinants. Any determinant can be used to analyze an AEC. Analyzing a determinant can show whether a factor is aiding or blocking, or whether there is a barrier or opportunity for a particular AEC.

The 23 determinants can be viewed through three different scopes. The first scope, the *intra-barge scope*, contains the determinants of the first three building blocks; production system, product performance & quality, and product price. The second scope, the *intra-fleet scope*, contains the determinants of the next two building blocks; complementary products & services, and customers. The third and last scope, the *actor-based scope*, contains determinants of the last two building blocks; network formation & coordination, and innovation-specific institutions. The three scopes can be used to analyze whether the three scopes align for an AEC. This occurs when the mix of determinants in every scope is equally ready for implementation. When the three scopes align for an AEC, it is ready for implementation in IWT.

This framework with three scopes and their 23 determinants can be applied to any AEC, so not only the ones which were used in this research. It can be used by any actor or stakeholder in the sector to analyze which AECs are ready for implementation by them. Similarly, it can also be used to analyze where specific AECs are misaligned between scopes.

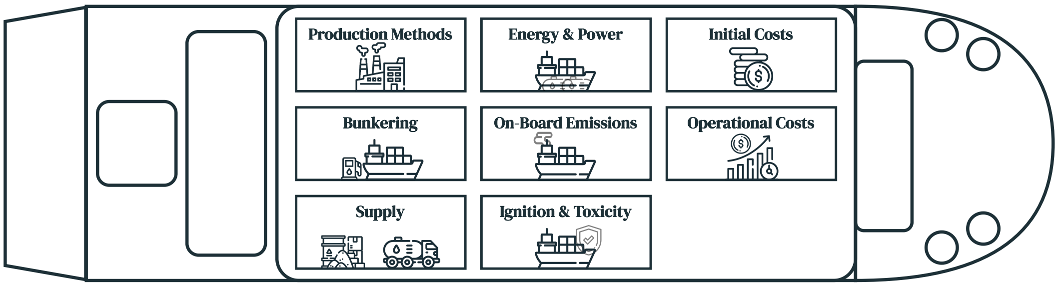


**Figure 1:** Determinants in the Intra-Barge Scope

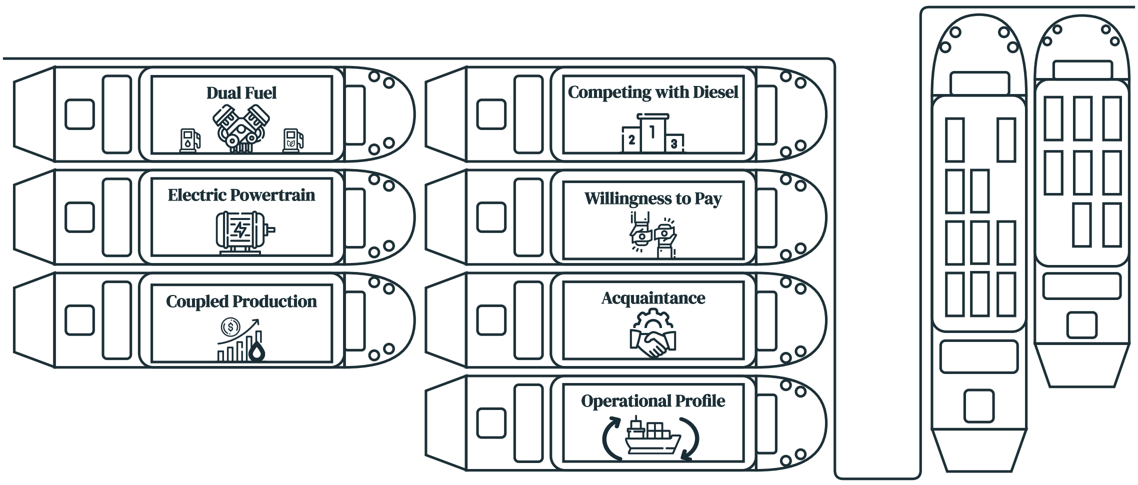


**Figure 2:** Determinants in the Intra-Fleet Scope

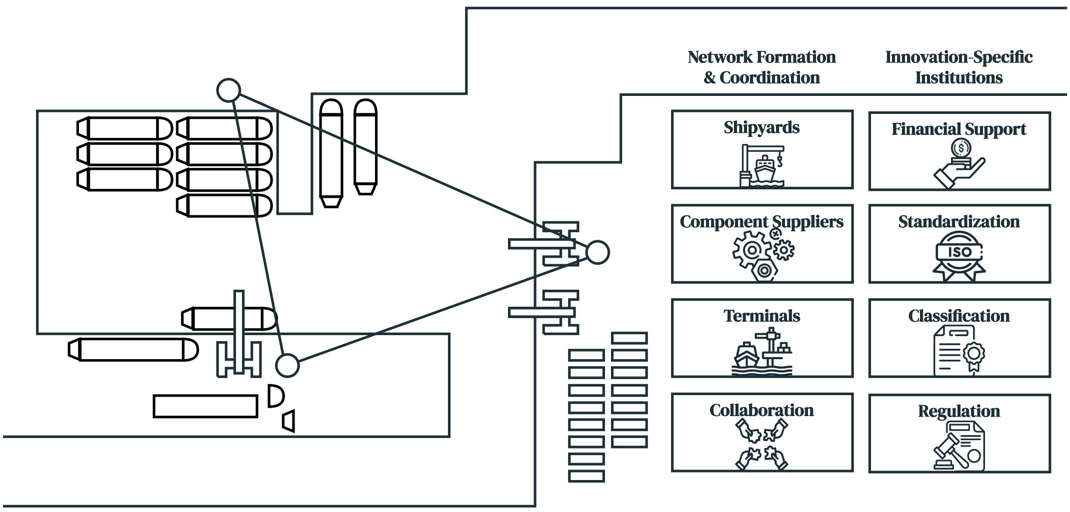


**Figure 3:** Determinants in the Actor-Based Scope

# Contents

# Nomenclature

$ADN$ European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways

$ADR$ Agreement concerning the International Carriage of Dangerous Goods by Road

$AEC$ Alternative Energy Carrier

$AFIR$ Alternative Fuels Infrastructure Regulation

$NH_3$ Ammonia

$CO_2$ Carbon Dioxide

$CO$ Carbon Monoxide

$CCNR$ Central Commission for the Navigation of the Rhine

$CENELEC$ European Committee for Electrotechnical Standardization

$CEN$ European Committee for Standardization

$CESNI$ Comité Européen pour l'Élaboration de Standards dans le Domaine de Navigation Intérieure

$CH_3OCH_3$ Dimethyl Ether

$DME$ Dimethyl Ether

$ES-TRIN$ European Standard laying down Technical Requirements for Inland Navigation vessels

$ETD$ Energy Taxation Directive

$CH_3CH_2OH$ Ethanol

$ETS$ Emissions Trading System

$FAME$ Fatty Acid Methyl Ester

$GHG$ Greenhouse Gas

$GT$ Gross Tonnage

$HVO$ Hydrotreated Vegetable Oil

$H_2$ Hydrogen

$IACS$ International Association of Classification Societies

$IMO$ International Maritime Organization

$IMPCA$ International Methanol Producers and Consumers Association

$ISO$ International Organization for Standardization

$IWT$ Inland Waterway Transport

$LFL$ Low Flashpoint Liquid

$LH2$ Liquid Hydrogen

$LNG$ Liquefied Natural Gas

$LOHC$ Liquid Organic Hydrogen Carrier

$CH_3OH$ Methanol

$N_2$ Nitrogen

$NO_x$ Nitrogen Oxide

$NRMM$ Non-Road Mobile Machinery

$O_2$ Oxygen

$PM$ Particulate Matter

$RED$ Renewable Energy Directive

$RNG$ Renewable Natural Gas

$SO_x$ Sulphur Oxide

$Syngas$ Synthetic Gas

$TIS$ Technological Innovation System

$UNECE$ United Nations Economic Commission for Europe

$VO_2$ Vanadium Dioxide

$VO$ Vanadium Oxide

$V_2O_5$ Vanadium Pentoxide

$V_2O_3$ Vanadium Trioxide

# Part I

# Introduction, Literature & Methods

# 1 Introduction

IWT is a key part of our society. Compared to other modes of inland transport, like trucking, IWT has its own benefits. It is one of the most efficient modes of inland transport as it can bring along large quantities of cargo on one trip (European Environment Agency, 2021). This has resulted in this type of transport being an integral part of today's society. Regardless of our dependence on this sector, changes are imminent for IWT. It is still largely dependent on fossil fuels and in Europe the transition towards cleaner fuels will impact IWT as well. This brings along a challenge to which the sector has to respond well.

## 1.1. Upcoming Regulation

To battle climate change, the European Union has established the *European Green Deal*, which aims for net-zero greenhouse gases by 2050. As a part of this deal, the *Fit for 55* package has been called to life, which aims for a 55% reduction of GHG emissions by 2030. Within this package are several rules and regulations which also impact shipping. Five important regulations for the maritime sector are the Energy Taxation Directive (ETD), the Renewable Energy Directive (RED), the Alternative Fuels Infrastructure Regulation (AFIR), FuelEU, and the Emissions Trading System (ETS) (Sustainable Shipping, 2023). These are all regulations that aim for GHG reduction and directly impact the maritime sector.

These regulations are also enforced on IWT specifically. This means that all actors and stakeholders in the sector have to adjust to these regulations. This involves barge owners, shipyards, crew, bunkering stations, customers, and so on. Meanwhile, IWT also needs to remain competitive. Customers could switch to the aforementioned trucking sector when these become more attractive. With so many actors, the transition in IWT is just as difficult as it is in other sectors. But there are more reasons why it is particularly difficult to implement AECs on a large scale in IWT.

## 1.2. A mix of Energy Carriers

Barges vary largely in shapes and sizes. With many different desires from customers come many different operational profiles. This has resulted in barges varying in properties like size, cargo type, and shipping routes. Because of this, there is not one simple alternative to transition to. In the automotive sector, electrification is currently powered by batteries, but this same technology is not ready to power all the operational profiles of IWT.

One example where batteries have been applied on a barge is a barge called *De Alphenaar* (Margaronis, 2021). This barge has two containers full of batteries on-board and can sail about 100 kilometers on a single charge. While this works for the specific route this barge sails, it would not be feasible for all the operational profiles in IWT. Kirichek et al. (2024) mention that the main strategy for making IWT zero emission, is by using sustainable AECs, but there is not yet a clear answer as to which AEC. "... there is no single route currently able to deliver a noticeable emission reduction over the whole fuel supply chain in a manner which is cost-competitive compared to conventional petroleum-based marine fuels" is stated by Wang and Wright (2021) when comparing energy carriers. So, there is no clear answer. Multiple alternatives are needed in the transition to net-zero in IWT, but who is going to implement which one and when?

## 1.3. First Movers

In IWT in Europe there have already been some early adopters using renewable propulsion technologies. For example, Heineken has a battery-electric barge in service (*De Alphenaar*) (Margaronis, 2021) and similarly, Nike has one which is hydrogen-powered (Nike, 2023). While these are good examples of the feasibility of these technologies, these companies are early adopters who can afford to take these risks. If the aim of 2030 is to be reached, the early majority should also be targeted. The ways Heineken, Nike, and their respective collaborative parties have pushed these projects is by investing a lot and acquiring large subsidies. Heineken and Nike also have agreements with the barge's owners to keep using these barges for the coming years, keeping the risk of the project to a minimum for those owners. There is only a finite number of these types of companies which can carry the burden of being first movers and adopting innovative technologies at an early stage, but eventually the entire IWT fleet has to transition to AECs. Barge owners don't typically choose to implement these technologies because they are more expensive than contemporary diesel options. In a market where customers choose the cheapest option, a more expensive barge will not pay for itself.

In IWT many barge owners own just one barge. They are often families who live on their own barge. They have a mortgage on their barge, their job is their living, and vice versa. For these people, to own a barge which is not paying for itself is like having a house which is losing its value while at the same time losing their income. Implementing an AEC with the chance that this is the result is not an option for them. So, how can a barge with an AEC pay for itself? Are there options available for the early majority which could be implemented early with higher certainty for success?

## 1.4. The Alternatives

There are several AECs available right now which have relatively high potential to enter IWT at a certain point. The aforementioned options, hydrogen and batteries, have already been proven to work in barges. When they are provided with renewable energy, they are fully emission-free. But, they also have their disadvantages. For example, hydrogen is rarely available in ports as a fuel for barges and similarly, a largely increased infrastructure would be needed for battery-powered barges to be able to recharge in ports. Because of this, the aforementioned barges from Heineken and Nike have containerized energy storage on-board which can be swapped at container terminals. This means that these supply chains have to be implemented in every port where barges with this energy carrier want to go. This creates a large bottleneck for these new energy carriers when it comes to large-scale roll-out in IWT.

So maybe the answer lies with the fuels that do already have largely implemented infrastructure. The most largely distributed energy carrier for IWT is diesel. An AEC which has already been implemented is biodiesel. Biodiesel is already mixed up to 7% with diesel in Europe. This AEC still has relatively similar emissions to diesel, but the main difference here is that these same greenhouse gases have already been captured during the growth of the feedstock. But this is also a disadvantage for biodiesel, because this feedstock cannot be grown at an infinite scale (Overmars et al., 2011). Feedstock for biodiesel is biomass, which requires large areas of land to produce, which at a certain scale would mean less land is available for e.g. food production. On top of that, biodiesel combustion engines still have emissions. So, biodiesel has its pros and cons, meaning it might not be the perfect solution.

LNG is an alternative that decreases $CO_2$ emissions, and even more $NO_x$ emissions (Pavlenko et al., 2020). It has been proven in other ships to be a good alternative to diesel (or to HFO in other maritime sectors). What has also been proven, however, is that LNG, which consists mostly of methane, when combusted, falls prey to a phenomenon called methane slip, where parts of the methane is left uncombusted in the engine and ends up in the air Jensen et al. (2021). Methane is a much higher potent greenhouse gas than $CO_2$, so LNG is not the solution when it comes to GHG emissions.

Methanol is an AEC that does have similar benefits to emissions as LNG, but without the methane slip. It can have production methods that do not rely on biomass and can still be renewable Gielen et al. (2021). Additionally, it could be used in fuel cells, so in the long run it can decrease emissions even further (Scott et al., 2013). A downside is that methanol still emits $CO_2$ when used, so it might not be the ultimate solution. Ammonia, in its turn, is an alternative which carries no carbon atoms and therefore it would be a good alternative to methanol as it can also be combusted and used in fuel cells. However, also ammonia is not perfect, because it is a toxic solution and when it is not compressed or cooled, it becomes gaseous, meaning that in the case of leaks it becomes an airborne toxic gas.

A last AEC with potential for IWT the flow battery. Flow batteries are relatively comparable to batteries and hydrogen. While also being a zero emission solution for powering barges, they also currently lack the infrastructure in ports. On top of that, flow batteries are a much less acquainted technology. So, this technology has potential, but still a long way to go.

## 1.5. Determinants of the Introduction

It seems that no matter what, there is no perfect solution for IWT. And yet, the pressure is on to transition to AECs. So, what is really the problem with all these alternatives and what is still missing before introduction to IWT becomes feasible? It is clear that just continuing with diesel is not the solution, because, eventually, regulations will catch up with diesel barges. So, what is stopping the sector from implementing the currently available alternatives? They are not absolutely bad for application in barges. But, the absolute limits for barges with regards to AECs are also not clear. This leaves the objective to search for the reasons why current alternatives are not applied in barges. This creates the following research question.

***”What are determinants for the large-scale introduction of alternative energy carriers in inland waterway transport?”***

One way to find the answer to this question is to analyze the current alternatives to see what makes them infeasible. AECs are systems with a production method, a distribution system and an application. This research will identify determinants which are affecting their large-scale introduction to IWT. These determinants are identified using the seven building blocks of Technological Innovation Systems (TIS) from Ortt and Kamp (2022). These building blocks consist of *product performance and quality*, *product price*, *production system*, *complementary products and services*, *network formation and coordination*, *customers*, and *innovation-specific institutions*. Seven AECs with a potential application in IWT are analyzed by viewing them as TIS using these seven building blocks to identify the blocking factors. These alternatives include *diesel*, *LNG*, *hydrogen*, *methanol*, *ammonia*, *batteries*, and *flow batteries*.

# 2
# Literature

The objective of this research is to define determinants for large-scale introduction of AECs to IWT. Determinants can impede introduction if they slow it down and diminish it. Hence, the question lies in why this delay and reduction take place. One model that can be used to define the requirements for the introduction of AECs is by using the TIS model from Ortt and Kamp (2022). Technological innovation systems (TIS) are systems that have a method for production, a distribution system and an application. Energy carriers on their own are not necessarily one technology, but rather a combination of many technologies combining production, distribution and application. In that sense, they can be viewed as TIS. When analyzing energy carriers as TIS, the seven building blocks from Ortt and Kamp (2022) can be used to outline the factors that are slowing down the timing and diminishing the scale of the introduction of AECs. These factors would essentially be the determinants for the large-scale introduction of AECs to IWT.

The reason why this framework in particular is useful for this exact research is because it splits up the concept of introduction into seven smaller parts. This makes it possible to analyze these parts individually, making it simpler to tackle all the different determinants one by one. Next to that, the goal of the research is to create a framework for any type of AEC. This is done by using multiple AECs throughout the research. It is therefore important to use a framework that can easily switch between different examples. The TIS framework provides for this by stating predetermined building blocks for introduction which work for any IWT.

## 2.1. Technological Innovation Systems

Ortt and Kamp (2022) showcase seven building blocks of technological innovation systems.

1. Product performance and quality
2. Product price
3. Production system
4. Complementary products and services
5. Network formation and coordination
6. Customers
7. Innovation-specific institutions

These building blocks can be used to outline the readiness of TIS, or in this case AECs. Ortt and Kamp (2022) mention that once the seven building blocks have been scored for TIS and they are all sufficient, a TIS is ready to be introduced on a large scale. Hence, finding the reasons why AECs would not score sufficient would give an answer to what the determinants are for the large-scale introduction of AECs in IWT. The following subsections outline how the seven building blocks can be viewed in the context of IWT.

### 2.1.1. Product Performance and Quality

"In the case of many sustainable products, environmental performance can be valued highly, but early product versions may suffer from low quality and may be unable to meet the customers' requirements." (Ortt and Kamp, 2022, p. 4). When analyzing the different energy carriers, performance and quality is the first building block that can be studied. The AECs are supposed to ultimately be sustainable products, but they also have to perform according to the requirements of IWT. For instance, the energy carrier can be fully net-zero, but if they do not deliver the required performance, like range, they will not be of much use. Therefore, there are two aspects; *technological performance* and *sustainable quality*.

#### Technological Performance

Technological performance covers aspects like energy density, power density, specific energy, specific power, and efficiency (tank-to-wake) in order to determine the weight and volume a carrier would require on-board a barge to be able to reach desired distances. It also includes other extraordinary specifications, like the lifetime of a fuel or toxicity.

Batteries are a good example of how energy density might create a problem for the range of a barge. Margaronis (2021) mentions how the battery-electric barge *De Alphenaar* sails between Moerdijk and Zoeterwoude and uses two cargo TEU containers filled with batteries, enabling it to sail for 50-100km. This works for this specific use case, but would it also work for longer distance shipping? It might be worth it (if possible) to place more battery containers on the barge, leaving off more cargo. Or every 100km there could be battery swapping stations, but this might also create large congestions, so maybe it only works up to a certain number of barges.

Biodiesel is a good example where an extraordinary specification could create a hard requirement. Komariah et al. (2022) mention how microbial growth in biodiesels poses a challenge as this phenomenon can cause problems like corrosion, filter plugging, and blockage in storage, fuel lines, and/or dispensing facilities. The longer biodiesel is not being used, the more microorganisms grow, so this might pose a problem for barges that sometimes have to wait a while until their next shipment is due.

Ammonia is also a good example of how an extraordinary specification poses hard requirements. Ammonia is toxic and even though it is stored as a liquid, when it is not compressed and cooled, it will become gaseous and thus be airborne in the case of leaks (Padappayil and Borger, 2023). This not only poses a potential threat to mechanics who enter a machine room where there could be an ammonia leak, but also to the stakeholders in the vicinity of a barge with ammonia.

#### Sustainable Quality

On the topic of sustainable quality, the on-board conversion technologies can be analyzed on aspects like emissions ($CO_2$, $NO_x$, $SO_x$, PM), carbon capture possibilities, efficiency (tank-to-wake (TTW)) and component materials.

LNG is a good example where on-board emissions raise a difficult question. LNG is liquefied natural gas which consists mostly of methane which is a potent greenhouse gas. (Pavlenko et al., 2020, p. 3, 17) discuss how LNG has higher equivalent greenhouse gas emissions due to methane slip, but less harmful emissions like $NO_x$ and $SO_x$, meaning it could be more suitable for areas closer to humans, like inland waterways in the case of shipping. This raises the question whether LNG is a good alternative for IWT or that the higher greenhouse gas emissions are a deal-breaker.

### 2.1.2. Product Price

The product price of an energy carrier depends on both the initial costs of installation of all the systems for an energy carrier and the costs for eventual use of the energy carrier. This splits up the building block of product price into two aspects; *capital costs* and *operational costs*.

### Capital Costs

Capital costs are costs related to, for example, installing storage and propulsion components, but also installing bunkering stations outside of the barge. These costs can change over time when the use of an energy carrier increases. The value of this cost is also dependent on the lifetime of components.

Flow batteries are a good example where capital costs can create a large obstacle. (Hillen, 2021, p. 76) mentions a case study where vanadium bromide flow batteries are used. Here, the cost of the battery stack and electrolyte fluid is so high, that it is difficult to become cost-competitive. Skyllas-Kazacos et al. (2011) also mentions how the cost of the vanadium electrolyte specifically is so high. Once the electrolyte is inside the barge's tanks, it can be used for many trips, only requiring a recharge in between shipments, but this initial cost creates a bottleneck. The batteries from the *Alphenaar*, as mentioned before, offer a solution to such a problem. The battery owners "rent out the battery power to lower the capital costs to vessel operator" (Margaronis, 2021). There might be more possible solutions like this, and this raises the question of which solutions need to be available to lower the capital cost for the early majority.

### Operational Costs

Operational costs consist of variable costs like fuel costs, and fixed costs like port and canal dues, and insurance. The fuel costs can change over time when use increases. When a fuel's production process becomes more sustainable its cost can also be impacted through, for example, subsidies. Similarly, fixed costs can change with new regulations stimulating sustainable alternatives, for example with discounts on port dues or cheaper insurance because of increased standardization and classification (Port of Rotterdam, 2024).

Methanol is a good example of how dual fuels could be applied to account for variable costs over time. Methanol is a promising fuel, but its green production is currently still upcoming. In IWT large companies are exploring their options with green methanol (MAERSK, 2023). Whilst the green production of methanol is still growing, other efforts are being made to integrate it more with current technologies. Methanol can be mixed with many other fuels, like diesel, biodiesel, DME, and hydrogen and also in many different ratios (Zhen and Wang, 2015). This means that barge owners can mix their fuels in more ways than one, giving them more flexibility with regards to fuel price fluctuations over time. The application of dual fuels in barges seems like a strong solution to secure implementation of AECs. This raises the question whether dual fuels are the only solution to create a smooth transition with regards to operational costs to AECs or whether there are also other options. Which solutions would aid the transition by creating more certainty and how do these solutions do this?

## 2.1.3. Production System

The production systems of energy carriers differ from each other on several different aspects. *Production methods* can differ in how sustainable they are, depending on their source and their well-to-tank efficiency (WTT). *Bunkering* applications also require multiple aspects to analyze, like current bunkering availability, potential bunkering locations, shipping routes and energy carrier specific range, and the difference between replaceable containers and refueling.

### Production Methods

Energy carriers get assigned colors for the source of their production. For example, grey methanol is methanol made from natural gas, green hydrogen is hydrogen produced from electrolysis with renewable energy, and like this, every production technique can be assigned a color. The perfect future is one where all energy carrier production is green, but that is not the reality yet.

Hydrogen is a good example where production technologies can make a difference. Hydrogen production is rapidly rising and therefore the use of hydrogen is also increasing. Simultaneously, the question arises whether blue or green hydrogen production should be prioritized. Whilst green hydrogen is produced from renewable energy and blue hydrogen from natural gas with carbon capture, some say that focusing on blue hydrogen is more beneficial (Clifford, 2022). The reason being that the production of green hydrogen is not very efficient and uses a lot of renewable energy which could also be spent directly elsewhere with less losses. All the while, blue hydrogen is already more sustainable than other alternatives and could give hydrogen a bigger boost. This raises the question of what the difference is between production technologies and how they are important for the IWT.

#### Bunkering

For some energy carriers bunkering solutions are closely available. For example, methanol is already transported by barge, so the bunkering infrastructure is close to ready. However, for other alternative fuels this is not necessarily the case, which means that bunkering solutions are a part of the problem for introduction.

Hydrogen again shows a good example of how the challenge of bunkering poses a difficult question. Hydrogen is typically stored in pressure tanks (Cheng et al., 2024) and there are two ways to refuel a barge which has hydrogen stored in pressure tanks. The first way is to refuel using a pressure line onto the barge and the second way is by placing the tanks inside containers and swapping empty containers for filled ones (Nike, 2023). Both have their own benefits. For example, container swapping is already readily available in every port, but it also raises the question whose container it is and who is going to pay for all the containers. Built-in fuel tanks do not raise this question of ownership, but do introduce high initial costs for bunkering installation and storage systems installation on-board the barge. This raises the question of what it would mean if new bunkering solutions would have to be applied to the entire sector. Is it even feasible to fully transition towards a fully different bunkering infrastructure or does a part of the current fleet have to keep using energy carriers with traditional bunkering solutions?

### 2.1.4. Complementary Products and Services

In this fourth building block, an analysis can be performed on how energy carriers for IWT can complement each other. For example, whether they share anything on the topic of their production technique, their on-board storage or their conversion technology.

Methanol is a good example of an AEC which has many complementary products and services. In terms of its production process, it can be produced from methane (the main compound found in LNG), or it is produced with hydrogen and can be processed back into hydrogen as well (Fausto Gallucci and Drioli, 2007). Methanol is also liquid at room temperature, meaning it could be stored in regular storage tanks without too many alterations. On the topic of energy conversion, methanol has an application in both combustion engines and fuel cells with electric motors, meaning it complements combustion fuels like biodiesel and LNG, and simultaneously complements fuel cell fuels like ammonia and hydrogen. Additionally, it also complements fuels that rely on propulsion with internal combustion engines or electric motors, which essentially mean any type of fuel. So, how important is it actually for an AEC to be complementary to other energy carriers and how could this complementariness make the sector grow from one alternative to the other?

### 2.1.5. Network Formation and Coordination

All the factors that have been mentioned so far have their own responsible parties and in order to get all the factors to be solved and to ensure smooth introduction to the sector, strong network formation and coordination is an important factor as well.

For example, one party might be committed to the implementation of hydrogen fuel cells in barges with the assumption that other parties will keep developing hydrogen fuel cells and eventually the price for components will decrease. But, when this does not happen, the first party will be affected badly, while both parties could have supported each other to grow together. Similar to this example, there are many ways in which involved parties will have to collaborate to make sure that their development not only aids themselves, but also others, so everyone can grow the fastest.

### 2.1.6. Customers

Customers of the IWT sector are generally companies that need their cargo distributed. IWT is an open market, where customers opt for the cheapest solution available to bring their cargo from one specific location to another. This makes it difficult for more expensive alternatives to compete with the energy carriers in the current market. There are some proven solutions to get around this problem, however. For example, Nike (2023) mention how they have introduced a hydrogen-powered barge which they will use for transport of their own product. This way, the customer is directly responsible for sustainable innovation and pays the price for this themselves. This is, of course, a consideration which not every customer can afford to take. So, are there other marketing options where sustainable barges have customers, or is the only option to boost AECs to make diesel more expensive up until the point that alternatives are the less expensive option?

### 2.1.7. Innovation-Specific Institutions

Examples of innovation-specific institutions are policy-makers, legislators and regulation bureaus, standardization organizations, and classification societies. Policies, laws and regulations can be both on a national and international level. For example, a country can have stricter regulations on a specific energy carrier than the EU has on that specific carrier. Standardization is dependent on technology, but many energy carriers can rely on multiple technologies. For example, standardization in fuel cells will aid all fuel cell ready energy carriers. There are several classification societies for the maritime sector and some are also members of the international association of classification societies (IACS). Some classification societies are more concerned with certain AECs than others and this can have a big impact on the future of specific energy carriers.

## 2.2. Alternative Energy Carriers

As could be read throughout the previous section, multiple different energy carriers are mentioned as feasible alternatives for the IWT sector. To analyze several AECs as TIS, a generalized list of these carriers must be created. Swift and Valencia (2023) mention available alternative propulsion technologies for IWT, naming liquefied natural gas (LNG), methanol, ammonia, hydrogen, biofuels and batteries. Through literature research on these alternatives, a more generalized list of potential net-zero AECs can be defined as such that they can be seen as TIS.

- Diesel
- LNG
- Hydrogen
- Methanol
- Ammonia
- Batteries
- Flow Batteries

The basic information on each of these energy carriers is mentioned below. In chapter 3 the production methods for every AEC are elaborated. In chapter 4 the applications for all of these energy carriers are mentioned and, for some, also, the different types of storage are discussed.

### 2.2.1. Diesel

Diesel is currently the most used fuel for IWT. Whilst combustion of diesel is not a zero emission type of propulsion, there is currently a lot of on-going innovation for synthetic diesel and biodiesel which could potentially make diesel combustion a net-zero technology (Vyas et al., 2010). By implementing these different types of diesel, it can become a green energy carrier.

Whilst the idea of having a green diesel sounds perfect, there are some downsides. Most green diesels are not compatible with contemporary diesel engines, for example, because they do not contain as much oil as contemporary diesel, so current engines would have to be altered in order to still reach their intended lifetimes (Jääskeläinen and Majewsk, 2021). On top of that, propelling the entire IWT sector fully on green diesel would require a large amount of biomass. To produce this large amount of biomass, a large portion of land needs to be used solely for the biomass needed for IWT, which could limit land use by other sectors, posing a different problem (Overmars et al., 2011).

### 2.2.2. Liquefied Natural Gas

LNG is natural gas which has been cooled to its liquefying point. So far, it has been the only AEC that has been applied commercially in ships (Swift and Valencia, 2023). Technically, it reduces $CO_2$ emissions on a barge, which makes it promising as a combustion fuel on-board barges. However, as natural gas consists of 97% of methane and not all this methane is combusted in the engine, there is a methane slip which means it ends up in the air (Jensen et al., 2021). Methane is a more potent GHG than $CO_2$, meaning this type of emission is essentially worse (Pavlenko et al., 2020). Carbon emissions can, however, be lowered further with LNG, as biomass can also be used to create renewable natural gas (RNG), a gas that can be fully interchangeable with LNG, creating a green alternative for LNG (Kirk and Gould, 2020). This still poses the same problem that biodiesel had, where land is required in order to fulfill the needs of the IWT sector with RNG.

### 2.2.3. Hydrogen

Hydrogen ($H_2$) can be applied in many different applications and, similarly, it could also be used for IWT. Hydrogen is the first element in the periodic table and so it comes as no surprise that it is common in many applications. Most hydrogen that is being produced currently is grey hydrogen, meaning that it originates from natural gas (Prato-Garcia et al., 2023; MT et al., 2023, p. 3). The promise of blue and green hydrogen is steadily growing, but hydrogen still has a long way to go. The storage technologies for hydrogen and the mobile applications of hydrogen still need a lot of development (Langmi et al., 2022, p. 477). Still, hydrogen has a lot of interfaces with other AECs; its grey production has the same resources as LNG (Prato-Garcia et al., 2023), it is used for production of methanol and ammonia (Fausto Gallucci and Drioli, 2007) and it can be a type of storage for electric energy like batteries can. With the growth of other energy carriers, hydrogen will likely also grow. It is just a question of how and with which type of storage exactly. There are numerous ways of storing or carrying hydrogen and there are still many upcoming hydrogen carriers, so it will be interesting to keep an eye on hydrogen through the energy transition.

### 2.2.4. Methanol

Methanol ($CH_3OH$) is an alcohol which is liquid at room temperature. It is also in many ways related to other AECs; it can be made from methane (the main compound found in LNG), it has relatively similar production processes to ammonia, and it is produced with hydrogen and can be processed back into hydrogen (Fausto Gallucci and Drioli, 2007). Similarly, it is not only useful as an energy carrier, but also has a lot of use in other industries. For this reason, there is already a large methanol infrastructure, also in the shipping sector. This has resulted in methanol being a topic of interest for the shipping sector as an energy carrier. Methanol can be used both in combustion engines and in fuel cells, creating kinetic or electric energy, respectively. Methanol can be created from coal, natural gas or carbon capture together with hydrogen from electrolysis. This makes methanol production techniques range from brown methanol to green methanol. As green methanol here not only refers to methanol produced from biomass, but also to the other option where it is produced from carbon capture and hydrogen from electrolysis (both powered by renewable energy), this gives methanol an edge over biodiesel and RNG (Hickling, 2023). It could theoretically be a net-zero fuel that can actually scale without hindering other sectors as much.

### 2.2.5. Ammonia

Ammonia ($NH_3$) is an inorganic compound that is similar to methanol in many parts of its application. For example, its production processes are much like the ones used by methanol, but with carbon dioxide and carbon monoxide replaced with nitrogen, so ammonia can also be made from coal, natural gas and green hydrogen. Similarly, ammonia can also be used for both combustion engines and for fuel cells. Ammonia also has a similar energy density to methanol, granted that it must be liquefied through cooling and pressurizing (Jacobsen et al., 2021). The big advantage of ammonia over methanol is that it is inorganic and therefore contains no carbon atoms, meaning that no $CO_2$ emissions are created when converting ammonia to kinetic or electric energy. The big downside to ammonia is, however, that it is toxic to both humans and aquatic life. Currently, there is hardly any green ammonia available and the ammonia that is available is used for fertilizers and chemicals (Galucci, 2021).

### 2.2.6. Batteries

Batteries are an option for full-electric barges, which is already being applied right now. Being a widely deployed technology in the automotive industry, it is expanding to other sectors as well. Zhang et al. (2023) mention how batteries are applied on barges where the batteries are located in containers which can be replaced with fully charged battery containers in ports. Whilst batteries are capable of propelling barges, they are still relatively expensive and do not deliver the range that most barges require (Allen, 2022). So, for specific use cases, they definitely deliver the expectations, but solely the batteries that are available with the technology today will not be able to decarbonize the entire shipping industry. Yet, maybe they also have a good use case in hybrid applications with other electric energy carriers and they could give a boost towards net-zero that way.

### 2.2.7. Flow Batteries

Flow batteries can be seen as a combination of battery technology and fuel cell technology. They rely on a cell stack with membranes like fuel cells and on electrolytes like batteries. The big difference here is that the electrolytes have to be pumped through the cell stack in order to create a potential over the cells and thus create an electric current when needed. To do this, both fluids have to be stored in separate tanks (Zhang et al., 2014). A specific type of redox flow battery is the vanadium redox flow battery, which uses oxidized and ionized vanadium in order to create a charge potential between the anode and the cathode. Hillen (2021) mentions a proof of concept of vanadium redox flow batteries in the shipping sector. Vanadium flow batteries are currently not providing a similar range as diesel does, meaning they will also face the problem of limited range. However, flow batteries have the advantage that the energy component and power component are separated, opposite to batteries. This gives the possibility to make designs more optimized for their use case. With flow batteries being net-zero as long as they are charged with renewable energy, but also having little to no infrastructure for shipping, it is interesting to see how the pros and cons can outweigh each other for this type of energy carrier through the energy transition.

# 3

# Production Methods of Alternative Energy Carriers

In order to understand the difference between the different AECs, a first step is to know what they are made up of. Every energy carrier has its own composition and hence they all have their own production methods. To analyze this determinant, firstly, all the production methods for all seven different AECs are described for the sake of understanding the underlying responses of interviewees.

## 3.1. Alternative Diesel Production

Diesel is the most commonly used energy carrier in IWT at the moment. For shipping in general, there are three types of diesel available (van Lieshout et al., 2020).

1. Heavy Fuel Oil (HFO) is the remnant oil from the distillation and cracking process of petroleum, therefore also called residual oil. It is desulfurized up to a point where it meets requirements.
2. Marine Diesel Oil (MDO) is a blend of residual oil and distillate fuel.
3. Marine Gas Oil (MGO) is fully distilled and therefore has the lowest sulphur content (<0.1%), which makes it suitable for Emissions Control Areas (ECA).

The EU Sulphur Directive (2016/802) states that the maximum allowable sulphur content of marine fuel used by ships at berth in Union ports is 0.10% by mass, which is why these ships typically use MGO. While this is true for sea ports, the restrictions for inland waterways are even tighter, with a maximum of 10ppm sulfur content in fuels (2003/17/EC). That is why barges use a specialized form of diesel (MDO), which conforms to EN590 standards.

There are three major alternative types of diesel, which are synthetic (Fischer-Tropsch) diesel, biodiesel (FAME), and renewable diesel (HVO).

### 3.1.1. Synthetic Diesel

When combining carbon monoxide with hydrogen in a process called the Fischer-Tropsch process, synthetic diesel can be created. section 3.3 contains a more in-depth description of the production of hydrogen and explains how syngas (a combination of hydrogen, carbon monoxide and carbon dioxide) can be created from either coal, natural gas, or biomass. Syngas could also be formed by combining hydrogen and carbon dioxide, which could originate from hydrogen from an electrolyser and captured $CO_2$.

### 3.1.2. Fatty Acid Methyl Esters

Combining an alcohol with an ester to create a different alcohol and ester is called transesterification. When combining methanol (as alcohol) and vegetable oil (as ester) into a transesterification process, an ester called fatty acid methyl ester (FAME) is created. The molecules found in biodiesel are primarily FAME, usually obtained from vegetable oils, but animal fat feedstock, and other non-edible raw materials such as used cooking oil could also be used. Biodiesel itself is not necessarily used fully on its own, but rather it is often mixed with diesel in order to keep certain properties from diesel that aid the engines. There are several types of mixes of diesel with different percentages. For example, BD30 is a mix of 30% biodiesel and 70% diesel.

### 3.1.3. Hydrotreated Vegetable Oils

When adding hydrogen to the same vegetable oils as used for FAME production and then removing oxygen as water or carbon dioxide, hydrotreated vegetable oils (HVO) are produced (Zeman P et al., 2019). HVO is not officially called biodiesel, rather it has the name renewable diesel. Similar to FAME, HVO is typically obtained from vegetable oils, but can also be produced with animal fat feedstock or used cooking oil.
The chemical formula for HVO is $C_nH_{2n+2}$, similar to synthetic diesel originating from Fischer-Tropsch production.
The question about biodiesel and renewable diesel is its source; it can be created from waste products like used cooking oil or waste animal fats, but it can also be created from plant-based products directly. Using waste is sort of a good thing, but you are not storing the captured carbon (at least not efficiently). Using it from plants directly does use the captured carbon fully, but these plants could also have been used for food, raising a whole different dilemma.

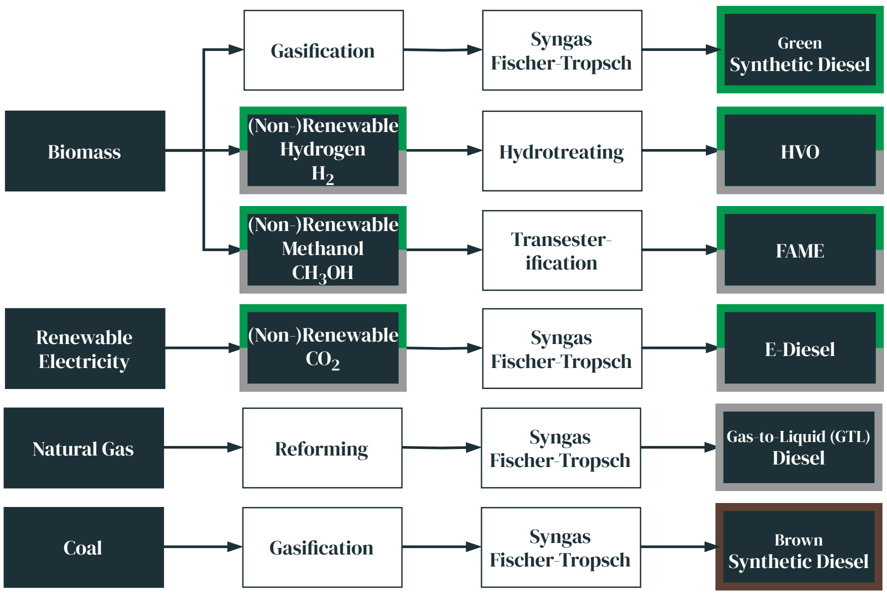


**Figure 3.1:** Diesel Production Methods

## 3.2. LNG Production

There are two types of LNG, the first being LNG made from fossil natural gas and the second being LNG made from renewable natural gas (biogas).

### 3.2.1. Natural Gas

Natural gas is one of the primary energy sources on the world, after oil and coal (Ritchie and Rosado, 2020). Traditionally, natural gas is extracted from subsurface rock formations which contain permeable material, topped by non-permeable rock. The natural gas from these formations is the most practical way of acquiring natural gas and hence it is also referred to as conventional gas. There are also newer techniques to reach natural gas formations at less practically reachable locations in the Earth's crust. The natural gas acquired through these techniques is called unconventional gas (National Geographic, 2023). One form of unconventional gas is deep natural gas, which is acquired from further below the Earth's surface (at least 4,500 meters, compared to a conventional few thousand meters). Another unconventional gas is shale gas, which is sandwiched between sedimentary rock (shale) and can be accessed through hydraulic fracturing (also known as fracking). Some other examples of unconventional gas are tight gas, coalbed methane, gas from geopressurized zones, and methane hydrates. All in all, every type of either conventional or unconventional natural gas originates from the inside of the Earth's crust and is a fossil fuel.

### 3.2.2. Biogas

Through anaerobic digestion (where microorganisms break down biodegradable material), biomass can be converted to biogas. When this biogas is purified, it creates a pipeline quality gas which is fully interchangeable with conventional natural gas. Hence, biomass can be used to produce carbon neutral LNG as the carbon dioxide that would be produced when combusting the biomass-based LNG is compensated for by the biomass which has absorbed this $CO_2$ from the air (Kirk and Gould, 2020). Similarly to biodiesel, biogas can be produced from biomass feedstocks such as fats, oils (vegetable oils or used cooking oil), and food waste.

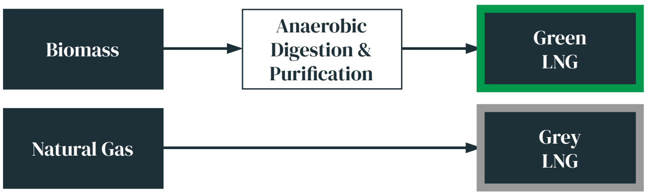


**Figure 3.2:** LNG Production Methods

## 3.3. Hydrogen Production

Hydrogen can be produced through a variety of options. These options have been evolving over the past decades and now consist of a range of options from black hydrogen production to green hydrogen production.

### 3.3.1. Gasification

Gasification is a process that converts biomass or fossil-based carbonaceous materials into gases at high temperatures. The gases which are created in this process are mainly carbon monoxide (CO), hydrogen ($H_2$), carbon dioxide ($CO_2$) and their collective name is synthetic gas, or syngas. Carbon capture could be applied at the exit of a gasification unit in order to decrease its environmental impact.

- **Coal**
  One largely used raw material for gasification is coal. Production of syngas from coal is the most environmentally damaging production type for hydrogen. Hydrogen produced from black coal or lignite (brown coal) gets its respective name of black or brown hydrogen and is the polar opposite of green hydrogen on the hydrogen spectrum.
- **Biomass**
  Another option for gasification to create syngas is using biomass. Generally, biomass does

not gasify as easily as coal, which results in the production of additional unwanted hydrocarbons (US Department of Energy, 2024). For this reason, often an extra step must be taken to reform these hydrocarbons with a catalyst in order to have a clean syngas mixture.

### 3.3.2. Steam Reforming

Steam reforming, or steam-methane reforming, is a process where sources of methane are combined with steam at high temperatures under pressure in the presence of a catalyst, in order to produce syngas. Carbon capture can also be applied at the exit of a steam reforming unit in order to decrease its environmental impact.

- **Natural Gas**
  As the steam reforming process requires methane and natural gas consists of 97% of methane, natural gas is a commonly used resource to create syngas. The hydrogen created by this process is called gray hydrogen. When CCUS is applied to natural gas steam reforming, the hydrogen that is created is called blue hydrogen. This is called a low-carbon emitting process as the process does not prevent the creation of greenhouse gases (Prato-Garcia et al., 2023).
- **Biogas**
  As stated before, when biogas is purified it becomes renewable natural gas which is so similar to natural gas that it can be interchanged and it can therefore also be used in steam reforming. Once again, this process does not prevent the creation of greenhouse gases, but in this case the biomass from which the RNG is created does compensate for the carbon emissions (Prato-Garcia et al., 2023).

### 3.3.3. Methane Pyrolysis

A more recent discovery is the process of methane pyrolysis, where methane molecules are decomposed in the presence of high temperatures, resulting in hydrogen and solid carbon (Patlolla et al., 2023, p. 9). The large benefit here is that there are no $CO_2$ emissions, resulting in the name of turquoise hydrogen for this type of hydrogen production. While this technology is promising for the future of hydrogen production, it is still in early development.

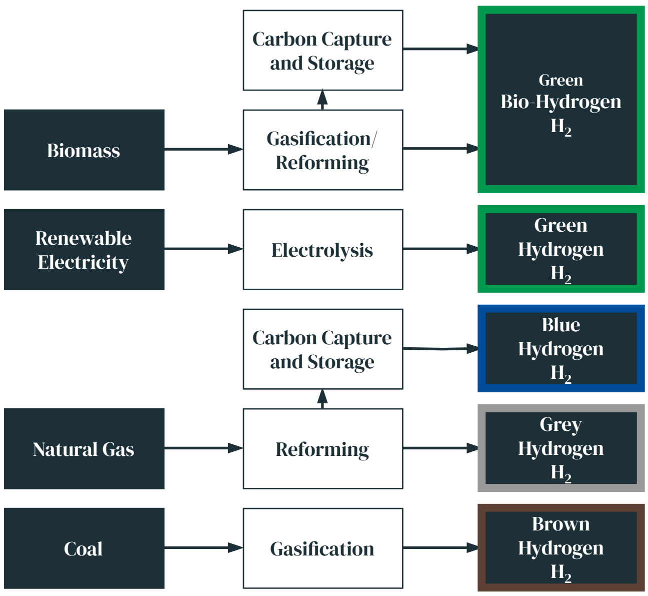


**Figure 3.3:** Hydrogen Production Methods

### 3.3.4. Electrolysis

Electrolysis is an electrochemical reaction where an electric current is applied to water through which the water is split into hydrogen and oxygen. When surplus renewable energy like wind or solar power is used for electrolysis, the resulting hydrogen is called green hydrogen. Electrolysis can also be applied with nuclear energy, which results in the hydrogen being called pink hydrogen. In some contexts, when referring to electrolysis powered solely by solar power, the produced hydrogen is called yellow hydrogen.

### 3.3.5. Biomass

Apart from steam reforming or gasification, there are also other options to make hydrogen from biomass. Examples are biophotolysis, photo-fermentation, and dark fermentation. These relatively new processes use algae and bacteria to create hydrogen. Putatunda et al. (2023) explain how these technologies could become a game changer.

## 3.4. Methanol Production

Methanol can be synthesized using syngas, which consists of carbon monoxide, carbon dioxide and hydrogen. More about the synthesis of syngas can be found in section 3.3 on hydrogen. The main reactions of importance for methanol synthesis are the following three (Fausto Gallucci and Drioli, 2007).

$$2H_2 + CO \rightleftharpoons CH_3OH \tag{3.1}$$
$$CO + H_2O \rightleftharpoons CO_2 + H_2 \tag{3.2}$$
$$CO_2 + 3H_2 \rightleftharpoons CH_3OH + H_2O \tag{3.3}$$

In order to make sure that all the syngas is converted into methanol, a process called the water-gas-shift reaction is applied, making sure that all the gases are converted to methanol.

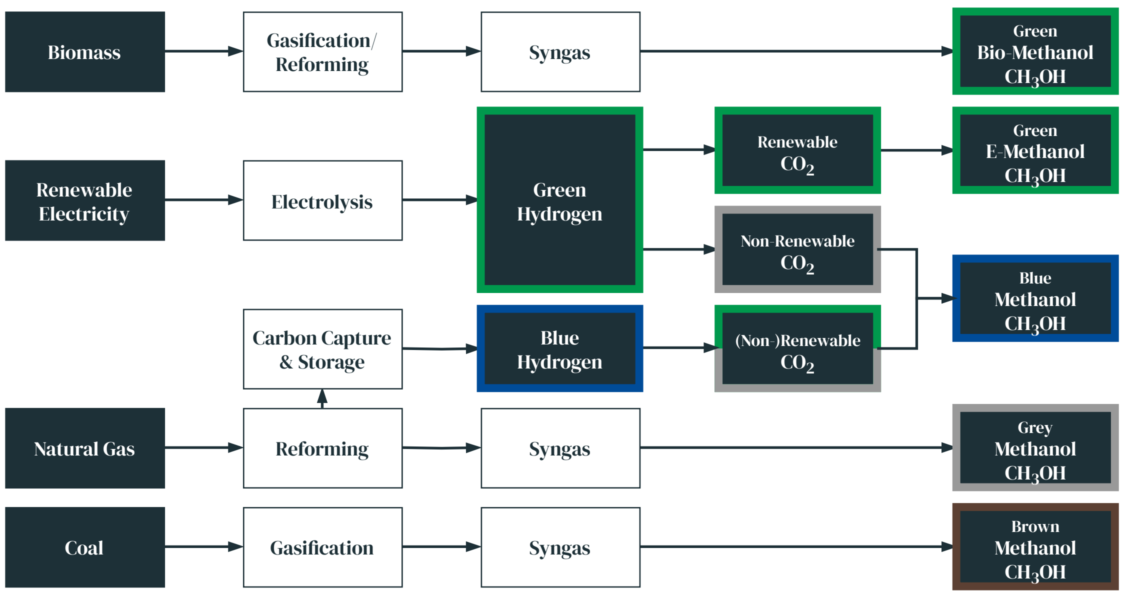


**Figure 3.4:** Methanol Production Methods
*Adopted from Gielen et al. (2021) (IRENA)*

### 3.4.1. Synthetic Gas

Hydrogen in a mix of syngas can be created primarily from coal, biomass, natural gas and biogas, as described in section 3.3. Depending on the source of the syngas, the methanol produced from it can be described using the same colors as the hydrogen in the syngas. For example, methanol produced from brown coal is called brown methanol, from natural gas it is called gray methanol and from biomass (and biogas) it is called green methanol (Hickling, 2023).

### 3.4.2. Hydrogen and Captured Carbon

As can be seen from Equation 3.3, just carbon dioxide and hydrogen together can initiate a methanol production process. When hydrogen is created using blue hydrogen production and the carbon dioxide originates from a carbon capture process, for example, the carbon capture at the end of blue hydrogen production, the produced methanol can be described as blue hydrogen. When using green hydrogen and renewable $CO_2$, methanol can even be called green methanol, but $CO_2$ is only considered renewable when the energy intensive direct air capture (DAC) process is performed under green energy or if the $CO_2$ is captured directly from exhaust fumes (Hickling, 2023).

## 3.5. Ammonia Production

The major production type of ammonia synthesis is through a process called the Haber-Bosch process. In general terms, this process combines hydrogen and nitrogen to create ammonia (Ghavam et al., 2021).

$$N_2 + 3H_2 \rightleftharpoons 2NH_3 \tag{3.4}$$

Hydrogen can be obtained from many sources, as is also explained in section 3.3, hence the ammonia production color spectrum can also range from brown to green ammonia. The nitrogen that is used for the Haber-Bosch process, originates from an air separation unit, where air is split into nitrogen and oxygen. Pattison and Baldea (2014) mention how energy-demanding the process of air separation is and that "operating air separation units at variable capacity [...] can serve as a means for mitigating grid load during peak times." A distinction could be made for green or blue ammonia between their sources of nitrogen and whether the electricity used for air separation and the Haber-Bosch process was also green or blue. Some alternative, yet not largely applied, production methods for ammonia are biocatalysis, photocatalysis and electrocatalysis (Shen et al., 2021).

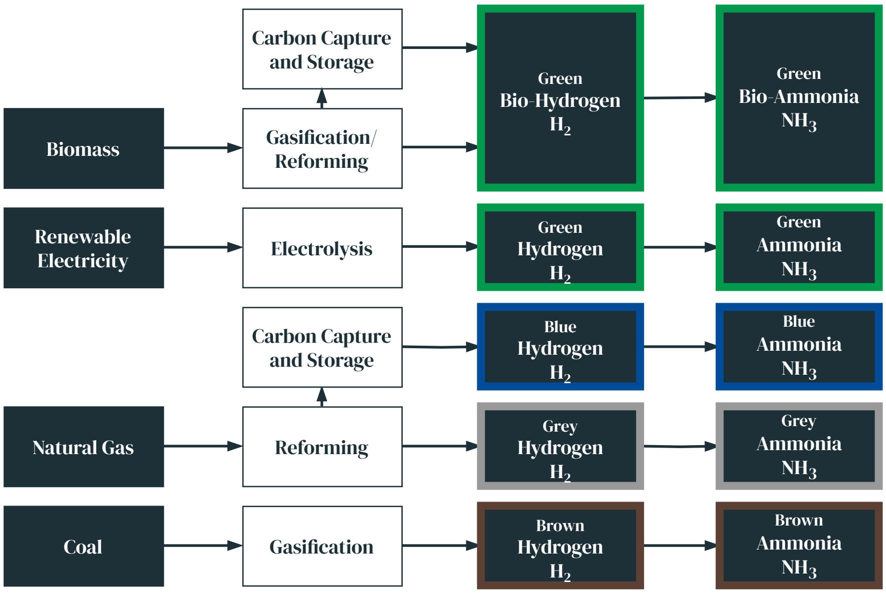


**Figure 3.5:** Ammonia Production Methods

## 3.6. Battery Production

Lithium ion batteries are the most common battery technology nowadays. These are the type of batteries which can be found in devices varying from mobile phones to EVs. There are several different types of lithium ion batteries. Li-ion is a collective name for multiple types of battery chemistries which all rely on lithium ions being exchanged between the anode and cathode (Väyrynen and Salminen, 2012). Some examples of li-ion battery chemistries are Lithium Cobalt Oxide (LCO), Lithium Nickel Cobalt Manganese Oxide (NCM), Lithium Nickel Cobalt Aluminium Oxide (NCA), Lithium Iron Phosphate (LFP), and Lithium Manganese Oxide (LMO).

The main feedstock materials for li-ion batteries are lithium, graphite, cobalt and manganese (Igogo et al., 2019). These materials can be gathered by mining from different locations. For example, lithium is abundant in Australia and Chile, and cobalt is abundant in the Congo. After mining, the lithium is refined into lithium carbonate, which happens in China and Chile in the largest quantities.

Li-ion battery cells exist in three different shapes; pouch, cylindrical, and prismatic. All three have relatively similar production techniques. Weimes et al. (2018) explains how cells are produced. The first step is to manufacture the electrolyte, which is a process with multiple stages, essentially making a big roll of electrodes. After this, the cell is assembled by either stacking or winding the electrode and packaging it. Lastly, the cells are finished, preparing them to be applied in, for example, a barge.

## 3.7. Vanadium Production

A flow battery, also known as a redox flow battery because it uses a reduction-oxidation (redox) process, works similar to a battery, but it does have its differences and, therefore, it also has different benefits and downsides than batteries. Whereas battery cells are the entire energy carrier and power generator in one package, a flow battery has three different components; two tanks containing the positive and negative electrolytes and a cell containing two electrodes and a membrane. The tanks are the component which store the energy and the cell is the component which converts the chemical energy into electrical energy when the electrolytes are pumped through their corresponding electrodes in the cell. The basic characteristics and workings seem very similar to either a battery or a fuel cell, but there are some fundamental differences which make flow batteries inherently different and therefore an interesting alternative to analyze for the IWT sector.

The state of the art for flow batteries are vanadium redox flow batteries (VRFB), which use vanadium in the electrolytes in both the tanks (Stauffer, 2023). Vanadium is the chemical of choice because of its superior performance. For example, vanadium does not degrade, and cross-contamination between the positive and negative electrolyte is easily remediated. Buitendijk (2021) mentions how the company *Portliner* is planning on integrating VRFB into a barge and that their plan also includes the installation of a bunkering station. Hillen (2021) mentions a case study on vanadium redox flow batteries in a short sea ship.
A major difference between vanadium as an energy carrier and most other energy carriers is that it does not deplete when being used, rather it transitions between states. This means that it only needs to be produced once to be used in a barge for its entire lifetime. Yet, vanadium production is still a key process in its use as an energy carrier.

### 3.7.1. Titanomagnetite Ore

The main source for vanadium globally is titanomagnetite ore, a mineral that consists mostly of titanium and iron, but also contains vanadium oxide (Volkov et al., 2023). Refining the ore creates steel and vanadium slug as a co-product.

### 3.7.2. Carbon Materials

There are several natural carbon materials which also contain vanadium. Oil fields contain vanadium, varying from percentages of $4*10^{-5}$% to $9*10^{-2}$% (Volkov et al., 2023). Similarly, black and brown coal and natural bitumen contain vanadium. These carbon materials can be refined, after which the high-boiling fractions contain the vanadium. Vanadium slug can be extracted from the ash that results from combusting these high-boiling fractions.

### 3.7.3. Vanadium Oxides from Vanadium Slag

The vanadium slag contains vanadium in the form of an iron-vanadium spinel ($FeO \cdot V_2O_3$). Yang et al. (2021) shows how vanadium pentoxide ($V_2O_5$) can be extracted from vanadium slag through oxidation, sodium salt roasting, and purification. $V_2O_5$ on its own is a brown solid. Vanadium pentoxide is one of four important oxidation states of vanadium for its use in flow batteries. All four of vanadium's oxidation states are shown in Table 3.1. Important for the production process of vanadium is that $V_2O_3$ can be produced from $V_2O_5$ through reduction. How VO and $VO_2$ are then created, is explained in section 4.7, which explains the application of vanadium in flow batteries.

**Table 3.1:** Vanadium Oxidation States

| Compound | Molecule | Oxidation State | (Dis)charge Symbol |
|---|---|---|---|
| Vanadium Oxide | VO | Vanadium(II) Oxide | $V^{2+}$ |
| Vanadium Trioxide | $V_2O_3$ | Vanadium(III) Oxide | $V^{3+}$ |
| Vanadium Dioxide | $VO_2$ | Vanadium(IV) Oxide | $VO^{2+}$ |
| Vanadium Pentoxide | $V_2O_5$ | Vanadium(V) Oxide | $VO_2^{+}$ |

# 4

# Application & Storage of Alternative Energy Carriers

Another step to understanding the difference between the different AECs is to know how they can be applied on-board barges. Every energy carrier has its own ways of converting its carried energy into electric energy and some also have their own type of on-board storage. To analyze the energy and power determinant, firstly, all the applications of all seven different AECs are described for the sake of understanding the underlying responses of interviewees.

## 4.1. Application of Alternative Diesel

Diesel can be applied through internal combustion engines (ICE). The two main types of diesel engines are two-stroke and four-stroke engines. Two-stroke engines are typically used in large applications, which in this context are sea-going vessels (Thomsen, 2024). Four-stroke engines are the engines which are most typically used for inland waterway vessels (Braun et al., 2024). Four-stroke engines perform better at high speeds and are typically smaller than two-stroke engines. Wu et al. (2023) discuss how biodiesel can be mixed with diesel to be used in standard four-stroke internal combustion engines. Current regulations in the EU have already resulted in a standard mix of 7% biodiesel with diesel (COM (2021) 557).

## 4.2. Application of LNG

Similar to diesel, LNG can also be combusted in an internal combustion engine. A typical application of LNG in barges is through four-stroke dual-fuel engines (Tazelaar, 2017). The idea behind the dual-fuel engine is that it works with both diesel and LNG. These engines are not similar to contemporary diesel engines. Not all the LNG is fully burned in the engine and therefore the leftover natural gas is emitted. As LNG consists mostly of methane, this creates a methane slip, meaning the methane ends up in the air (Jensen et al., 2021).

## 4.3. Application & Storage of Hydrogen

Hydrogen as a gas at atmospheric pressure and room temperature takes up a lot of space; one kilogram would take up a space of $11 m^3$ (Züttel et al., 2010). However, there are many ways to carry hydrogen more densely, some of which are mentioned below.

### 4.3.1. Hydrogen Storage in Pressure Tanks

A common way of storing hydrogen more densely is by pressurizing it. There are five types of tanks that can store hydrogen at a high pressure (Cheng et al., 2024).

- **Type I**
  The first type of tank is made solely from metal. They typically go up to 200 bar and are the heaviest type of tank. These are mostly used for stationary applications.
- **Type II**
  These tanks are similar to Type I tanks, but have a carbon fiber or glass fiber filament wrapped around the metal tank, making them stronger than Type I tanks. This type typically works for up to 300 bar pressures.
- **Type III & IV**
  These are two fairly similar types of tanks, as both are wrapped with composite, usually carbon fiber. The main difference is that Type III uses a metallic liner whereas Type IV uses a polymeric liner. These tanks are often used in automotive applications where standard pressures are 350 bar or even 700 bar.
- **Type V**
  The last type of tank is made fully from composites. These are about 20% lighter than Type IV tanks and can even withstand pressures of up to 1000 bar. However, this technology is still in development currently.

### 4.3.2. Liquid Hydrogen Storage

Liquid hydrogen, also referred to as cryogenic hydrogen, is hydrogen which has been cooled to around 20K (-253°C) which is the temperature where hydrogen liquefies (Hosseini, 2023). The liquefaction of hydrogen results in it being much denser than when compressed at room temperature, so more hydrogen can be stored. Liquid hydrogen does have to keep its cool temperature when stored, because otherwise it will boil off and diminish over time.

### 4.3.3. Cryo-compressed Hydrogen Storage

Slightly above its condensation temperature, hydrogen can be compressed further than when in full liquid state, even so far that the hydrogen can effectively be stored at a higher density than standard liquid hydrogen (Ahluwalia et al., 2010). This is a relatively new development which has a lot of potential, but still faces challenges like infrastructure availability and cost.

### 4.3.4. Liquid organic Hydrogen Carriers

Liquid organic hydrogen carriers (LOHC) are literal hydrogen carriers. Once unloaded, LOHC (LOHC-H0) is combined with $H_2$, an exothermic reaction takes place and the LOHC and hydrogen are combined, creating the loaded LOHC-Hx. In the presence of a catalyst and a lot of heat, this loaded carrier can be converted back to LOHC-H0 and $H_2$ again (Niermann et al., 2021; He et al., 2015). Due to this high energy demand, the process is regarded to be better applicable for stationary or large mobile applications. Barges are relatively large mobile applications, so there could be a future application of LOHC for shipping. However, the technology is currently still in development.

### 4.3.5. Methanol as Hydrogen Carrier

Methanol ($CH_3OH$) is an alcohol that can be used to carry hydrogen. Methanol as a standalone energy carrier is mentioned in section 4.4. There are four main ways of converting methanol into hydrogen (Fausto Gallucci and Drioli, 2007).

- **Steam Reforming**
  Methanol Steam Reforming is very similar to the earlier explained steam-methane reforming process. The methanol is combined with steam at high temperatures under pressure in order to produce syngas, consisting of hydrogen for a part.
- **Oxidative Methanol Steam Reforming**
  The process of partial oxidation is often carried out in the presence of water. The combination of methanol steam reforming and partial oxidation of methanol is called oxidative methanol steam reforming. By tuning the quantities of oxygen and water, the process can be made isothermal, meaning that there is no net temperature difference.

- **Methanol Decomposition**
  At higher temperatures and in the presence of the right catalysts, methanol can decompose to $H_2$ and CO.
- **Methanol Oxidation**
  At low temperatures and in the presence of the right catalysts, combined with oxygen, methanol can be oxidized to become $H_2$ and $CO_2$. As methanol is a liquid at room temperature and it carries a lot of hydrogen, this makes it a strong hydrogen carrier.

### 4.3.6. Ammonia as Hydrogen Carrier

Ammonia ($NH_3$) is a chemical compound which is also often used as a feedstock for fertilizer. It can be dissolved in water to become liquid, or it can be compressed or cooled in its pure form to liquefy. The benefit of ammonia as a hydrogen carrier is that it needs less pressure and/or cooling than pure hydrogen to liquefy. Ammonia as a standalone energy carrier is mentioned in section 4.5. Ammonia can be converted back to hydrogen in the presence of high temperatures and the right catalyst (Wan et al., 2021, p. 7).

### 4.3.7. Other Hydrogen Storage Materials

There are numerous substances containing hydrogen, however not all of them are being considered for large-scale hydrogen storage. Kojima (2019) mentions some alternative options for materials that can carry hydrogen. One topic that it brings up is hydrides, which is a collective name for compounds in which hydrogen is combined with another element. Hydrides are capable of carrying hydrogen and could be split again through, for example, hydrolysis, thermolysis or ammonolysis. An interesting application of hydrides is through hydrolysis of sodium borohydride, which is mentioned by Abdelhamid (2021). Hydrogen can be carried quite densely and by adding water the hydride can be split. Recently, the production of a ship that will use sodium borohydride as its hydrogen energy carrier has started (Buitendijk, 2022). This shows that there are still many possibilities available for alternative hydrogen carriers, but they have to be proven first in order to subsequently be applied at a larger scale.

### 4.3.8. Hydrogen Combustion

Hydrogen can be combusted in internal combustion engines, similar to diesel and LNG. Just as with LNG, standard diesel engines do not work with hydrogen, so new engines need to be designed to use hydrogen with combustion (Mitsubishi, 2024).

### 4.3.9. Hydrogen Proton Exchange Membrane Fuel Cell

A Proton Exchange Membrane Fuel Cell (PEMFC) turns hydrogen and oxygen into water, electric energy and excess heat, so there are no $CO_2$ or $NO_x$ emissions. The hydrogen which is located at the anode and the oxygen which is located at the cathode are separated from each other using a membrane (Sudhakar et al., 2018, p. 159). This membrane is structured in such a way that only hydrogen protons can move through it. When this happens, the hydrogen combines with the oxygen on the cathode side to create water and while this happens, an electric current moves between the anode and the cathode through an external circuit, creating electric energy.

### 4.3.10. Hydrogen Alkaline Fuel Cell

The Alkaline Fuel Cell (AFC) also turns hydrogen and oxygen into water, electric energy and excess heat, but it does this a little differently to a PEMFC. Whereas the PEMFC uses a membrane between the anode and cathode, the AFC uses a liquid electrolyte solution of potassium hydroxide (KOH). Here, hydroxil ions ($OH^-$), move through the electrolyte from the cathode to the anode to create water on the anode side. This is the other side than where the water is created in the PEMFC. While the hydroxil ions move through the electrolyte, an electric current moves between the anode and the cathode through an external circuit, creating electric energy.

### 4.3.11. Hydrogen Solid Oxide Fuel Cell

The Solid Oxide Fuel Cell (SOFC) works very similar to the alkaline fuel cell, but instead of the liquid electrolyte, the SOFC uses a solid metallic oxide electrolyte through which negatively charged oxygen atoms move from the cathode to the anode side to create water on the anode side (Sudhakar et al., 2018). SOFCs operate at much higher temperatures, usually around 1000°C. Because the oxygen needs to be ionized at the cathode, the electrons move from between the anode and the cathode, creating an electric current through the external circuit.

### 4.3.12. Hydrogen Molten Carbonate Fuel Cell

The Molten Carbonate Fuel Cell (MCFC) has an electrolyte that consists of, as the name implies, a molten carbonate salt mixture. When this electrolyte is heated to around 650°C, it conducts carbonate ions ($CO_3^{2-}$) from the cathode to the anode. At the cathode, oxygen is reduced by carbon dioxide and electrons to create these carbonate ions. At the anode, water and carbon dioxide are created, but as the carbon dioxide is also needed at the cathode, this is fed back through, making it a net-zero system. While the carbonate ions move from the cathode to the anode, an electric current moves between the anode and the cathode through an external circuit to create electric energy.

### 4.3.13. Hydrogen Phosphoric Acid Fuel Cell

The Phosphoric Acid Fuel Cell (PAFC) is very similar to a PEMFC, as the hydrogen protons move from the anode to the cathode to create water at the cathode. PAFCs use phosphoric acid ($H_3PO_4$) as an electrolyte through which only the hydrogen protons can move, just like a PEMFC (Sudhakar et al., 2018). While the hydrogen protons move from the anode to the cathode, an electric current runs between the anode and cathode, creating electric energy. The electrolyte is tolerant of $CO_2$, which is why this type of fuel cell is often combined with hydrogen produced from steam reforming processes.

## 4.4. Application of Methanol

Methanol can be used as either a fuel for combustion or as feedstock in fuel cells.

### 4.4.1. Methanol Combustion

Methanol can be combusted in an internal combustion engine, similar to diesel and LNG. Methanol can be combusted as a pure compound (100% methanol), but there are also many mixes available with e.g. diesel. Methanol in its pure form cannot be used in contemporary diesel engines, but engines can be made to combust pure methanol (Moirangthem, 2016).

### 4.4.2. Direct Methanol Fuel Cell

The direct methanol fuel cell is a proton exchange membrane that works with a mix of methanol and water at the anode. The cathode side still behaves very similarly to a hydrogen PEMFC where the hydrogen, oxygen and electrons come together to create water, but on the anode side a new side product is created; $CO_2$ (Scott et al., 2013). Wang and Fu (2020) mentions how a direct methanol fuel cell could also work with the alkaline fuel cell technology as described in subsection 4.3.10 instead of the proton exchange membrane fuel cell technology.

### 4.4.3. Methanol Solid Oxide Fuel Cell

Methanol can also directly be used in a SOFC. The inner workings of the fuel cell are still the same as in subsection 4.3.11. When methanol is used as a fuel for a SOFC, it is thermally decomposed at the anode (Liu et al., 2008):

$$CH_3OH \rightleftharpoons CO + 2H_2 \tag{4.1}$$

The resulting fuel compositions, $H_2$ and CO then react with the $O_2$ ions which have been transported through the electrolyte to create water and $CO_2$ at the anode:

$$H_2 + O^{2-} \rightleftharpoons H_2O + 2e^- \tag{4.2}$$

$$CO + O^{2-} \rightleftharpoons CO_2 + 2e^- \tag{4.3}$$

As can be seen, by using methanol in a SOFC instead of hydrogen, the fuel cell emits $CO_2$.

### 4.4.4. Methanol Reforming

As explained in section 4.3, methanol can be a hydrogen carrier. Hydrogen can be created from methanol in four different ways, one of which is methanol steam reforming. By doing this, syngas is created from methanol, consisting of $H_2$, $CO_2$, and CO. The hydrogen can then be used in a fuel cell, for example a PEMFC, to create electric energy (Li et al., 2023). As methanol reforming creates syngas, containing CO, some carbon monoxide can end up going through the fuel cell. A PEMFC can be subject to a phenomenon called CO poisoning, which leaves CO molecules blocking gaps in the membrane which would otherwise be used by $H_2$ molecules to pass through during regular use, meaning the fuel cell becomes less effective. Valdés-López et al. (2020) mention several strategies to mitigate this effect. The PEMFC with integrated methanol reforming is called a Reformed Methanol Fuel Cell (RMFC). According to Siqens (2023) the RMFC can yield a higher system efficiency than the DMFC, but is a more complicated system.

### 4.4.5. Mixing Methanol with other Fuels

Methanol can also be mixed with other fuels. Some of these mixes include, but are not limited to diesel, hydrogen, and DME (Zhen and Wang, 2015).

- A common mix of methanol and diesel consists of 85% of methanol and 15% of diesel, but other percentages are also possible. It is important to note that this is not called M85, as that would be a mix of methanol and gasoline (petrol). Mixes with gasoline are not considered as there are currently no gasoline barges. Diesel, being a largely integrated fuel in the IWT sector, could aid the transition through small increases in blending percentages with methanol.
- Adding hydrogen to methanol can increase the break thermal efficiency (BTE) and decrease carbon emissions compared to pure methanol engines.
- Methanol and dimethyl ether, or DME ($CH_3OCH_3$), can also be mixed. While the addition of DME to methanol seems to increase $NO_x$ emissions, it could also improve ignition, thus broadening the operating range of the engine.
- BDM10 is an example of a mix of methanol with biodiesel and diesel, where methanol is mixed with BD50 (50% biodiesel and 50% diesel) to a 10% volume percentage additive, but other percentages are also available, for example with B20/M5 (5% methanol in a 20/80% biodiesel/diesel mix). The latter has shown to decrease $CO_2$ emissions, but increase $NO_x$ emissions compared to refined diesel.

### 4.4.6. DME

Dimethyl Ether ($CH_3OCH_3$), as previously mentioned, is made from methanol. By dehydrating methanol, two methanol molecules are combined into one DME molecule. DME can also be used in a four-stroke diesel engine (Pham et al., 2021).

### 4.4.7. Other Alcohols

Methanol is methyl alcohol ($CH_3OH$), with one carbon atom. Ethanol is ethyl alcohol ($CH_3CH_2OH$), with two carbon atoms. Ethanol is a relatively similar energy carrier to methanol and could also be applied in internal combustion engines ('t Hart et al., 2023). Methanol and ethanol are alcohols, but not the only ones. For example, propanol, butanol, and glycerol are also alcohols. Dybiński et al. (2023) mention how these alcohols could also be applied using fuel cells.

## 4.5. Application & Storage of Ammonia

Ammonia is gaseous at atmospheric pressure and room temperature, but it does not have to be cooled or pressurized as much as hydrogen to become liquid. Hence, there are two types of liquid ammonia storage (M. et al., 2020, p. 11). The first type of liquid ammonia storage is through cooling. When ammonia is cooled down to -33.4°C, it becomes liquid, even at atmospheric pressure. Therefore, this type of storage only needs to remain cooled and does not need a pressure vessel. The second type of liquid ammonia storage is through pressurizing. Placing ammonia under a pressure of 9.9 bar at room temperature liquefies it. This does require a pressure vessel. Ammonia storage is relatively similar to propane and therefore propane infrastructure could also be adopted to store liquid ammonia.

One downside of ammonia is that it is poisonous and becomes airborne at room temperature and atmospheric pressure, which means that a leak in either of the aforementioned tanks would endanger anyone nearby. One alternative option would be to store ammonia in a solid, for example using a metal amine. Christensen et al. (2005) show that it is possible to store ammonia in $Mg(NH_3)6Cl_2$, which stores 9.1% hydrogen by weight, compared to pure ammonia which stores 17.6% hydrogen by weight.

### 4.5.1. Ammonia Combustion

Ammonia can be combusted in an internal combustion engine, but it does give inconsistent combustion under low engine loads and/or high engine speeds, which results in combustion promoters like diesel or hydrogen being needed to facilitate stable combustion (M. et al., 2020, p. 12). Reiter and Kong (2011) have found that a blend of ammonia and diesel in a diesel engine increased the $NO_x$ emissions, but decreased PM emissions.

### 4.5.2. Ammonia Alkaline Fuel Cell

The Ammonia Alkaline Fuel Cell (AAFC) is an alkaline fuel cell as described in section 4.3, but uses ammonia as feedstock instead of hydrogen (M. et al., 2020, p. 14). As can be seen in the following equations, the AAFC creates nitrogen on the anode side as well as water, in contrast to the standard AFC which only creates water.

$$2H_2O + O_2 + 4e^- \rightarrow 4OH^- \tag{4.4}$$

$$2NH_3 + 6OH^- \rightarrow N_2 + 6H_2O + 6e^- \tag{4.5}$$

### 4.5.3. Ammonia Solid Oxide Fuel Cell

The Solid Oxide Fuel Cell (SOFC) as previously mentioned in subsection 4.3.11 could also be used with ammonia as a feedstock. When ammonia is used as a fuel for a SOFC, it is thermally decomposed at the anode (Liu et al., 2008):

$$2NH_3 \rightleftharpoons 2N_2 + 3H_2 \tag{4.6}$$

The resulting $H_2$ then reacts with the $O_2$ ions which have been transported through the electrolyte to create water at the anode:

$$H_2 + O^{2-} \rightleftharpoons H_2O + 2e^- \tag{4.7}$$

### 4.5.4. Ammonia Reforming

As explained in section 4.3, ammonia can be a hydrogen carrier. Hydrogen can be created from ammonia decomposition through a thermo-catalytic reaction. The hydrogen can then be used in a fuel, for example a PEMFC, to create electric energy (M. et al., 2020). Unlike methanol reforming, ammonia reforming does not create carbon monoxide (CO), creating cleaner hydrogen for use in a PEMFC, eliminating CO poisoning.

### 4.5.5. Mixing Ammonia with other Fuels

Ammonia can be mixed with various fuels to improve its combustion stability. Some of these fuels include, but are not limited to hydrogen, diesel, and methane (M. et al., 2020).

- Mixing ammonia with hydrogen keeps the benefit of not emitting $CO_2$ while improving combustion stability.
- Diesel is a readily available fuel which is commonly used in internal combustion engines in IWT. Therefore, a gentle shift towards non-carbon-based fuels like ammonia through small increases in blending percentages could aid the transition.
- Not only diesel, but other hydrocarbons, such as methane, can also be mixed with ammonia. Methane, being the main composition of LNG, has the same potential as diesel to aid the transition by blending with ammonia as the LNG readiness in the shipping sector is already established.

## 4.6. Application of Batteries

In chapter 3, it was explained how battery cells are produced. One cell will not be able to power a barge, which is why batteries are created by combining multiple cells. Cells can be combined both by connecting them in parallel or in series (Väyrynen and Salminen, 2012). Multiple cells combined create a module. Increasing the number of series connections increases the module voltage. Increasing the number of parallel connections increases the maximum allowed current of the module. Modules can be combined again to create a pack, which is multiple modules within one package. Multiple packs together can create a system.

Every battery cell is unique, which can lead to changes in behavior. When combining multiple battery cells together, it is important to keep all battery cells at the same state of charge (SOC) (Väyrynen and Salminen, 2012). When this is not the case, cells can start charging each other, leading to overcharged or overdischarged cells, causing irreversible damage. To keep the cells evenly charged, a battery management system (BMS) is used, which checks the balance of the cells. The BMS keeps the battery and its surroundings safe by regulating the voltage, temperature and SOC of every cell and the total module.

## 4.7. Application of Flow Batteries

Skyllas-Kazacos et al. (2011) mention a few different types of vanadium redox flow batteries. One option is the all-vanadium redox system, but mixes of vanadium with, for example, bromine, magnesium, cerium, and others are also possible.

### 4.7.1. All-Vanadium Redox Flow Battery

subsection 3.7.3 explains how $V_2O_5$ and $V_2O_3$ are produced, also known as Vanadium(V) Oxide (V(V)), and Vanadium(III) Oxide (V(III)), respectively. It also shows in Table 3.1 that there are two more oxidation states of vanadium. For an all-vanadium redox flow battery, the positive electrolyte tank contains the V(V) and the negative electrolyte tank contains the V(III). When a current is able to flow between the positive and negative electrodes in the cell, two reactions take place, depending on the direction of the current.

$$VO^{2+} + H_2O \rightleftharpoons VO_2^+ + 2H - e^- \tag{4.8}$$

$$(VO_2 + H_2O \rightleftharpoons V_2O_5 + 2H - e^-)$$

$$(V(IV) \rightleftharpoons V(V))$$

$$V^{3+} + e^- \rightleftharpoons V^{2+} \tag{4.9}$$

$$(V_2O_3 + e^- \rightleftharpoons VO)$$

$$(V(III) \rightleftharpoons V(II))$$

In general terms, at the positive electrode, the V(V) can be converted to V(IV) when removing an electron on this side. When adding an electron to the negative electrode, V(III) is converted to V(II). The same can happen the other way around on both the positive and negative electrodes.

# 5 Methods

The goal of the thesis is to find determinants for the large-scale introduction of AECs for the IWT sector. As mentioned in the introduction, the research question is as follows.

***"What are determinants for the large-scale introduction of alternative energy carriers in inland waterway transport? ?"***

A method to tackle the task of finding these determinants could have been to construct sub questions. For example, sub questions could have been to find aiding factors, blocking factors, barriers and opportunities. This is not the case with this research. The idea behind the research is to ultimately create a framework which could be applied to future AECs, and not just the seven which are used in this thesis. Aiding factors and blocking factors can be factors which change over time. A blocking factor could block until it reaches a certain point, after which it could become an aiding factor. Similarly, a barrier can remain a barrier up to a certain point, after which it could become an opportunity. Therefore, in order to keep the framework more resilient to changes over time, all factors will be considered as determinants only. The seven AECs used in this thesis are used as examples at this moment in time to describe determinants.

The method used to find the determinants is to use the TIS framework defined by Ortt and Kamp (2022), as described in chapter 2. This TIS framework consists of seven building blocks which each have their own determinants. Therefore, the determinants have been found by analyzing every building block separately. This eventually resulted in a total of 22 determinants, spread over the seven building blocks. Before taking a closer look at how the determinants relate to their building blocks, it is important to understand the context first.

The following sections will explain the methods used to obtain, process, and analyze data. Firstly, a description of the actors and stakeholders in the IWT sector is presented. After this, the method of obtaining data from these actors and stakeholders is discussed. Lastly, the methods used for processing and analyzing the data are mentioned.

## 5.1. Actors and Stakeholders in the Inland Waterway Transport Sector

The IWT sector is a sector unlike any other and has its own way of operating. To fully understand how AECs have an impact on the sector, it is important to know how it operates and who is operating in it or affected by it.

- **Barge Owners**
  The owners of the barges are the first actors that are analyzed for this research. They are the ones in charge of making the decision to apply a certain AEC in their barge. There are

two types of barge owners. On the one hand, there are private individuals who own their own barge, live on it and make their living with it. On the other hand are the shipping companies, which often own multiple barges at the same time.

- **Customers**
  The customers are the reason the IWT sector exists, because there are actors who need their products shipped. There are also other options for transporting products, for example by truck, train or plane. The IWT sector is often used because of its efficiency. Not necessarily efficiency in time, but efficiency in cost. Barges can take along relatively much cargo on a trip. Customers who are not pressed by time, but look to minimize costs for their transport are often customers of the IWT sector.
- **Terminals**
  When a customer needs to ship their product, they often bring it to a terminal. This is the location where the product is transferred onto the barge. A typical terminal is a container terminal, which is specialized in moving containers from and onto barges. Terminals are often also the operators of barges, programming the routes of the barges and determining what cargo is picked up where.
- **Ports**
  Ports are the facilities for barges and their cargo. They facilitate everything from docks to cranes and warehouses and are often the locations where terminals or bunker stations can be found. Ports have their own infrastructure, but also their own regulations.
- **Bunkering Stations**
  Barges use energy to move from one place to another. This energy has to be re-obtained at certain moments in time. This is done through refueling, which is known in IWT as bunkering. Bunkering stations can be compared to refueling stations for cars. Bunkering stations are typically placed on pontoons, located on waterways.
- **Energy Carrier Suppliers**
  The bunkering stations do not produce the energy carriers themselves. There are suppliers of energy carriers who produce and supply them.
- **Barge Crew**
  Barges are not fully autonomous machines and therefore need a crew. The crew generally maintains the barge and there is always a skipper on board who steers the barge. As mentioned earlier, the skipper could also be the owner of the barge.
- **Shipyards**
  When a barge owner has to perform large maintenance on their barge, or wants to refit certain components on their barge, they do not do that themselves. In this case, they bring their barge to a shipyard which does the maintenance or refit for them. In the case of refitting to an AEC, they handle the entire project of removing the old engine and storage and integrating the new technology.
- **Component Suppliers**
  The components that need to be supplied for a refit are not manufactured by the shipyards. These components originate from component suppliers. Components used for refits can range from engines to storage, but also from pipes to pumps and control systems.
- **Municipalities containing Ports and Inland Waterways**
  Moving one level up from terminals, there are municipalities which contain ports and inland waterways. These municipalities have their own benefits and disadvantages to IWT. Municipalities can therefore have their own regulations for IWT.
- **Countries containing Inland Waterways**
  Another level up from municipalities are the countries which contain ports and inland waterways. Similar to municipalities, they have their own dependence on IWT and therefore also have their own regulations for IWT.
- **European Union**
  As described in the introduction, the European Union has established and is still establishing regulations for the IWT sector.

- **Classification Societies**
  There are specific classification societies for the shipping sector that establish and maintain technical standards for the construction and operation of ships. There are specific classification certificates for barges. With AEC come new technologies and thus new technical standards for classification societies to establish and maintain.
- **Other Regulatory Institutions**
  There are also other regulatory institutions which set regulations and standards for the IWT sector. Similar to classification societies, they also have to adjust to the introduction of AECs.
- **Residents nearby Inland Waterways**
  Residents near inland waterways are stakeholders in the IWT sector. Barges can have a direct influence on their lives. For example, barges emit noise and other emissions.
- **Environmental Organizations**
  IWT is not net zero currently, so environmental organizations are stakeholders in the IWT sector who would prefer to see the sector becoming net zero rather sooner than later.

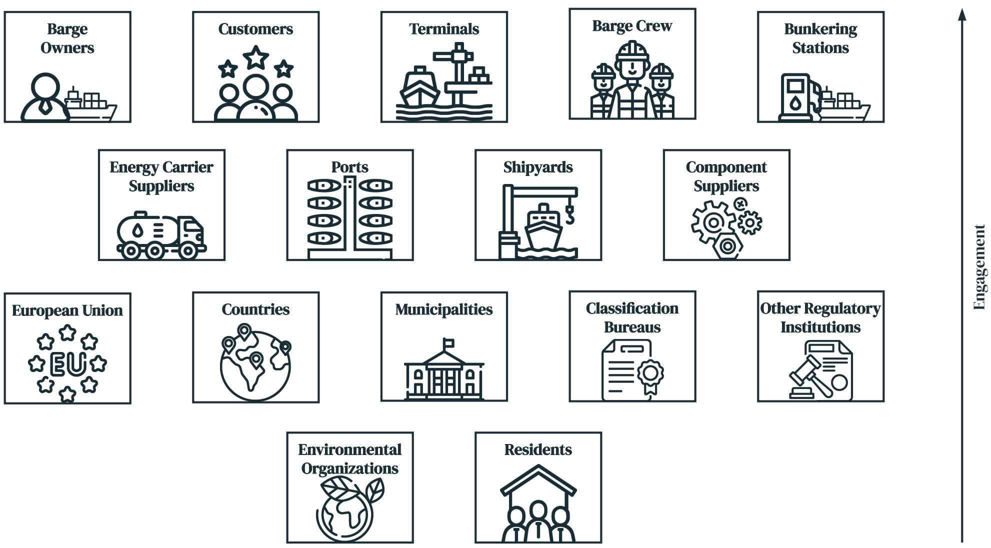


**Figure 5.1:** Actors and Stakeholders in the Inland Waterway Transport Sector

### 5.1.1. Gathering Data through Interviews

There are many actors and stakeholders in the IWT sector. As mentioned in chapter 2, the first chapter of the literature, there are already actors who have made first introductions of AECs in the IWT sector. To find out what is determining the large-scale introduction of AECs in the IWT sector, these actors could give the best insights on what does and what does not work in their attempt to bring these AECs to the IWT sector. Therefore, the decision was made to interview actors and stakeholders who were in any way connected to these first introductory projects.

Using the list of actors and stakeholders in the IWT sector, a list of companies and organizations was created, specifically focusing on companies and organizations which are connected to AECs. These companies and organizations were contacted to invite employees as representatives for an interview. This eventually resulted in eight interviews being conducted with ten interviewees in total (during two interviews, two representative employees were present). The types of actors and stakeholders which were interviewed were the following.

- A shipyard working with hydrogen-powered barges
- A fleet owning company working with hydrogen-powered barges

- A researcher coordinating inland skippers with alternative energy carriers
- A company working on the implementation of flow batteries in IWT
- An energy carrier supplier supplying biodiesel and biomethanol
- A classification society for barges
- A component supplier supplying containerized batteries
- A container terminal providing containerized bunkering

All interviewees combined were able to represent all seven different energy carriers mentioned in this research, thereby giving a well-represented overview of determinants.

The interviews were conducted either in person or online. The interviews generally lasted 45 to 60 minutes during which questions were asked according to the interview guide as mentioned in Appendix A. This interview guide was written with the aim at finding out what the interviewees' experience was and currently is with the AEC which they have experience with. Questions like what kinds of problems they have run into and are currently running into right now, and what opportunities there are for them with their specific energy carriers were mostly used to start the interviews. After these questions, the conversation was kept going according to the guide, leaving most room to the interviewees to elaborate on their experiences. Only when interviewees were finished talking, new questions were asked in order to steer the answers as little as possible.

### 5.1.2. Analyzing and Processing Data

Every interview was recorded and transcribed afterwards. The transcribed interviews were coded deductively using *ATLAS.ti*. For the first round of coding, the TIS framework was used to connect different responses from interviewees to any of the seven building blocks. Once all interview codes had been grouped into the seven building blocks, every building block could be divided into codes. These results can be seen in Appendix B. This created different determinants per building block. To improve readability of the entire document, the TIS building blocks have been slightly rearranged to have a naturally flowing order in determinants throughout the results of this research. The eventual layout of the results is the following.

- **Production System**
  Different AECs have different production systems. It starts with the production method, after which the energy carrier needs to be bunkered into the barge. The supply is also important throughout the production system, both before the production method and after.
- **Product Performance & Quality**
  The performance and quality of AECs can also differ. Some energy carriers offer more energy and power than others. Energy carriers and their applications have differing onboard emissions, and some energy carriers are safer than others.
- **Product Price**
  The product price of AECs relates to their total costs. These costs are built up from initial costs and operational costs. The technological systems around AECs have different costs for different energy carriers.
- **Complementary Products & Systems**
  While AECs can have their differences, they can also be complementary. Some fuels can be mixed and used in dual fuel engines, all AECs can work with an electric powertrain, and many AECs have similar production methods and thus have correlating energy prices.
- **Customers**
  Customers of the IWT sector eventually pick the mode of transport for their product. This means that the IWT sector should remain attractive to its customers. Therefore, AECs will have to be able to compete with diesel. When AECs still come with a premium, some actor needs to be willing to pay this premium. This means that actors have to be acquainted with AECs. Lastly, the large variety of customers results in a large variety of operational profiles.

- **Network Formation & Coordination**
  The IWT sector consists of a large network with many actors and stakeholders. Some actors hold a particularly important place in the transition to AECs. Shipyards are required to build barges with AECs on-board, component suppliers need to produce the new components, and container terminals need to aid with the implementation of containerized bunkering. It is also important that all actors collaborate.
- **Innovation-Specific Institutions**
  The implementation of AECs can be determined by innovation-specific institutions. Financial support can have an impact on the implementation. Standardization can also influence this, similar to classification. Regulation can occur on many levels, from regional to international, and plays an important role in the introduction of AECs.

# Part II

# Results

# 6
# Production System

The production system of an AEC was a topic that was mentioned often by interviewees. Their comments consisted mainly of three parts; the production method, bunkering solutions, and supply. Production methods for the seven AECs have also been mentioned in chapter 3 and they are also a determinant, which is explained in section 6.1. In the shipping sector, refueling is referred to as bunkering and is an important step in acquiring an AEC on-board a barge. AECs bring along challenges and opportunities for bunkering solutions, which are discussed in section 6.2. Both production methods and bunkering solutions acquire a supply. This can either be a feedstock for production or infrastructure for the bunkering location. This is discussed in section 6.3. To better understand these determinants and act as a discussion starter, they have also been illustrated on cards in section C.1 in the Appendix.

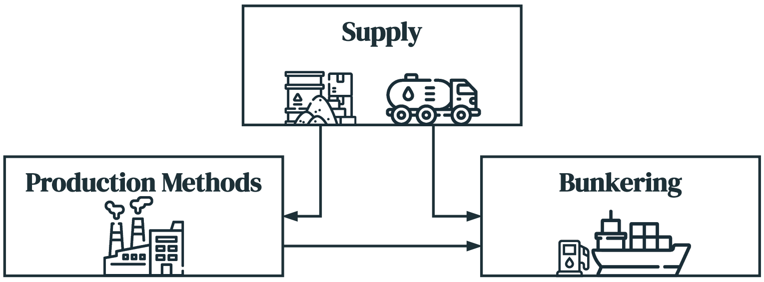


**Figure 6.1:** Determinants for Production System

## 6.1. Production Methods

Production methods are a determinant for large-scale introduction of AECs because they determine the origination of the energy carrier. AECs are being considered as an option for IWT primarily because they would reduce emissions. But if production methods are still emitting GHG, $NO_x$, $SO_x$ or PM, this would defeat that purpose.

During an interview, the interviewee representing a fleet owning company using hydrogen mentioned that "if you were to use grey hydrogen..." (more elaborately explained in Figure 3.3) "... you would be better off burning diesel", because that would emit less GHG overall. This already shows how big of an impact production methods can have as a determinant for large-scale introduction. However, it also only shows one side of the determinant. It still leaves the question how green the production method should be in order to enable AECs like hydrogen in the IWT sector. For example, blue hydrogen already captures the otherwise emitted GHG, but it is still not as renewable as green hydrogen. The captured $CO_2$ can be stored or used in other applications. In either way, it does not return to the supply chain it came from.

When asked about the origination of energy carriers, interviewees almost always answered that it ultimately all has to be green. Independent of their position in the sector, everyone states that green energy is the way to go. One major reason they mention when asked to elaborate is the image, mostly focused on customers, barge owners, or other directly involved actors. How production methods influence customers with regards to large-scale introduction is elaborated on in chapter 10, where determinants in the building block of customers are discussed.

### 6.1.1. Green Energy Carrier Production

The figures describing the different production methods in chapter 3 show that it is possible to produce sustainable energy carriers. Biomass can be used to create sustainable energies such as diesel, LNG, and methanol and renewable electricity can be used to create sustainable energies such as hydrogen and ammonia and to charge batteries and flow batteries. Yet, this does not mean that these sustainable energy carriers are always available.

Whereas the idea of green energies is popular, the existence of their production facilities is not as evolved. If a barge is ready to sail on an AEC, but there is not enough green production, the barge will eventually still not be green. On the other hand, if there is more production than demanded, because barges might not convert to AECs fast enough or they convert to another AEC, the producer is stuck with this overproduction. This creates a chicken and the egg problem between producers and users of AECs as both are waiting for each other.

Step one of scaling up the implementation of a green energy carrier is scaling up its green production. Interviewees working with hydrogen mention that more electrolysers are needed, and interviewees working with batteries and flow batteries mention the need for more renewable electricity production. Also, section 3.5 shows that Haber-Bosch plants are needed for green ammonia production. Multiple interviewees have expressed actors' dependence on green production methods as a determining factor. An example given by the interviewee who works with hydrogen at a shipyard mentioned a potential project with liquid hydrogen, but that project is struggling with infrastructure to get the desired quantities of green hydrogen and it "only passed because it would really be green".

### 6.1.2. Production Methods as a Determinant

The uncertainty and dependence of green production of AECs makes production methods a determinant for the large-scale introduction of AECs to the IWT sector. Actors would be more inclined to implement an AEC when they know that green production is imminent to scale up. This does not mean that green production is the only solution throughout the transition. For example, blue production methods can also aid the introduction.

## 6.2. Bunkering

Bunkering, more commonly known as refueling, is a crucial part of shipping, as it provides a ship with energy through an energy carrier. Currently, almost all barges use diesel, which is bunkered by pumping the diesel into barges' tanks. This type of bunkering where a barge is connected through a pipe or any other type of line is feasible for many AECs. In fact, it could be applied to all of the AECs that are analyzed in this thesis. This is described here as direct bunkering. AECs can, however, also be bunkered by placing them inside a container and moving this container onto the barge. This determinant will elaborate on both options.

### 6.2.1. Direct Bunkering

Diesel is a liquid and can therefore be pumped into barges, but gases can also be pumped into barges. Gaseous energy carriers can be cooled or compressed to be stored more compactly, as is explained in chapter 4. By cooling and/or compressing gases up to their liquefying point, they can be pumped into a barge as well. Gases can also be compressed into a compression tank by applying a higher pressure from the bunkering station, in which case they do not have to be liquefied. Electric energy can also be bunkered onto a barge when connecting the barge to shore power. In this case, a large plug connected to the shore through an electric cable is plugged into the barge. With these aforementioned techniques, all the analyzed AECs could be bunkered onto barges.

Direct bunkering mainly happens through either of three options. The first option is bunkering from ship to ship, which can happen when a barge is berthed, but is also possible while a barge is sailing. The interviewee who is working on the implementation of flow batteries mentioned that bunkering pontoons are currently being designed and built to pump charged electrolyte into a barge. The second option is pipe-to-ship bunkering, which is comparable to refueling a car at a gas station. The last option is truck-to-ship bunkering. Here, a truck comes to the location where the barge is berthed and pumps the energy carrier into the barge. This is comparable to pipe-to-ship bunkering, but requires less infrastructure at the location where the barge is berthed.

### 6.2.2. Containerized Bunkering

Since the first introduction of battery and hydrogen electric barges, a new type of bunkering has emerged. This type of bunkering uses containerized storage where the batteries or hydrogen tanks are inside a container which are swapped at terminals by use of a crane, similar to how regular cargo containers are exchanged with a container barge (Margaronis, 2021; Nike, 2023). The interviewee working at a component supplier of containerized batteries mentions that there is a "chicken and the egg problem between barges with an electric powertrain and charging stations." With containerized storage, they could potentially bring a recharged/refilled container to any container terminal and bunker the barge there. This can remove the uncertainty of having a recharging station in the wrong location, or not being able to recharge because the recharging stations are in the wrong locations.

### 6.2.3. Bunkering as a Determinant

Direct bunkering unavailability creates a dependence for skippers and barge owners. If an AEC is not available in every port, the barge cannot bunker everywhere, while contemporary diesel is available almost everywhere. Containerized bunkering removes this dependence as it allows for bringing the containers to any container terminal. Inland skippers currently know that they can bunker almost anywhere. This would change with the introduction of AECs. The availability of bunkering solutions for different AECs makes bunkering a determinant for the large-scale introduction of AECs to IWT.

## 6.3. Supply

Supply is a two-sided problem, because it is both necessary before production, but also after production, before bunkering. Production methods need feedstock. Bunkering solutions need a supply of energy carriers to bunker. Containerized bunkering has an especially different supply chain for AECs. With an increase in renewable electricity, the supply of electric energy to ports and terminals becomes important too. Lastly, the supply of AECs could also be necessary for use by other sectors.

### 6.3.1. Feedstock

Supply starts before production, because many production facilities require feedstock. One example that half of the interviewees mentioned was biomass as a feedstock. Biomass can be used to make many different energy carriers, like biodiesel and biomethanol. The interviewee working at a biodiesel and biomethanol supplier mentions that there is "not enough feedstock for biodiesel to reach the same quantities as we are currently pumping from the Earth [to make contemporary diesel]." It would take up a lot of space to reach this quantity of feedstock. Space which can also be used to grow food, for example. Another interviewee, who works at a container terminal where they operate barges and thus decide which barge bunkers which fuel where, stated that “in The Netherlands, HVO producers do not use feedstock which can also be food, but in other countries they still do, which poses a risk.” The availability of feedstock is important for the large-scale introduction of AECs. If there is not enough feedstock available, or if it is not available without harming other sectors, it determines the amount of production of that particular energy carrier.

### 6.3.2. Containers

One specific problem which came up during multiple interviews is the topic of containerized storage and its supply chain. The currently used battery and hydrogen storage containers are an example of the types of problems that the supply chain for containers faces. The main problem always comes back to the availability of containers, which can pose a problem. When there are not enough charged or filled containers available for a barge, these barges cannot be used.

Firstly, the containers need to be swapped from and onto the barge. The interviewee working at a component supplier for containerized batteries stated that these containers are not like regular containers, and “they need to be handled differently” because they contain energy carriers. Bad handling can damage the containers and also create dangerous situations. The same interviewee mentioned that “both the crew on the barge and the crew in the terminals are well-trained to handle the containers, but it still happens that a container is sometimes damaged. When this happens, one less container is available in the supply chain until it is repaired.”

The previous interviewee also mentioned that “battery containers are currently often charged in the terminal”, so they do not have a very complicated supply chain after the handling from and onto the barge. However, the interviewee who works at a fleet owning company and works with hydrogen mentions that “hydrogen is often not refueled in terminals, so these containers need to be moved to and from a nearby refueling station for hydrogen.” This extra step complicates the supply chain.

When a container barge with containerized storage arrives at a terminal, the charged or filled containers need to be ready before the barge needs to leave again. There are multiple scenarios where a container could not be ready before this time. For example, if some containers are unavailable because they broke down, or if a container is still not back in the terminal from refueling. In this case, delays are imposed on the barge’s departure. The interviewee working with hydrogen barges mentioned that “for this reason there is already a preference to perform containerized bunkering in less crowded terminals, so other barges are less likely to be impacted by the delays too.”

### 6.3.3. Electric Grid

The electric grid is a topic which was mentioned multiple times during interviews. This is mainly aimed at batteries and flow batteries as they can directly store electric energy without needing external production methods. The interviewee working with containerized batteries mentions that they are “dependent on and often waiting for infrastructure for charging their containers.” Especially with an eye to scaling up, it could pose a difficult challenge to charge multiple containers at the same time. Apart from having to increase the infrastructure to transport the electricity from the generating facility to the charging facility, the power generation also needs to be scaled up at a certain point. The interviewee who works at a container terminal mentions that they “... place solar panels in the terminal” and the interviewee who implements flow batteries mentioned that they “... place wind mills on the bunkering pontoon.” When these solutions do not supply enough energy, the initial costs and complexity can increase and therefore the electric grid can have an impact on the implementation of certain AECs.

### 6.3.4. Use by Other Sectors

One last point that was mentioned with regard to the supply of AECs is its use by other sectors. An example of the use by other sectors that the interviewee who works at a biodiesel supplier mentioned was that "much of the HVO will also be used in the aviation sector." In this sector not all the AECs that are mentioned in this research are feasible to use, which is mostly true because of their performance. With a higher demand for biodiesel from another sector, availability might decrease or prices could increase, also for the IWT sector. Similar to biodiesel in the aviation sector, chapter 3, which describes production methods for the seven energy carriers, mentions examples of alternative energy carriers which are also used by other sectors. Ammonia is also used in the agriculture sector for fertilizer production. Methanol is also widely used in industry, and hydrogen is, for example, also used for ammonia and methanol production. The use of AECs by other sectors can therefore have an impact on supply.

### 6.3.5. Supply as a Determinant

The supply of AECs, either before or after production, is a determinant for the large-scale introduction of AECs to the IWT sector. The availability and reliability of this availability of supply can have a determining role on actors who could implement an AEC. Supply has an influence on the cost of AECs and therefore it also has an influence on demand.

# 7

# Product Performance and Quality

Every AEC performs differently and their applications have different qualities. Applications for the seven AECs have also been mentioned in chapter 4. The performance and quality also make AECs stand out from diesel. This topic was also mentioned often by multiple interviewees. Most comments were aimed mainly at three aspects; range, emissions and safety.

The primary function of energy carriers is to carry energy. The amount of energy which they can carry and the amount of power that their applications can provide are therefore important specifications. That is why energy & power is a determinant and it is discussed in section 7.1. As previously discussed, the emissions during production are a determinant, but the on-board emissions are also important. On-board emissions as a determinant is discussed in section 7.2. Lastly, as energy carriers contain a lot of energy, it is important that it is contained safely. Safety is a determinant which is discussed in section 7.3. To better understand these determinants and act as a discussion starter, they have also been illustrated on cards in section C.2 in the Appendix.

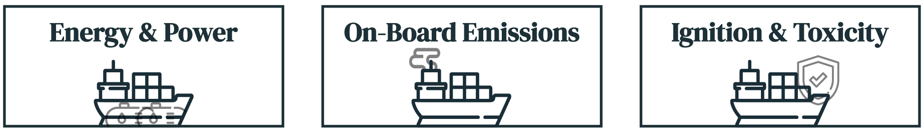


**Figure 7.1:** Determinants for Product Performance and Quality

## 7.1. Energy & Power

Energy and power are correlating units. Energy is the amount of power that is used over a certain time span. Energy relates to the range of a barge, because more energy on-board means that a barge can provide the same amount of power for a longer time. This results in the barge sailing longer distances. During interviews, when talking about energy requirements with regards to AECs, the most reoccurring topic is range. A large range is favorable, but it is not always feasible to keep adding energy to a barge. In particular, currently available zero emission options typically do not provide a large range.

### 7.1.1. Zero Emission Range

Batteries are relatively heavy. In batteries, energy and power are coupled; when doubling the amount of batteries, the amount of energy and power both double. So, a battery system will always have to be optimized for either of them. Typically, it is the energy on-board a barge that plays the leading role, but that means that, in a sense, batteries use up a lot of volume and weight to provide unnecessary power, making them the most valuable on shorter distance trips, where the least amount of energy is needed, keeping the useful amount of power closest to the rated power. The interviewee working with containerized batteries also stated that “batteries are sufficient for the relatively shorter distances."

To expand on range, compressed hydrogen is one of the first available options that decouples energy and power in its application, using compressed hydrogen tanks for energy storage and a separate fuel cell system to determine the power. The interviewee representing a fleet owning company with hydrogen-powered barges mentions that "to go further we looked into compressed hydrogen." This increases the range, but also not up to current standards. The same interviewee mentioned that "to go one step further, the next phase could be liquid hydrogen." This makes the storage more compact, but still, liquid hydrogen does not provide the range that can currently be provided by diesel.

Further options to increase range would be methanol or ammonia, used either in a fuel cell or a combustion engine, as was previously mentioned in chapter 4 where different applications of alternative energy carriers were discussed. However, these technologies are currently not in larger scale production. They might be ready soon, but the fact that they are not ready now underlines the problem that there are no zero emission options right now that provide the customary range.

### 7.1.2. Volume & Weight

To provide barges with a large range using AECs, currently the only options that come close to the customary range are alternative types of diesel or LNG. It is either using this option or losing out on other aspects of the barge. Energy carriers have two very distinct properties which scale with required energy and power. These are weight and volume. When increasing range (the amount of energy) on a barge, both of these properties also increase for the energy carrier.

Energy carriers often have what is referred to as an energy density and a power density, which relate to how much energy and power fit into a predetermined volume. Needing more volume for an energy carrier on-board a barge, means that there is less volume left over for cargo and being able to take less cargo, means that a barge is less profitable. This does not have to be a direct problem when barges are not always filled to the brim, but from a certain amount of energy onward it will be at the expense of profitable cargo space.

Similar to density, energy carriers also have specific energy and specific power, which relate to how much energy and power take up a certain weight. Adding more weight to a barge to fit more of a certain energy carrier means that the barge becomes heavier and thus the barge will be positioned lower in the water. Firstly, this could be a problem because this might mean that the barge would not be able to move everywhere it was able to move before because of the depth of the water. So, the operational profile is an important first consideration.

Secondly, taking on more water means that a barge is less efficient. Whilst the ultimate reason to implement AECs is to decrease emissions, they are not the only option to achieve this. Emissions can also be decreased by increasing the efficiency of a barge. Additionally, efficiency does not only have an impact on emissions, but also on operational costs. If a barge is less efficient, operational costs also increase. An increased weight of a barge can thus have negative impacts as well.

### 7.1.3. Energy & Power as a Determinant

Conclusively, the first thing that should be analyzed to determine the desired amount of energy and power is the operational profile. This is elaborated on in section 10.4 where the operational profile is discussed as a determinant. Once this is established, the desired AEC can be determined. If the barge sails short distances and has many bunkering opportunities, they could opt for a zero emission option with a smaller range, like batteries or hydrogen. If this is not the case, a decision has to be made. This decision showcases why energy and power is a determinant for the large-scale introduction of AECs to the IWT sector.

The decision can either be to use a polluting AEC with on-board emissions. Another option is to bunker frequently, extending range by hopping from one bunker location to the next. The last option is to add more of the AEC to the barge, using up more space and taking on more weight. Essentially, range is a consideration of sustainability, time (delays), and profitability.

Newer, better technologies are being developed to increase energy and power density, and specific energy and power of AECs. Before they are available, energy and power will remain a determinant for the large-scale introduction of AECs in the IWT sector.

## 7.2. On-board Emissions

There are four types of emissions that are closely watched in the shipping sector, which are Greenhouse Gases (GHG), Nitrogen Oxides ($NO_x$), Sulphur Oxides ($SO_x$), and Particulate Matter (PM). GHG are a familiar type of emission, being the cause for global warming (IPCC, 2023). Primary GHG examples are carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$). $NO_x$, nitrogen oxide (not to be confused with nitrous oxide) is a shorthand for two different compounds, nitric oxide (NO) and nitrogen dioxide ($NO_2$), which are the most relevant nitrogen oxides for air pollution as they contribute to smog and acid rain. $SO_x$ is also a shorthand for compounds, consisting of sulphur and oxygen, like sulphur dioxide ($SO_2$) and sulphur trioxide ($SO_3$), and also contributes to smog and acid rain. PM are small particles which can be present in the air. They can be split up into two groups, $PM_{10}$ and $PM_{2.5}$. $PM_{10}$ are inhalable particles with a diameter smaller than $10\mu$m, which is the size of parts like dust, pollen or mold. $PM_{2.5}$ are also inhalable particles, but with a diameter smaller than $2.5\mu$m, like combustion particles, organic compounds and metals. Because of the size of these particles, they can be inhaled and can reach deep into human lungs and sometimes even into the bloodstream.

Knowing the bad effects of these polluting elements, it makes sense that they are being closely watched, but they are still emitted in remarkable quantities. Diesel engines emit all four of the aforementioned types of emissions and they will continue to do so for the foreseeable future, but steps are continuously taken to reduce them. For example, because of regulations like the EU Sulphur Directive and Emission Control Areas as mentioned in section 3.1, diesel fuels can only contain up to a certain percentage of sulphur, so the $SO_x$ emissions after combustion are kept to a minimum.

Similar to these regulations for $SO_x$ emissions, more and more regulations are being constructed. Most notably, the European Green Deal has been invoked, which gives way to new directives aimed at decreasing all four types of previously mentioned emissions. More about regulations can be read in section 12.4 where regulations are discussed as a determinant. The consequences of emissions are what makes on-board emissions a determinant for large-scale introduction of AECs in the IWT sector. Barge owners want to implement cleaner applications in their barges so the lifespan of these barges is extended.

Ultimately, all barges would have zero emissions, but as mentioned in the previous section, this is currently likely to decrease the range of a barge. That does not mean that emissions cannot be reduced on a barge. One way to reduce emissions is to increase the efficiency of the barge. Another would be to adjust the amount of emissions emitted per amount of energy used. This can be achieved in three ways. The first is to use a ”cleaner” energy carrier, the second uses applications that emit less, and the last is to capture the emissions directly after the application.

### 7.2.1. Cleaner Energy Carriers

Like explained before, diesel is already made to contain less sulphur in order to have less $SO_x$ emissions, but there are more examples of cleaner AECs. For example, interviewees often described LNG as cleaner, because it emits less $CO_2$, $NO_x$, $SO_x$ and PM when combusted than diesel combustion. On the other hand, it does consist mostly of methane and because LNG is not always fully combusted in ICEs, there is a methane slip, meaning methane is emitted as well

(Pavlenko et al., 2020, p. 3, 17). Methane is 86 times more potent as a greenhouse gas than $CO_2$ over a span of 20 years. It could be said that LNG would have a good application in IWT, being applied close to humans and with emissions like $NO_x$, $SO_x$, and PM having bad effects on human health. In this case, GHG emissions would increase in order to decrease other emissions. GHG emissions have been mentioned roughly three times more than the other emissions on average during interviews. Additionally, the interviewee working at the biodiesel and biomethanol supplier stated that "LNG is recently decreasing in interest in the IWT sector because of the methane slip." So, while there is an aim to decrease all emissions, the priority among actors seems to be to decrease GHG emissions.

### 7.2.2. Low Emission Applications

Another way of applying methanol, other than through combustion, is by applying it in a fuel cell. Using methanol in a fuel cell has a large benefit, which is that it does not mix with the air and, therefore, the emissions are cleaner. As can be read in section 4.4 which discusses methanol applications, methanol fuel cells always have an anode and a cathode and the air always passes the cathode side while the methanol always passes the anode side. The air comes out in the same composition that it came in, but with less oxygen, meaning that there are no $NO_x$, $SO_x$, and PM emissions in the air. There are still $CO_2$ emissions, however.

### 7.2.3. Emission Capturing

The capture of emissions is one solution to make sure that these emissions do not end up polluting the sky. One example that often comes up during interviews is carbon capture technology as being one of the solutions for GHG emissions. Carbon capture can be performed through multiple applications. The first distinction that could be made is whether the carbon is captured directly on the barge, or indirectly on land. When interviewees mentioned carbon capture technology, they most often referred to it being used directly on the barge. For example, the interviewee working at a fleet owning company with hydrogen mentioned methanol as an option to carry hydrogen more densely, but "then we would probably also want to have carbon capture on-board." The reason for this is that the barge then does not emit $CO_2$, which could make it a zero emission barge. This does depend on the application of the energy carrier. For example, diesel combustion still has $NO_x$, $SO_x$, and PM emissions which are not captured through carbon capture technology. On the other hand, when using the previously mentioned methanol fuel cell, it only emits $CO_2$ and in this case, carbon capture can make the barge fully zero emissions. However, it is still important to have a plan on what to do with the $CO_2$.

Carbon capture is often referred to as Carbon Capture, Utilization and Storage (CCUS) and this distinction between utilization and storage is an important note for deciding whether a certain application of an AEC is renewable. For example, methanol, when applied using fuel cells, could be renewable, but only if the captured $CO_2$ is reused to combine with hydrogen to produce methanol again. This is shown in Figure 3.4 which addresses the different production methods for methanol. When the $CO_2$ is stored afterwards, it is essentially a waste product and new carbon is needed for methanol production.

### 7.2.4. On-board Emissions as a Determinant

On-board emissions are an important consideration when determining which AEC to implement and how. In this sense, on-board emissions of AECs are a determinant for their large-scale introduction to the IWT sector. AECs have three options to emit less on-board. By being cleaner themselves, by being applied through a cleaner application, or by capturing emissions on-board, AECs can be less emitting on-board. This can allow them to change according to regulations and to achieve a better image, similar to emissions from production methods as described in section 6.1 which described production methods as a determinant.

## 7.3. Ignition & Toxicity

Safety has been an aspect that has been mentioned several times during interviews and is an important value. While the current standard, diesel, is not inherently safe, alternatives also have other safety aspects which are slightly different than diesel and should be handled in their own way.

### 7.3.1. Ignition

Ignition is a safety aspect that also refers to diesel, but it is not the same for every energy carrier. A first distinction can be made by looking at flash points for fuels. A flash point of a fuel, in simple terms, describes the lowest temperature at which that fuel gives off vapors that could be enough to ignite. The distinction is made through temperature, where fuels with a flash point lower than 60°C are called flammable fuels and fuels with a flash point higher than that are called combustible (Hamptom, 2023). For example, diesel has a flash point between 52-93°C, while methanol has a flash point around 12°C. This means that methanol is flammable, while diesel can differ between being flammable or combustible. Flammable liquids are also called Low Flash Point Liquids (LFL) and require protective cofferdams to be placed around their fuel tanks. These cofferdams are essentially empty spaces which keep in dangerous vapors in case of a leakage. This means that it takes up more space to carry AECs which are a LFL.

Not all AECs are liquids, some are also gaseous. The IMO has created the International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels, or the IGF code for short. This IGF code provides standards for safely handling gases and LFL. When LNG started gaining popularity in the maritime sector, this code was updated with standards for handling LNG. Recently, standards have also been amended for methanol, ammonia and hydrogen (Lloyd's Register, 2023).

Handling gases is slightly different from handling liquids. For example, compressed hydrogen can pose other challenges. Examples of different types of storage for gases are mentioned in chapter 4. Compressed hydrogen tanks at first glance are relatively safe. Firstly, no oxygen can get inside because of the pressure difference between the inside and outside of the tank, meaning that an ignition inside the tank is only possible when the tank is nearly empty. Secondly, these types of tanks are made to withstand enormous pressures, so they are already difficult to break. So, the problem is not with the compressed hydrogen tanks themselves, but it is their surroundings that face a challenge. When a compressed tank starts leaking, the high pressure inside can result in the space around the tank filling up rapidly with hydrogen and this space does contain oxygen. In this case, a leak becomes dangerous and in order to prevent the buildup of dangerous amounts of hydrogen, precautions have to be taken. The interviewee working at the shipyard with hydrogen mentions several examples of how hydrogen needs to be handled safely. They mention that spaces with hydrogen systems need constant ventilation, hydrogen sensors need to be integrated in every space, and hydrogen tanks need to be able to close in a matter of milliseconds.

### 7.3.2. Toxicity

Toxicity is another safety reason why some AECs are less likely to be implemented. For example, ammonia is toxic and as it is currently most likely to be stored as a compact liquefied gas, a leak would rapidly spread as a toxic airborne gas. This creates a dangerous situation for two reasons, the first being for people in close proximity (on-board) and the second being for surroundings.

A barge's crew is continuously walking around the barge to maintain it. In case there is an ammonia leak in the machine room or any other ammonia-containing space and a crew member walks in there, the consequences could be severe. High concentrations of ammonia can produce rapid respiratory arrest (Padappayil and Borger, 2023).

The other side of toxicity covers the surroundings of a barge, considering both life below and above water. One of the United Nation's 17 sustainable development goals is to conserve life below water (United Nations, 2023). One way to aid this goal is by making sure that, in case of a leak, sea life is not affected. A study performed by the Environmental Defense Fund (2022) shows how ammonia leaks can have negative impacts on sea life. Now, this is only a problem if the ammonia dissolves in the water, but ammonia can also become airborne. When this happens, areas around a barge will be affected. As stated earlier, exposure to ammonia can cause bad effects on human health. The interviewee working at the shipyard with hydrogen mentions that "in the case of a leak of ammonia, all surroundings in a radius of 500 meters would have to be evacuated." An ammonia leak in proximity to urban areas would therefore impact a lot of people, and barges often sail in close proximity to urban areas.

### 7.3.3. Ignition & Toxicity as a Determinant

Safety is very important and should never be disregarded by any actor in the IWT sector. Some AECs are less inherently safe than others. Actors are more keen on implementing safer energy carriers. This makes ignition & toxicity a determinant for the large-scale introduction of AECs to the IWT sector.

# 8 Product Price

The first question asked during interviews to get the conversation going was "why are AECs not introduced on a large scale in the IWT sector yet?" The first answer almost all interviewees gave was cost. The main point of analysis for product price is the total cost of an AEC. Initially, when implementing an AEC on a barge, there are initial costs involved. This determinant is discussed in section 8.1. Once the AEC is implemented, the barge still has operational costs. This determinant is discussed in section 8.2. To better understand these determinants and act as a discussion starter, they have also been illustrated on cards in section C.3 in the Appendix.

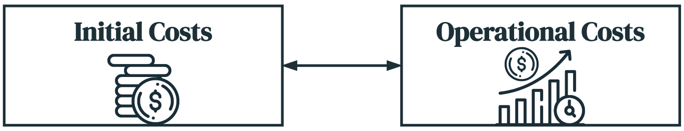


**Figure 8.1:** Determinants for Product Price

## 8.1. Initial Costs

A topic that often comes up during interviews is that the costs of newer technologies are typically higher. While this is a statement that directly shows why initial costs are a determinant for large-scale introduction of these technologies, there are some underlying features which can adjust its impact.

Initial costs cover many aspects of previous determinants. Firstly, if an actor wants to implement an AEC they would also need infrastructure, meaning the production system has to be there as well. So, bunkering systems need to be in place and these bunkering locations need a supply. Then, once the carrier is available, it needs to be stored on the barge. As has been shown in previous chapters, standard storage systems often do not suffice, so new storage systems need to be installed. Lastly, applications of AECs are also often different, meaning components like the engines have to be replaced as well.

### 8.1.1. Production System

Installing an entire production system from beginning to end can be a large investment which an actor who wants to transition to an AEC in their barge might not be able to afford alone. As described in section 6.2 which describes bunkering as a determinant, there are two main possibilities for bunkering solutions. One is direct bunkering and the other is containerized bunkering.

In the case of direct bunkering, the installation of a bunkering station would be large, but if other actors also started using this bunkering station, it might pay for itself. That is still a big if. What could also be possible, is that another actor decides to build this bunkering station to exploit it. This would remove the initial costs from the first actor and convert them into operational costs. That does not mean that the costs are gone, but they are spread out over time. In this case, multiple actors are needed to implement that specific energy carrier in their barge, so that the installing actor can recover their investment.

It is also possible to use truck-to-ship bunkering, but that is mostly feasible with liquids (or liquefied gases). Containerized bunkering would be a smaller investment for the implementing actor when they want to use an AEC which is not liquid. Most of the infrastructure is already there. Cranes to move containers from and onto the barge and trucks to move the containers to and from refueling/charging stations. There is not much more that needs to be implemented for this to work. Therefore, containerized bunkering makes for a strong solution in terms of initial costs when there are not many other actors who are also considering implementing that AEC.

### 8.1.2. Storage

As can be read in chapter 4 which gives some examples of storage of AECs, there are many different types of storage available for AECs and these alterations to storage can become a large investment for implementing actors. One option to decrease these costs for the implementing actor, however, is if there is a lease option. For example, if containerized storage becomes available through a third party who leases the containers with batteries, hydrogen tanks, or maybe even a different type of storage. The interviewee working on implementing flow batteries in barges mentions another example. "Skippers do not buy our electrolyte, but they rent it." This diminishes the impact of high initial costs of vanadium electrolytes which were mentioned in chapter 2. Here, again, there would have to be enough actors who implement the specific AEC in order to create a business model for the third party. When that happens, the initial costs can be reduced even more for the implementing actor.

### 8.1.3. Application

When solutions like container leasing are available for an implementing actor, the main initial leftover costs for them are for implementing the application inside the barge. For example, they might have to swap their diesel engine for an electric motor and, on top of that, they could have to install a fuel cell on-board the barge. These are initial costs that are currently not avoided by the implementing actor. The interviewee from the fleet owning company with hydrogen-powered barges stated that "initial costs of fuel cell systems are quite a lot higher, probably double the cost of doing it the combustion engine route." This still leaves a reason not to implement an AEC which is dependent on such technologies.

### 8.1.4. Initial Costs as a Determinant

All in all, there are many additional initial costs connected to the implementation of an AEC. The main costs are mentioned in this section. There are multiple ways of decreasing initial costs for actors who want to implement AECs in barges, but it is difficult to fully decrease it up to a point where it is less expensive than current standards. That on its own makes initial costs a determinant already why the large-scale introduction of AECs is not taking place right now. Different AECs have different options to decrease initial costs and therefore these costs will remain a determinant for this large-scale introduction.

## 8.2. Operational Costs

There are always operational costs connected to exploiting barges. The operational costs of AECs have been mentioned often during interviews. The price of an AEC is typically referred to as the price per weight, but this does not tell the full story, because one kilogram of a certain energy carrier can contain more energy than the other. On top of that, different applications of certain energy carriers can be more efficient than others. So, a more effective way to describe the price of an energy carrier is to look at its price per effective unit of energy.

$$P_e = \frac{€/E}{\eta} \tag{8.1}$$

Here, $P_e$ is the effective price of the energy carrier, $€/E$ is its price per unit of energy, and $\eta$ is the efficiency of its application. These last two variables are interesting to analyze in order to understand how operational costs are a determinant.

### 8.2.1. Efficiency

The efficiency of a barge has already shortly been mentioned in section 7.1 which mentions energy & power as a determinant, and has a large impact on the operational costs of an energy carrier. As can be seen in Equation 8.1, when the efficiency increases, the effective cost of an energy carrier decreases. Whilst the efficiency of the overall barge is important, the efficiency of the specific application of an energy carrier inside the barge is one of the two reasons that make the operational cost a determinant specifically for AECs.

An example of how efficiency could make a difference in the effective price of two AECs can be seen when comparing batteries to hydrogen fuel cells on a barge. Batteries are very efficient in converting their chemical energy to electric energy, more so than hydrogen fuel cells (Tsakiris, 2019). If hydrogen would be twice as cheap as electricity in a battery per unit of energy, but the fuel cell is half as efficient as the battery system to convert it back into electric energy, then both options effectively have the same operational cost. Hydrogen can only be applied as AEC through conversion, while batteries pack their own -efficient- conversion. This is one reason why one AEC could be prioritized over the other because of operational cost as a determinant.

### 8.2.2. Energy Price

The other side of operational cost is the price per unit of energy. As mentioned before, the price of an energy carrier is often referred to as the price per weight, so to know the energy price, this value needs to be divided by the amount of energy per weight. When charging electricity, prices are referred to in price per kilowatt hour (kWh), which is already a unit of energy. Once all these units of prices have been normalized, they can be compared and then it shows that different types of energy carriers have different energy prices. This already creates a reason why one AEC could be prioritized because of operational cost as a determinant, but it is also interesting to analyze why this is the case.

To understand why different AECs have different energy prices, it helps to look at chapter 6 once more. This chapter mentions the determinants in the building block of production systems. All the AECs have their own production methods, supply, and bunkering systems, and this explains mostly why different energy carriers have different energy prices. Every step that has to be taken before the finished carrier ends up inside the barge costs money. Transporting electricity from a solar farm to an electrolyser, converting electricity in an electrolyser, refilling empty containerized storage, pressurizing and cooling a carrier. All these steps take energy, time and effort, and therefore they all add up to the eventual price of an energy carrier.

To keep operational costs down as much as possible, it is therefore also important to keep the number of steps before bunkering to a minimum. For example, recharging a battery container in the terminal instead of having to move it to an external location and back. Or, having renewable electricity production close to a flow bunkering station instead of having to transport it from offshore farms. These are both examples from interviews which show that it is possible to reduce operational costs when a slightly higher investment is made at the beginning of a project.

### 8.2.3. Operational Cost as a Determinant

Operational cost is a determinant that can be diminished in many ways, but often times at the cost of another determinant. Increasing efficiency could be at the cost of range and moving infrastructure closer to reduce service costs could create higher initial costs. How to increase profitability by reducing operational costs has different options for different AECs. As every actor in the IWT sector is looking to minimize cost, operational cost is a determinant for large-scale introduction to the IWT sector.

# 9
# Complementary Products and Services

The past three chapters have mostly been aimed at how differences between AECs can create determinants. However, AECs can also be complementary to each other, which can also create determinants. Firstly, some AECs can be mixed. These dual fuel applications are discussed in section 9.1. Then, there are mainly two types of propulsion, combustion or electric. Some AECs can only be combusted, some can only be applied with electric motors, and some can do both. The determinant following from complementariness through propulsion types is discussed in section 9.2. Lastly, production methods, as discussed in chapter 3, can be complementary. This can result in correlation in energy prices, which is discussed in section 9.3. To better understand these determinants and act as a discussion starter, they have also been illustrated on cards in section C.4 in the Appendix.

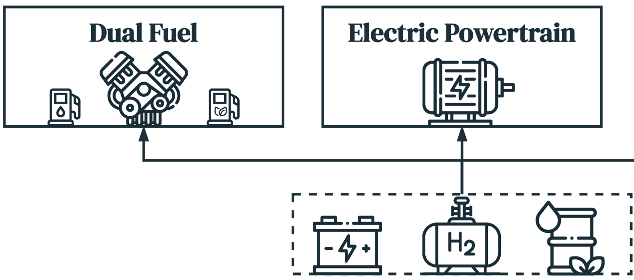


**Figure 9.1:** Determinants for Complementary Products and Services

## 9.1. Dual Fuel

Dual fuel is a subject that does not come up often during interviews, but it has been mentioned and deserves some attention. It has the potential to shape the introduction of AECs to the IWT sector. The concept of dual fuel is a type of application that can use two or more different energy carriers, either at the same time or even separately. An example is a dual fuel engine that allows use of both LNG and diesel (Tazelaar, 2017). Dual fuel engines have two main benefits, the first being that energy carriers can be mixed to create lower emissions, and the second being that in the future a decision can always be made between two, or even multiple different energy carriers, so operational costs can be kept to a minimum.

### 9.1.1. Mixing Fuels

As was mentioned in chapter 4 which mentions the applications of different AECs, many AECs can be mixed. A simple example is diesel with biodiesel. Regulations in the EU have already stated that diesel should already be mixed with 7% FAME (2009/28/EC). This regulation is more thoroughly discussed in section 12.4 which mentions regulation as a determinant. Diesel can also be mixed with methanol or ammonia. The fact that it can be mixed, however, does not mean that it can always be applied in that manner on a barge. To apply such a mix, the engine also needs to be fit to combust such combinations. This means that initial costs could be increased to implement such an engine, but it might pay for itself as the barge can expand its longevity by adjusting to regulations and decrease operational costs by responding to energy prices.

### 9.1.2. Other Dual Fuel Technologies

There are more ways of applying dual fuel than through combustion engines. For example, a solid oxide fuel cell (SOFC) can be powered using methanol and ammonia, as is explained in chapter 4. This means that a SOFC can be implemented in a barge with the use of methanol in the first place, but if ammonia ever becomes a more sensible option, only the storage has to be adjusted. Similarly, a proton exchange membrane fuel cell (PEMFC) is powered by hydrogen, but if methanol or ammonia reforming systems ever become a more effective hydrogen storage system, then again only the storage system has to be swapped out.

### 9.1.3. Dual Fuel as a Determinant

The application of dual fuel can aid complementary AECs as they can grow together. This is especially true for AECs that score lower on other determinants at this moment in time. These kinds of carriers can use better established energy carriers as a platform to grow when they are complementary. For example, the implementation of methanol in IWT could grow because of its complementariness to diesel and biodiesel through mixing and combustion engines. In turn, the implementation of ammonia could grow if the implementation of methanol SOFCs has grown and ammonia could also be used in these fuel cells. Systems that are able to run on multiple energy carriers are more future proof than others as they can adjust more easily to certain developments. This makes the concept of dual fuel a determinant for large-scale introduction of AECs in IWT as it decreases uncertainty for implementing actors.

## 9.2. Electric Powertrains

One thing that stands out when analyzing all the different types of applications is that there are only two options to convert the energy from the carrier into kinetic energy. The first and currently most largely applied option is through internal combustion engines. The second option is through electric motors.

As mentioned in the previous section, AECs that have an application through combustion engines can be complementary to each other if the combustion engine allows dual fuel applications. Currently, combustion of energy carriers offers the simplest solution to achieve a large range, as was discussed in section 7.1 which mentions energy & power as a determinant. Yet, the reasons for electric powertrains with, for example, batteries or compressed hydrogen are also outlined in section 7.2 which mentions on-board emissions as a determinant.

Many upcoming technologies are electric. All of these different types of applications are explained in chapter 4. Batteries and hydrogen-electric powertrains have already been implemented in the IWT sector, the first flow battery powered barges are around the corner and methanol and ammonia also have upcoming applications in electric powertrains. An electric powertrain could also work with a diesel generator on-board. Hybrid options with electric motors can already increase efficiency on-board. An example of this is mentioned for an inland waterway tugboat by Hayton (2023). The interviewee representing a biodiesel and biomethanol supplier mentioned that "newly-built barges nowadays are typically built with an electric drivetrain, but still have a diesel generator on-board." Implementing an electric powertrain in a boat offers a large variety of AECs, while a combustion engine commits to one or two energy carriers.

### 9.2.1. Electric Powertrains as a Determinant

The application of an electric powertrain could aid the introduction of AECs. There are many different AECs that rely on electric powertrains. Currently, many barges are not provided with an electric motor. The interviewee who is a researcher, coordinating inland skippers with AECs mentioned that “going electric is often seen as a no-regret solution.” This is beneficial for AECs. It should be possible to go electric in the first place and, with an increase in technological development for electric applications of AECs, it becomes more feasible to implement electric powertrains. Electric powertrains are a determinant for the large-scale introduction of AECs in the IWT sector because every AEC is complementary with an electric powertrain, but not every powertrain is electric.

## 9.3. Coupled Production

Energy price has been mentioned in section 8.2 as one of the two main influences on operational costs of energy carriers. Energy prices are volatile and as more AECs come to market, it is difficult to predict how prices of specific energy carriers will evolve. Because of this, the implementation of a specific AEC could feel like a gamble. However, energy prices of different AECs can also be complementary. As was also stated in section 8.2, the reason why energy prices can differ is because of their production system. So, if energy carriers have a lot of overlap in their production systems, their energy prices can change comparably.

The interviewee representing a fleet owning company with hydrogen-powered barges stated “the nice thing about hydrogen is that you cannot make [methanol or ammonia] without it.” Even if they would fully commit to hydrogen, the prospect of an AEC like methanol or ammonia becoming less expensive should not scare them. The reasoning behind this is most clearly visible by looking at the production methods of methanol and ammonia in chapter 3. Methanol and ammonia are both produced using hydrogen, so if the price of hydrogen ever increases, the prices of methanol and ammonia are likely to increase as well. Similarly, if the price of renewable electricity were to increase, not only would charging batteries become more expensive, but so would producing green hydrogen.

### 9.3.1. Coupled Production as a Determinant

Energy prices are a part of operational costs as a determinant and therefore play a role in the large-scale introduction of AECs in IWT. They do not, however, only play a role because they are linked to operational costs. Energy prices of different AECs can be inherently linked to each other through their production methods. Therefore, the complementariness of production methods of AECs can increase the certainty of energy prices for certain groups of AECs. This makes coupled production a determinant for the large-scale introduction of AECs to the IWT sector.

# 10 Customers

Customers in the IWT sector are not the direct actors who make the decisions in the sector. The major decision they make is whether to use IWT for their transport or another type of transport, like trucking or rail. There are many different types of customers with different types of cargo, different shipping routes, different moral values, and so on. This makes the building block of customers for the IWT sector an interesting one to analyze, especially with an eye on the transition to AECs. While the customers are deciding which type of transport to use, it is up to the IWT sector to keep themselves attractive to these customers. This chapter delves into how the sector keeps itself attractive to its customers. Firstly, AECs need to be able to compete with diesel. This is discussed in section 10.1. This is not always possible, so some actors or customers need to be willing to pay for the premium that comes with the implementation of AECs at the moment. This willingness to pay is discussed in section 10.2. Actors and stakeholders also have to be acquainted with their options. Acquaintance as a determinant is discussed in section 10.3. Lastly, there is currently a large variety of operational profiles in the IWT sector. These operational profiles as a determinant are discussed in section 10.4. To better understand these determinants and act as a discussion starter, they have also been illustrated on cards in section C.5 in the Appendix.

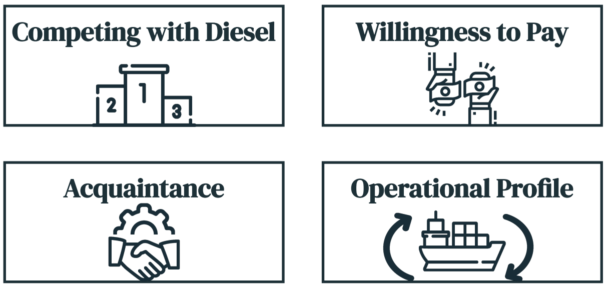


**Figure 10.1:** Determinants for Customers

## 10.1. Competing with Diesel

In chapter 8 it was mentioned that the costs of AECs are currently high, compared to the conventional diesel fuel. This means that, to compete with diesel, the costs should be compensated in other ways which would not be possible with diesel. Interviewees have given some insights into how some AECs are able to compete with diesel through alternative models.

### 10.1.1. Long-term Agreements

The first aspect of competing with diesel is closely related to willingness to pay, which is mentioned in section 10.2 as a determinant. If there is a customer who is willing to pay for the implementation of an AEC, a long-term agreement with this customer could be a simple model to compensate for the premium on diesel. One example that interviewees who work with hydrogen-powered barges referred to is the willingness to pay from *Nike* for the project with the hydrogen-powered barge. The interviewee representing a container terminal where Nike's barge also swaps containers stated that "they were willing to pay because they wanted to be ahead with zero emission options." In this case *Nike* made a long-term agreement with the involved parties that they would pay the extra costs for the hydrogen for a specified amount of time. This made the project feasible to start with for all the other actors involved.

### 10.1.2. Carbon Insetting

AECs are an alternative to diesel and are being considered mostly because of their lower emissions compared to diesel. This decrease has an impact on the environment, but also poses a potential revenue model. To compete with diesel, using AECs can be rewarded. A reward that is mentioned by multiple interviewees is the use of carbon insetting.

Carbon insetting and carbon offsetting are often mentioned together. Carbon offsetting involves compensating for unavoidable GHG emissions by funding GHG saving projects somewhere else. Carbon insetting does a similar thing, but within the company's own value chain (Sullivan, 2023). The previously mentioned example of *Nike* also applies here, because *Nike* has invested in a carbon reduction within their own value chain. The products which *Nike* need to transport carry less GHG emissions because *Nike* has ensured that it is powered by renewable energy. "It is a real emission reduction and someone is financing it" is how the interviewee from the fleet owning company with hydrogen-powered barges describes it. Carbon insetting therefore allows AECs to compete with diesel because it adds another value. This value can then be used to attract customers.

### 10.1.3. Energy Provider

As was mentioned in section 9.2 which mentions electric powertrains as a determinant, there are many applications with AECs which are electric. Electrification opens up a whole other option to compete with diesel. Batteries are a good example, which have been mentioned multiple times by interviewees in the context of being able to apply new revenue models. These new revenue models are for the owner of containerized batteries who can be an energy provider in more ways than for the propulsion of barges.

"A part of the business model of a containerized battery is that you can trade on the imbalance market" states the interviewee who works at the component supplier which supplies containerized batteries. Batteries are connected to their recharging station and can be recharged when electricity prices are lowest. For example, at night or when there is an overcapacity of renewable energy. This would reduce the cost of energy for a barge. Subsequently, when there are peak energy moments in the electricity grid, the batteries could be used to even out these peaks. This makes batteries valuable at times when they would otherwise not be used.

Barges are not always sailing. During these moments, the barges often berth in one place, but still consume energy. Most barges have a generator on-board which generates electricity and heat for the other loads that are present on-board. The same diesel that is used to propel the barge is also used to power these generators. This causes a lot of unnecessary emissions and therefore, more and more docks provide shore power, so there are fewer emissions in these areas like ports and harbors. However, not all locations can provide shore power, so what the interviewee from the containerized battery supplier mentions is "there is a shore power project where the battery container is brought to the barge to provide it with shore power. So, they do not have to turn on the generator and they do not pollute the local air and have no $CO_2$ emissions." This confirms another revenue model of using containerized batteries to provide shore power where it is not yet available.

### 10.1.4. Competing with Diesel as a Determinant

It is currently difficult to compete with diesel. This is mostly because there is an uneven playing field with diesel, which is explained more elaborately in section 12.4. This does not mean that it is impossible to use an AEC. Every AEC has its own benefits compared to diesel and these eventually allow them to compete with diesel. These benefits can be converted into opportunities to expedite the large-scale introduction of AECs to the IWT sector. Competing with diesel as a determinant is aimed at decreasing total costs and exploiting added values to even the playing field between diesel and AECs. This is done by using properties of specific AECs which diesel cannot exploit. These properties make this a determinant for the large-scale introduction of AECs to the IWT sector.

## 10.2. Willingness to Pay

One point that many interviewees make, is that someone has to be willing to pay the premium that currently comes with AECs. It is not always possible to compete with diesel. This means that the implementation of an AEC brings along a premium. The total costs of such an implementation currently outweigh the costs of conventional energy systems. This leaves the question of who is willing to pay for this premium, the customers or other actors in the sector?

### 10.2.1. Dispersed Sector

"IWT is quite dispersed. You have the small companies which you could call the family companies and you have the shipping companies who own multiple barges." This is a statement from the interviewee who works as a researcher, coordinating inland skippers with AECs. The collection of barge owners consists of many separate companies. Most barge owners own just one barge. There are also shipping companies which own multiple barges, but the total number of such companies is relatively low. The fact that there are so many separate companies has an effect on the willingness to pay of barge owners.

#### Family Companies

Many barges are skippered and owned by families who make their jobs their living and vice versa. They typically own one barge, which is their home. The interviewee representing a containerized battery supplier states that "they often have a mortgage on this barge", so their future is dependent on the value and profitability of their barge. Taking a risk by implementing an AEC means risking their livelihood. Switching to an AEC while all the other barge owners stick to diesel and their switch does not pay off, can result in losing more than just their business.

#### Shipping Companies

On the other side of the barge owner spectrum are the larger companies which own multiple barges. The interviewee who is a researcher, coordinating inland skippers with AECs mentioned that "these companies often just wait and see until regulation affects them." They aim to maximize profitability and keep their customers. This results in them holding off changes for as long as possible until regulation catches up with them in order to maximize the profitability of their most recent investments.

### 10.2.2. Zero Emissions

Hardly anyone takes a risk without a potential benefit. The IWT sector is dispersed and barge owners are likely to go for the most certainty and profitability. But there is a reason why some actors are already willing to invest in AEC. Zero emissions is starting to get an image which is about more than adhering to regulation. The interviewee representing a component supplier of containerized batteries mentions "people who believe in the step towards sustainability" as major actors who value zero emissions so much already that they are willing to pay the premium. Such actors aid to initiate the transition. Yet, there is one big challenge, which is that when these companies say zero emissions, they really do mean zero emissions, not just on-board.

The companies who are willing to pay the premium for zero emission technologies really do expect zero emissions, which means both in the production methods (mentioned as a determinant in section 6.1) and the on-board applications (mentioned as a determinant in section 7.2). So, the production method has to be green, the supply chain has to be zero emission, and the on-board application has to be clean. This increases the total cost of zero emission solutions. This could result in companies who might have been willing to pay the premium for zero emission applications not being willing to pay for the full picture of zero emissions. Yet, they also do not want to pay for something that is not fully zero emission. This leaves them at exactly the same place as they were.

### 10.2.3. Willingness to Pay as a Determinant

Zero emission IWT seems to be feasible, but still at a premium. In a dispersed sector, the question is mostly who is going to be the first to implement it and pay this premium. Family companies rely strongly on the profitability of their barge to keep their livelihood and hipping companies aim to maximize profitability. Interviewees mentioned *Heineken* and *Nike* as the companies that were willing to pay. They are examples of how it is possible to find the right customers. As long as there are no customers or other actors who are willing to pay the premium, willingness to pay will remain an important determinant for the large-scale introduction of AECs to the IWT sector.

## 10.3. Acquaintance

The attentive reader might by now have realized that one of the AECs is mentioned relatively little compared to others. Flow batteries are a relatively new and upcoming technology -at least in Europe- and are therefore not often mentioned during interviews. This is exactly why acquaintance is a determinant for large-scale introduction of AECs. To apply a certain technology, someone has to know of its existence first. But, acquaintance is about more than just knowing about the existence of a technology, it is also about knowing how it works and what it could do.

### 10.3.1. The Waiting Game

Because actors in the IWT sector are not always acquainted with AECs and they are continually hearing new stories of rapidly evolving technologies, it is difficult for them to get the full picture. Actors want to know about all the determinants, but can often not find how specific AECs relate to certain determinants. For example, it could be unclear what kind of emissions an energy carrier has, what regulations and certification there are, whether it is safe, how it is produced, and so on.

As the interviewee who is working on implementing flow batteries in IWT stated “this results in most actors waiting to see which AEC comes out on top.” While this makes sense because actors are trying to increase the certainty of their barge, terminal, bunkering station, etc. remaining profitable, it is also an endless waiting game. New technologies keep arising and new insights into these technologies keep being brought to the table, so by the time a current technology comes out on top of other current technologies, multiple new technologies are available to compete with this one again. Therefore, actors could wait for a long time to see it, but they do not have very long before they have to make a decision to implement an AEC, because, for example, regulations are catching up with them.

### 10.3.2. Acquiring Correct Information

Acquaintance is not only about acquiring enough information to make a well-informed decision, but it is also about acquiring the correct information. For example, the interviewee representing a fleet owning company with hydrogen-powered barges mentioned that “the idea of hydrogen is often still associated with the Hindenburg [disaster of 1937].” They stated that this picture of hydrogen is sometimes enough to get customers to refrain from using hydrogen. While hydrogen should definitely be handled with care, there are enough solutions available nowadays to safely implement hydrogen as an energy carrier on-board a barge. Therefore, hydrogen should not be discarded purely because of an image of bad safety.

The other way around, the interviewee working on integrating flow batteries in IWT also mentioned that they have had an experience where an actor did not have the right image of how difficult a specific technology could also be to implement. The actor thought that refueling a compressed hydrogen tank was as simple as “just connecting the hose, like a garden hose”, while in fact this technology is more complicated, often relying on compressing the gas hundreds of times more than atmospheric pressure. Finding out such characteristics after having made the decision to implement a certain AEC, can be a bad surprise to actors. It is therefore important to be correctly informed before making certain decisions.

### 10.3.3. Acquaintance as a Determinant

Acquaintance with AECs is important for actors to know what their options are. If they are only aware of diesel as an option, they will never consider AECs. If they are aware that there are other options, but still unaware of the differences and impacts between them, they cannot make informed decisions and might make the wrong decisions. If they make the wrong decisions, they will make IWT less attractive to customers. Yet, if they wait too long to make a decision, it is possible that the same will happen. It is therefore important for actors in the IWT sector to quickly become acquainted with all the available options to find out whether one is already (partly) fit for them. This makes acquaintance a determinant for large-scale introduction of AECs to the IWT sector.

## 10.4. Operational Profiles

An important aspect to consider when deciding whether an AEC could be suitable for a barge is its operational profile. There are two features that are mainly mentioned during interviews to depict the operational profile. These are the shipping route and the type of cargo of the barge. These features are dependent on the demand of the customers and are therefore important to keep customers in the IWT sector.

### 10.4.1. Shipping Route

The shipping route of a barge is important for the type of energy carrier that can be used for several reasons. One reason is the distance of the route, which has been mentioned before in section 7.1 where range is mentioned as an important factor of energy and power as a determinant. Another reason is the locations where the barge passes. As has been mentioned in section 6.2, bunkering is an important determinant and therefore, barges with AECs will be dependent on the locations of bunkering stations. Thirdly, the areas through which the barge sails are an important reason. As will be discussed in section 12.4, regulations are an important determinant and while the EU has overall regulations, different countries, municipalities, and ports also have their own regulations.

#### Route Distance

The distance of the standard route of a barge can have an influence on the type of AEC that suits the barge best. The interviewee representing a component supplier of containerized batteries states that “when a barge often shuttles between two specific locations which are not far apart and containers are (off-)loaded constantly, currently, batteries make a lot of sense.” When the same applies, but for slightly larger distances, the interviewee representing a fleet owning company with hydrogen-powered barges states that “to reach further distances, compressed hydrogen starts to make sense.” When further distances are sailed and the route changes every day, it would make more sense to use an AEC that is available in more places, like HVO.

#### Locations along Route

When choosing to use, for example, HVO because of its wider availability, it is still important to check which locations the barge often passes. For example, the interviewee representing a biodiesel and biomethanol supplier stated that “HVO infrastructure is well available in The Netherlands, but when you use the Rhine to go to France, it will be difficult to obtain HVO”. In the case that a barge sails through France a lot, it makes less sense to use HVO in that barge.

#### Areas covering Route

Regulations can differ per area, because of different countries, municipalities, or ports and this can have an impact on which type of AEC could suit a barge best. An example that was also mentioned by the interviewee representing a biodiesel and biomethanol supplier was that “some municipalities are currently already banning polluting trucks from entering specific cities. You can expect similar regulations for barges some time in the future.” When this starts to be implemented, it is important for a barge to adhere to these regulations and thus have the right AEC on-board which fulfills the right requirements to enter certain areas.

### 10.4.2. Cargo Type

The type of cargo which the barge is designed to transport also has an influence on which type of AEC would suit the barge best. Some examples of different types of cargo are containers, dry bulk and wet bulk, and passengers.

Containerized storage has been mentioned several times throughout this thesis. This type of storage suits container barges best, because they already pass container terminals in their operational profile. As is explained more thoroughly in section 6.2 which discusses bunkering as a determinant, these containers can be swapped for recharged/refilled ones in container terminals. It would make less sense for a barge that transports dry or wet bulk to pass through a terminal to only swap the containers which contain the AEC. This makes these types of barges more suited to other AECs.

The interviewee who is a researcher, coordinating inland skippers with AECs mentioned that “tankers can be used as warehouses, in which case they can lie dormant for a long time.” Tankers are barges which transport liquids or gases. Not every AEC lends itself for this. For example, as is explained in chapter 4 which mentions different types of storage for AECs, energy carriers which are liquefied, like LNG, ammonia or liquid hydrogen, will have to remain cooled while the barge is inactive for a long time. Similarly, as has been mentioned in the literature research in chapter 2, FAME can grow micro-organisms over time, so leaving them in a tank for a longer time without using them leaves them to degrade. This makes these types of barges more suited to other AECs.

Barges often transport hazardous substances for which many regulations have been established. Some regulations restrict the combination of two different substances on-board, because they might react. For example, the interviewee representing a classification society mentions that for containerized hydrogen in the beginning they “left a space between the hydrogen containers and other containers with dangerous goods.” Similarly, low flash point liquids can not simply be combined with substances that also easily ignite. Some AECs loan themselves better to be used in combination with certain hazardous cargo than others. Another example given by the interviewee who represents a classification society mentions that “there is a barge that is already dedicated to transporting methanol and looking to implement a methanol propulsion system and even that project is questioned on safety.”

### 10.4.3. Operational Profiles as a Determinant

The operational profiles of barges are important to keep the sector functioning. Some operational profiles already accommodate the use of specific AECs, in which case it makes most sense to apply them already. Eventually, all the operational profiles have to be accommodated by AECs. A healthy mix of AECs could provide for a full coverage of all operational profiles in the IWT sector. This could ensure that customers will remain a customer of the IWT sector. That is what makes operational profiles a determinant for the large-scale introduction of AECs to the IWT sector.

# 11
# Network Formation and Coordination

There are many actors in the IWT sector, as discussed in chapter 5 (Methods). These actors form a network which establishes the IWT network. This chapter mentions some key actors for the large-scale introduction of AECs to their sector. Firstly, shipyards play an important role in the building of barges with AECs on-board. As an actor, they form a determinant which is discussed in section 11.1. Component suppliers are also actors who play an evenly important role. They supply the new technologies required for AECs to operate on barges. They are discussed in section 11.2. The last actor which is discussed are terminals, specifically container terminals. With an eye to the introduction of containerized energy storage, terminals play a key role in scaling up this technology. They are discussed in section 11.3. Lastly, it is important for AECs that actors collaborate in the IWT sector. What these collaborations could entail is discussed in section 11.4. To better understand these determinants and act as a discussion starter, they have also been illustrated on cards in section C.6 in the Appendix.

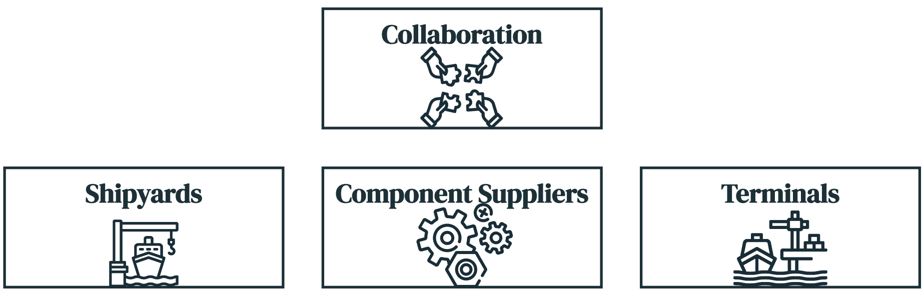


**Figure 11.1:** Determinants for Network Formation and Coordination

## 11.1. Shipyards

An important actor in the IWT network is the shipyard. With an eye on the implementation of AECs, shipyards are an especially critical part of the energy transition. Shipyards are where new barges are built or where barges can be refit from a diesel barge to a barge with an AEC on-board. During interviews, the importance of shipyards in the transition to AECs was outlined. Shipyards could pose a bottleneck to the large-scale introduction of AECs.

There is not an infinite number of shipyards and shipyards are also not infinitely big. Barges are relatively large, so there cannot be too many barges at one shipyard at the same time. Currently, the barge builds and refits are relatively simple, so barges do not need to be at the shipyard for too long. Builds and refits to AECs, however, currently take longer, meaning that the barges have to be at the shipyard for longer. The interviewee representing a shipyard where hydrogen-powered barges are built states that "the first hydrogen-powered barge laid in the shipyard for 10 months." Currently, barges only refit when parts of the barge are past their lifetime. With upcoming regulations and technology, however, barges might switch to an AEC earlier than this, resulting in more barges going to the shipyard at the same time.

Upcoming technologies for AECs will be changing constantly. With a mix of AECs becoming the norm, it will become more difficult for shipyards to efficiently build and refit barges. Components are being updated continually, so designs keep on changing. Suppliers need to keep up with changes, but when one supplier has delays, a refit can already stall and a barge remains at a shipyard for longer. All in all, there is a challenge ahead for shipyards.

### 11.1.1. Shipyards as a Determinant

It will become more difficult for shipyards in the future to build and refit as many barges to AECs as they can to diesel. The number of refits will not decrease, so either one of two things needs to happen to prevent shipyards becoming a bottleneck. Either shipyards increase capacity or they increase the efficiency with which they refit to AECs. Increasing capacity is not always an option, so a difficult task remains for shipyards. This makes shipyards a determinant for large-scale introduction of AECs to the IWT sector.

## 11.2. Component Suppliers

AECs require new technologies to prosper. Dual fuel engines need to be developed, fuel cell technologies need more work, storage technologies need to be improved, and so on. These technologies are developed by component suppliers, which are an important determinant for the large-scale introduction of AECs.

The first point which was mentioned by interviewees is that some technologies are not available on the market yet. An example is given by the interviewee representing a biodiesel and biomethanol supplier who states "there is not a single decent methanol engine for IWT available yet." Where many other determinants are ready for large-scale introduction of methanol with (dual fuel) combustion engines, there do not seem to be feasible engines ready for barges. This starts with the component suppliers who need to research, develop, and produce these technologies so they can be applied in the IWT sector.

Once a technology is ready to be distributed by the component supplier, it helps when the component is type approved, mentioned the interviewee representing a fleet owning company with hydrogen-powered barges. "It does help when they have gone through type approval processes for their systems. When we enter talks for classification, it now moves along much faster than it used to." To acquire type approval the component meets a minimum set of regulatory, technical and safety requirements. Eventually, the entire barge needs to be certified, so if the component is not approved, it still needs to be certified at a later point. In either case, it takes time before a component can be brought to use after it has been developed.

Not every component is as simple to produce as others, so even when a component has been developed and approved, it does not mean it can instantly be implemented in a barge. One example that was mentioned by multiple interviewees was the production of hydrogen storage tanks. These pressure tanks seem to be a particularly difficult component to produce and approve, which has already caused delays in multiple hydrogen barge projects, because they could not be delivered in time. The interviewee representing a shipyard where hydrogen-powered barges are built mentions that "compressed hydrogen tanks came six months too late." Right now, hydrogen tanks are the components which are difficult to produce and approve and this will probably improve over time. Yet, with constantly changing technology, the availability of new components will remain a challenge.

### 11.2.1. Component Suppliers as a Determinant

With a transition to new technologies, the suppliers of these new technologies form to be a crucial actor. The supply is dependent on a few factors, however, which can pose bottlenecks in the transition. Components need to be researched and developed in the first place, then they need to be type approved, and then they need to be produced. All these steps can pose delays which ultimately delay the large-scale introduction of AECs to the IWT sector, which is why component suppliers are considered a determinant for this.

## 11.3. Terminals

As was explained in chapter 6 which mentions the determinants in the building block of production systems, there are two types of bunkering; conventional direct bunkering and containerized bunkering. With the implementation of zero emission options like batteries or hydrogen, the use of containerized bunkering was initiated. For now, these are the most feasible solutions for zero emission AECs like batteries and compressed hydrogen. If these AECs are to be implemented increasingly in IWT, this means that the supply of containerized storage bunkering solutions needs to increase accordingly with its demand. This is also mentioned in section 6.3 which discussed supply as a determinant. Since containers are typically swapped at container terminals, this leaves these terminals with a large task at hand.

With an increase in containerized bunkering demand, container terminals need to scale with this demand. There are two options, the first is to increase the number of terminals at which this bunkering is possible, and the second is to increase the capacity at the terminals which already facilitate this. Both of these options face some (shared) challenges. There are multiple tasks which have to be fulfilled at the terminal to swap a container with a recharged/refilled one. Each of these tasks can pose a challenge for containerized bunkering and the scaling up of this solution.

Firstly, the empty container needs to be moved off the barge, after which a full one can be placed onto the barge. As was previously mentioned in section 6.3 which discusses supply as a determinant, it tends to happen that something is damaged inside the container during swapping. Because of this, the interviewee representing a containerized battery supplier mentioned that currently “more effort is being put into preparing terminal crew on how to handle these containers.” With an increase in the number of terminals where this bunkering is available, this means more training of crew is required, or otherwise a higher total of damaged containers could form.

Before the recharged/refilled container is available, this recharging or refilling can happen either at the terminal itself or at an external location. The interviewee representing a container terminal where hydrogen container swapping takes place mentions that in the case of an external location, for example with refilling hydrogen pressure tanks, “the container needs to be transported by truck.” In this case, increasing the capacity of the terminal mostly depends on the available space for short-term storage of the container and the accessibility for multiple trucks. In the case of recharging or refilling at the terminal, this means that the infrastructure needs to be ready to support charging/filling multiple containers at the same time. This aspect has also been mentioned in section 6.3 which discusses supply as a determinant.

#### Terminals as a Determinant

Terminals can pose a bottleneck for the scaling up of containerized bunkering. Terminals that already provide containerized bunkering need to be available to increase their capacity. Terminals that do not yet provide this service need to be available to start doing it. Because of this, terminals will be a determinant for the large-scale introduction of certain AECs to the IWT sector.

## 11.4. Collaboration

When mentioning the network, interviewees did not only mention singular actors, but one topic they deemed important as well was the collaboration between important actors. They gave some examples which are mentioned here to describe collaboration as a determinant.

Starting off by mentioning previously discussed determining actors, the interviewee who is a researcher, coordinating inland skippers with AECs mentions that "it is important that component suppliers exchange information." Component suppliers who collaborate improve the overall work flow of a project with AECs. Eventually, all the components inside the barge or at the bunkering location need to comply with each other, but there are multiple new components which need to be designed, so these design flows need to be coordinated. In a similar mention, the collaboration between shipyards and component suppliers was noticed to also improve a project's efficiency. It has already been mentioned in section 11.1 which discusses shipyards as a determinant, that shipyards are dependent on component suppliers, so it is sensible that they would prefer to collaborate and that they move their multiple suppliers to collaborate as well.

The collaboration to develop containerized storage is also an interesting topic which has been mentioned during interviews. As was mentioned in section 6.2 which discusses bunkering as a determinant, containerized bunkering poses a strong solution which minimizes initial costs and uncertainty for one barge. As was similarly mentioned in section 8.1 which discusses initial costs as a determinant, it is beneficial when an external party owns the containers, because this transforms the initial costs into operational costs for the barge owner. The interviewee who is a researcher, coordinating inland skippers with AECs mentions that "there is a project with many involved parties who are working together on a containerized hydrogen storage system." Such collaborations are beneficial to all involved parties.

One last interesting point which was made is that collaboration also tends to form among competing companies. When the same interviewee refers back to the previous collaboration, they state "if you look at which companies are working together in this project, you can easily spot competitors, [..] to learn from each other" This competition can be any type of actor, and typically the companies which compete are a bit bigger, but there are also smaller companies connected. This also aids the smaller companies as they can grow with the involvement of the larger companies. Essentially, it grows into a win-win situation for all parties involved when the consortium performs well.

### 11.4.1. Collaboration as a Determinant

Without collaboration, development in the IWT sector would slow down. Collaboration can take place between many different actors and results in different outcomes, but in the end they can all be beneficial to the large-scale introduction of AECs to the IWT sector. The amount of collaboration between actors who are involved with AECs in this sector is therefore a determinant for the large-scale introduction of them to the IWT sector.

# 12
# Innovation-Specific Institutions

Innovation-specific institutions is the last building block of the TIS framework and contains the last determinants for the large-scale introduction of AECs to the IWT sector. Interviewees mentioned many innovation-specific institutions and these have been condensed to four types of institutions. The first type covers financial support, which is discussed in section 12.1. The second collection of institutions is standardization institutions. This determinant is discussed in section 12.2. Classification societies are important actors in the IWT sector. They are discussed as a determinant in section 12.3. Lastly, regulation is discussed in section 12.4. To better understand these determinants and act as a discussion starter, they have also been illustrated on cards in section C.7 in the Appendix.

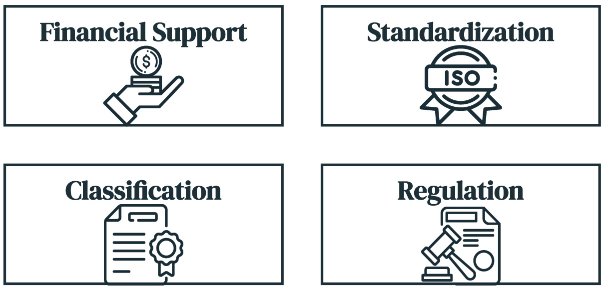


**Figure 12.1:** Determinants for Innovation-Specific Institutions

## 12.1. Financial Support

The initial costs of the implementation of AECs are relatively high, as was also described in section 8.1 which mentions initial costs as a determinant. Financial support is sometimes necessary to support projects with AECs. There are two types of financial support which were mentioned during interviews. The first is subsidies, which are financial support which typically does not have to be repaid. The second is banks, which can provide actors with a loan.

### 12.1.1. Subsidies

Subsidies are financial support which is typically supplied by governmental bodies, like countries or the EU, to support certain sectors in their development. Subsidies have been granted before to support projects like the building or refit of a barge to an AEC, or the production of containerized batteries. Barges, bunkering solutions, storage solutions, and infrastructure could all acquire a subsidy. The interviewee representing a fleet owning company with hydrogen-powered barges states “we got a lot of subsidies which helped us do it” when referring to the first hydrogen-powered barges.

To give an example, when retrofitting a diesel barge to a battery-electric barge, costs can be higher than retrofitting to a new diesel engine. For the sake of the example, let's say that the retrofit to battery-electric is twice as high as to a new diesel engine. A subsidy can lower these costs by compensating for a part of it. It could be that a portion of the costs is subsidized for the battery-electric barge because this project aligns with a long-term vision of the subsidizing entity. While this aids the implementation of an AEC, it does not necessarily level the playing field with diesel.

The interviewee representing a containerized battery supplier mentions that "there are also subsidies for the newest, least emitting Stage V engines." The regulations around these engines are elaborated on in section 12.4 which mentions regulation as a determinant. This decreases the cost of the conversion to diesel, increasing the relative price of conversion to battery-electric. This example was adopted from a statement from an interviewee, who mentioned that subsidies generally do not cover the initial costs, let alone the operational costs, which can also be higher for AECs. They stated that because current subsidies do not cover the premium of implementing an AEC, it always leaves projects dependent on actors who are willing to pay this premium. This leaves a difficult question because, preferably, the early-adopters would ultimately benefit the most from adopting. With a mix of AECs coming up, there is not one clear early-adopter, however. There is not an infinite amount of subsidies and barges are relatively expensive investments. So, subsidies can aid the transition to AECs, but are still only part of the solution. Simultaneously, subsidies for diesel engines could also work against the transition to AECs.

### 12.1.2. Banks

Another type of financial support can come from banks in the form of loans. A loan from a bank might make it feasible to start a project with an AEC. As was discussed in section 10.2 which mentions willingness to pay as a determinant, many barges are owned by families who live on their barge and have a mortgage on their barge. The interviewee working on implementing flow batteries in IWT states that "the barges that are currently being built are financed by banks." This leaves a difficult dilemma for these banks.

Banks can choose to loan to projects with AECs in barges. The sooner these projects become ready for large-scale introduction, the sooner the older barges they had loaned to will decrease in value. With barges being able to reach decades of age, this could mean that the mortgages from these banks start to degrade in value. It is therefore essential for banks that there is a gradual transition towards AECs. It also makes banks an important actor in the large-scale introduction of AECs.

### 12.1.3. Financial Support as a Determinant

Financial support can come from subsidies and banks. Both of these options have a correlation with AECs. Subsidies aid AECs, but cannot fully cover all the costs for all the upcoming AECs, leaving some willingness to pay. They can also work against AECs when diesel is subsidized. Banks have to think about their long-term value as well as the investments they make in the short-term. This leaves financial support as a determinant for the large-scale introduction of AECs in the IWT sector.

## 12.2. Standardization

Standardization is a topic which was mentioned in different examples by interviewees. European standards for IWT are established by CEN and CENELEC. For example, the technical body of CEN/TC 15 is responsible for establishing standardization in the field of shipbuilding for inland waterway vessels and of inland waterway navigation. The idea behind standardization is that all actors benefit as product quality and safety increase and their costs and prices decrease. Standardization can act both as a barrier and as an opportunity for the transition to AECs.

An example mentioned by the interviewee representing a biodiesel and biomethanol supplier is “the IMPCA spec for methanol which has been around for years. It was made for industry for producing plastic cups, but we now also use it as a spec for engines.” The International Methanol Producers and Consumers Association (IMPCA) is an organization which is representative for all stakeholders in the methanol industry. The IMPCA has established standardization which was initially for use in industry, like plastic production, but not for engines. This resulted in a strict limit on the amount of chloride inside methanol through standardization. Engine manufacturers are now developing methanol engines which have a specification with the same limit for the fuel. Currently, “biomethanol is being produced with a chloride level slightly above this limit, because there is also chlorine in nature” states the same interviewee. This makes the biomethanol out of spec for these engines, while it would theoretically be suitable to use in these engines. Diesel has European standards (EN 590) as a fuel, but methanol does not have this yet. Currently, the IMPCA standards are blocking biomethanol in its introduction to the IWT sector. New European standards could aid it.

Another example of standardization is given by the interviewee representing a container terminal which also operates barges. “We try to conform to ISO 14083 when it comes to the environment, to show that our calculations are correct.” The International Organization for Standardization (ISO) has established standards for quantification and reporting of greenhouse gas emissions arising from transport chain operations (ISO 14083). “We can certify our products using models we have created according to these ISO norms” states the same interviewee. Suppliers can certify their own product to have a certain $CO_2$ reduction using internationally endorsed standards like the ISO 14083. Reflecting on section 10.1 which mentions competing with diesel as a determinant, creating value by exploiting lower GHG emissions from an AEC is enabled by such standardization.

The interviewee representing a fleet owning company with hydrogen-powered barges mentions “we are currently trying to get a standardized [hydrogen] container on the market.” These containers with batteries or compressed hydrogen tanks inside are new technologies and therefore have no standardization. It would help for these technologies to be standardized. As mentioned before, standardization benefits all actors. With standardized containers, all the best safety protocols can be established and the components can be made more reliable in collaboration with all stakeholders. Components are also standardized, meaning that they can be produced in higher quantities with more certainty, lowering the price and cutting back delivery times.

### 12.2.1. Standardization as a Determinant

A lot of standardization has already been established, and with the transition to AECs more standardization is imminent. Current standardization can sometimes act as a barrier for AECs. For example, when they just fall out of spec for current standards which were established for other industries. New standardization could act as an opportunity for them. For example, when standards for $CO_2$ emission reduction enable actors to create certificates. Or when containerized storage becomes standardized, to decrease costs. This results in standardization being a determinant for the large-scale introduction of AECs to the IWT sector.

## 12.3. Classification

Classification is an important feature of a barge. If a barge is not “in class”, it is less valuable and can be restricted in use. A barge can be declared in class by a classification society when it meets all requirements. Classification societies use regulations to set up these requirements.

### 12.3.1. CCNR Regulation

The Central Commission for the Navigation of the Rhine, or CCNR for short, is an organization which was established to “promote the development of close cooperation with the other international organizations working in the field of European transport policy and with non-governmental organizations active in the field of inland navigation” (CCNR, 2024). The Mannheim

Act, signed in 1868, defines the Rhine as an inland waterway and appoints the CCNR as an international institution (2020/0283(NLE)). Much of the technical, legal, economic and environmental regulation is established by the CCNR.

#### ES-TRIN

The European Standard laying down Technical Requirements for Inland Navigation vessels, or ES-TRIN, includes technical requirements for inland vessels. The ES-TRIN was established by CESNI, which comes from the French Comité Européen pour l'Élaboration de Standards dans le Domaine de Navigation Intérieure. CESNI was established by the CCNR in 2015 to draw up standards for IWT. The ES-TRIN contains rules which, for example, state strict restrictions for the use of fuels with a flash point lower than 55°C, like methanol or LNG.

Since its founding in 2015, the CESNI has had a permanent working group, the CESNI/PT, which has drawn up the technical standards until now. Recently, several temporary working groups have been established, one of which is the CESNI/PT/FC (CESNI, 2023). This working group was tasked with drawing up standards for alternative fuels on-board barges. It is currently working on these standards, with the priority set as follows.

1. Storage of Methanol
2. Storage of Hydrogen (liquefied and gaseous)
3. Methanol in Internal Combustion Engines
4. Storage and Use of Compressed Natural Gas
5. Other Alternative Fuels

Even though these standards have been set up and are strictly checked, the interviewee representing a classification society states that "it is possible to request exemptions. It is possible to make such a request once every three months," making it a lengthy and strenuous process for actors.

#### ADN & ADR

The European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways, or ADN, was established in 2000. It is a joint agreement, established by the CCNR, together with the United Nations Economic Commission for Europe (UNECE). The ADN is very similar to the ADN, which is the Agreement concerning the International Carriage of Dangerous Goods by Road, also established by the UNECE, but earlier, in 1957. The ADN was written specifically for inland waterways and contains regulations such as specifying requirements for handling dangerous goods on-board.

The interviewee representing a classification society states that "this gives strict restrictions for vessels coming side-by-side when one of them is carrying dangerous goods." This also means that, for example, when a bunkering vessel (floating pontoon) also offers methanol bunkering, a barge which is not certified for methanol, cannot come alongside (ADN 2023 Volume 1, Art. 7.1.2.19). This makes it difficult to offer methanol from an existing bunkering station. Similarly, containerized bunkering has to adhere to both ADN and ADN if the container is recharged or refilled at an external location from the terminal.

Similar to the ES-TRIN, the interviewee representing a classification society states that "exemptions can also be requested from the ADN, but the ADN Safety Committee only gathers once every six months," making it an even lengthier process.

### 12.3.2. Classification Societies

Classification Societies set technical rules and check and survey ships to ensure that they follow regulations. Marine classification is a system for promoting the safety of life, property and the environment. Currently, there are over 50 classification societies, twelve of which are members of the International Association of Classification Societies (IACS). The IACS is a collaboration between classification societies with the goal of ensuring universal and uniform application. It has, for example, implemented the Transfer of Class Agreement (TOCA), which ensures that no society will accept an unimproved ship which has already been denied classification by another society.

Classification societies will check all regulations to establish their own requirements, among which are the ES-TRIN and ADN for barge requirements. Depending on whether a barge meets all requirements, a classification society can state a barge to be in or out of class. Classification is sometimes necessary before being allowed to enter certain ports or waterways. It is also interesting for charterers and potential buyers to be assured that they have chosen a fit barge. Classification societies are therefore important actors in the IWT sector as they state whether a barge is built according to regulation or not. The interviewee representing a classification society mentioned that "classification societies also aid in the process of requesting exemptions from organizations like the CCNR and the ADN Safety Committee." This gives classification societies an important position in the sector for the transition to AECs.

### 12.3.3. Classification as a Determinant

There is a lot of regulation to safely handle energy carriers on waterways in Europe. This regulation is mostly established by the CCNR in collaboration with other organizations. The ES-TRIN and ADN state specific regulations which can currently act as a barrier for AECs. Classification societies are actors who check requirements to see whether barges adhere to the regulations. They also assist other actors in requesting exemptions to certain regulations. Classification is therefore a determinant for large-scale introduction of AECs to the IWT sector.

## 12.4. Regulation

A hot topic during interviews with experts on AECs in the IWT sector is regulation. A phrase that is often stated is that there is no reason for barge owners to transition to another energy carrier. This reason starts with the fact that there is no regulation which physically forbids the use of diesel and is followed by the fact that there is no incentive in regulation to use anything else than diesel. Regulation as a determinant is a broad topic with many examples of how diesel is still favored.

### 12.4.1. NRMM Stage V Engines

The most recent regulation that has been forcing barge owners to transition has been the European Commission's Stage V standard for non-road mobile machinery (NRMM). This standard was included in EU Regulation 2016/1628 and, among others, limits big engines (>560kW) on their PM emissions. While this regulation enforces a reduction in emissions, it still allows for diesel to be used on-board barges. It would be a big leap to prohibit the use of diesel entirely at this moment in time. Reasons for this are all the previously mentioned determinants; there is no mature infrastructure in terms of production methods, supply, and bunkering, the performance of alternatives is insufficient for every barge, costs are too high, and so on.

So, diesel will not be phased out through one regulation, which is not unexpected. Yet, to encourage the transition, AECs should be as favorable as diesel to make it attractive to some barge owners. As was mentioned in section 10.2 which discusses willingness to pay as a determinant, the IWT sector is dispersed, so in order to compete with other barge owners, AECs would have to be as good as diesel on paper. According to interviewees, this is currently not the case, for multiple regulatory reasons.

### 12.4.2. Fit for 55

Before understanding how regulation is a determinant for large-scale introduction of AECs in the IWT sector, it is important to know what regulation is currently in development. In 2021, the European Commission published the Fit for 55 package, which is aimed at reducing net emissions by at least 55% compared to 1990 and being the first climate neutral continent by

2050. The European Commission has five proposals to deliver this package for the shipping sector (European Commission, 2024b).

### Emissions Trading System

The Emissions Trading System (ETS) has existed since 2005 and is a 'cap and trade' system to reduce emissions through a carbon market. The cap is expressed in emission allowances, where one allowance gives the right to emit one tonne of $CO_2$-eq (equivalent). Each year, companies must surrender enough allowances to account for their emissions. Companies can also trade allowances, but if they do not have enough allowances at the end of the year they receive fines.

This system includes the $CO_2$ emissions of large ships since January 2024, but does not yet include barges. The interviewee representing a containerized battery supplier mentioned "one thing that hopefully comes in 2027 is the ETS2." The hope is that barges will be included as well. As it stands now, there is the possibility of barges being included too, but this is no certainty (European Commission, 2024a). The inclusion of general cargo ships with a gross tonnage of 400-5000GT, which is the majority of barges, is to be considered as part of the ETS review.

### Energy Taxation Directive

The Energy Taxation Directive (ETD), or EU Directive 2003/96/EC, was aimed at restructuring the framework for taxation of energy products and electricity. It has existed since 2003, but gained increasing relevance a few years ago for the IWT sector. (Schroten et al., 2019, p. 99) mention how in 1868 the Mannheim Act was signed. In its third Article, it was stated that "the Member States must refrain from imposing any toll, tax, duty or charge based directly on the act of navigation." Then, in 1952, the additional Strasbourg Agreement was signed, which provides for the exemption of tax on gas oil used on the Rhine and its tributaries and other waterways.

In 2021, the European Commission tabled a proposal for a revision of the Energy Taxation Directive (2021/0213/CNS). "Since fuel used for waterborne transport should be equally taxed in the EU, the Member States parties to the Strasbourg Agreement have to take all appropriate steps to effectively eliminate the incompatibilities". This was included in the proposal to change the Energy Taxation Directive. This ETD, however, does not solely cover the IWT sector, but all energy sectors. The European Parliament has until now not been able to agree on all points in the proposal and therefore the alterations are still on-going. This means that diesel is still exempted from taxation in most EU states, whereas other energy carriers are not. This leaves an uneven playing field for AECs.

### Renewable Energy Directive

The Renewable Energy Directive (2009/28/EC), or RED for short, is aimed at increasing the share of renewable energy sources. After it was instated in 2009, it received a first amendment in 2018 (2018/2001) to become the RED II. In 2023 it received another amendment (2023/2413) to become the RED III. This latest amendment was adopted in 2023 by the European Commission and Member States now have until May 21st 2025 to implement according laws and regulations.

The newest amendment has the most impact on the IWT sector through the renewed article 25. This article enforces that every Member State obligates fuel suppliers to either two of the following. The first option is to have a share of 29% renewable energy in the final consumption of energy in the transport sector. The second option is to have at least a 14.5% reduction of GHG by using renewable fuels and electricity in the transport sector.

According to the interviewee representing a biodiesel and biomethanol supplier, "in the short term, the introduction of RED III means that more biodiesel will be mixed with regular diesel." Currently, the standard is B7, which is a mix of diesel with 7% FAME. RED III also states that this standard will have to be increased from B7 to B10. The same interviewee states that "currently FAME is less expensive than HVO and this would be the reason why FAME is mixed with diesel."

### FuelEU

As part of the Fit for 55 package, the EU is also aiming to increase the uptake of greener fuels in the aviation and maritime sectors. Therefore, the ReFuelEU and FuelEU initiatives have been established for the aviation and maritime sectors, respectively. The FuelEU regulation covers the entire shipping sector, so not only IWT. It most generally states that the entire shipping sector should reduce GHG intensity gradually, starting with 2% in 2025 up to 80% in 2050, compared to levels in 1990. The FuelEU was proposed in 2021 and accepted in 2023 (2021/0210/COD).

### Alternative Fuels Infrastructure Regulation

The Alternative Fuels Infrastructure Regulation (2023/1804), or AFIR for short, is a package which is aimed at the deployment of alternative fuel infrastructure for all modes of transport in the EU. For the IWT sector, the AFIR "requires ship operators to reduce the amount of emissions produced by their vessels while berthed at the quayside" (Sahitava, 2023). To support this, it also requires all TEN-T (Trans-European Transport Network) core inland waterway ports to have at least one installation providing shore power for barges. Reflecting on section 10.1, containerized batteries can aid this shore power supply, which would create another method to compete with diesel.

## 12.4.3. Regulations per Region

The regulations discussed for this determinant are all EU regulations. Countries, municipalities, ports, etc. all create their own regulations as well. These actors have to follow regulations from the EU, but they can also establish their own additional regulations. Regulation can have big impacts, but it can also be difficult to ensure that it has the right impact. For example, one country could impose a regulation, stating that a fuel mix has to be a certain percentage of biofuel and this percentage is higher than stated in the EU regulations. In this case, it is likely that the fuel is more expensive in that country, resulting in barge operators choosing to bunker in other countries where the fuel is cheaper.

## 12.4.4. Regulation as a Determinant

Regulations can force actors to transition to AECs. When applied correctly, it can keep pushing certain parts of the sector and specific actors who were not willing to transition before. Since the EU has introduced the Fit for 55 package, recent regulations have been established to push actors to act more on AECs. The currently established regulation is not yet enough to fully transition to a zero emission sector, but there are helpful proposals on the horizon. Regulation will therefore remain a determinant for the large-scale introduction of AECs to the IWT sector throughout the transition.

# Part III

# Discussion, Conclusion & Reflection

# 13
# Discussion

This research was set out to find out why AECs have not been introduced on a large scale to the IWT sector. The seven building blocks of technological innovation systems have been applied to analyze these reasons. The data from interviews with experts has been coded into determinants per building block. This has resulted in 23 determinants in total.

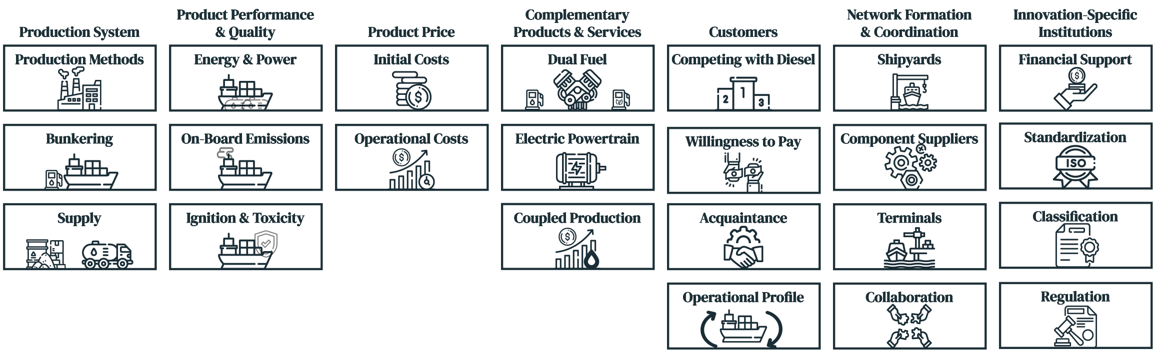


**Figure 13.1:** Determinants per Building Block

## 13.1. Three Scopes of Determinants

With regard to the large-scale introduction of AECs, three large generalizations can be taken away from these determinants. First, on the left, the determinants resulting from differences in properties between energy carriers are described. Every energy carrier has its own production system, its own performance and quality, and its own price. Then, the middle shows determinants for creating a healthy mix of energy carriers for the IWT sector. Energy carriers can complement each other and different customers need different energy carriers. On the right are the determinants resulting from actors with an important role in the transition in the IWT sector. The introduction of AECs is dependent on all the actors in its network and the innovation-specific institutions.

This research was set out to find determinants which impact the large-scale introduction of AECs in the IWT sector. These determinants can be divided into three scopes in the IWT sector. The first scope is inside the barge, where a decision has to be made to use a certain energy carrier. Zooming out to the second scope shows relations among barges, where the combination of energy carriers is dependent on the combination of barges. Zooming out to the third scope shows which actors need to be prepared for the energy carriers. The reason why the determinants have been split up into these three scopes is explained in the next section.

## 13.2. Using the Determinants

Every determinant can be either blocking or aiding and it can be a barrier or an opportunity. For example, if there is only gray production available for an energy carrier, that becomes a blocking factor. If there is a lot of green production available, that same determinant becomes an aiding factor. Similarly, if container terminals do not provide support for containerized bunkering, this becomes a barrier. If they do support this, and maybe even place solar panels to charge the containers, this determinant becomes an opportunity. When an actor in the IWT sector is in the position to implement an energy carrier, they can analyze this framework. The framework can help them to compare and choose from AECs or it can help them see where they can improve to increase the uptake of an AEC.

The first scope of determinants, intra-barge determinants, can be used by actors who are tasked with implementing an AEC inside a barge. These determinants can help them identify key parts of AECs which could either be working for or against it. Knowing where the opportunities are and what the barriers are, is an important step in being able to implement an AEC inside a barge.

The second scope of determinants, intra-fleet determinants, includes important determinants for the sector as a whole. During the energy transition there will not be one specific AEC that can be used throughout the whole sector. The sector should as one whole be able to bring AECs to all their customers. Energy carriers can be complementary to each other, so these determinants can be used to find the barriers and opportunities for AECs when combining them.

The third scope of determinants, actor-based determinants, can be used to see where bottlenecks might start to form in the sector. These determinants can be used especially well to identify aiding and blocking factors for AECs overall, compared to conventional fuels. In the case of certain AECs it is also possible to define barriers and opportunities using these determinants. The following sections go more in-depth into how the determinants fit inside their scope.

### 13.2.1. Intra-Barge Determinants

When deciding to implement an AEC inside a barge, there are eight determinants to keep in mind. These relate to the three building blocks of the production system; the product performance & quality, and the product price.

#### Production System

Production methods are important for the implementation of an AEC inside a barge. If there are no green production methods for an energy carrier, this is a barrier to its implementation. The increase of green production methods could create an opportunity for an energy carrier.

Bunkering solutions are necessary to use an energy carrier on-board a barge. If there are no bunkering solutions for an AEC on the desired route of the barge, this becomes a blocking factor. If these do exist, this is an aiding factor. Truck-to-ship bunkering or containerized energy storage could be an opportunity for the implementation of an AEC.

The supply of an AEC can be determining for its implementation on a barge. If there is not enough feedstock for production of an energy carrier, or the infrastructure is not ready to implement bunkering solutions for it, or the feedstock is also needed by other sectors, this becomes a barrier.

#### Product Performance & Quality

The energy and power an AEC can provide can be determining for a barge. The amount of energy on-board a barge correlates to its range. If an AEC cannot provide enough range for a barge's operational profile, this becomes a blocking factor.

On-board emissions differ per AEC. If an AEC has a lot of on-board emissions, this forms a barrier. Energy carriers can also be inherently clean, in which case this forms an aiding factor.

Specific applications of energy carriers can also be cleaner or more efficient, which creates opportunities for them.

Some AECs are safer than others. If an energy carrier has a high flash point, it ignites less easily and is therefore an aiding factor. Similarly, if an energy carrier is not toxic, this is also an aiding factor.

### Product Price

The initial costs of AECs can be high. Bunkering solutions, storage solutions, and application solutions can all be large investments, which create barriers. Third parties which can convert some of these investments into operational costs through, for example, lease options, can be opportunities.

The operational costs of AECs can also be higher than conventional fuels. High efficiency applications of AECs decrease operational costs and form aiding factors. A very complicated production system increases operational costs and forms a blocking factor.

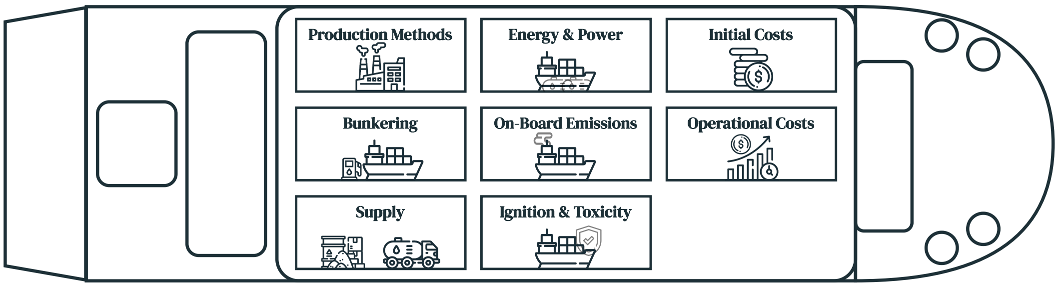


**Figure 13.2:** Determinants through the Intra-Barge Scope

## 13.2.2. Intra-Fleet Determinants

Creating a healthy combination of AECs will be important for the IWT sector to remain attractive to its customers. There are seven determinants which can help to create this healthy combination and attractiveness to customers. They relate to the building blocks of complementary products & services, and customers.

### Complementary Products & Services

Some energy carriers can be mixed or used in the same applications. When multiple energy carriers mix, a slow transition can be initiated and this can be an aiding factor. Similarly, if multiple energy carriers can be used by the same application, they are interchangeable, which is also an aiding factor.

All energy carriers can work with an electric powertrain, some easier than others. The use of an electric powertrain on-board a barge is an opportunity to implement any AEC. Barges with combustion engines on-board are facing a barrier. If an AEC does not require a generator or hybrid solution on-board, this would be an aiding factor.

Some AECs have overlapping production methods, which results in correlating energy prices. Using an AEC which is complementary in its production method with other AECs, gives more certainty of its energy price, which is an aiding factor.

### Customers

To remain attractive to customers, AECs have to remain competitive with diesel. Every AEC has properties which create value that diesel does not have, which creates an opportunity.

It is not always possible to be fully competitive with diesel, which leaves a premium that needs to be paid by some actor or stakeholder. The willingness to pay for this premium is therefore an important determinant. When AECs are zero emission, this increases the willingness to pay, which makes it an aiding factor.

The acquaintance with AECs can be determining. If not many actors and stakeholders are acquainted with an AEC, it is unlikely to be implemented, which would be a blocking factor. When many actors are acquainted, this becomes an aiding factor.

With a large variety of customer demands comes a large variety of operational profiles. Operational profiles can vary in shipping routes and cargo types. When AECs loan themselves for specific operational profiles, this creates an aiding factor.

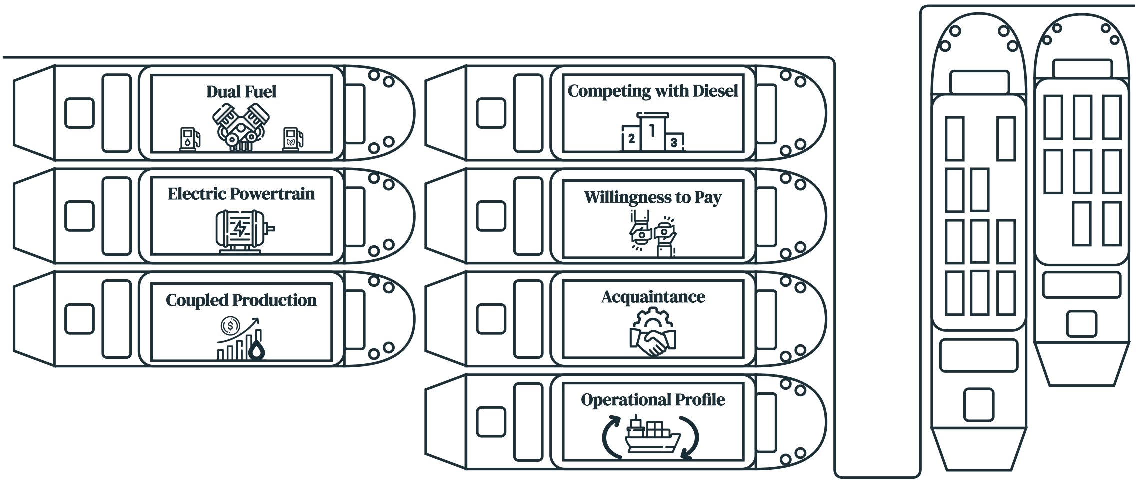


**Figure 13.3:** Determinants through the Intra-Fleet Scope

### 13.2.3. Actor-Based Determinants

Actors in the IWT sector need to be ready to adopt AECs. There are eight determinants in the two building blocks of network formation & coordination, and innovation-specific institutions.

#### Network Formation & Coordination

Shipyards will hold a particularly important position in the transition to AECs. With an increasing number of different applications, it becomes increasingly difficult for shipyards to implement them. If shipyards cannot handle the capacity of barges with AECs, this would become a barrier for AECs overall.

Component suppliers hold a similar position as they need to create continually improving components for the transition. If component suppliers cannot keep up with the transition and cannot create enough new components, this would become a barrier for AECs overall.

Container terminals are important for scaling up containerized energy storage. Capacity in terminals needs to scale with the desired capacity for containers with AECs. If this cannot keep up, this would become a barrier to AECs overall.

Collaboration between all types of actors and stakeholders is beneficial for the implementation of AECs. Collaboration forms an opportunity and aiding factor for AECs.

#### Innovation-Specific Institutions

Financial support can have determining effects on AECs. Subsidies can support projects with the implementation of AECs in which case it becomes an aiding factor. They can, however, also support conventional fuels, in which case they form a barrier. Banks invest in AECs at a certain rate, which forms a barrier and opportunity at the same time.

Some standardization can be made for AECs before they were considered as an AEC. This can work against them and therefore be a barrier. Standardization can, however, also create a lot of opportunities in the future.

Classification is specific to shipping. With many requirements, it can work against the implementation of AECs, forming a barrier. Classification societies do, however, aid in requesting exemptions and the establishment of new requirements, which forms an aiding factor.

Regulation slowly pushes the sector to be cleaner and is therefore a determinant for AECs. Regulation can push the energy transition in different ways, sometimes aiding one AEC more than the other. In certain cases, regulation can create opportunities for specific AECs.

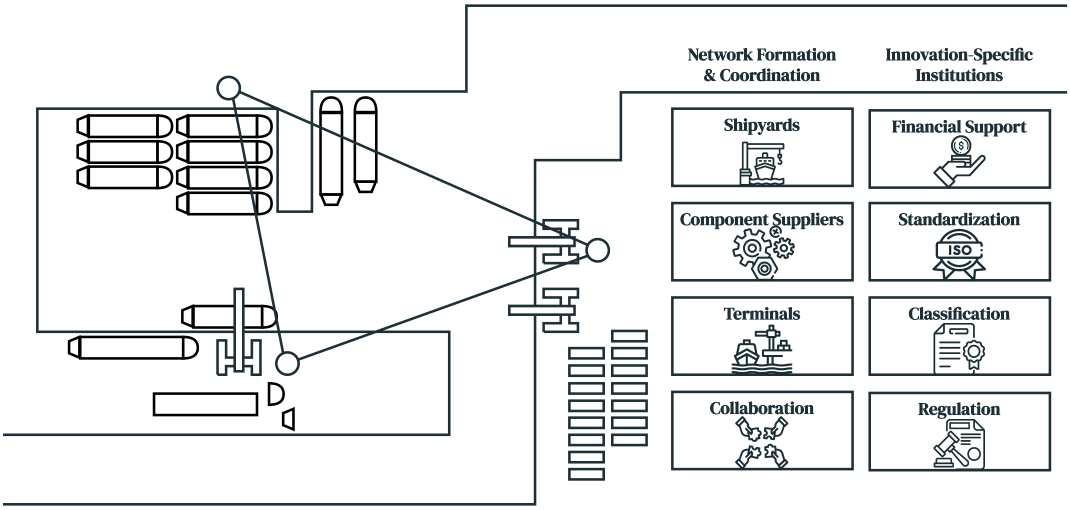


**Figure 13.4:** Determinants through the Actor-Based Scope

# 13.3. Aligning the Scopes

Knowing how to apply one determinant is the first step towards integrating an AEC into the IWT sector. The second step is understanding that these determinants have to align. To align all 23 determinants for an AEC would be impractical, which is why the three scopes have been established. When all three scopes are aligned, an AEC has the best chance of being implemented.

Aligning the scopes means that among every one of the three scopes, the determinants are evenly ready. A determinant can be blocking, aiding, or somewhere in between. Sometimes a blocking determinant is simpler to be referred to as a barrier. When a determinant is blocking or a barrier, it will work against the introduction of that energy carrier, because it performs the worst relative to other energy carriers. In this case, the determinant can be colored red in the framework. Similarly, an aiding determinant can also be referred to as an opportunity. When a determinant is aiding or an opportunity, it will benefit the introduction of that energy carrier, because it performs well, relative to other energy carriers. In this case, it will be colored green in the framework. As there are many energy carriers, an energy carrier is also likely to be neither relatively good nor bad, in which case it can be denoted as neutral.

Once an analysis has been made on the determinants, the three scopes can be compared. A simple count of red and green determinants per scope is enough to perform an analysis. When all three scopes have a similar number of green determinants, they are partially aligned, in which case this AEC is more likely to be implemented on a larger scale. When one or two scopes have less green determinants than the other(s), it narrows down in which scope(s) improvements have to be made to be able to implement the AEC.

Red determinants can also be present in scopes. The presence of red determinants does not necessarily mean that this AEC can not be implemented, but more red determinants do obviously make this implementation more difficult. What is important, however, is that the red determinants are also aligned. Similar to the green determinants, when all three scopes have a similar number of red determinants, they are partially aligned, in which case it is more likely to be implemented on a larger scale. When one or two scopes have more red determinants than the other(s), it outlines in which scopes, and maybe even in which determinants specifically, improvements have to be made.

An AEC is fully aligned when both the red determinants are present in similar amounts throughout the scopes, as well as the green determinants. Whether scopes are aligned or not is not a binary thing; an AEC can also be slightly misaligned, or close to being aligned. It is susceptible to perception, so it is important to understand that the framework should not be used to decide whether an AEC is good or bad. Rather, the framework should be used to analyze where improvements can be made with certain AECs.

### 13.3.1. LNG

LNG has had a two-sided story, both of which can be analyzed using the three scopes. Comparing both sides of the story also highlights an example on how the alignment of the scopes works. For this reason, LNG will be mentioned first and more elaborately to allow for a thorough understanding of the framework before mentioning the other AECs.

The first part of LNG's story started in the early 2010's, when LNG was regarded as a cleaner alternative to diesel. Back then, from the intra-barge scope, LNG had less on-board emissions because it had less $SO_x$, $NO_x$, and PM emissions. LNG also had relatively low operational costs, compared to diesel. From the intra-fleet scope, engines were built in such a way that LNG could be applied using dual fuel engines which could also be powered using diesel. It was also able to compete with diesel because of the low operational cost. From the actor-based scope, eventually standardization and classification were created for LNG in IWT. At that point, all three scopes aligned for LNG in IWT and therefore LNG was implemented on several barges.

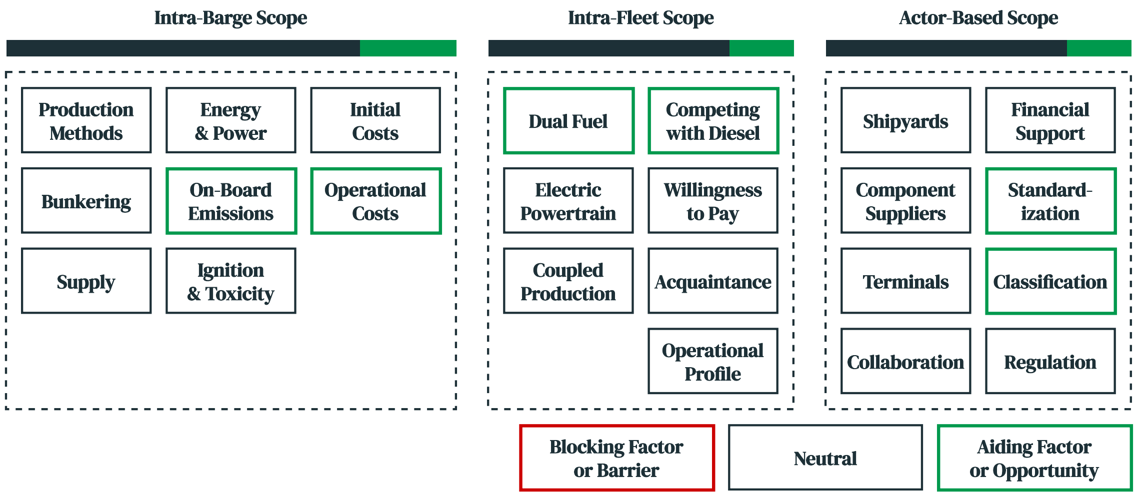


**Figure 13.5:** About a decade ago, the three scopes were aligned for LNG

In Figure 13.5 six determinants have been colored green because, about a decade ago, they performed relatively well for LNG compared to other AECs. These six determinants are distributed evenly over the three scopes, which shows that all three of the scopes are aligned in this case.

About a decade later, it had become clear that LNG is actually not cleaner than diesel, because of methane slip. On top of that, operational costs kept increasing. From the intra-barge scope, LNG was starting to lose its edge. The results from this effect can be seen in Figure 13.6, where on-board emissions has gone from being green to being red and operational costs has become neutral in the intra-barge scope. Competing with diesel has also become neutral because of these two previous changes. At this point, there is only a red determinant in the intra-barge scope, there is one green determinant in the intra-fleet scope, and there are two green determinants in the actor-based scope. This shows that the scopes are less aligned than they used to be. This has eventually resulted in the fact that LNG applications are currently hardly being implemented in barges anymore.

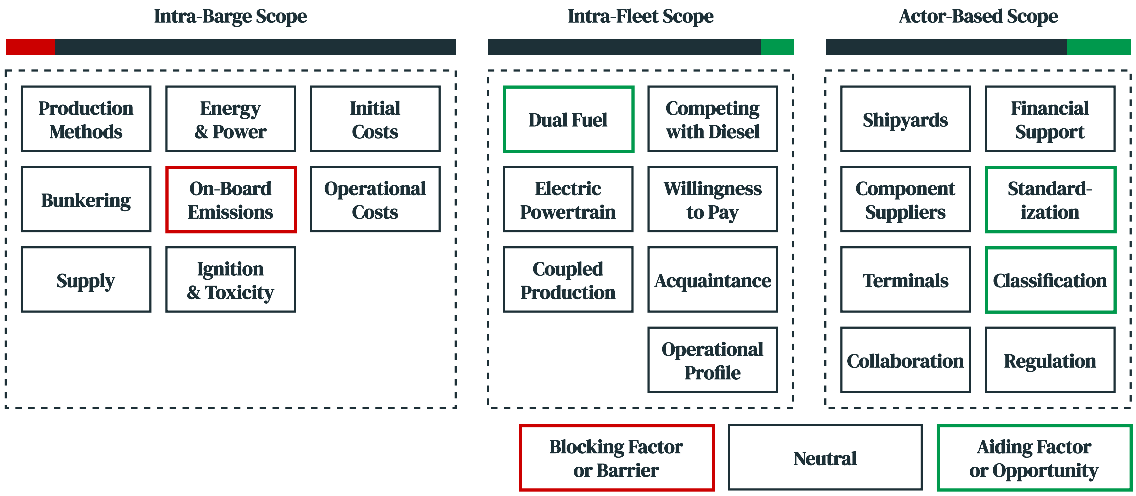


**Figure 13.6:** Currently, the three scopes for LNG have become misaligned

## 13.3.2. Biodiesel

Biodiesel is a good example of how the three scopes align well. From the intra-barge scope, biodiesel has a green production method, it performs well on energy & power, and it has a slightly higher operational cost than contemporary diesel. From the intra-fleet scope, biodiesel can be mixed well with diesel, is able to compete well with diesel in terms of this low operational cost and delivers well on many operational profiles. From the actor-based scope, little needs to be prepared by shipyards and component suppliers, and regulation is pushing the implementation of it. Figure 13.7 shows that the three scopes for biodiesel are well aligned and many determinants are currently in the advantage of biodiesel. This is why it comes as no surprise that diesel is already mixed for 7% with biodiesel.

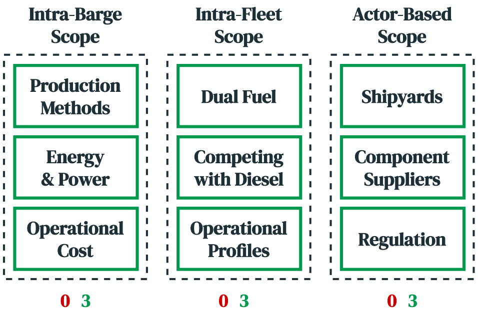


**Figure 13.7:** Scope alignment for Biodiesel

## 13.3.3. Batteries

Batteries have been applied in a barge recently, so it is interesting to see how the three scopes aligned for this energy carrier. From the intra-barge scope, bunkering and energy & power perform relatively badly for batteries, but this is largely compensated for by the on-board emissions. From the intra-fleet scope, they work with an electric powertrain and they are mostly dependent on the energy price of electricity. They still have difficulty competing with diesel, al-though there are novel models to compete in different ways. Batteries are also very dependent on the operational profile of barges. From the actor-based scope, battery bunkering is dependent on container terminals, but largely benefits from collaboration and financial support.

These determinants have been assigned the correct colors in Figure 13.8. It is clear that batteries have many red determinants and struggle in every scope. On the other hand, they also have many green determinants by bringing unique values in every scope. This shows that the three scopes are aligned, which is why it was already feasible to have the first battery-powered barge. The presence of this number of red determinants also shows why the implementation is still on a small scale. If the implementation of batteries is to scale up, it does mean that all three scopes have to scale accordingly, so they remain aligned. For example, to extend the operational profile of batteries in the intra-fleet scope, bunkering availability can be increased in the intra-barge scope, but this means that terminals have to scale accordingly in the actor-based scope. Similarly, to better compete with diesel in the intra-fleet scope, battery containers could be used as relievers for the energy grid. This ultimately lowers operational costs in the intra-barge scope, but it does require that terminals have the necessary infrastructure and that regulation allows for netting electricity in the actor-based scope.

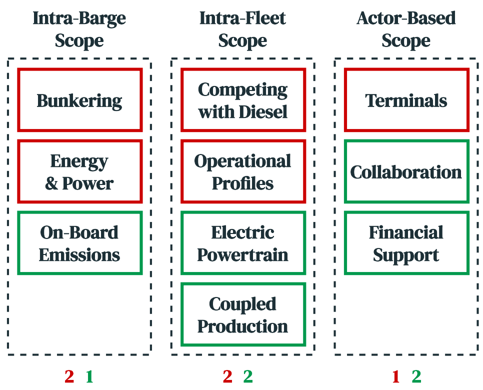


**Figure 13.8:** Scope alignment for Batteries

## 13.3.4. Hydrogen

Hydrogen using compressed hydrogen tanks and PEM fuel cells has been used in more than one barge already. This can be analyzed using the three scopes. From the intra-barge scope, compressed hydrogen performs relatively similar to batteries, but hydrogen performs somewhat better on energy & power. From the intra-fleet scope, hydrogen also uses an electric powertrain and the energy price of green hydrogen is largely dependent on the energy price of electricity. For hydrogen it is more difficult to compete with diesel in terms of novel models compared to batteries, but it does provide for a larger range of operational profiles. From the actor-based scope, hydrogen is also dependent on container terminals, but largely backed by collaboration and financial support. Hydrogen is still a bit more dependent on classification, with hydrogen being a combustible and volatile gas. Compressed hydrogen has similarly aligned scopes as batteries.

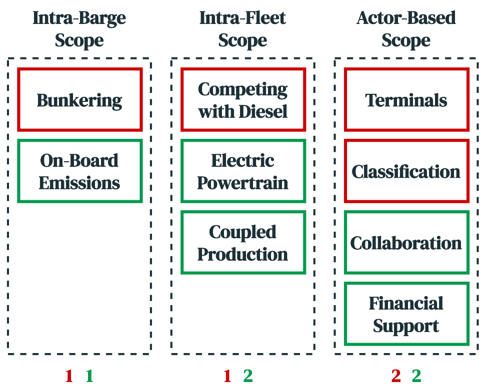


**Figure 13.9:** Scope alignment for Hydrogen

Analyzing Figure 13.9, shows that hydrogen is similarly aligned to batteries. Hydrogen also has quite some red determinants, but both the red and the green determinants are quite aligned. With a combination of struggle and added value in each scope, it was possible to implement hydrogen in the first barges. The number of red determinants shows why it is still on a small scale. Increasing the implementation of compressed hydrogen would require removing struggles from each scope. One option is arising with alternative storage for hydrogen. For example, to extend the operational profile of hydrogen in the intra-fleet scope, the development of liquid hydrogen or LOHCs could improve hydrogen in the energy & power determinant in the intra-barge scope. This does require component suppliers in the actor-based scope to provide such technology.

## 13.3.5. Methanol

Biomethanol has three scopes which are slowly starting to align. From the intra-barge scope, the production method is green, supply is already largely supported by industry, and there are fewer on-board emissions than diesel when combusted. From the intra-fleet scope, biomethanol can be mixed with diesel and support a large range of operational profiles. The challenge for biomethanol, however, still lies with the actor-based scope. Standardization for methanol is still aimed at its use in industry, making some current biomethanol out of spec. All the while, component suppliers are still working on dual fuel methanol engines. Next to that, methanol is a low flash point liquid, which currently makes it fall outside of the requirements for classification. Figure 13.10 shows that the actor-based scope needs to be aligned with the others to scale up the use of biomethanol in the IWT sector.

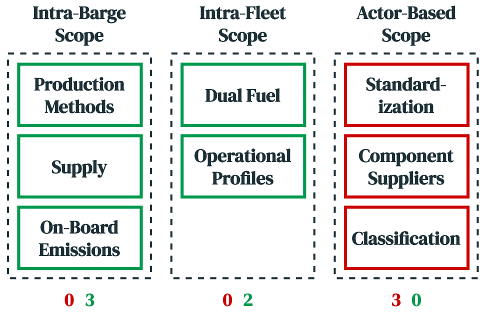


**Figure 13.10:** Scope alignment for Biomethanol with a combustion application

Methanol can also be produced through a blue or green (non-bio) production method and applied using fuel cells. While this is the same energy carrier, it brings some different insights when looking at the scopes. From the intra-barge scope, determinants remain relatively the same, only the production methods might be a little less clean if the majority is blue methanol. From the intra-fleet scope, the use of the fuel cell makes it compatible with electric powertrains and the use of blue or green production relates the energy prices to that of green hydrogen. From the actor-based scope, the technology behind methanol use in fuel cells still has to be developed largely by component suppliers. Next to that, classification requirements still remain a challenge. Figure 13.11 shows that for the use of methanol in fuel cells, particularly with blue or green methanol, the scopes are also not aligned. The intra-fleet scope, however, is looking better than for biomethanol in dual fuel engines. It might take longer for the blue/green methanol fuel cell scopes to align, but it does look promising for the future.

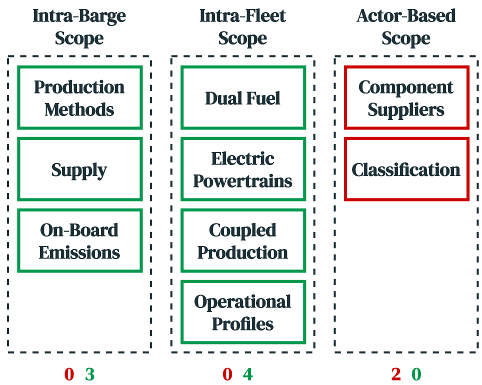


**Figure 13.11:** Scope alignment for green/blue Methanol with a fuel cell application

Do note that biomethanol can just as well be applied in fuel cells and blue or green methanol can also be combusted. These examples have been set up and compared in this way to emphasize the importance of context when applying the framework in certain cases.

## 13.3.6. Ammonia

Starting from the intra-fleet scope for this example, ammonia could be used both in combination with diesel engines, or with fuel cells, similar to methanol, making it suitable for electric powertrains as well. Ammonia's energy price is also closely related to that of hydrogen. From the intra-barge scope, green production is possible with ammonia, supply is largely available because of its use in industry, ammonia performs well on energy

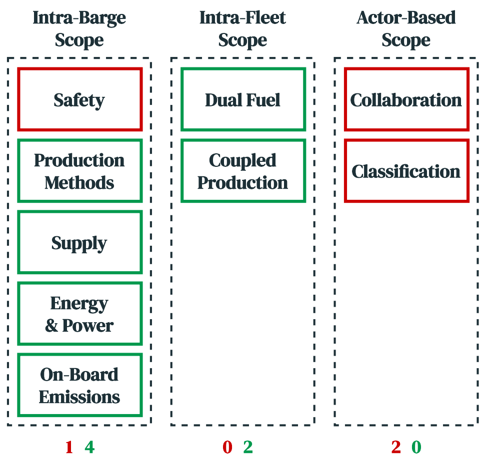


**Figure 13.12:** Scope alignment for Ammonia

& power, and it carries no carbon, giving it very low or, in some applications, even no on-board emissions. Up until here, ammonia sounded remarkable, but there is one large downside. On the determinant of safety, ammonia performs worst of all AECs because it is very toxic. This is reflected in the actor-based scope, where the attitude of the actors is clearly reluctant to implement ammonia. The actor-based scope is therefore largely misaligned with the other two scopes, which is also reflected in Figure 13.12. Ammonia could be stored in solid options, but this technology is hardly developed. If component suppliers can develop new techniques to make ammonia safer, it is likely that collaboration and classification follow in the actor-based scope. This could be a way to align the actor-based scope for ammonia with the other two scopes.

### 13.3.7. Flow Batteries

Flow batteries are a relatively new technology, especially for the application in IWT. From the intra-barge scope, bunkering is hardly ready, but the technology compensates for that by having relatively good energy & power, no on-board emissions, and inherent safety. From the intra-fleet scope, flow batteries work with electric powertrains and their energy price scales with that of electricity. Through this same scope, however, a hurdle can also be seen, which is that the technology is hardly acquainted. From the actor-based scope, classification seems to be ready for flow batteries where it typically is not for other alternatives because of its safety. On the other hand, there is still a large task at hand for component suppliers to develop this new technology for barges. Flow batteries are still in their infancy, but the scopes are close to being aligned and offer room for scaling up. This means that the first introduction of flow batteries is possible. If infrastructure scales up in the intra-barge scope, acquaintance scales up in the intra-fleet scope, and component suppliers' support scales up in the actor-based scope, and this all happens concurrently, there is also enough room for growth for flow batteries in the IWT sector.

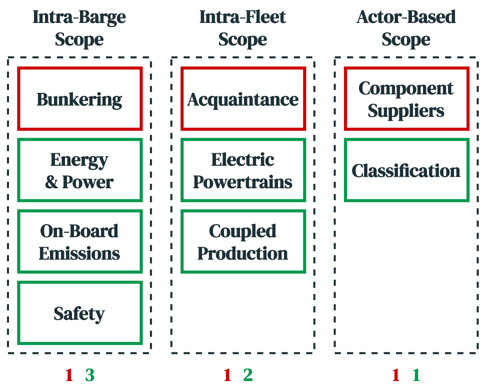


**Figure 13.13:** Scope alignment for Flow Batteries

## 13.4. Relations between Determinants

It is important to understand that these determinants are not isolated determinants, but that they are related to each other. When looking at a determinant through a certain scope, a change in one determinant can have an impact on other determinants as well. Moreover, a change in a determinant in one scope can even have an impact on a determinant in another scope. There are many of these relations, most of which can be found throughout the results of this research. Any determinant could theoretically impact another determinant. That is why it is important for actors who apply this framework to at all times realize what the potential impact could be of altering a determinant. Some examples of relations between determinants are mentioned here to understand the implications they could have.

- To increase willingness to pay, production methods could be made green. Green production methods often bring along increased operational costs, which means that there will ultimately be more to pay for. This could in its turn decrease willingness to pay.
- To extend the operational profile of an AEC, bunkering availability could be increased. This does bring along higher initial costs and in the case of containerized bunkering, container terminals need to be available for this.
- Standardization to, for example, outline calculations for $CO_2$ emissions can create new models to compete with diesel.
- When component suppliers make sure that their components are developed according to classification requirements, this makes the components more likely to be integrated by shipyards.

- Increasing the efficiency of an application on-board a barge to lower operational costs, can increase initial costs.
- Leasing a type of storage of an AEC to lower initial costs, increases operational costs.
- Regulation to, for example, reinstate tax on diesel, can make it easier to compete with diesel for AECs.

## 13.5. Recommendations

This research has shown three scopes to view determinants for large-scale introduction of AECs in the IWT sector. There is a total of 23 different determinants which affect this introduction. The determinants and their scopes outline where AECs require development. They also highlight potential bottlenecks and opportunities for AECs in general. The specific types of development, potential bottlenecks and opportunities can be researched using the framework established in this research as a foundation. The following recommendations are allocated to the three different scopes.

Firstly, a transition to AECs in IWT is imminent, but the implementation of the alternatives first needs to be made attainable. The technologies available today still require much development before they can be integrated into barges on a large scale. There are many opportunities ahead for the technologies at hand to increasingly improve the feasibility of their integration into IWT. The dependency on these opportunities, however, is also significant. The intra-barge scope stipulates where development is needed on the many technological aspects of AECs before their large-scale implementation becomes feasible. Some examples of opportunities for technologies of the AECs used in this research are given in subsection 13.5.1.

Secondly, the IWT sector has been spoiled by the availability of diesel. With the transition to AECs, there will not be one energy carrier to power the entire sector anymore. This was already clear from previous research, but there is not enough clarity on the future energy carrier mix in the sector. Using the intra-fleet determinants, this mix can be approached through research. The complementariness of AECs and the desires of the customers both contain determinants which can be used for upcoming research.

Thirdly, from a policy point of view, there are multiple different actors which influence the uptake of AECs in IWT who will have to adjust their mindsets to the new landscape with a mix of AECs. Shipyards will have to be on top of the changes in the field to make sure that the implementation of AECs will remain viable. With a shift away from one contemporary energy carrier to a mix of AECs, refits will become less standard and increasingly more difficult for shipyards, so they will require more modular designs which can be integrated efficiently. Container terminals also have to shift away from a mindset where they are solely the movers of containers. They will also hold an important position in containerized bunkering, so this should be reflected in their core competencies.

This policy side not only resides in actors, but also in standardization, classification, and regulation. Standardization of fuels for the use in engines and standardization of emissions calculations for AECs are important to increase the implementation of AECs in IWT. Similarly, classification requirements for bunkering and application of low flash point liquids are an overall challenge for many AECs which should be updated to aid their implementation in IWT. Upcoming regulations in the Fit for 55 package from the EU, specifically aimed at IWT, will also make a difference to AECs. For example, the Energy Taxation Directive should include IWT in order to level the playing field with diesel.

### 13.5.1. The Seven Alternative Energy Carriers

After having used the seven different AECs as a handle for this research, some insights have been developed for every energy carrier. These insights are discussed here shortly.

Biodiesel has been present for a while as a mix with diesel in many sectors. It started off with FAME, but more recently HVO has also gained potential. HVO is a cleaner option than FAME and has more similarities to diesel, but it is still a bit more expensive than FAME. With the Renewable Energy Directive being updated to increase biodiesel mixtures to higher percentages, biodiesel implementation will already grow in IWT the coming years. With HVO, this share can still become larger if production can increase and its price lowers.

LNG had a big spurt when it was seen as the cleaner energy carrier. However, when it became clear that methane slip created a much larger problem for GHG emissions, LNG fell off. While $NO_x$, $SO_x$, and PM emissions are important to keep to a minimum, so are GHG. LNG has played its role in the energy transition, but will now make way for other alternatives which have similar performance, but not the effect of methane slip.

Methanol is one of such alternatives. It can also be mixed with diesel, or even be used in dual fuel engines. It will be a while until these dual fuel engines roll out on a larger scale, but they will pose a big opportunity for barges. If methanol combustion really takes off in IWT, this could also become an opportunity for methanol fuel cells. This can either be done with reforming and hydrogen fuel cells, or with direct methanol fuel cells. Both options have their own benefits. Either way, these fuel cells will aid electrification and will be a cleaner application of methanol.

Batteries are currently also aiding electrification. While they can only cover the operational profiles with the shortest ranges, this already has an impact. They will face a challenge with the scaling up of containerized bunkering; with the availability of container terminals, the number of battery containers, and with the supply. As long as this can scale, batteries can have a strong impact in the short term.

Hydrogen is battery's big brother, being able to deliver more range and still have zero emissions. The application of hydrogen in transport is still in its infancy, but there is much development currently. While hydrogen is also facing the challenge of scaling up containerized bunkering, there are alternatives for hydrogen bunkering. There are many alternative types of storage for hydrogen and, for example, liquid hydrogen, LOHCs, and hydrides are either liquid or solid and can be bunkered directly. Hydrogen could even be stored in methanol or ammonia, making the development of hydrogen applications more significant.

Ammonia faces a big challenge in the IWT sector because of its toxicity. Ammonia is seen as a high potential in the shipping sector in the long term. With the barges passing through rural areas, however, that is likely to create an exception for this specific sector. Ammonia still has the option for solid storage, which can make it safer. In the case of a leak, only the non-solid ammonia would pose a danger. If that technology becomes feasible for application in barges, ammonia can in the long term have a big role in the sector.

Flow batteries are relatively new in Europe, especially with an eye on barges. That does not make them a bad option. Flow batteries have many beneficial properties for application on barges. The main challenge right now is the unavailability of bunkering locations and the fact that the technology is still unknown to many actors and stakeholders. Flow batteries can have a strong potential for IWT, so it will be interesting to see whether they can be implemented well in the near future.

### 13.5.2. The Future for Energy Carriers in Inland Waterway Transport

At this moment in time, diesel is still the dominant fuel in the IWT sector in Europe. EU regulations have pushed biodiesel to be mixed with diesel up to 7% already. With more regulations coming up towards the 2030 deadline of the Fit for 55 package in the European Green Deal, the uptake of more alternative energy carriers is imminent. The EU Renewable Energy Directive, which enforces a higher share of renewable energy, will increase the amount of biodiesel mixed with diesel over the coming years, starting with the first big changes in 2025. The EU Emission

Trading System is set to roll out to a large portion of the shipping sector and the question is whether IWT will be included. If it is included, the first impacts can be noticed around 2027 when actors would be fined if they emit a surplus of carbon emissions. This would be a first step towards leveling the playing field with diesel. Another step would be to remove the tax exemption on diesel in IWT. This is set to be done through the EU Energy Taxation Directive which is yet to be implemented, so the question remains when this will take effect. Diesel is phasing out, and there will be multiple AECs to use in IWT. Some examples of what can be expected from AECs can be approached using the results from this research.

In the short term, it would make sense that the uptake of biodiesel increases. As has been mentioned, this is already integrated into EU regulation through RED III. Two other alternatives with potential in the short term are batteries and hydrogen. Electrification in IWT has been shown to be feasible with both batteries and hydrogen. They are available in the short term because they need hardly any new infrastructure with containerized bunkering. For now, their implementation is likely to be increased if there remain enough customers who are willing to pay the premium until regulation starts leveling the playing field with diesel, which is most likely to happen through the aforementioned EU regulations.

In the medium term, (bio)methanol can get a larger place in IWT. It could be the next step to mix with diesel to make it more sustainable, similar to how biodiesel is currently mixed with diesel. Or, methanol could be used in dual fuel engines, similar to how LNG is used together with diesel. The technology for methanol combustion is not yet ready for IWT, but once dual fuel applications are available and feasible, methanol uptake would likely be increased. Flow batteries are also likely to get a similarly larger place in IWT. They are a promising technology with a feasible application in barges. They currently still lack infrastructure and are less likely to be applied using containerized bunkering. If this infrastructure can be implemented sufficiently, flow batteries have strong potential in the medium term.

In the long term, combustion engines will slowly be replaced by electric powertrains and the combustion engines that remain will become cleaner. A large hurdle for fully electric applications still remains to be range. AECs like methanol and ammonia can be combusted, but in the long term they also have strong applications in fuel cells. This would be one way to increase range with fully electric applications. Similarly, hydrogen storage technology is also developing, so storage options like LOHCs, hydrides, solid ammonia, and more, can all become feasible options in the long term to increase range with fully electric applications.

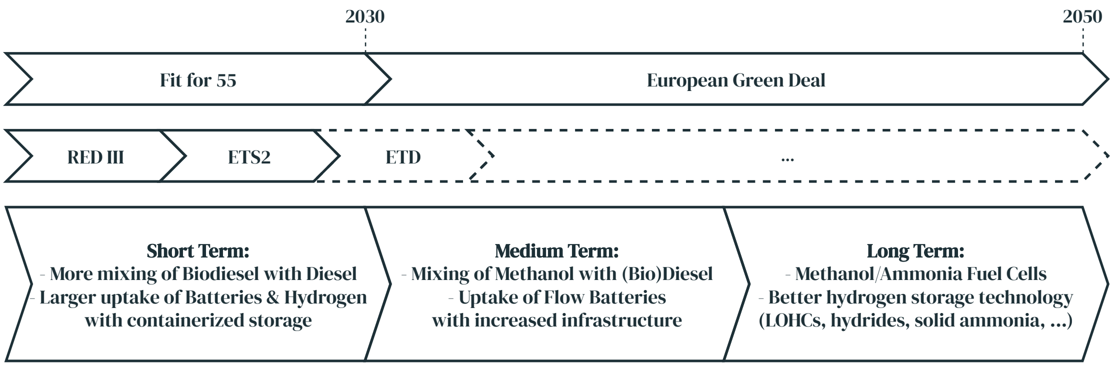


**Figure 13.14:** An example of what can be expected from which alternative energy carrier during the energy transition in inland waterway transport

# 14 Conclusion

To find the determinants for the large-scale introduction of AECs to the IWT sector, the seven building blocks for technological innovation systems have been used. These building blocks consist of *product performance & quality*, *product price*, *production system*, *complementary products and services*, *network formation and coordination*, *customers*, and *innovation-specific institutions*. Interviews have been conducted with experts in the IWT sector who have experience with AECs. The results of these interviews have been processed and analyzed to classify the building blocks into determinants.

## 14.1. The Seven Building Blocks

The seven building blocks all have their own determinants. A total of 23 determinants has been established through the analysis of the interviews. These determinants can be used to analyze the feasibility of the implementation of an AEC.

### 14.1.1. Production System

The production system of AECs consists of three determinants, which are production methods, bunkering, and supply. Production methods should be green to make the entire IWT sector green. This means well-to-wake, not only tank-to-wake. Currently, the majority of production methods is not green yet. A transition with some intermediate steps could be possible, with, for example, blue production methods. Bunkering methods are currently not available for every AEC. This means that either initial costs need to be increased to build a bunkering station, or alternative solutions are needed. One alternative solution is to store the energy carrier in a container and swap empty containers with full containers in a container terminal. This solution removes the chicken and the egg problem because container terminals already exist. Both the bunkering solutions and the production methods depend on a reliable supply chain. Production needs feedstock and bunkering needs an infrastructure.

### 14.1.2. Product Performance and Quality

The performance and quality of AECs also consists of three determinants, which are energy & power, on-board emissions, and security. Every alternative energy is different and therefore has its own pros and cons. In terms of range, it is currently difficult for AECs to compete with diesel without giving in on other aspects of the barge, like cargo space or efficiency. On-board emissions can be reduced through several options, most of which are dependent on the type of energy carrier used. Some energy carriers are inherently cleaner than others, some have applications which emit less and some types of emissions can be captured. Safety can also differ per energy carrier. Some have lower flash points than others, making them easier to ignite. Some energy carriers can also be toxic, posing a potential danger to their surroundings.

### 14.1.3. Product Price

Product price comprises the total costs of implementing an AEC. The total price consists of a combination of initial costs and operational costs. Initial costs can be higher for alternative carriers on three topics; production system, storage, and application. In the production system, the bunkering solution can be a large investment. It is possible that a third party actor implements this bunkering solution or that a small-scale solution is available. On-board storage solutions can also be a large investment. One solution could be to lease this storage, for example by leasing a container with an energy carrier, or by leasing flow battery electrolyte. On-board applications, like new engines, a fuel cell, or an electric motor, can also be expensive. Operational costs depend on two main variables; efficiency and energy price. The efficiency of a barge and the application of an energy carrier impact the amount of required energy. The energy price is mostly dependent on the production system.

### 14.1.4. Complementary Products and Services

Complementary products and services also relate to AECs. There are three determinants for the complementariness of AECs; dual fuel, electric powertrains, and energy prices. Some energy carriers can be mixed, which means they could be used together in an engine. This could allow for a slow transition from one energy carrier to the other and gives actors more room for choice. All energy carriers could work with an electric powertrain, also diesel, for example, with a generator. Some AECs can only work with an electric powertrain, so they are dependent on a transition to this technology, which could be aided by this complementariness. As mentioned before, energy prices are mostly dependent on production systems. Many AECs are complementary in their production methods, making their energy prices correlate.

### 14.1.5. Customers

Customers are important for the IWT sector. They essentially decide whether their product is transported by barge or by another mode of transport, like trucking or rail. It is therefore important that the IWT sector remains attractive to these customers. There are four determinants for AECs to keep IWT attractive to customers. These compete with diesel, willingness to pay, acquaintance, and operational profiles. To be attractive to customers, it is important to be able to compete with the conventional system, which in this case is diesel. This can be done by exploiting properties which add value to AECs, but diesel does not have. Examples are being able to emit less, or focusing on electrification. In most cases, there will still be a premium left for the implementation of AECs, which some actor has to be willing to pay. This actor can be difficult to find, as the IWT sector is dispersed. Actors who are willing to pay this premium are usually because the solution is zero emission, but that has to be well-to-wake, making the premium higher. Actors and stakeholders have to be acquainted with AECs, otherwise they might make uninformed decisions, or stick with diesel anyhow. Lastly, operational profiles vary a lot in the IWT sector because the types of customers and their desires vary a lot. These operational profiles can differ in shipping routes and cargo type. Different energy carriers loan themselves best for different operational profiles.

### 14.1.6. Network Formation and Coordination

Network Formation and Coordination in the IWT sector is important to align the actors. There are three actors who hold a specifically important position for the introduction of AECs. Firstly, shipyards are an important actor because they physically implement the AEC systems in barges. With the transition coming up, they will have a large task ahead to build and refit barges to have AECs on-board. Component suppliers need to research, design, and produce new components for AEC systems continually and get them approved. Without new components there is no place for new technologies. With the introduction of containerized storage, container terminals are important actors in the production system. If the implementation of containerized storage increases, the capacity at such terminals needs to increase accordingly. Lastly, collaboration in the IWT sector aids the implementation of AECs. Collaboration can take place between many different actors. For example, between component suppliers, or between a component supplier and a shipyard. Large, competing companies could also join consortia to learn from each other and smaller companies could join these consortia to grow.

### 14.1.7. Innovation-Specific Institutions

Innovation-Specific Institutions is the last building block and is split up into four different determinants; financial support, standardization, classification, and regulation. Financial support can originate from subsidies or from banks. Subsidies can aid the implementation of AECs by lowering initial costs, but are often still not enough to level the playing field with diesel. Sometimes subsidies can also work against AECs because there can, for example, also be subsidies for the implementation of diesel. Banks can invest in projects with AECs, but they also have long-lasting investments in many diesel-powered barges. This means that a new investment needs to be well-considered, because it could have an impact on the value of contemporary barges.

## 14.2. The Three Scopes of Determinants

A generalization among the 23 established determinants in this research has been drawn by condensing them into three scopes of the sector. The first scope is the intra-barge scope, where determinants can be used to analyze an AEC in the context of one barge. The second scope is the intra-fleet scope, where determinants can be used to see how an AEC would fit inside a healthy mix of AECs throughout the fleet. The third scope is the actor-based scope, where determinants can be used to identify whether actors are also ready for the implementation of an AEC.

Determinants can be used in their own scope to identify aiding and blocking factors, and barriers and opportunities. For the implementation of an AEC in the IWT sector, it is important that the determinants align. It is impractical to align all 23 determinants for an AEC, which is why the three scopes have been established. It is most feasible to implement an AEC in the IWT sector when all three scopes align on a general basis. This does not mean that all determinants have to be in favor of that energy carrier. As long as they generally align between the intra-barge, intra-fleet, and actor-based scope, they have the best chance for implementation. For example, if there are only some determinants in all three scopes in favor of a particular AEC, but every scope has a similar number of determinants in favor, this already allows for it to be implemented. When, later on, more determinants become in favor of that energy carrier and these determinants remain evenly distributed over the three scopes, this energy carrier can be implemented on a larger scale.

It is also important to understand that determinants can have an impact on each other. If one determinant changes, it can also change another determinant. Changing one determinant to align that scope with other scopes, can have an effect on a determinant in the other scope. This could result in the problem being moved from one place to the other, and not being solved.

## 14.3. Starting the Discussion

To use the framework from this thesis, it is important to understand how the three scopes can be compared and how they can align. This is explained in the discussion in chapter 13. Before this is possible, first, the 23 determinants have to be understood. Because there are so many determinants, it can be difficult to fully grasp all of them in the first place. That is why Appendix C contains a card for every determinant to better understand them. These cards can also be used to gamify the discussion starter. In the first place, to understand why certain AECs have more difficulty being implemented in IWT, every one of these determinants is important. Among a group of interested persons, these cards can be divided so everyone individually thinks about their specific determinant(s) for any AEC. After this, the discussion can be started among the group, and while discussing the different determinants, the group will learn about the different determinants and their effect on the discussion. Once everyone understands most of the determinants, the next step could be to start applying the framework.

## 14.4. The Challenge for Large-Scale Introduction

The reason to start this research was to find out why it is so difficult to implement AECs in the IWT sector. What is the challenge of introducing them on a large scale? After interviewing experts in the sector, analyzing their responses, establishing 23 determinants, and condensing them into three scopes, the answer to this question can now be better formulated. The main reason is that it is not as simple as just improving on one determinant at a time. Only implementing more bunkering solutions, lowering on-board emissions, converting barges to electric powertrains, making more components for AECs, establishing regulations, etc.; determinants like these are not useful by themselves, unless determinants from the other two scopes also scale accordingly.

Multiple determinants need to be improved for an AEC at the same time to increase the feasibility of its implementation. All the while there are also multiple AECs. As a healthy mix needs to be established in the sector, it can be difficult to focus. Actors and stakeholders have to keep a vision through an increasingly difficult problem. To keep a clear path, the framework created in this research can be used as support. It can outline where AECs are lacking the most and where actors and stakeholders can make the biggest differences.

# 15 Reflection

Over the span of this research, the question was often asked "which energy carrier will be the one?". There is a pursuit of the one energy carrier that is going to replace diesel. In a sense, our current society has been spoiled by the existence of contemporary fossil fuels and still needs time to adjust. While this comes as no surprise, it does sometimes counteract the transition to AECs. Getting stuck by fixating on one energy carrier can result in looking right past the bigger picture. The bigger picture is a less polluting industry, preferably without adjusting society's standards too much. No-one is principally against becoming more sustainable, but when standards need to change, that becomes a barrier.

Ultimately, that is where the problem originates. The IWT sector covers a broad range of our society's demands. So broad that it has one of the largest varieties of operational profiles. It would be nearly impossible to involve all these demands with one solution. It was possible with diesel, but that does not mean that any other energy carrier will be able to do the same. Change is imminent, but the challenge will be to implement alternatives without impacting the manners of the current society. It would be so simple to just be able to implement one AEC that solves all the problems, but there is not such an alternative. At least, not yet. While anticipating this perfect alternative, the next best options need to be exploited to initiate the transition. Every step taken now is already a step in the right direction.

The next best options are the AECs which have been used in this research to establish the determinants for large-scale introduction of AECs to the IWT sector. These energy carriers will not be the only options throughout the transition towards a net-zero sector. Technology is developing rapidly and new innovations keep being added to the current system. The AECs used for this research have already been very useful in analyzing aiding and blocking factors, and barriers and opportunities. Similarly, the determinants that have been defined using these AECs can also be used to analyze future potential energy carriers. It seems that the future will hold a healthy mix of multiple AECs. The framework established in this research can be used by all actors and stakeholders to analyze any AEC in the context of IWT.

Barge owners can use the framework to analyze which AECs suit their types of barges best. Bunkering stations can use the framework to identify AECs that they could support. Terminals can analyze the framework to create opportunities for AECs at their sites. Ports can view the framework to see which AECs are most misaligned for them. Shipyards can start preparing for approaching AECs which have aligning scopes. Component suppliers can view where the biggest opportunities are for specific AECs. Regulatory institutions can use the framework to see where they can make the actor-based scope align with other scopes for AECs. Classification societies can view where requirements are posing barriers to AECs. The framework is useful for any actor in the IWT sector to view which AEC works for them and to analyze where they are misaligned to further increase uptake of any AEC.

All in all, this research and its results, the 23 determinants and the three scopes of determinants can show the bigger picture. The sector, all its actors and stakeholders should analyze this framework to understand the complexity of the energy transition and their place in it. It is not a battle of AECs, but rather it is a careful consideration of the pros and cons in order to put every energy carrier in its right place. It is up to the sector to create the healthy mix of AECs to keep facilitating their customers' demands while adhering to regulations.

The IWT sector is not the only inland transport sector. Customers could also opt for solutions like trucking or rail. Currently, there are enough reasons for many customers to choose for IWT, but the sector should remain attractive to keep it that way. If the sector does not keep up with other inland transport sectors in terms of emissions, it will become less attractive. In the long run, this could harm the entire sector. The framework established in this research can aid actors in the sector to increase the uptake of AECs by showing where adjustments should be made. If these adjustments are made in time, the sector can remain attractive to customers and maybe even flourish.

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# A Interview Guide

Date:
Place:
Interviewer: Peer Kalk
Interviewee:

## A.1. Instructions

For these interviews, companies and organisations in the inland shipping sector have been contacted with the intention of finding out what their core values are and what their stance on alternative energy carriers is. To strategically search for these answers, the questions have been split up into three different types of questions. The most in-depth questions can be asked if the interviewee has been involved in, or is currently involved in a project with alternative energy carriers. These questions are stated in subsection A.3.1. Some interviewees will not have any experience through a project, but are considering alternatives. Because they do not have one specific preference yet, questions for them are stated in subsection A.3.2. It might be the case that interviewees have no interest in alternatives at the moment. In that case, questions from subsection A.3.3 can be asked to find out why they have a certain disregard towards specific alternatives. subsection A.3.4 also states some more in-depth problems which can be mentioned when there is time left to take the conversation a bit further.

The interview always begins with an introduction, followed by an introductory question and afterwards the interview questions can be asked. Once all the questions have been asked, the interview can be wrapped up.

## A.2. Introduction

*Start with mentioning the following points:*

- My name is Peer Kalk, I am currently doing this research for my thesis in my master Management of Technology at the Delft University of Technology. I did a bachelor study in Electrical Engineering, also at the TU Delft, after which I joined a student team where we designed, built and raced a hydrogen boat. This sparked my interest in alternative energy carriers in ships and such I switched to this master and am now researching alternative energies in inland ships for my thesis.
- This was a bit about myself, I will tell a bit more about the specific research in a moment, but maybe you would like to introduce yourself as well first? [Space for interviewee to introduce themselves and have a small conversation about them]
- The research that I'm doing involves inland shipping and alternative energy carriers for this sector. I'm looking at all the major potential energy carriers for inland shipping, so that includes biodiesels, LNG, hydrogen, methanol, ammonia, batteries and flow batteries.

I'm trying to identify factors which help or hinder the large-scale introduction of these energy carriers to the inland shipping sector and therefore I'm talking to many experts in this sector to try and identify some key bottlenecks. That is why I also contacted you and I've prepared some questions which I hope you could help me with.

- *In case the interviewee has not yet consented via email:* I have not yet received consent for this interview via email. Have you received and read the informed consent form and do you consent to taking this interview? If you would prefer not to take the interview or continue with it, you are always free to say so.
- Are you okay with the audio of this meeting being recorded? That helps me to focus on the conversation.
- Before I get started asking any questions to you, do you have any questions for me?
- I have enough questions to fill the time we have, but please feel free to talk about anything you think is important to share, also if it feels like it is not within the scope of the question.

## A.3. Questions

*If you already know they have (had) a (on-going) project with alternative energy carriers, continue to subsection A.3.1 after a short conversation about the project.*

1. Does your company have ongoing projects with any alternative energy carrier? Or did you have one?
   If the answer is yes, continue to subsection A.3.1.
   If the answer is no:
2. Is your company considering any alternative energy carriers?
   If the answer is yes, continue to subsection A.3.2.
   If the answer is no:
3. There are quite some alternative energy carriers for the inland shipping sector and with upcoming regulation, chances are quite big that pure diesel will not be allowed in the future. If you would choose by deduction, which ones would you deduct first?

   - Biodiesel
   - LNG
   - Hydrogen
   - Methanol
   - Ammonia
   - Batteries
   - Flow Batteries

   Continue to subsection A.3.3.

### A.3.1. One Prioritized Alternative Energy Carrier

1. Which alternative energy carrier did you eventually pick for this project?
   (a) What were the reasons for choosing this alternative?
2. Which other alternatives did you evaluate?
   (a) What were the reasons for not choosing any of the other options?
3. Were there any problems you have had to overcome with the chosen alternative?
   (a) How did you overcome these problems?
   (b) Could something else have helped in solving these problems?
4. *Choose examples from subsection A.3.4 about their chosen alternative energy carrier*
   (a) How did you overcome this problem?
   (b) Could something else have helped in solving this problem?

5. There is some uncertainty as to the fuel prices of alternatives in the future. How do you plan on tackling this problem?
6. If any external party could have done something to have helped with the project, who or what could have helped?
7. Are there any alternatives that you would definitely not use? *Continue to subsection A.3.3.*

### A.3.2. Considering Alternative Energy Carriers

1. Which alternative energy carriers are you considering?
   (a) What would be the benefits of these alternatives?
   (b) What would be the downsides of these alternatives?
2. What are the problems that are keeping you from implementing them?
3. *Choose examples from subsection A.3.4 about any of the alternative energy carriers they are considering*
   (a) Is this a problem that is also keeping you from implementing it?
   (b) How could you solve this problem?
4. If any external party could do something to help with the implementation, who or what would help?
5. Are there any alternatives that you would definitely not use? *Continue to subsection A.3.3.*

### A.3.3. Discarded Alternative Energy Carrier

1. What were the problems with this alternative?
2. What would change your view on this alternative?
3. Could any external party do anything to make this alternative better?
4. *Use examples from subsection A.3.4 about aforementioned alternatives*
   (a) Do you consider this a problem as well?
   (b) What could be a solution to this problem?

### A.3.4. Example Problems per Alternative

Every alternative has its own problems. This list of problems per alternative will help to keep the conversation going and to go more in-depth into possible barriers.

#### Biodiesel

- Biodiesels need waste material or land to grow crops which could be used to make biodiesel. It is said that there is not enough land to grow crops for all the biodiesel we would need to fully replace diesel.
- FAME, the original biodiesel, cannot be stored for more than a few months without being used before it starts growing micro-organisms.
- Biodiesel combustion still has emissions.

#### LNG

- LNG consists mostly of methane which is a much more potent greenhouse gas than CO2 and during its production and application there is methane slip.
- LNG combustion still has emissions.
- LNG is not applied largely in inland shipping at the moment.

**Hydrogen**

- Fuel cells and hydrogen pressure tanks are expensive at the moment.
- Hydrogen storage is not very compact, meaning limited range or a lot of volume used for storage.
- Hydrogen fuel cells have lower power density.
- Fuel cells are less efficient than batteries.
- Hydrogen refueling is difficult; either need pressure lines or container swapping facilities.
- Most hydrogen produced right now is ”grey” hydrogen.
- Hydrogen is relatively expensive and the inland shipping sector is an open market, which means customers will probably not pick a more expensive option.

**Methanol**

- Methanol still emits CO2.
- Methanol fuel cells are less efficient than direct hydrogen fuel cells.
- Direct methanol fuel cells undergo CO poisoning.
- Most methanol produced right now is “grey” methanol.
- Methanol bunkering is not readily available in most ports.
- Methanol is relatively expensive and the inland shipping is an open market, which means customers will probably not pick a more expensive option.

**Ammonia**

- Ammonia is poisonous and airborne in case of leaks.
- Ammonia fuel cells are less efficient than direct hydrogen fuel cells.
- Ammonia bunkering is not readily available in most ports.
- Ammonia is relatively expensive and the inland shipping is an open market, which means customers will probably not pick a more expensive option.

**Batteries**

- Batteries are heavy.
- The amount of batteries needed to power an inland ship sum up to a large sum of money.
- There are some ethical question around battery production (sourcing, energy demand, etc.).
- Battery recharging is done through container swapping, which is not readily available in most ports.
- Some battery technologies are flammable.
- Most battery technologies degrade over time.

**Flow Batteries**

- Flow battery material, e.g. vanadium, is very expensive.
- Flow battery charging is not readily available in most ports.
- Flow batteries are not a largely developed technology.

### A.3.5. Follow-up

Who do you think I should follow up with to learn more about my questions?

### A.3.6. Wrapping Up

- Thank you for taking the time to meet with me and to share your expertise.
- Do you have any questions left for me?
- Would you like to keep updated on my progress?

# B

# Code Results

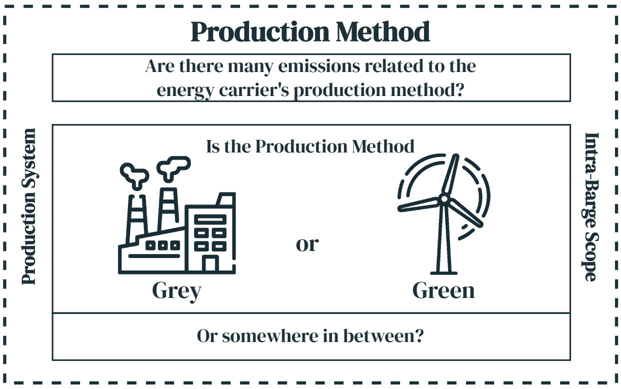
**Table B.1:** Amount of Quotations per Code

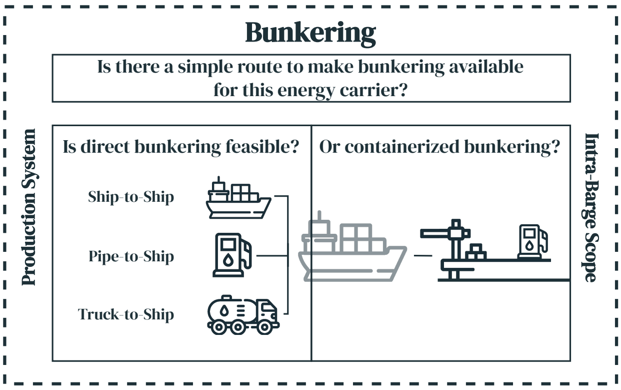
| Groups | Codes | # Quotations |
|---|---|---|
| Product Performance & Quality | | 122 |
| | Energy Demand | 58 |
| | On-board Emissions | 42 |
| | Safety | 26 |
| Product Price | | 85 |
| | Initial Cost | 34 |
| | Operational Cost | 62 |
| Production System | | 148 |
| | Bunkering | 63 |
| | Production Method | 51 |
| | Supply | 58 |
| Complementary Products & Services | | 16 |
| | Dual Fuel | 6 |
| | Electric or Combustion | 8 |
| | Energy Prices | 2 |
| Network Formation and Coordination | | 45 |
| | Collaboration | 10 |
| | Component Suppliers | 20 |
| | Shipyards | 3 |
| | Terminals | 14 |
| Customers | | 135 |
| | Acquaintance | 21 |
| | Marketing Models | 44 |
| | Operational Profile | 40 |
| | Willingness to Pay | 39 |
| Innovation-Specific Institutions | | 172 |
| | Certification | 99 |
| | Financial Support | 21 |
| | Regulation | 84 |
| | Standardization | 13 |
| | Total: | 591 |

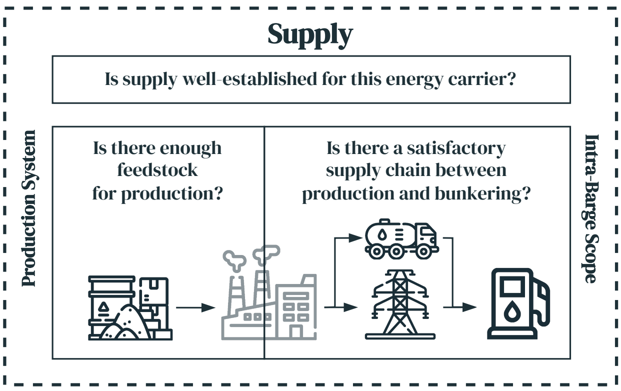
# C

# Determinant Cards

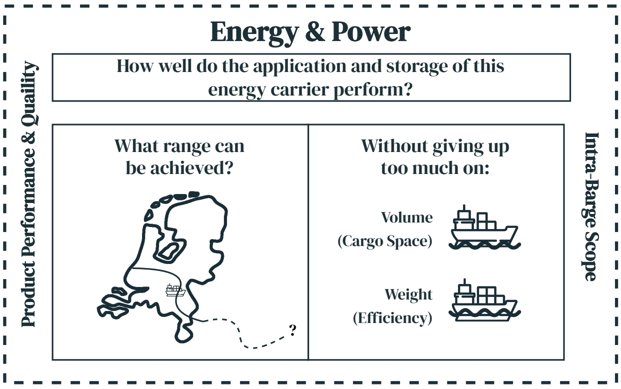
## C.1. Production System Determinants

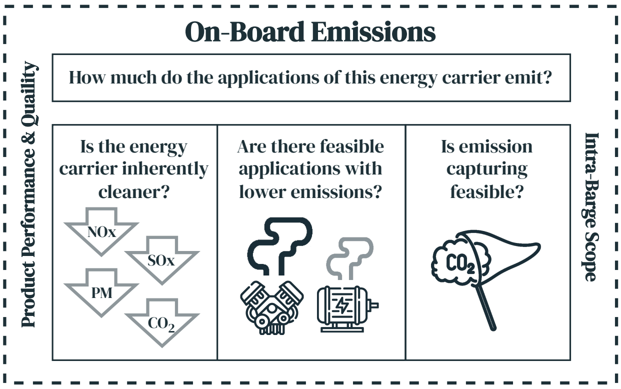


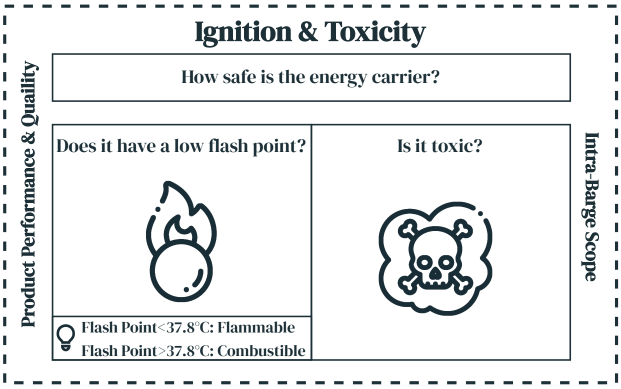



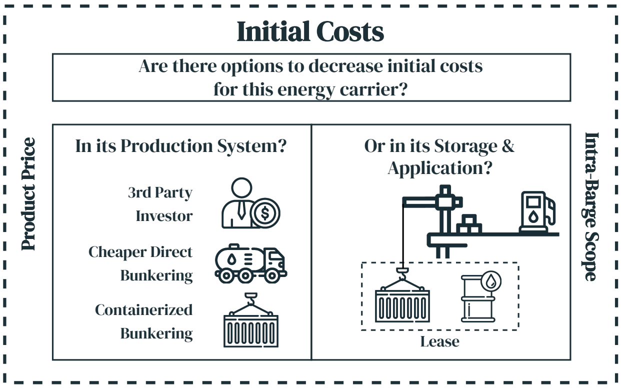
# C.2. Product Performance & Quality Determinants

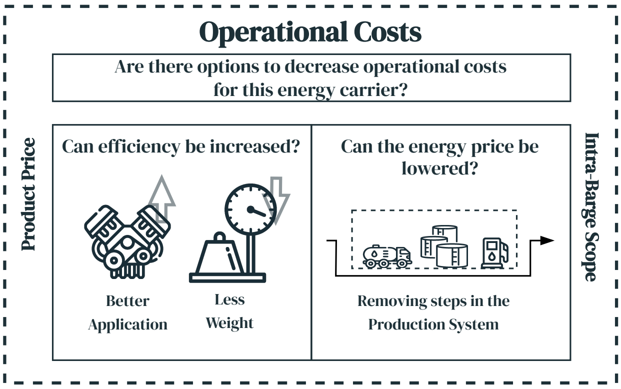


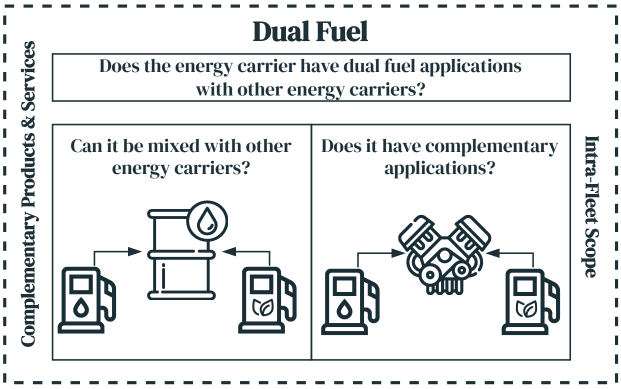



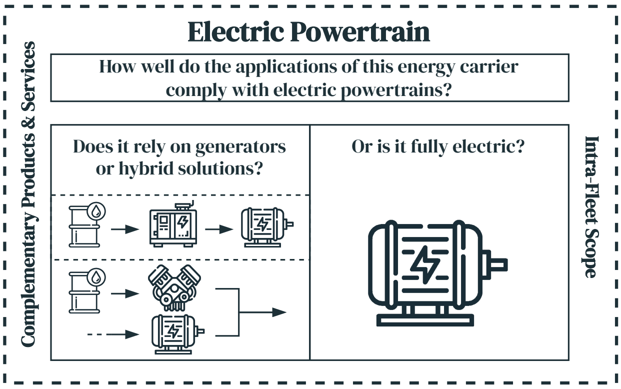
# C.3. Production Price Determinants

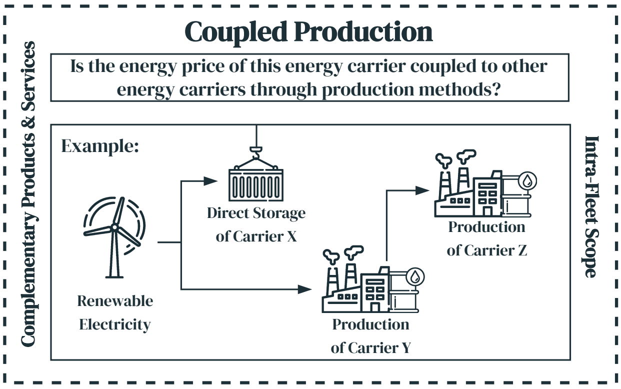


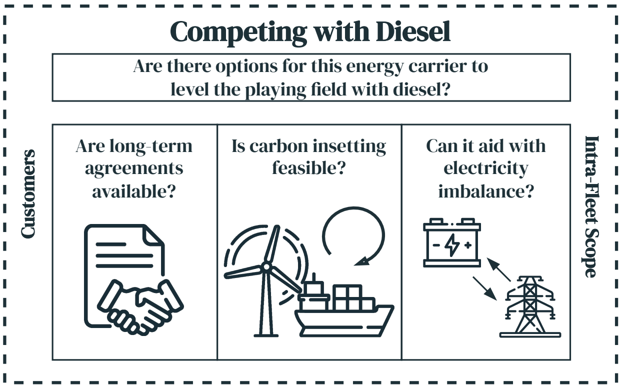
# C.4. Complementary Products & Services

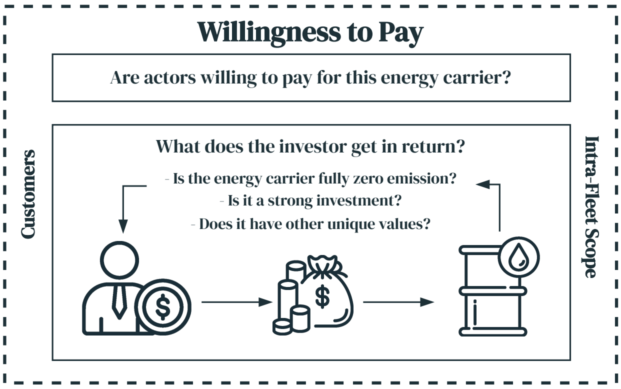


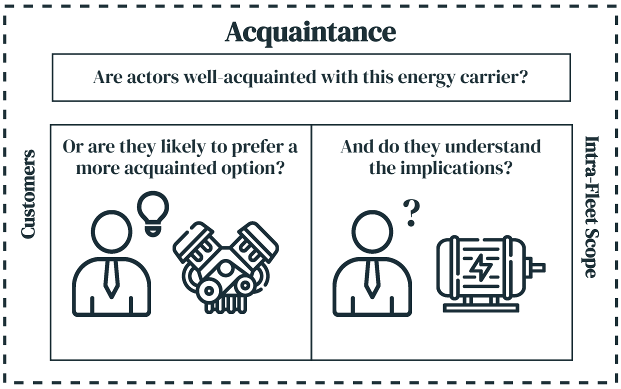



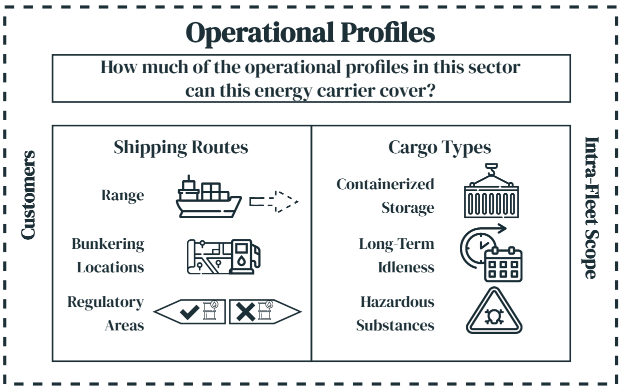



# C.5. Customers Determinants

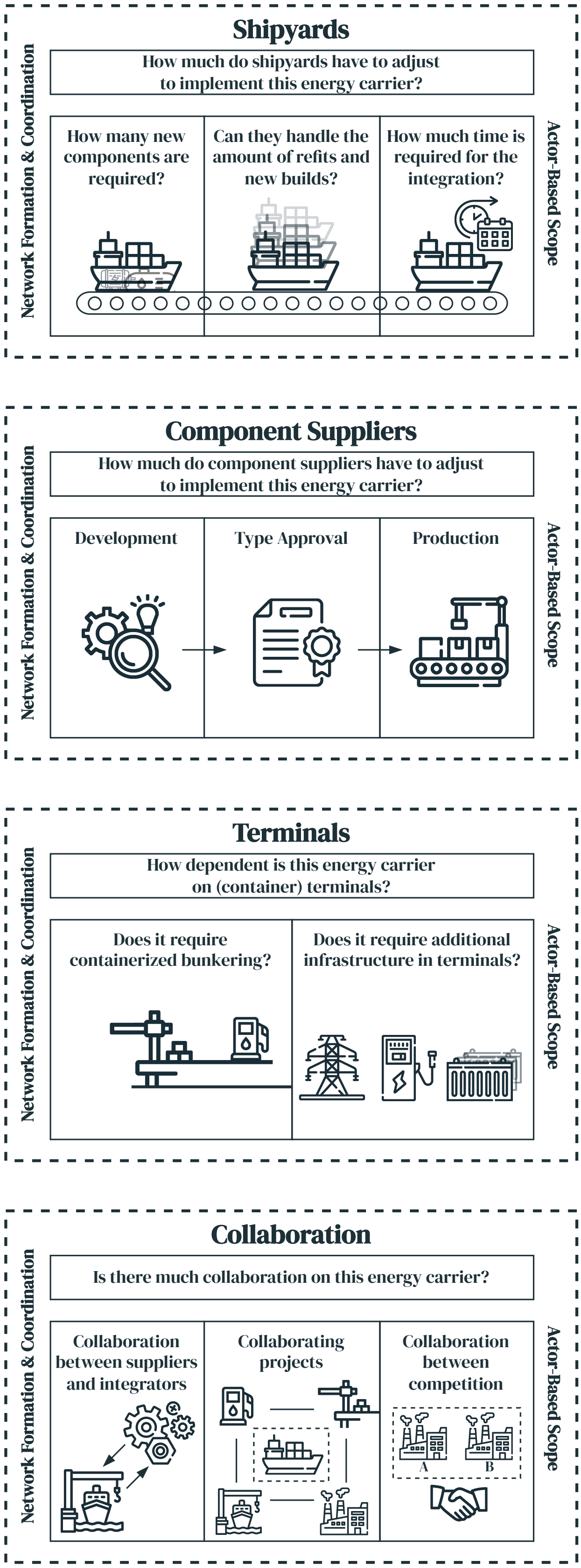


# C.6. Network Formation & Coordination Determinants



# C.7. Innovation-Specific Institutions Determinants