The feasibility of zero-emission ferries in the Wadden Sea

J.Y. Looijenga
Student nr 4513819

Chair:	Prof.dr. G.P. (Bert) van Wee	TU Delft
First supervisor:	Dr. J.A. (Jan Anne) Annema	TU Delft
Second supervisor:	Dr.ir. J.N. (Jaco) Quist	TU Delft
Company supervisor:	Ir. P. A. (Peter) Lankreijer	C-Job Naval Architects

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Jidde Yntse Looijenga

Student number: 4513819

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Graduation committee

Chairperson:	Prof.dr. G.P. (Bert) van Wee	TU Delft T&I
First Supervisor:	Dr. J.A. (Jan Anne) Annema	TU Delft T&I
Second Supervisor:	Dr.ir. J.N. (Jaco) Quist	TU Delft E&I
External Supervisor:	Ir. P.A. (Peter) Lankreijer	C-Job Naval Architects

Preface

In front of you lies my Master thesis as the final part of the master programme Management of Technology at Delft University of Technology. For me, this ends a period in my life where I had many opportunities to explore and develop many interests as a student.

Since I was a child I was interested in ships and the improvement of ship-design. As a result of this interest I finished a bachelor programme in Marine Technology, where I learned that the ship-building industry and ship-owners are not known for innovation and shipbuilding often is lacking behind compared to other industries. I am motivated to change this, and to create a more innovation-driven industry, together with other young engineers and entrepreneurs. This was one of the reasons to enrol in the master programme Management of Technology, where technology and innovation are seen as a resource towards a better and more competitive environment.

Since 2017, I worked part-time as a naval architect at C-Job, a young, innovative engineering company that designs of a wide variety of ship-types. At C-Job, I got the opportunity to perform a master thesis at a topic which I found very interesting: the potential adoption of zero-emission propulsion technologies for ferries.

During this research and interviews, the support for zero-emission innovations for ferries in the Wadden Sea surprised me. This provides a positive prospect for many innovative, interesting ship-designs in the future.
It was satisfactory to combine the technical knowledge and experience of colleagues at C-Job with the knowledge I obtained at the Management of Technology programme and place technical innovations in a broader, societal context.

I hope this research helps to create more knowledge about the possibilities of zero-emission ferries in the Wadden Sea and might help to realize successful adoption of such innovations in the future.

I would like to thank C-Job for giving me this opportunity and for providing me valuable information and contacts. First of all, I would like to thank Peter Lankreijer for the support, the help with calculations and for the meetings that often led to new ideas.
Next to that, I would like to thank my first supervisor Jan Anne Annema for his valuable advice and his positive feedback. Furthermore, I would like to thank Jaco Quist and Bert van Wee for their feedback and guidance. Also, I want to thank all interviewees and other experts that provided me with valuable information and new thoughts.

Finally, I would like to thank my friends and family for their support during the past six months and for their feedback and discussions that helped me to improve this report.

I am looking forward to a new period in my life, where I will continue at C-Job as a naval architect and hopefully can contribute to numerous innovative ship-designs.

Jidde Looijenga

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Executive summary

In 2015, the world's first sea-going battery-electric ferry was launched. This ferry, MV Ampere, was followed by several other battery-electric ferries that are operational today. This proves that zero-emission ferries are feasible, at least for these ferry crossings. In the Wadden Sea, a vulnerable area with a UNESCO world heritage status, the newest ferries are powered with less polluting fuels such as LNG and CNG. However, no initiatives for zero-emission ferries have been taken yet. Therefore, the research question of this thesis is: "What is the potential technical, economic, social, and political feasibility of zero-emission ferries in the Wadden Sea?"

To determine the feasibility of zero-emission ferries in the Wadden Sea, the political economy model for transport innovations of Feitelson and Salomon (2004) is used. This framework identified factors and agents that influence the technical, economic, social, and political feasibility of an innovation. A selection of four zero-emission innovations is analysed based on literature and experts at C-Job. These suggested innovations are battery-electric, hydrogen, methanol, and ammonia. For each innovation, two potential configurations are analysed. Diesel is used as a reference fuel.
Because the differences between ferry crossings in the Wadden Sea affect the feasibility of certain innovations, the Wadden Sea is divided into three areas: Texel, the western Wadden Sea and the eastern Wadden Sea. Each area has different characteristics and a different ferry operator is active.
Scientific literature in combination with grey literature and policy papers are used to analyse the potential feasibilities. Ferries that are currently sailing in the three areas are used to determine the energy consumption. This is used to calculate the weight and volume of the application of suggested innovations, which resulted in the required frequency of bunkering or charging.
This is complemented with input from experts from C-Job and six interviews with relevant actors. These interviews are conducted with actors with different interest and perspectives. The interviews are documented and used as sources, especially for the analysis of social and political feasibility.

The most important results of the analysis of feasibility are:

- Battery-electric propulsion is the most developed and proved technology. For Texel and the eastern Wadden Sea, a ferry can make two crossings before charging is required and only one charging station (on the mainland) is required. Although the capital expenditures (CAPEX) is relatively high and batteries have a limited lifetime, the efficiency and low operational expenditures (OPEX) make this the least costly option, with a lower Total Cost of Ownership (TCO) than diesel-powered ferries.
- Liquid hydrogen, stored at -253°C, is technically feasible for all areas. Hydrogen that is used in this study is produced with electrolysis with renewable electricity. The storage tanks are relatively heavy, and bunkering is required multiple times a week. Despite the use of efficient Proton Exchange Membrane Fuel Cells (PEMFC), the energy loss during the production of hydrogen, the liquefying process, and boil off result in a higher OPEX than the diesel reference.
- Compressed hydrogen, stored at 700 bars, has lower costs than liquid hydrogen. Nevertheless, the storage tanks are large and heavy. Only for Texel this is suitable, for the other areas bunkering multiple times a day is required.
- Methanol is technically feasible for all areas. However, due to high efficiency-losses during the production process of green methanol (produced with hydrogen and CO_2), the OPEX is high. When an Internal Compression Engine (ICE) is used, the low efficiency increases the OPEX further. The use of Solid Oxide Fuel Cells (SOFC) increases efficiency, but the OPEX remains high. SOFCs are still in an R&D phase and not available yet.

- The production of ammonia is more (energy)efficient than the production of methanol and therefore the OPEX is lower. However, the OPEX is still higher than for diesel. The use of SOFCs will be an improvement, but these are not available yet. Since ammonia is toxic, it is likely that regulations, the general public, and environmental organisations do not support this innovation in the Wadden Sea until this technology has been proven on other ships.
- All interviewees support zero-emission ferries and think society is in favour of these innovations. Nevertheless, there are several adverse characteristics of the suggested innovations that can have negative effects on social feasibility. For example, the use of rare metals for batteries, inefficient use of renewable energy and potential health risks. These characteristics must be justified to reduce the negative impact on social feasibility.
- The concession system for the western and eastern Wadden Sea areas can be used as a policy tool to stimulate zero-emission ferries. However, the new concession period starts in 2029 and the influence on ferries that are built before this new concession is questionable. This study includes a model that visualises the windows of opportunity and the influence that actors have on the decision for potential zero-emission ferries.

Overall, it can be concluded that zero-emission ferries in the Wadden Sea are feasible in a technical, economic, social, and political perspective. However, there is a difference in feasible innovations per area and not all suggested innovations are feasible (yet) for each area.

This thesis focuses on the broad feasibility of zero-emission ferries in the Wadden Sea. However, for the application of one zero-emission technology for one specific ferry, additional and more specific studies are required. For battery-electric ferries, the strength and potential reinforcements of the local electricity grid should be studied. The costs of reinforcements of the electricity grid, other than the local charging infrastructure, are not included in the scope of this study.

Several recommendations are made which can support the adoption of zero-emission ferries and to improve the decision-making process:

- An efficient and low-weight ferry design will reduce the energy demand and increase the feasibility of some zero-emission technologies for Wadden Sea ferries. Secondary energy sources such as solar panels can meet a part of the energy demand.
- Communication will be important to increase the feasibility of zero-emission ferries. All interviewees support the development of zero-emission ferries. However, the concession system can result in a situation where a window of opportunity is missed due to a lack of available information. This might be the case when a ferry operator has to meet demands from a concession, but the demands of the next concession are not available when new ferries are acquired.
- Due to the visibility of ferries in the Wadden Sea, zero-emission ferries can be used to highlight the environmental importance of the Wadden Sea and the UNESCO world heritage status.

A window of opportunity for zero-emission ferries in the Wadden Sea might open in the coming years. Wagenborg Passagiersdiensten is planning to start the replacement process for ferries in the eastern Wadden Sea to replace ferries soon. Also, TESO will replace a ferry for Texel in approximately 2031 and will determine design criteria several years before this. A specific study to determine feasibility in combination with specific design criteria can improve the chance that this window of opportunity is used to introduce zero-emission ferries in the Wadden Sea.

Samenvatting (Dutch)

In 2015 werd de eerste batterij-elektrische veerboot ter wereld te water gelaten. Deze veerboot, de Ampere, is sindsdien opgevolgd door een reeks aan emissieloze veerboten die momenteel gebruikt worden. Dit bewijst dat emissieloze veerboten haalbaar zijn, in ieder geval op de locaties waar ze nu gebruikt worden. Voor de Waddenzee, een kwetsbaar gebied dat benoemd is tot UNESCO-werelderfgoed, zijn de nieuwste veerboten uitgerust met motoren die varen op (relatief schoon) aardgas, in de vorm van LNG en CNG. Hoewel dit een verbetering is t.o.v. diesel, zijn er nog geen initiatieven genomen voor emissieloze veerboten. De onderzoeksvraag voor deze scriptie is daarom: "wat is de potentiele technische, economische, sociale en politieke haalbaarheid van emissievrije veerboten in de Waddenzee?"

Om de haalbaarheid van emissievrije veerboten in de Waddenzee te analyseren is er gebruik gemaakt van het 'political economy model for transport innovations' van Feitelson en Salomon (2004). Dit raamwerk gebruikt factoren en actoren die de technische, economische, sociale en politieke haalbaarheid beinvloeden. Met behulp van literatuur en experts van C-Job is er een selectie van vier gesuggereerde innovaties gemaakt. Dit zijn batterijen, waterstof, methanol en ammoniak. Voor elk van deze innovaties zijn twee verschillende configuraties meegenomen.
Aangezien de verschillen tussen veerbootroutes relevant zijn voor de haalbaarheid van de innovaties wordt er onderscheid gemaakt tussen drie verschillende gebieden: Texel, Waddenzee west en Waddenzee oost. In elk van deze gebieden is een andere reder actief.
Wetenschappelijke literatuur, grijze literatuur en beleidsstukken zijn gebruikt om de haalbaarheid van de gesuggereerde innovaties te analyseren. Typische veerboten die momenteel actief zijn in de Waddenzee zijn gebruikt om de energiebehoefte te bepalen en het gewicht van de energiedragers en opslagsystemen te berekenen. De frequentie van bunkeren of opladen kon hier ook uit berekend worden. Dit is aangevuld met bijdrages van experts van C-Job en zes interviews met relevante actoren. Deze interviews zijn afgenomen met actoren met diverse achtergronden met andere belangen.

De belangrijkse bevindingen van de analyse van de haalbaarheid zijn:

- Batterij-elektrische voorstuwing is het verst ontwikkeld en inmiddels bewezen technologie. Voor Texel en de oostlijke Waddenzee kunnen kunnen twee oversteken gemaakt worden voordat de batterijen opgeladen moeten worden. Één laadstation (op het vasteland) is hier dus voldoende. Ondanks dat de investeringskosten (CAPEX) relatief hoog is en de levensduur van de batterijen beperkt is, zorgen de lage operationele kosten (OPEX) (door een hoog rendement en lage electriciteitsprijs) voor lage totale kosten (TCO). De totale kosten zijn lager dan voor referentiebrandstof diesel.
- Vloeibaar waterstof, gekoeld tot -253 °C, is technisch haalbaar voor alle gebieden. Voorwaarde voor deze studie is dat de waterstof geproduceerd is door middel van elektrolyse met hernieuwbare elektriciteit. De tanks die nodig zijn voor vloeibare waterstof zijn relatief zwaar en bunkeren zal meerdere keren per week nodig zijn. Ook met een efficiente Proton Exchange Membrane Fuel Cell (PEM FC) is het energieverlies tijdens de productie, koelen en de boil-off groot, wat resulteerd in een hogere OPEX dan voor referentiebrandstof diesel.
- Gecompresseerde waterstof, onder een druk van 700 bar, is goedkoper dan gekoeld waterstof. Echter zijn de tanks hiervoor zwaarder en is dit alleen een mogelijkheid voor Texel. Voor de

andere gebieden kan een tank het het maximale gewicht niet voldoende waterstof voor één dag meenemen.

- Methanol is technisch haalbaar voor alle gebieden. Echter, door de hoge energieverliezen tijdens de productie van methanol uit waterstof en CO_2 is de OPEX erg hoog. Wanneer een verbrandingsmotor met een relatief laag rendement wordt gebruikt stijgt de OPEX nog meer. Het alternatief, een Solid Oxide Fuel Cell (SOFC) heeft een hoger rendement, maar is momenteel nog niet mogelijk.
- Hoewel er bij de productie van ammoniak met behulp van waterstof en stikstof minder energieverliezen optreden dan bij methanol zijn de kosten nog steeds een stuk hoger dan bij referentiebrandstof diesel. Evenals bij methanol kunnen SOFCs het rendement verhogen, maar deze zijn nog niet beschikbaar. Doordat ammoniak giftig is, is de steun van gebruikers, milieuorganisaties en regelgeving niet vanzelfsrpekend en kan praktijkervaring op andere schepen noodzakelijk zijn voor brede steun.
- Alle geinterviewden steunen emissievrije veerboten en denken dat het grotere publiek ook deze innovaties zal steunen. Echter heeft elke gesuggereerde innovatie ook nadelen die een negatief effect kunnen hebben op de sociale haalbaarheid. Voorbeelden zijn het gebruik van zeldzame metalen voor batterijen, inefficient gebruik van (schaarse) hernieuwbare elektriciteit en een mogelijk gezondheidsriscio van bijvoorbeeld ammoniak. Deze eventuele nadelen moeten gerechtvaardigd worden om een negatieve impact op de sociale haalbaarheid te voorkomen.
- Het concessiesysteem voor alle eilanden behalve voor Texel kan gebruikt worden als middel om innovaties zoals emissievrije technologien te stimuleren. Echter zal de volgende concessie in 2029 starten en het is onduidelijk wat de invloed hiervan is op veerboten die voor de nieuwe concessie gebouwd zullen worden. Deze scriptie bevat een model waarin de ‘windows of opportunity’ en de invloed van actoren hierop gevisualiseerd worden.

Er kan geconcludeerd worden dat emissievrije veerboten in de Waddenzee haalbaar zijn vanuit een technisch, economisch, scoiaal en politiek perspectief. Tussen de gebieden zit er echter wel verschil in mogelijkheden en niet alle gesuggereerde innovaties zijn (op de korte termijn) mogelijk voor elk gebied.

Dit onderzoek is gericht op de brede haalbaarheid van veerboten in de Waddenzee, echter zal voor de toepassing van emissievrije technieken voor een specifieke veerboot meer en specifieker onderzoek nodig zijn. Vooral voor batterij-elektrische veerboten zal er specifiek onderzoek gedaan moeten worden naar de sterkte en eventuele versterkingen van het lokale electriciteitsnet. Versterkingen van het electriciteitsnet buiten de directe aanlegplek zitten niet in de scope van deze studie.

Enkele aanbevelingen die voortkomen uit deze scriptie zijn:

- Een licht en efficient scheepsontwerp kan de energiebehoefte van veerboten verlagen en de haalbaarheid van verschillende emissievrije systemen vergroten. Ook ondersteunende systemen zoals zonnepanelen kunnen een deel van de energiebehoefde voldoen.
- Communicatie zal van belang zijn om de haalbaarheid van emissievrije veerboten te vergroten. Door het concessiesysteem kan de situatie ontstaan dat ondanks dat alle partijen voorstander zijn, er een gebrek aan informatie is en er ‘windows of opportunities’ gemist worden. Dit kan bijvoorbeeld zo zijn als de reder zich moet baseren op de concessie eisen, maar schepen vernieuwd worden voordat de nieuwe concessie er is.

- Doordat veerboten erg zichtbaar zijn, kunnen emissievrije veerboten gebruikt worden om de bijzonderheid van het gebied en de UNESCO werelderfgoedstatus te benadrukken.

Het is goed mogelijk dat er op korte termijn een ‘window of opportunity’ voor emissieloze veerboten opent. Wagenborg Passagiersdiensten wil voor de oostelijke Waddenzee binnenkort het proces starten voor het vervangen van schepen. Ook TESO wil rond 2031 een schip vervangen en aangezien een vervangingsproces jaren duurt zullen de ontwerpeisen jaren van te voren bekend moeten zijn. Specifieke studies om de haalbaarheid van emissievrije technieke in combinatie met specifieke ontwerpeisen kunnen de kans dat deze ‘window of opportunity’ benut wordt vergroten.

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List of abbreviations

BV	Bureau Veritas
CAPEX	Capital Expenditures
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
DoD	Depth of Discharge
DNV-GL	Det Norske Veritas – Germanischer Lloyd
ECA	Environmental Control Area
FC	Fuel Cell
GHG	Greenhouse Gas
GO	Guarantee of Origin (certificate)
HFO	Heavy Fuel Oil
ICE	Internal Combustion Engine
IMO	International Maritime Organisation
LH2	Liquid Hydrogen (H_2)
LNG	Liquified Natural Gas
LR	Lloyd's Register
MDO	Marine Diesel Oil
MLP	Multi-Level Perspective
NGO	Non-Governmental Organisation
NMC	Nickel Manganese Cobalt oxide (batteries)
NOx	Nitrogen Oxides
OPEX	Operational Expenditures
PEMFC	Proton Exchange Membrane Fuel Cell
PM	Particulate Matter
SOFC	Solid Oxide Fuel Cell
SOx	Sulphur Oxides
TA	Technology Assessment
TCO	Total Cost of Ownership
WPD	Wagenborg Passagiersdiensten

1 INTRODUCTION

1.1.1 *Emission reducing developments the shipping industry*

Despite being an energy-efficient way of transport, the shipping industry is a source of emissions. Just like other industries, there is an increasing demand for a less polluting shipping industry (International Maritime Organisation, 2018b).

The design efficiency of new ships has improved significantly over time, with fuel prices as the major driver. These changes in efficiency were mostly the results of changes in hull and propeller design (Faber, ’t Hoen, Vergeer, & Calleya, 2016). Also, efficiency improvements in machinery such as the main engines contributed to the overall efficiency and fewer emissions. Another example of the reducing fuel demand for vessels is the instalment of wind assistance systems such as the Flettner Rotor or towing kites, although these systems depend on weather and route and are not widely used yet (Rehmatulla, Parker, Smith, & Stulgis, 2017; Traut et al., 2014). However, reducing the hull resistance and other solutions for a lower energy demand have their limits (Makkonen, Inkinen, & Saarni, 2013).

Another option to reduce emissions in the shipping industry is by switching to alternative fuels. Traditional fossil fuels used in the maritime industry are Heavy Fuel Oil (HFO) for ocean-going vessels and Marine Diesel Oil (MDO) used by for example coastal vessels. Regulations such as the introduction of Environmental Control Areas (ECAs) have led to the adoption of less polluting fuels (such as Liquified Natural Gas) in specific areas (Herdzik, 2011). Liquified Natural Gas (LNG) and Compressed Natural Gas (CNG) are used as ‘cleaner’ fuels since these fuels contribute fewer local pollutants than traditional fuels. CNG and LNG are compatible with a range of standard marine engines, which makes it possible to switch between fuel types and reduces the risks and costs (Hoang & Pham, 2018; Verbeek et al., 2013). However, these fuels are not renewable and still produce greenhouse gasses (GHGs), such as CO_2.

To completely phase out both local emissions and GHGs, zero-emission propulsion systems are required. Renewable energy can be stored in a liquid such as hydrogen, ammonia, or methanol. The shipping industry has experience with the transport of these liquids, but these systems are not widely used as a fuel. Another type of energy carrier are batteries, which are used in a battery-electric propulsion system (Balcombe et al., 2019; Dale, Hebner, & Sulligoi, 2015).

However, zero-emission systems have some disadvantages which makes it very difficult to apply on sea-going vessels. The most important is the limited operational range, most alternative energy carriers require much more volume than traditional fuels, which is an issue on cargo vessels, because it replaces cargo space and therefore affects the productivity of these vessels. For some vessels, a limited range is not a problem, for example workboats and ferries (DNV-GL, 2018).

1.1.2 *Zero-emission ferries*

Within the maritime industry, ferries proved to be a suitable niche to start with the development of sustainable propulsion systems. There are multiple reasons for this:

Ferries are often designed for a specific area and since most times they only sail one specific route, they often do not require a large operational range. Also, there is often enough space left for machinery and storage systems inside the ship (ITF, 2018). Often, ferries are sailing in sensitive areas such as cities or nature reserves.

The first battery-powered ferry, called MV Ampere, was launched in 2015 in Norway and is operating in a fjord that is part of a protected UNESCO world heritage area (Lambert, 2018). Several new battery-powered ferries have been launched since, for example MV Ellen, which has currently the largest range (Leclanché, 2019). Also, there are some ferries that are converted from diesel to battery-electric, for example two ferries sailing between Denmark and Sweden (ITF, 2018). In the Netherlands, several smaller hybrid ferries are sailing in the Amsterdam area. These vessels do have a diesel engine, although this is only for special occasions, such as sailing in bad weather or when they are sailing outside their standard route.

1.1.3 *Wadden Sea ferries*

This study will focus on the feasibility of zero-emission ferries in the Wadden Sea. In 2009, this area became part of the UNESCO world heritage, just like the Norwegian fjords (UNESCO, 2018). In the Netherlands, there are five ferry routes that connect the habited islands with the mainland. The unique vulnerable environment makes this an area where sustainability is important. Recently built ferries use alternative fuels such as CNG and LNG. However, zero-emission ferries similar to the operational zero-emission ferries in Scandinavia are not present yet.

As examples have shown, zero-emission ferries are technically feasible for the situations where they currently exist. However, as a quick comparison of existing zero-emission ferries (Table 1) and operational Wadden Sea ferries (Table 2) shows, the Wadden Sea ferries have a relatively high capacity and some routes have relatively high route distance. Furthermore, the situation of infrastructure and availability of energy is different. Therefore, the technical feasibility of zero-emission Wadden Sea ferries is uncertain on this moment.

For Wadden Sea island citizen, the ferries are a crucial connection to the mainland. To guarantee enough (unprofitable) departures in wintertime, the Dutch government licenses ship-owners and give them a monopoly position in return (Ministerie van I&M, 2011a, 2011b). Nevertheless, the ship-owners are commercial parties. The relationships between multiple types of government, the ship-owners and users of the ferries can therefore be complex and result in difficult decision-making processes (Muconsult, 2019). Furthermore, there are several interest groups that have different interest in sustainable transportation in the Wadden Sea.

Table 1; Summary of zero-emission ferries (Hall et al., 2018)

Technology	Vessel	PAX	Vehicles	Route length (km)	Into service
Battery-electric	Ampere	360	120	5,6	2016, Norway
Battery-electric	Elektra	-	90	1,6	2017, Finland
Plug-in hybrid	Vision of the Fjords	400	-	36	2017, Norway
Battery-electric	Tycho Brahe	1250	500	4	2018, Denmark
Battery-electric	Ellen	200	30	40	2019, Denmark

Table 2; Summary of operational Wadden Sea ferries

Island	Vessel	PAX	Vehicles	Route length (km)	Into service
Texel	Texelstroom (2)	1750	350	5	2016
Vlieland	Vlieland	950	50	36,2	2004
Terschelling	Willem Barentsz	600	66	40,6	2020
Ameland	Oerd	1200	72	12,8	2003
Schiermonnikoog	Rottum	1000	48	11	1985

1.2 Knowledge gap & problem statement

1.2.1 *Knowledge gaps*

The majority of research concerning zero-emission propulsion systems for the maritime industry is focusing on technologies such as batteries (Dale et al., 2015), hydrogen (Møller, Jensen, Akiba, & Li, 2017), and ammonia (Giddey, Badwal, Munnings, & Dolan, 2017). None of these papers is focusing on the maritime industry as a whole and none of those papers is focusing on ferries alone. Although some of these technologies are not realized on ferries yet, there is literature that describes recent developments in sustainable maritime projects. Olmer et al. (2017) sketch an overview of the current status of zero-emission ferries, where they indicate that most zero-emission ships today are operating in northern Europe, especially in Norway. Policy measures and the availability of cheap renewable electricity are two factors that are mentioned to explain this (Olmer et al., 2017).

The Wadden Sea is a UNESCO world heritage area, just like the Norwegian fjords where the first zero-emission ferry was introduced. Furthermore, the newest ferries in the Wadden Sea use alternative fuels (CNG and LNG), which indicates that there is a need for more sustainable ferries in the Wadden Sea.

On this moment, the technical feasibility of zero-emission ferries for the Wadden Sea is not clear. The requirements for capacity, range of operations and infrastructure differ from the existing zero-emission vessels, therefore research is required to determine the technical feasibility.

However, purely technical feasibility is a necessary but not sufficient condition for an innovation to be adopted (Feitelson & Salomon, 2004). An innovation will be adopted only if it is seen as technically, economically, socially and politically feasible. Design changes that are required for the technical feasibility affect the cost price of such vessels. This, together with for example operational costs, and the availability and costs of electricity are relevant for the economic feasibility, which is not clear at this moment. The social and political feasibility is a result of the perception of the need for these ferries by the public at large, the users and the relevant experts and policymakers.

To summarise, most studies focus on specific technologies, often for a wide range of ship types. There are studies that are describing the zero-emission ferries that are operational. However, most of these ferries are operating in northern Europe where several factors stimulated such developments (e.g. the availability of hydropower and government funding). Although recently built ferries in the Wadden Sea suggest that there is a need for sustainability, there are no studies that combine the technical, economic, social and political perspectives of zero-emission ferries in a context similar to the Wadden Sea. Therefore, the feasibility of such vessels in the Wadden Sea is unknown.

1.2.2 *Problem statements*

Following the introduction and knowledge gaps, the following problem statement is defined:

“Although zero-emission ferries have been introduced in Northern Europe, the technical, economic, social and political feasibility of zero-emission ferries in the Wadden Sea is unclear.”

1.3 Research objective and questions

1.3.1 *Research objective*

The aim of this study is to gather knowledge on the feasibility of zero-emission ferries in the Wadden Sea based on technical, economic, social, and political factors. The research objective is as follows:
'To gather knowledge on the technical, economic, social and political feasibility of zero-emission ferries in the Wadden Sea'

Besides this main research objective, some sub-objectives are formulated:

- To determine the conditions and implications of the transition from fossil fuel-based propulsion systems to zero-emission propulsion systems for ferry designs
- To identify barriers to the diffusion of zero-emission ferries in the Wadden Sea
- To identify developments relevant for future adaption of zero-emission ferries in the Wadden Sea.

1.3.2 *Research question*

Following the problem statement, the research question is formulated.
The research question for this thesis is:

"What is the potential technical, economic, social and political feasibility of zero-emission ferries in the Wadden Sea?"

Several sub-questions have been formulated to give guidance to the research. First, to understand the current situation, the following sub-questions are formulated:

1. Which actors are currently involved in ferry transportation in the Wadden Sea and decision-making processes concerning the purchase of new ferries?
2. Which regulations and policies are relevant for ferry transportation in the Wadden Sea and how do these affect a transformation to zero-emission ferries?

The answers to these questions provide a context for which the next sub-questions can be answered. These sub-questions are:

3. Which zero-emission propulsion systems are suitable for Wadden Sea ferries and how does the implementation of such systems affect the design of vessels and infrastructure?
4. What is the total cost of ownership of zero-emission alternatives compared to fossil fuel configurations?
5. What is the potential social and political feasibility of zero-emission ferries in the Wadden Sea?

1.3.3 *The scientific and societal relevance*

The contribution of this research is, from a scientific perspective, to address the knowledge gap in the literature in evaluating the feasibility of zero-emission ferries in a wide context. This study will identify barriers and success factors to the diffusion of zero-emission technologies for ferries and therefore contribute to the available literature concerning these technologies.
The societal relevance of this study is that it contributes to the understanding the barriers, opportunities and consequences of the implementation of zero-emission ferries in the Wadden Sea. Therefore, this study can stimulate the introduction of such vessels in this area. Furthermore, this study can be used to anticipate on required changes in the design of infrastructure and ferries.

1.4 Research scope and approach

1.4.1 *Research scope*

This research is performed as a master thesis and to be able to conduct an in-depth study, the scope is bounded by the criteria discussed below:
This study will focus on the ferries to the Dutch Wadden islands Texel, Vlieland, Terschelling, Ameland, and Schiermonnikoog. The feasibility will be determined based on the characteristics of the current ferries in the Wadden Sea. This includes capacity, speed, and installed power. It is assumed that the current ferries are optimised for their route and no new designs are made in this study. The focus of the technical feasibility is on the ferries and required infrastructure, not on the production or transportation of (liquid) zero-emission energy carriers.
Although the source of renewable energy will be discussed, this study will not include details of potential regional energy production.
The political feasibility will be determined based on existing regulations and policy, predictions on future policies will be from interviews.
The timeframe used for this study is based on the next generation of Wadden Sea ferries. Since the expected lifetime of ferries is approximately 30 years, this means that all ferries that are operational on this moment will have to be replaced by 2050. The feasibility of technologies is therefore discussed up to 2050.

1.4.2 *Research approach*

Before the research questions can be answered, a theoretical framework will be determined. This framework will be used to determine the context of the innovation of zero-emission ferries. Theories concerning socio-technical transitions, transitions and diffusion will be discussed and related to zero-emission ferries. Furthermore, innovation frameworks will be discussed and a suitable framework will be selected.
Next, the research context will be determined by analysing the current situation of ferries in the Wadden Sea. This includes an actor analysis and an exploration of relevant regulations. This will all be done by desk research.
The four types of feasibility (technical, economic, social and political) will be evaluated in the next part. This will be done by desk research and semi-structured interviews. Together, these feasibility types will be used to determine the feasibility of zero-emission ferries in the Wadden Sea. More detail about the approach of this part can be found in chapter 3 ‘methodology’.

1.4.3 *Role of C-Job*

This thesis is performed at naval architecture company C-Job. C-Job is the largest independent naval architecture firm in the Netherlands. C-Job has experience with designing sustainable ships, such as the Texelstroom, designed for TESO. C-Job is also investigating the use of zero-emission fuels such as ammonia. One of the focus markets of C-Job is ferries and therefore C-Job is interested in potential developments in this market. Although C-Job has experience with technical and economic perspectives, the firm is interested in the overall feasibility, including social and political factors.

1.4.4 *Link with TU Delft master Management of Technology program*

This thesis is the last assignment to complete the master ‘Management of Technology’. This master is based on the idea that technology is a resource that can be used to gain a competitive advantage. This master programme focuses on innovations and their potential developments in a broad perspective. In this thesis, technological innovations with a large social impact are studied in an environment where several actors (including commercial companies) influence the development of these innovations. Wadden Sea ferries are interesting because these are large investments (with a relatively long lifetime) owned by private ferry operators with a large social responsibility in a sensitive environment.

1.5 Thesis outline

After this introduction, a theoretical framework provides relevant theories that can help to answer the research question and recognize other relevant developments in chapter 2. In chapter 3, the research approach and methods are discussed. This is followed by chapter 4, where the legal structure, regulations and policies of the Wadden Sea ferries are discussed. Chapter 5 describes the technical feasibility of zero-emission Wadden Sea ferries. In chapter 6, the economic feasibility is discussed. In chapter 7, the social feasibility is discussed and in chapter 8, the political feasibility is described.
In chapter 9, an overview of the results is presented. At last, chapter 10 will conclude and discuss the results and the analysis of this study.

2 THEORETICAL FRAMEWORK

To identify relevant factors that determine the potential adoption of zero-emission propulsion systems for ferries, the broader context of socio-technical transitions and innovation diffusion is sketched. Relevant theories will be used as a basis for the feasibility study.

Most papers are discussed during the curriculum of the TU Delft master Management of Technology or are referenced in papers discussed during the curriculum. The theory is divided into four paragraphs: socio-technical transitions, transition phases, diffusion theory, and innovation frameworks.

2.1 Socio-technical transitions

2.1.1 *Socio-technical systems and transitions*

Geels (2012) labels a configuration of elements that include technology, policy, markets, consumer practices, infrastructure, cultural meaning and scientific knowledge as socio-technical systems. The elements in socio-technical systems are maintained, reproduced and changed by various actor groups. Geels (2012) indicates major shifts in socio-technical systems as socio-technical transitions. A transition is a process of structural system change and typically has a duration of at least 25 years (Meadowcroft, 2009; Rotmans, Kemp, & van Asselt, 2001).

According to Rip & Kemp (1997) technology is organized as 'a configuration that works'. These configurations cannot easily be bounded from the rest of society since things and skills are part of routines, of patterns of behaviour and of organizations. Because regulations, user practices, infrastructure, and maintenance networks are aligned with existing technology, it is difficult for radically new technologies to break through (Geels, 2002).

Rip (1995) suggest that in socio-technical systems, a so-called 'regime' is present in which organizations and other (societal) actors, technical, organizational, and social aspects are aligned. These regimes use a coherent set of rules and know a dynamic kind of stability. This means that innovation occurs with an incremental nature (Geels, 2002). Socio-technical systems are in general path-dependent.

A socio-technical regime is located in a socio-technical 'landscape', an external structure or context for interactions of actors. A socio-technical landscape changes even more slowly than regimes (Geels, 2002; Rip & Kemp, 1997). Usually, regimes generate incremental innovations. Radical innovations are generated in niches. These niches are protected from market selection in the regime (J. Schot, 1998).

According to Kemp et al. (1998) especially sustainable technologies face the barrier of long development times, uncertainty about market demand and social gains, and the need for change at different levels. They describe how a niche can be created and managed for a promising technology.

2.1.2 *Multi-level perspective*

In order to understand large scale transitions to new transport systems Geels (2012) applies the Multi-Level Perspective (MLP) framework. In this perspective, three levels are distinguished, the macro, meso and micro levels. The macro-level includes exist of socio-technical landscapes, the meso level exists of socio-technical regimes and the micro-level includes niches where radical innovations can develop (Geels, 2002).

As can be seen in Figure 1, the three levels described by Geels (2002) can be illustrated as a nested hierarchy. The niches are embedded in the regimes, which are embedded in landscapes. According to Geels (2002) *"niches are crucial for technological transitions, because they provide the seeds for change"* (p. 1261).

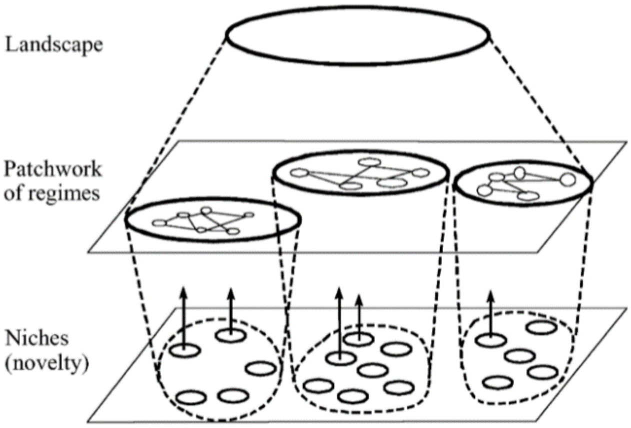


Figure 1; Multiple levels as a nested hierarchy (Geels, 2002).

2.1.3 *Windows of opportunity*

Regimes often find it difficult to compete in an existing regime. However, sometimes a regime is open for innovations from a niche. Such a 'window of opportunity' might occur when a regime is destabilized by (external) pressure (Turnheim & Geels, 2012). According to Turnheim and Geels (2012), policy change is one of the important sources of destabilization. Policies can directly support innovations (e.g. subsidies) or indirectly by changing the economic conditions (e.g. taxes, import restrictions, regulations).

2.1.4 *Lock-in*

According to Arthur (1989), modern, complex technologies display increasing returns to adoption. In other words: the more experience is gained with a technology, the more they are improved. This technology may then improve more than competing technologies. The result is that the system that is based on the dominant technology is locked-in, while alternative technologies are locked-out.

Unruh (2000) studied the lock-in of fossil fuel-based technological systems, also known as 'carbon lock-in'. In this study, technological systems and institutions are linked and named the 'Techno-Institutional Complex' (TIC). According to Unruh (2000), the carbon-based TIC is possibly the largest techno-institutional systems in history. The lock-in of carbon-based TIC locked out alternative carbon-saving technologies and are a barrier to the diffusion of these technologies.

2.1.5 *Innovation in the maritime industry*

Traditionally, the maritime industry is less permeable to innovation, compared to other industries (Jenssen & Randoy, 2002). According to Doloreux and Malancon (2008), high development costs and strict industry regulations have been discouraging companies in the maritime industry from innovating. However, more recently there has been a change, where the maritime industry believes that innovations are necessary to achieve the demands for increasing efficiency, safety and protection of the environment (Perunovic & Vidic-Perunovic, 2011).

Innovation in the maritime industry has traditionally been based on incremental innovations where new ships are based on previous successful designs (Perunovic & Vidic-Perunovic, 2011). Such incremental change is described by Lindblom (1959) as 'muddling through'.

2.2 Transition phases

2.2.1 *Multi-phase*

Besides multiple levels, technological transitions are characterized by multiple phases. One can recognize a distinction between four phases; the predevelopment, the take-off, the acceleration, and the stabilization phase (Rotmans et al., 2001). Each phase corresponds with roles for actors (Loorbach, 2010). In the first phase, the predevelopment phase, there is a dynamic equilibrium where the status quo does not visibly change. After that, the process of change gets underway in the take-off phase. This is followed by a breakthrough phase where visible structural changes take place. Socio-cultural, economic, ecological and institutional changes react to each other. In the final phase, the stabilization phase, the speed decreases and a new dynamic equilibrium is reached. The phases are visualized in Figure 2.

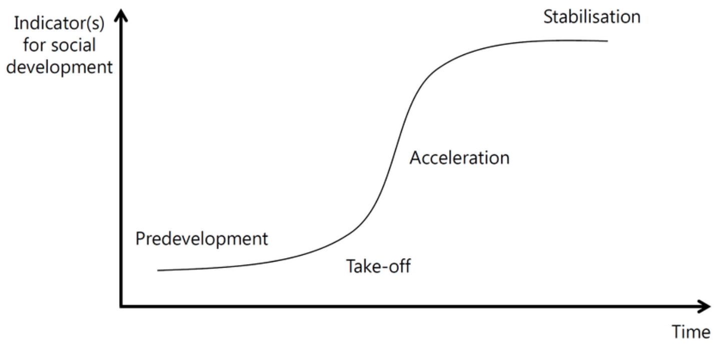


Figure 2; Four phases of transition (Rotmans et al., 2001)

2.2.2 *Multi-actor*

In transitions and transition management, multiple actors are involved (Loorbach, 2010; Meadowcroft, 2009) According to Geels (2012): *"The elements in socio-technical systems are maintained, reproduced and changed by various actor groups (e.g. firms and industries, policymakers and politicians, consumers, civil society, engineers and researchers".* (p. 471).

Rotmans et al. (2001) discuss the role of government in transition management. They argue that the role of government should be leading, although the role depends on the type of government (national, regional or local) and the phase of the transition process. Rotmans et al. (2001) argue that: *"the role of the government in transition management is in fact twofold: to realize certain content objectives such as CO_2 reductions (the content role) and to make sure that the process of variation-selection is working (the process role)"* (p. 26). Loorbach (2010) stresses that these roles are complementary.

2.2.3 *Dynamic multi-level perspective framework*

As discussed in the previous paragraphs, socio-technical transitions consist of multiple phases, on multiple levels where multiple actors are involved. Geels (2002) combined these perspectives in the multi-level perspective framework illustrated in Figure 3. Geels (2002) distinguished seven dimensions in the socio-technical regime: technology, user practices and application domains (markets), the symbolic meaning of technology, infrastructure, industry structure, policy and techno-scientific knowledge. As discussed before, these dimensions are linked. However, they have also internal dynamics, which may result in tensions that may weaken the linkages. Weak linkages may result in a window of opportunity for radical innovations to break out of the niche-level.

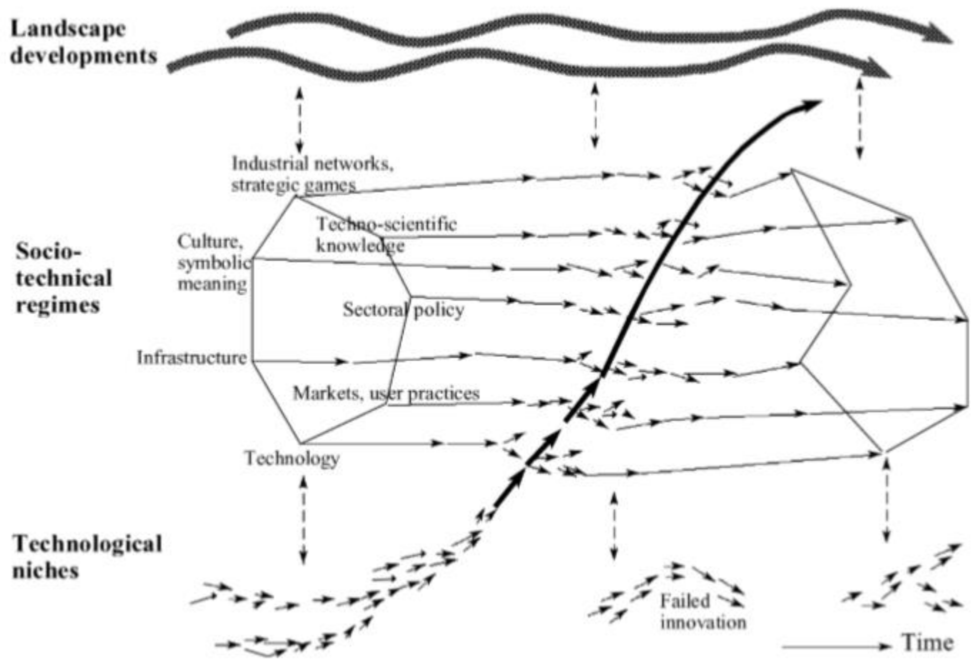


Figure 3; A dynamic multi-level perspective on technological transitions (Geels, 2002)

2.3 Diffusion theory

2.3.1 *Diffusion of innovations*

The diffusion of an innovation is described by Rogers (1995) in his book 'Diffusion of Innovations'. Rogers argues that the diffusion of an innovation is the gradual adoption by a society or the market. According to Rogers (1995), the adoption of innovation generally follows a normal, bell-shaped curve when plotted over time on a frequency basis. When the number of adopters is plotted cumulative, the result is an S-shaped curve. Both curves are illustrated in Figure 4.

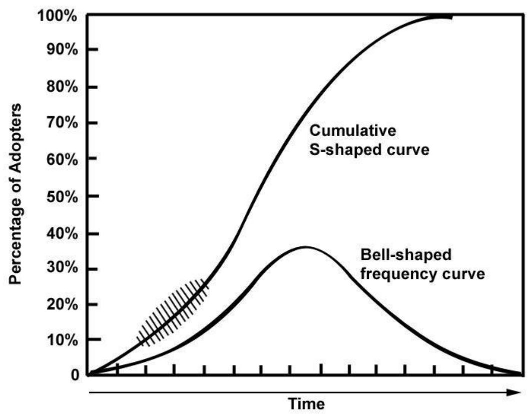


Figure 4; Curves for adopter distribution (Rogers, 1995)

Rogers (1995) says: *"The s-shaped adopter distribution rises slowly at first when there are few adopters in each time period. It then accelerates to a maximum until half of the individuals in the system have adopted. It then increases at a gradually slower rate as the few remaining individuals finally adopt. This s-shaped curve is normal. Why? The reasoning rests on the role of information and uncertainty reduction in the diffusion of an innovation."* (p. 244). Following this reasoning, Rogers (1995) divided the curve into categories based on a standardized percentage of adopters, which are: innovators (2.5%), early adopters (13.5%), early majority (34%), later majority (34%), and laggards (16%).

2.3.2 *Pre-diffusion phase*

Although the theory of Rogers is accepted as a mainstream theory of diffusion research, Ortt (2010) noticed that it focusses mainly on the diffusion rather than on the development of products. According to Ortt (2010), there is a lack of attention to the pre-diffusion period, which seems to imply that large-scale diffusion starts directly after the market introduction. However, in practice the S-shaped diffusion curve of Rogers (1995) starts several years after the first attempt to introduce a product in the market (Ortt & Schoormans, 2004).

Ortt (2010) introduced three phases: the innovation phase, the adaption phase and the market stabilization phase, illustrated in Figure 5.

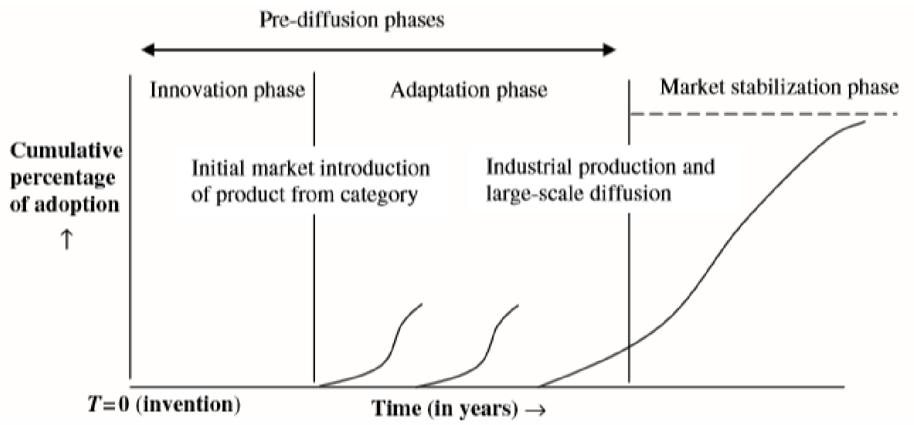


Figure 5; The pattern of development and diffusion of high-tech product categories (Ortt, 2010)

Between these phases, there are three milestones: invention, introduction and large-scale production and diffusion. The duration of the phases can vary considerably, and phases may even disappear. Also, the entire process can break off at each phase. Ortt (2010) sketches three scenarios after the invention of a technology: a long innovation phase after the invention, a long adaption phase after the invention (with unsuccessful attempts to diffusion) and large-scale diffusion directly after the invention.

2.3.3 *Valley of death*

Markham et al. (2010) describe that in the front end of product development, a relative lack of resources and expertise exist between the discovery of a new product and the commercialization. This is known as the 'valley of death'. Although the paper of Markham et al. (2010) mainly discuss this gap on a firm-level as the gap between R&D and a commercial business unit. However, the valley of death has also been used to describe the gap between governmental and private funding of renewable energy technologies (Murphy & Edwards, 2003).

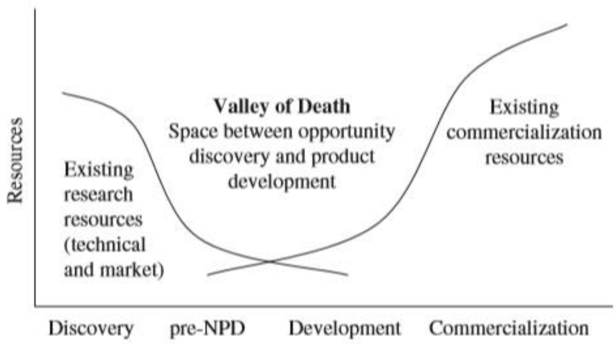


Figure 6; Valley of death (Markham et al., 2010)

2.4 Innovation frameworks

The main framework that is used for this study is the ‘political economy model for transport innovations’ of Feitelson and Salomon (2004). The four types of feasibility that are part of this model are used to determine the feasibility of zero-emission ferries in the Wadden Sea. However, there are some limitations of this model, and therefore other frameworks are discussed and some aspects of these frameworks are adopted into the political economy model.

2.4.1 *Political economy model for transport innovations*

The political economy model for transport innovations introduced by Feitelson and Salomon (2004) suggests that *‘an innovation will be adopted only if it is seen as technically, economically, socially and politically feasible’* (p. 15). The model focuses on actors and factors that influence the chance of widespread technological diffusion in society. The model is shown in Figure 7.

According to Feitelson and Salomon (2004), two groups advance transportation innovations. The first group is the industry, driven by a profit motive. The second group is composed of experts and professionals, also known as ‘policy entrepreneurs’ who advance various policy suggestions in which they believe. These ideas may become policy when ‘policy windows’ occur.

Technical feasibility is the first condition that is required for an innovation to be adopted. Technical feasibility is often determined by experts. Economic feasibility is not shown in the model in Figure 7, although it is mentioned as a separate feasibility in the paper of Feitelson and Salomon (2004). For economic feasibility, the benefits must outweigh the costs. If an innovation can not pass a benefit-cost criterion it is unrealistic from a societal perspective.

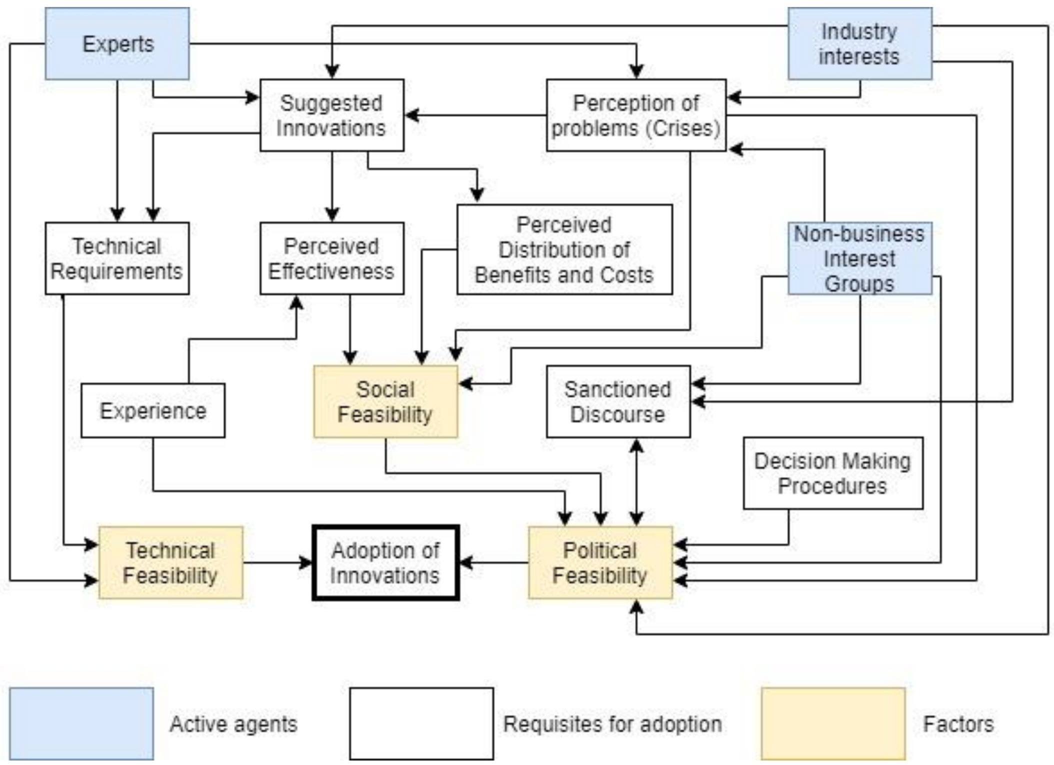


Figure 7; Political economy model for transport innovations (Feitelson & Salomon, 2004)

Social feasibility is suggested to be a combination of the public perception of problems and the perceptions of the effectiveness of the suggested innovation in solving these problems (Rienstra, Rietveld, & Verhoef, 1999). These perceptions are based on similar systems or policies. Policy entrepreneurs and (environmental) interest groups can affect the public perceptions by publications and media appearances. They do so by changing the 'sanctioned discourse'. This discourse is sanctioned by decision-makers as politically feasible. This sanctioning is a combination of dominant ideologies, and the perception of elites and media of what is publicly acceptable.

For political feasibility, social feasibility is an important factor because politicians do take account of the preferences of voters. However, for most transport investments the general public does not vote directly. Assuming that politicians want to be re-elected, other factors are relevant as well. For example, the support of interest groups for financial reasons or to avoid being the object of potential negative publicity that interest groups can create. Also, politicians often try to receive the maximal positive exposure, for example by supporting the most visible projects to areas where potential support groups are located. At last, politicians try to accomplish this at minimal costs (at least for their support groups).

This framework is very suitable for this study, because it focuses on political and social factors too and not only on technical factors. Furthermore, this model is specifically made for transport innovations and the complex decision-making structure that is involved.

A limitation of this framework is that it is static, changes over time are not included in the framework. Furthermore, although this model includes factors such as 'perceived effectiveness', and 'perceived distribution of benefits and costs', there is no factor that includes negative aspects of the suggested innovations.
Therefore, other frameworks are discussed in the next sections.

2.4.2 *Technology Assessment*

Technology Assessment (TA) is a framework that is used to explore technological advances and the effects that innovations have on society. Such effects in society include societal, social and environmental effects which might be of an adverse nature.
First, TA was developed as an 'early warning' to negative consequences of technological developments. This is especially important for cases that are 'path-dependent', because choices early in the process have large consequences for future developments. Nowadays, TA has other functions such as a decision-making tool where technologies are presented as alternative options.
Schot (1992) describes another form of TA, Constructive Technology Assessment (CTA). CTA focuses on the steering of internal developments of technology. In his paper, Schot (1992) includes a quasi-evolutionary model based on variations, selection and linking of technologies. The government can act as 'game' regulator.
Although TA is not used as the main framework, the negative consequences of technological developments will be discussed as part of the social feasibility in this study. The factor 'perceived effectiveness' of the suggested innovation is complemented with potentially negative consequences that can affect the social feasibility.

2.4.3 *Functions of innovation systems*

The functions of innovation systems theory is introduced by Hekkert et al. (2007). In their paper (2007) Hekkert et al. describe that the emergence of an innovation system and changes in innovation systems that already exist co-evolve with the process of technological change. This theory focusses on several processes that are relevant for well-performing innovation systems, which they named 'functions of innovation systems'. The theory pays attention to the idea that innovation processes are dynamic and includes the entry of new actors, new laws and other events.

The framework that is used for this study, the political economy model for transport innovations of Feitelson and Salomon, is a static framework. Since the study is investigating the feasibility of the 'next generation' Wadden Sea ferries, developments in the (near) future can influence the feasibility of these ferries. Therefore, developments that can influence the feasibility in the future are discussed in this study. This includes developments in all types of feasibility. The potential effects of developments, such as new actors (e.g. new ferry-operators), changes in regulations, and high energy prices are discussed in this study.

2.5 Chapter conclusion and discussion

The theories discussed in this chapter have shown that innovations and especially transitions can be complex and the road to diffusion is often long and difficult.

One of the theories for socio-technical transitions is the multi-level perspective (Geels, 2012). In this perspective, a change in the landscape (based on the interactions of actors) can create room for innovations. In this study, this would be a change in the landscape based on increasing attention to emissions and a willingness from actors to invest in technologies to reduce emissions. To stress this, experts will be asked in interviews if emissions are an issue and if this will affect the potential of zero-emission ferries.
The theory on transition phases will be used to locate suggested innovations on the diffusion curve and determine the phase they are located in on this moment. The multi-actor theory will be used to place interviewed actors and their interests and abilities in a context.

The main framework that will be used to determine the feasibility of zero-emission ferries in the Wadden Sea is the political economy model for transport innovations, made by Feitelson and Salomon (2004). This model identified factors that influence the feasibility and relations between these factors. These factors will be discussed in this study to determine the technical, economic, social, and political feasibility. The economic feasibility is not shown in the model but is explained in the paper (Feitelson and Salomon 2004). For successful adoption, an innovation should pass a benefit-cost analysis and therefore the cost has to be known.

For this study, it is argued that there are two issues that are not part of the political economy model but should be discussed: negative aspects of the new technology and potential dynamics and changes over time. The negative aspects will be discussed based on the Technology Assessment theory, the dynamic characteristic of innovations and potential effects of changes are discussed when projections and estimations of future developments are used.

Other theories discussed in the previous paragraphs such as the ‘valley of death’ and the ‘pre-diffusion phase’ will not be discussed by experts, but when signs of these theories are recognized in this study they will be investigated.

3 RESEARCH METHODS

3.1 Research typology

This thesis will be exploratory research with the goal to analyse the feasibility of zero-emission ferries in the Wadden Sea. This combine will combine quantitative research methods to analyse technical data, area characteristics and costs with qualitative research methods such as semi-structured interviews to perform a feasibility study.

The methodology and approach will be discussed in this chapter and is visualized in Figure 8.

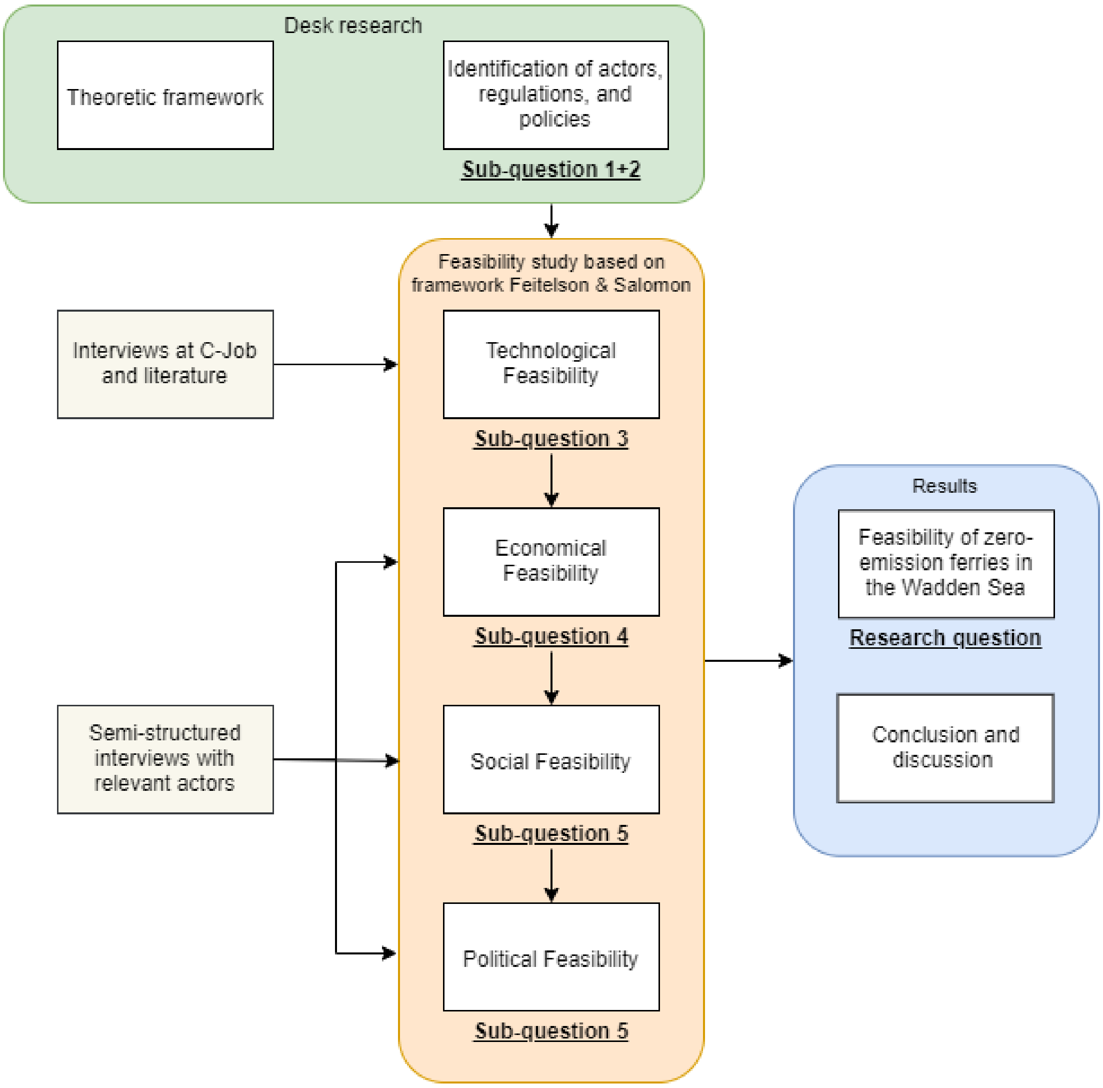


Figure 8; Research approach

3.2 Research approach

This research starts with desk research, followed by a feasibility study based on the framework of Feitelson and Salomon (2004). In this framework, both desk research and semi-structured interviews will be used. The results will be analysed and discussed. A flowchart of the approach can be found in Figure 8. Below, the approach will be explained, and methods will be discussed.

3.2.1 *Theoretical framework*

The first part of the desk research is the theoretical framework, where the relevant scientific literature regarding technology transitions and the diffusion of innovations are discussed. This theoretical framework will aid in understanding the current situation of the innovation of zero-emission propulsion systems and puts developments in perspective. This can be found in chapter 2.

3.2.2 *Research context*

The research context is an overview of the current situation of ferry transportation in the Wadden Sea and recent developments of zero-emission propulsion technologies.
First, the stakeholders that are involved in operating and purchasing (new) ferries are identified and relations between them analysed in a stakeholder analysis. A selection of these stakeholders will be approached for interviews in later stages of this study. The stakeholder analysis will result in answering the first sub-question.
Secondly, the regulations and policies that are relevant for the operating and purchase of (new) ferries, design of ferries and changes to infrastructure will be identified and analysed. Barriers and opportunities for the implementation of zero-emission ferries will be analysed. This will answer the second sub-question.
Furthermore, characteristics of the ferry routes at the Wadden Sea and ferries currently in use will be analysed.

3.2.3 *Feasibility study*

The four types of feasibility that Feitelson and Salomon (2004) distinguished, will be used as a structure for the feasibility study. First the technological feasibility will be determined. Desk research will be used to analyse the zero-emission propulsion technologies used for existing ferries and technologies that are expected to be available in the near future. With the help of engineers at C-Job and if necessary other experts, the feasibility of implementing zero-emission propulsion systems in ferry designs similar to the current Wadden Sea ferries will be determined. Adjustments of the ship design, infrastructural changes and other consequences that are required for the realization of zero-emission ferries will be discussed.
To determine if zero-emission ferries are economically feasible, an estimation of costs is required. The total costs are based on investment costs (CAPEX) and operational costs (OPEX). The difference of CAPEX between the propulsion technology of current Wadden Sea ferries and zero-emission Wadden Sea ferries will be a result of technical changes. Interviews with experts will be performed to estimate what the result of such changes will be. The OPEX difference between current and zero-emission propulsion technologies ferries is based on the fuel the ferry consumes. An estimation of changes in OPEX will be made based on desk research and expert interviews.
The social and political feasibility will be determined by semi-structured interviews conducted with experts. The results will be analysed and the research question will be answered.

3.3 Desk research

In the first phase of the research, the desk research method will be used. Scientific and grey literature will be used to discuss relevant theories and create a context for the feasibility study. Sub-questions 1 and 2 are answered by this research and desk-research will be used to create a base for answering the other sub-questions.
Besides scientific and grey literature used mainly in the first part of this study, other documents such as government reports, policy documents, and reports made by ship-owners and interest groups will be used to give insight in the feasibility. Also, news items may be used to identify relevant developments.
At the beginning of each chapter, the sources of desk research that is used for the chapter are explained.

3.4 Semi-structured interviews

To get an in-depth overview of how the factors described by the political economy model for transport innovations of Feitelson and Salomon (2004) work in the case of zero-emission ferries in the Wadden Sea, interviews with relevant stakeholders are conducted in this study. The interview protocol can be found in appendix IX. It includes general questions and specific questions for each type of feasibility.
The interviews are in Dutch, since all interviewed experts are Dutch.
There are multiple reasons for the choice of semi-structural interviews over structured interviews or other types of interviews. This makes it possible to compare answers because questions are pre-determined and to explore areas of interest, even when the interviewer did not consider the topic. Furthermore, a broad spectrum of interviewees with different backgrounds is selected with different specializations. Semi-structured interviews make it possible to focus on a specialization of an interviewee, e.g. technical or social feasibility.
The interviewees are selected based on the actor analysis of chapter 4. Also, interviewers are asked for other potentially relevant interviewees. The interviews are listed in table 3. The main criteria for the selection of interviewees are relevance (e.g. directly influencing demands for Wadden Sea ferries) and diversity of interest. The interviews can be grouped into environmental interest groups (1), industry/harbours (2), ferry operators (3,6), and (international) governmental organisations (4,5).

Table 3; List of interviews

#	Interviewee	Position	Organisation
1	Bas Bijl	Physical geographer	De Waddenvereniging
2	Paul Pot	Director	Port of Harlingen
3	Ger van Langen	Director	Wagenborg Passagiersdiensten
4	Rick Timmerman	Project Manager	Programma naar een rijke Waddenzee/ Rijkswaterstaat
5	Bernhard Baerends	Executive Secretary	Common Wadden Sea Secretariat
6	Cees de Waal	Director	TESO

The interviews are used as a qualitative source. Information received from the interviews that are used in the feasibility study is referred to as a source (in the appendices). Since the number of interviews is low and the background and specialization is different, the interviews are not coded. All interviews are recorded, and the relevant answers are summarized. The summary of each interview is checked and approved by the interviewee. These summaries can be found in the appendix.

4 IDENTIFICATION OF ACTORS, REGULATIONS AND POLICIES

4.1 Chapter introduction

4.1.1 *Introduction*

Before the feasibility of zero-emission ferries in the Wadden Sea is analysed, an overview of the current situation is described in this chapter. The sub-questions that will be answered to provide the research context are:

- Which actors are involved in Wadden Sea ferries and how can they influence the adoption of zero-emission technology on Wadden Sea ferries?
- Which regulations and policies are relevant for ferry transportation in the Wadden Sea and how can these influence the adoption of zero-emission ferries?

First, the stakeholders that are involved in operating and purchasing (new) ferries are identified and relations between them analysed in a stakeholder analysis. A selection of these stakeholders will be approached for interviews in later stages of this study. The stakeholder analysis will result in answering the first sub-question.

Secondly, the regulations and policies that are relevant for the operating and purchase of (new) ferries, design of ferries and changes to infrastructure will be identified and analysed. This will answer the second sub-question.
Furthermore, characteristics of the ferry routes at the Wadden Sea and ferries currently in use will be analysed in paragraph 4.3. This is necessary because characteristics such as route length and energy requirement can influence the feasibility of zero-emission ferries. It is a possibility that a suggested zero-emission technology is feasible for one area in the Wadden Sea, but not for the whole Wadden Sea.

4.1.2 *Methodology*

This chapter is based on desk research. The actor analysis started with basic knowledge of actors such as ferry-operators, harbours and ferry users. Documents provided by ferry-operators proved useful for much information about the organisations and operations. The concession documents provided information about the role of the government and a study by consultancy company Muconsult (2019) for a potential transfer of responsibilities of the concessions from national to regional level government provided an overview of actors relevant for the concessions.
The most relevant actors were confirmed by interviewees. Although no new actors were identified by interviewees, the context and role of some actors were provided by interviewees.

4.2 Actors

4.2.1 *Ferry operators*

Currently, the Wadden Sea ferry routes are used by three ferry operators. TESO is sailing to Texel, Rederij Doeksen is sailing to Vlieland and Terschelling and Wagenborg Passagiersdiensten (WPD) is sailing to Ameland and Schiermonnikoog.

Royal TESO (Texel's Eigen Stoomboot Onderneming, roughly translated as 'Texel's own steamship enterprise') is founded in 1907 as a non-profit organisation. TESO is listed as a public limited company, with a majority of the shareholders being citizen of Texel (TESO, 2019a). The Dutch government stated that this structure ensures the interest of local island inhabitants sufficient and is therefore excluded for the concession obligation (Rijksoverheid, 2019). TESO recently added a new flagship, the 'Texelstroom' with a number of sustainable design aspects. This includes a hybrid CNG/diesel propulsion system, solar panels on the upper deck, and renewable shore power (TESO, 2019b).

Rederij Doeksen is a family business founded in 1908 and is a part of Koninklijke Doeksen BV (Royal Doeksen limited.). Rederij Doeksen provides the ferry connection between Harlingen and Vlieland and Harlingen and Terschelling. These ferry routes are part of the 'Wadden concession West', which is granted to Doeksen until 2029 (Ministerie van I&M, 2011b). Recently, Doeksen ordered two new ferries, named 'Willem Barentsz' and 'Willem de Vlamingh'. These vessels use LNG as fuel, which leads to a significant reduction of NOx, SOx and Particulate Matter (PM) emissions (Doeksen, 2019a).
Wagenborg Passagiersdiensten (WPD) is part of Royal Wagenborg, a family business founded in 1898. WPD provides the ferry connection between Holwerd and Ameland and between Lauwersoog and Schiermonnikoog. Together, these routes are part of 'Wadden concession East', granted to Wagenborg until 2029 (Ministerie van I&M, 2011a). Royal Wagenborg is active in multiple branches such as cargo shipping, offshore and heavy lifting and has a fleet existing of over 230 ships (Wagenborg, 2019). Wagenborg has a CO_2 compensation foundation, which makes it possible for passengers to donate € 0.50 per crossing, which will be invested in sustainability projects on Ameland and Schiermonnikoog.
Ferry operators are privately-owned companies that make the decision to replace ferries and what the demands for these ferries are.

4.2.2 *Governments*

There is a wide range of governments involved with the Wadden Sea ferries.
The municipalities of the Wadden islands have a partnership called 'Samenwerkingsverband de Waddeneilanden' with the goal to strengthen the administrative power of each individual municipality (De Waddeneilanden, 2019).

Regional governments are represented by provinces. These provinces have multiple partnerships, such as the 'Program for a rich Wadden Sea'. This partnership focuses on transitions to a sustainable (economic) use of the Wadden Sea and published multiple vision documents (PRW, 2019)(Programma naar een rijke Waddenzee, 2018).
Another partnership in which the provinces are working together, is the Waddenfonds. In this fund, there is a budget of 600 million euros available between 2007 and 2027 for projects that strengthen the ecological and sustainable economic developments in the Wadden Sea area (Waddenfonds, 2019). One project that was stimulated is the two new ferries for Doeksen, which received a subsidiary of 1,2 million euros (Doeksen, 2019b).

The national Dutch government made the ministry of infrastructure and water management (infrastructuur en waterstaat, I&W), previously part of the ministry of infrastructure and environment (infrastructuur en milieu, I&M) responsible for the management of concessions of the Wadden Sea ferries. However, there have been studies to explore the option to assign this responsibility to decentral governments (Muconsult, 2019). The national government is responsible for regulations concerning air quality and emissions.

A number of stakeholders including provinces, municipalities and ministries are part of a partnership named 'Gebiedsagenda Wadden 2050', the goal of this partnership is to integrate the future planning and present a collective planning for the Wadden Sea in 2050 (Projectteam gebiedsagenda Wadden 2050, 2019).

The Wadden Sea is an international Sea and is beside the Netherlands also part of Germany and Denmark. These countries signed the 'joint declaration on the protection of the Wadden Sea' (Trilateral Governmental Conference, 2010). The three countries are represented in the Trilateral Wadden Sea Cooperation. The guiding principle of this cooperation is *'to achieve, as far as possible, a natural and sustainable ecosystem in which natural processes proceed in an undisturbed way'* (Trilateral Governmental Conference, 2010).

4.2.3 *Ferry users*

The Wadden Sea ferries are a crucial connection between the Wadden islands and the mainland. There are two main groups that use these ferries: island citizens and tourists. Most ferry users are tourists, data from 2017 shows that for Vlieland this was approximately 90% of all ferry users (Rederij Doeksen, 2018). Island citizens rely on the ferries to travel to the mainland, for example for work, school or to visit family. Ship-owners provide island citizens with a discount, for example Wagenborg which gives a discount of 50% (WPD, 2018). Several island citizens are part of advisory boards that advise the ship-owners.

The Wadden Islands are a popular destination for tourists. In 2015, 1,3 million tourists visited the Wadden Islands (CBR, 2016). Larger islands that are further offshore are more popular for longer stays and smaller islands close to shore like Schiermonnikoog are popular for tourist that are staying for just one day and sail back in the afternoon. This leads to peak moments for ferries, especially in weekends and with warm weather during the summer period. In winter, the number of tourists is much lower, and the full capacity of the ferries is not always needed.

4.2.4 *Interest groups*

There are multiple environmental interest groups operating in the Wadden Sea area. Most are focusing on one island or small area or are part of a larger organisation. Eight environmental interest groups cooperate in the 'Coalitie Wadden Natuurlijk'. The members of this coalition are: Waddenvereniging, Vogelbescherming, Landschap Noord-Holland, It Fryske Gea, Stichting Het Groninger Landschap, Stichting Wad, Natuurmonumenten, and Staatsbosbeheer (CWN, 2019).
The Wadden association is the largest environmental interest organisation dedicated to the Wadden area.

There are multiple industry interest groups involved with sustainable energy for shipping in the North of the Netherlands. One is 'Energy Valley', which is a cluster organisation for sustainable energy in the North of the Netherlands.

4.2.5 *Harbours and infrastructure*

The mainland harbours of the Wadden Sea have published a statement for sustainability in 2013 (Gemeente Den Helder, 2013). Since the Wadden Sea is a UNESCO world heritage area, the ferry harbours of Den Helder, Harlingen and Lauwersoog wish to develop as 'UNESCO-harbours'.

Following this, the harbour authority of Harlingen launched programs to stimulate sustainability in the next decades. The Port of Harlingen published a document called 'harbourvision 2019-2035' in which they state the goal for 2035 to be one of the most sustainable harbours in the Netherlands and the most sustainable fishery harbour in the European Union (Paarlberg, 2019).

The ministry of Infrastructure and Water Management is responsible for the maintenance of the fairways and harbour infrastructure required for the ferries. Rijkswaterstaat is the agency that is responsible for the execution of the management and maintenance of the fairways and harbour infrastructure. To accomplish this, they contract specialized third parties.

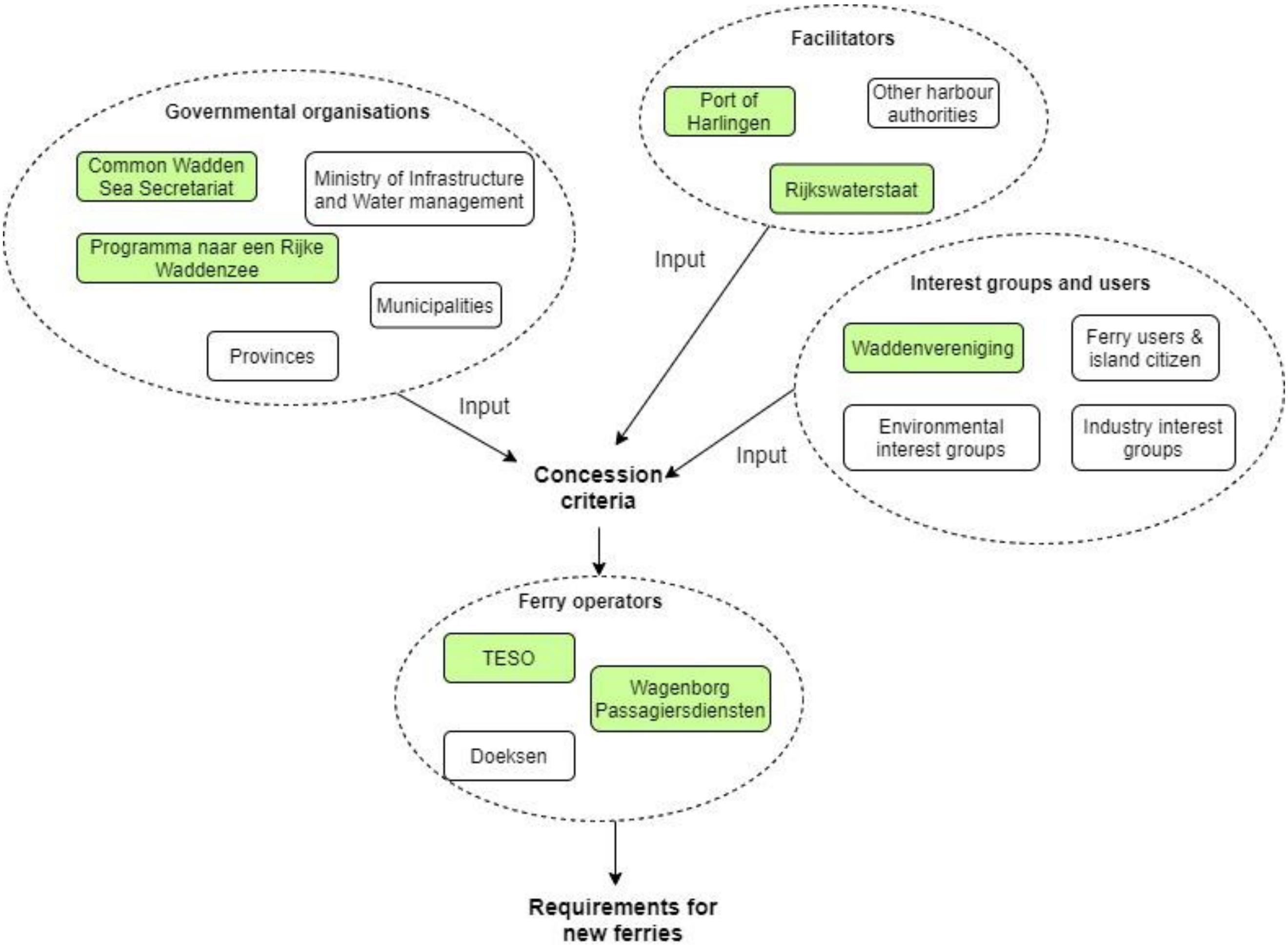


Figure 9; Actors and the relation between actors (interviewed actors are green)

In Figure 9, the actors that are identified in this paragraph are divided into four actor groups which have different roles and interest. Although only one actor is responsible for the criteria of new concessions (ministry of I&W or provinces), there are many actors that provide input for this concession. Not all actors provide direct input for the concessions but can influence other actors. The actors that are interviewed for this study are coloured green.

4.3 Legal structure, regulations and policies

In this paragraph, the legal structure, regulations and policies relevant for emissions and other demands for Wadden Sea ferries are discussed.

4.3.1 *Concession system*

For the Wadden Islands Vlieland, Terschelling, Ameland, and Schiermonnikoog the Dutch government made two concessions: Waddenveren West and Waddenveren Oost. These concessions include demands for quality, capacity and tariffs. In return, the concessions provide a monopolist position for the concessionaire. When the concessionaire has the intention to acquire a new vessel, this has to be in agreement with the ministry of I&W. When the concession period ends in 2029 and another party wants to become the new concessionaire, the vessels owned by the current concessionaire must be transferred to the new concessionaire for a predetermined rate. As part of the concession the ministry of I&W demands that the concessionaire demonstrably put effort in the limitation of CO2, NOx, PM and other harmful emissions they produce and the adaption of sustainable technology (Ministerie van I&M, 2011a, 2011b).
Texel does not have a concession system since the ferry owner, TESO, is a non-profit organisation that is for a large part owned by island citizen and therefore the ministry of I&W states that the interest of island citizen is guaranteed adequately.

4.3.2 *Concession Wadden ferries West*

The concession Waddenveren West includes the ferry routes to Vlieland and Terschelling and is awarded to Doeksen in 2011 (Ministerie van I&M, 2011b), this concession ends in 2029. The concession was awarded privately to Doeksen, the next concessions will be public (Muconsult, 2019).

Between 2008 and 2014 a second ferry-owner was active between Harlingen and Terschelling, called Eigen Veerdienst Terschelling (EVT). EVT was founded by a group of island citizen because they did not agree with the monopolist position of Doeksen. This led to the so-called 'ferry war' between EVT and Doeksen. EVT stated that the privately awarded concession was against European Law and started multiple procedures against Doeksen and the Dutch government. In 2014, Doeksen said it was forced to reduce the number of unprofitable crossings to Vlieland because of the loss in income caused by the EVT and the Dutch government paid off EVT for 9 million euros to stop their activities (Van Es, 2014).
To improve the involvement of island citizen, the ship-owners have to involve consumer organisations which are combined in a platform called 'Consumentenplatform Concessie Waddenveren West' and an advisory board.

4.3.3 *Concession Wadden ferries East*

The concession Waddenveren East includes the ferry routes to Ameland and Schiermonnikoog and is awarded to Wagenborg Passagiersdiensten (WPD) in 2011 (Ministerie van I&M, 2011a). Most of the criteria are the same as the Concession Wadden ferries West.

4.3.4 *IMO*

Following the third GHG study (Smith et al., 2014), the International Maritime Organization agreed to reduce CO_2 emissions by the maritime sector. All 173 member countries, including the Netherlands, agreed that overall GHG emissions from international shipping should be halved by 2050 compared to 2008 levels and that the sector should operate in an entirely climate-neutral fashion as soon as possible. By 2030, vessels should emit 40 % less CO_2 emissions (International Maritime Organisation, 2018a). Although Wadden Sea ferries are not part of international shipping, this regulation is seen as an example for national (inland shipping) regulations.

4.3.5 *Dutch national climate agreement*

To act on the Paris Climate Agreement, the Dutch government published the National Climate Agreement in 2019 (Ministry of Economic Affairs and Climate Policy, 2019). For shipping, only agreements are made for emissions within the Netherlands. The national climate agreement does not provide additional adjustments and to accomplish the IMO agreement of a 40 % CO_2 reduction in 2030 compared to 2008, a Green Deal approach plan is developed.

4.3.6 *Green Deals*

The green deal approach is to realize sustainability goals by accommodating agreements between the national government, local governments, companies, and societal organisations. For zero-emission ferries, GD230 is relevant.
GD230 is called 'Green deal inland shipping, maritime shipping and ports.'
This green deal has the goal for 2030 to reduce CO2 emissions of the inland fleet by 40% to 50% in comparison of 2015 and to provide 150 inland vessels with zero-emission propulsion systems. For 2050, the ambition is to reduce 70 % CO2 emissions for seagoing shipping compared to 2008 (Ministry of Infrastructure and Water management, 2019).

4.3.7 *National regulations*

The Wadden Sea is a sheltered sea and based on the significant wave height, it is legally part of 'zone 2', which makes it part of the Dutch inland waters. The ministry of I&M provided regulations for inland ferries, including technical requirements relevant for Wadden ferries (Ministry of Infrastructure and Water management, 2012; Rijksoverheid, 2017). This regulation provides requirements for design, stability, strength and safety measurements.
All ferries operating in the Netherlands are registered in the Netherlands.

4.3.8 *Classification societies*

Besides the regulations provided by the Dutch government, approval from a classification society is required. Classification societies are non-governmental organisations performing inspections on the design and construction of ships.
A naval architecture firm provides a series of drawings to a classification society. Approval from a classification society is required for the insurance company. There are multiple classification societies available, for example Lloyds Register (LR), Det Norske Veritas Germanischer Lloyd (DNV-GL) and Bureau Veritas (BV). Classification societies provide regulations for ship design, including demands for materials, structural strength, and machinery. Furthermore, Classification societies often provide additional notations, for example for ice-class, comfort, additional fire protection, and environmental measurements.
To ensure the safety of new technologies, the creation of new regulation often takes years. Although classification societies try to predict which regulations are required in the future, for example by the creation of pathways (Lloyd's Register, 2017). Despite this effort, the lack of relevant regulations can be a barrier to innovation in the maritime industry.

4.4 Characteristics per area

In this study, the ferry crossings are grouped into three areas. These crossings have similar characteristics and the ferries are purpose-built for these areas. The ferries are interchangeable between the routes in an area, but not between areas. The areas are the same as the concessions: Texel (no concession), western Wadden Sea (Vlieland and Terschelling, concession west), and eastern Wadden Sea (Ameland and Schiermonnikoog, concession east). The characteristics of the areas that are relevant for the feasibility of zero-emission ferries are described in this paragraph. These result in demands for a typical ferry that is operating in this area. In this study, it is assumed that ferries that are operational in the area on this moment have the most efficient capacity for the demand of the islands. These are described as 'typical ferries' for the area. Data about typical ferries can be found in Table 2 and a visualisation of the areas is shown in Figure 10.

4.4.1 *Texel*

Texel is the largest island and is closest to shore, the distance of the crossing is 5 km. A typical ferry has a high capacity for persons and cars. The time schedule is based on two crossings per hour and in total, the ferry makes 32 crossings per day. The energy consumption of one crossing is approximately 750 kWh.

4.4.2 *Western Wadden Sea*

This area is based on the concession 'waddenveren west' and include the ferry crossings to Vlieland and Terschelling. The distance from the mainland harbour Harlingen is respectively 36,2 and 40,6 km. To reduce the crossing time, a typical ferry for this area has a higher design speed than ferries for other areas. Since Vlieland has a no-car policy for tourists, the demand for cars is limited for this island. The ferries are interchangeable for this area. A typical ferry for this route makes 6 crossings per day and consumes 4200 kWh per crossing.

4.4.3 *Eastern Wadden Sea*

This area, consisting of Ameland and Schiermonnikoog, is based on the concession 'waddenveren oost'. The crossings are respectively 12,8 and 11 km and the ferries are interchangeable. The eastern Wadden Sea has problems with water depth and becomes shallower every year. This leads to delays and specific design criteria for future ferries to stay operational. To minimalize the depth of future ferries, the weight has to be minimal. This is a more critical requirement for this area than for the other areas. A typical ferry in this area requires 633 kWh per crossing and makes 14 crossings per day.

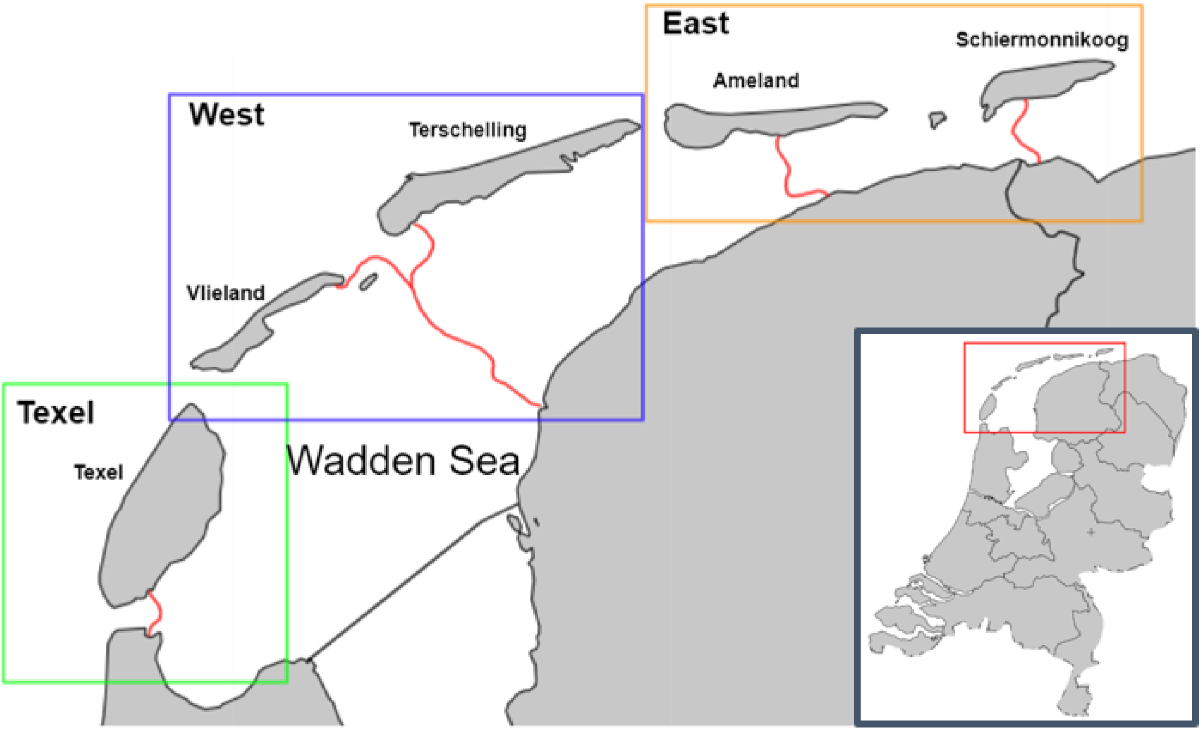


Figure 10; Areas in the Wadden Sea

4.5 Chapter conclusion

The first sub-question is:

'Which actors are involved in Wadden Sea ferries and how can they influence the adoption of zero-emission technology on Wadden Sea ferries?'

The ferry operators are the most important actors, since they provide the day to day operations of the crossings and decide the criteria for new ferries and the moment they order these ferries. Governments provide criteria for the concessions and therefore make demands for the ferry operators. The current concession is provided by the national government. It is however studied if this responsibility can be transferred to regional governments. Ferry users, island citizen and interest groups can influence these concessions indirectly. Other parties, such as harbour authorities and Rijkswaterstaat, have a more supportive role and can provide the infrastructure required for zero-emission ferries.

The second sub-question this chapter answer is:

'Which regulations and policies are relevant for ferry transportation in the Wadden Sea and how can these influence the adoption of zero-emission ferries?'

The legal structure that is relevant is the concession system. The next concession can include criteria for emissions and be a basis for zero-emission ferries. National policy such as green deals and the Dutch climate agreement provide the intentions of governments and can support initiatives for zero-emission shipping. These policies can stimulate cooperation between actors. Regulations provided by the ministry of I&M and classification societies are required to build ferries. For technical innovations, it can be a problem if these regulations are not yet available.

5 TECHNICAL FEASIBILITY

In this chapter, the technical feasibility of zero-emission ferries is analysed. First, the methodology and the role of the political economy model are explained and the criteria for the suggested innovations are discussed. The status and characteristics of each suggested innovation are analysed. At last, the technical feasibility of the suggested innovations applied on typical ferries of each area is discussed.

The sub-question this chapter answer is:

Which zero-emission alternatives are technically feasible for Wadden Sea ferries and how does the implementation affect the operation of these ferries?

5.1 Methodology

To answer the sub-question and determine the technical feasibility, the framework of Feitelson and Salomon is used. In this paragraph, the factors that are influencing the technical feasibility are explained, the criteria used for selecting technologies is determined and a selection of literature is provided.

5.1.1 *Factors relevant for determining the technical feasibility*

In Figure 11, a detail of the political economy model for transport innovations created by Feitelson and Salomon (2004) is shown. This detail consists of factors that lead to technical feasibility. The active agents 'actors' and 'industry interests' influence the factors 'suggested innovations', the 'perception of problems' and the 'technical requirements' of the suggested innovations. Experts directly influence the determination of the technical feasibility.

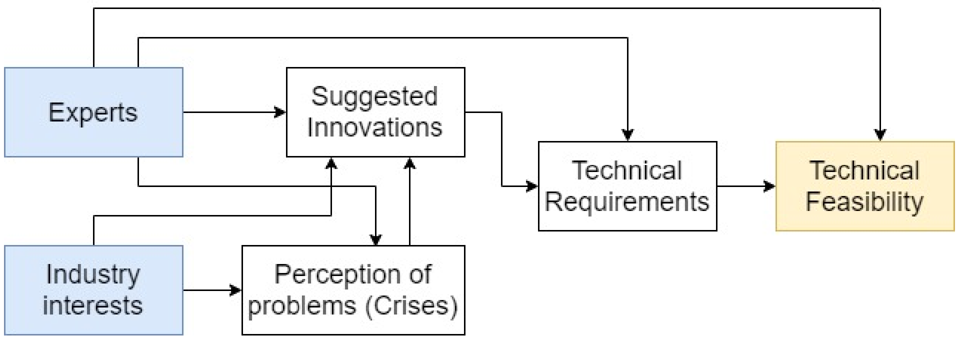


Figure 11; Detail of technical feasibility part of the model of Feitelson and Salomon (2004)

Feitelson and Salomon (2004) discuss two types of actors that are influencing the technical feasibility: experts and industry actors. Experts, also termed 'policy entrepreneurs', are advancing various policy suggestions in which they believe. Industry actors are motivated by profit and therefore develop products to sell, or advance measures that will increase productivity.

5.1.2 *Criteria used to select innovations*

Sustainable alternatives for traditional fuels are widely discussed in the shipping industry (DNV-GL, 2018). However, not all these alternatives are emission-free or reliable enough for a primary energy source for propulsion. Based on experts and literature, four alternatives are selected.
These alternatives are selected with the following criteria:
The suggested innovation should be:

- Emitting no well-to-propeller emissions
- The primary energy source, capable of providing enough power under all circumstances
- Available (production is scalable, without major price increases)
- Reliable
- Have a limited effect on the daily operations
- Available before all existing Wadden ferries are replaced (before 2050).

For the factor 'technical requirements', the requirements of the alternatives are analysed. The requirements that are similar to requirements for existing ships propulsion are not taken into account. Since weight is seen as one major limitation for zero-emission alternatives for ships (Lloyd's Register, 2017), this will be analysed for each area. However, when the amount of energy stored onboard is decreased and more frequent bunkering is required, this should not negatively affect the daily operation. The criteria for 'technical requirements' are therefore:

- A limited additional weight of installation and fuel compared to diesel configuration (max + 20%)
- Charging or bunkering should have no effect on the time schedule

A lower weight is preferable, especially on the shallow eastern Wadden Sea (interview 3).

5.1.3 *Selection of sources*

The analysis of the technical feasibility of zero-emission ferries can be found in appendix I. The definition of zero-emission that will be used in this study is 'a process or energy source that emits no waste products that pollute the environment or disrupt the climate'. An explanation of this definition and a list of technologies that are not included in the analysis can be found in appendix I. Furthermore, information about energy converters that are used in this study can be found here.

The suggested innovations are based on information from experts from C-Job and literature. One of the basic documents that provide a good overview is done by classification society Lloyds Register (2017). LR and other classification societies such as DNV-GL do not provide scientific sources but provide 'position papers' in which they provide their point of view on zero-emission shipping. Since regulation from these classification societies is required for shipbuilding, this point of view is relevant and provides a good overview of developments in the industry.
Scientific sources are used for a more in-depth analysis of the characteristics of the four suggested innovations. These are found in Scopus by searching for the technology in combination with 'ferries', or 'shipping'. The number of relevant sources specifically for marine applications was often limited, but specific.
In appendix I, the status and the technology and existing examples of the technologies are analysed. Some initial existing ships with zero-emission technologies are mentioned in the classification society papers. Further searches for scientific literature regarding these examples on Scopus did not lead to many results and most information about existing vessels is found in grey literature such as

newspapers and magazines. Publications from suppliers, for example for batteries or storage tanks, offers more technical information. For some existing vessels that received subsidiaries, (technical) reports are provided (e.g. MS Ellen).
For the calculations of the weight and volume of batteries and storage tanks of appendix II, III, and IV, publicly available information from ferry-owners and suppliers are used.

5.2 Results of analysis technical feasibility

5.2.1 *Perception of problems*

The suggested innovations are solutions for a problem. The perception of this problem is the motivation to develop and implement new innovations. The problem in this study is described as 'Wadden Sea ferries are emitting harmful emissions'. For the technical feasibility, the perception of this problem by experts and industry is relevant according to Feitelson and Salomon (2004).
Literature shows that emissions are seen as a problem by the shipping industry, for example by studies about zero-emission shipping and sustainability by classification societies (DNV-GL, 2018; Lloyd's Register, 2017). Some elements of the Dutch (inland) shipping industry have been involved in policies such as the Dutch climate agreement (Ministry of Economic Affairs and Climate Policy, 2019) and Green Deals (Ministry of Infrastructure and Water management, 2012, 2019).

The most relevant actors in the industry are ferry operators. TESO and Doeksen operate vessels which sail on respectively CNG and LNG. Both ferry operators did this to reduce the emissions they emitted into the air. Furthermore, the transportation plans of Doeksen and Wagenborg describe their efforts for sustainability (Rederij Doeksen, 2019; WPD, 2019).
In interviews both TESO and Wagenborg stated that they see emissions as a problem and that zero-emission is an ambition for the next ferries for these companies (interviews 3,6).

5.2.2 *Suggested innovations*

The zero-emission technologies that are suggested by experts and industry must meet the criteria mentioned in section 5.1.2. There are four energy carriers that meet these criteria: batteries, hydrogen, methanol, and ammonia. These suggested innovations are only zero-emission when produced under certain circumstances. A full analysis of each suggested innovation can be found in Appendix I.
The suggested innovations can be divided into two types of energy carriers: batteries and liquid energy carriers. Batteries are a proved technology to store energy and suitable for vessels with a small range of operation. The liquid energy carriers that are selected are synthetic and therefore scalable. Both batteries and liquid energy carriers will only be zero-emission options when renewable, zero-emission electricity is used. One scenario is that overcapacity of renewable electricity sources will be used to produce zero-emission liquid energy carriers. For this study, the synthetic liquid energy carriers that are considered are hydrogen, methanol, and ammonia.

The characteristics, status and technical requirements of the energy carriers are discussed briefly in the next sections and a full analysis can be found in Appendix I.
A visualisation of the production and energy conversion of the suggested innovations is shown in Figure 12. This visualisation provides the well-to-propeller process and is based on interviews at C-Job and the analysis of each suggested innovation (see Appendix I). The blue rectangles are the electricity and other requirements for the suggested innovations (CO_2 and N_2 are obtained from the air), the liquid energy carriers are shown in green. The white rectangles are the storage methods on board of the ferries and the yellow boxes are energy converters on board of the ferry. The deep blue rectangle is the propeller and is the same for each alternative.

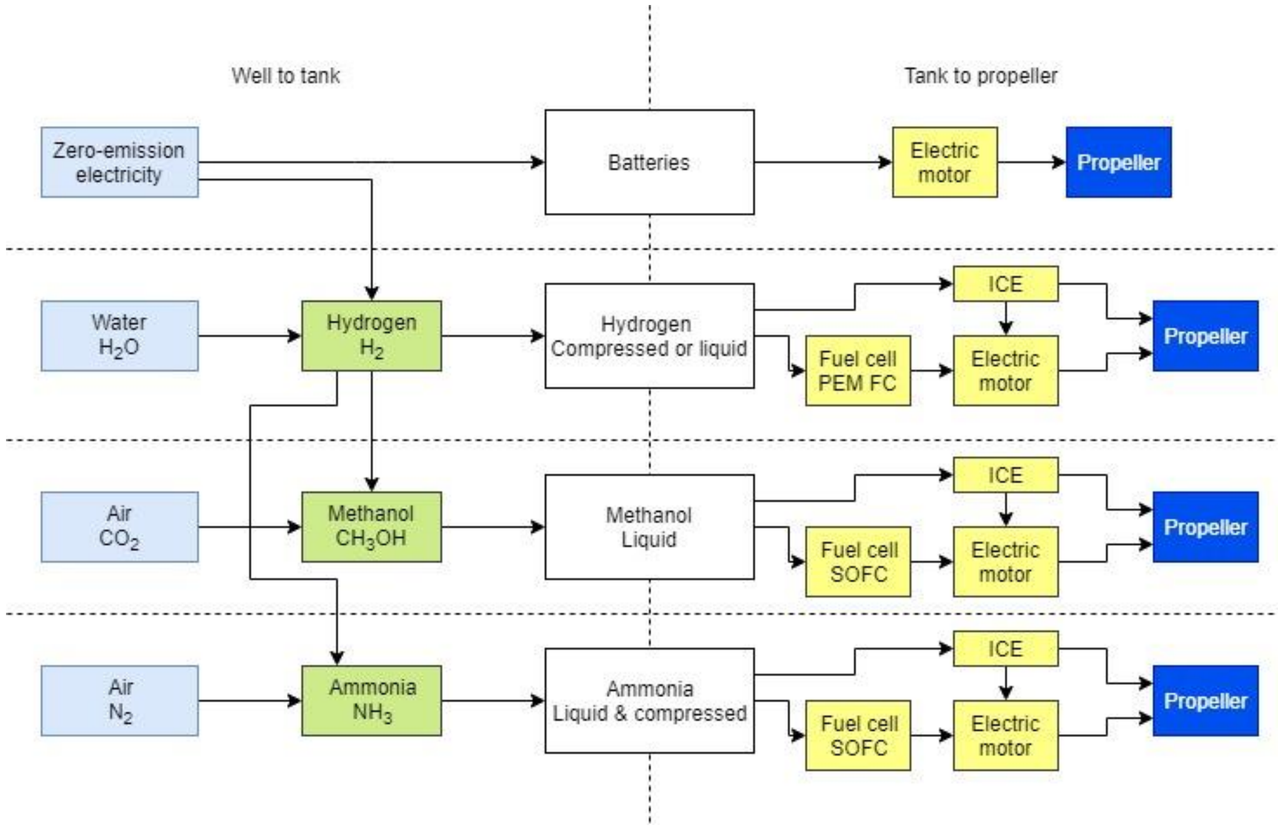


Figure 12; Zero-emission technologies, well to propeller

5.2.3 *Suggested innovation: batteries*

Batteries are a widely used energy carrier in the marine industry for peak shaving, hybrid propulsion and battery-electric propulsion systems. Lithium-ion (Li-ion) batteries are the most used batteries for marine applications. Because of the small likelihood of fires and explosions, lithium nickel manganese cobalt oxide (NMC) (a type of li-ion) batteries are most widely used for zero-emission vessels. For example, the zero-emission ferries MS Ampere and MS Ellen have installed lithium NMC batteries (Amanieu, 2016; Puchalski, 2015). Nevertheless, the energy density is low and marine battery packs require more safety and ventilation measures than most other applications.

Besides Li-ion, there are other battery types under development such as Lithium-Sulphur (Li-S) and Li-O_2 (Zhang, Li, & Zhang, 2017). Although the potential energy density is much larger, these are still in an R&D phase and not included in this study.

Existing zero-emission battery-electric ferries are charged when moored. The available time is limited and therefore the batteries are charged with high power. The battery packs on board are larger than required for the crossings to reduce the C-rate and Depth of Discharge (DoD). Higher C-rates result in lower efficiency due to heat loss, more complex (water-cooled) installations and a lower life expectancy. A large DoD has also a negative effect on life expectancy. Charging installations on land often require reinforcements for the local electricity grid.

Another method which does not affect the operability is to change or 'swap' battery packs when the ferry is moored. Mobile battery packs have more time available for charging, which results in lower C-rates for charging.

5.2.4 *Suggested innovation: hydrogen*

Hydrogen (H_2) is a colourless, odourless and non-toxic gas. It is seen as one of the main sustainable fuels that can be used for transport applications without emitting any emissions. One of the reasons for this is the high energy density of 120 MJ/kg. However, the density of H_2 is very low and for the use on ships, it has to be stored as a cryogenic liquid, as compressed gas, or chemically bound (DNV-GL, 2018). Although currently almost all hydrogen is produced with natural gas (CH_4) and is not sustainable, hydrogen can be produced without emissions by electrolysis of water, which results in hydrogen and oxygen. Although 'green' hydrogen produced with sustainable electricity is not available on a large scale yet, the Northern provinces of the Netherlands are investing in a green hydrogen network (H2 Platform, 2019).

There are no commercial vessels with hydrogen as their main fuel yet. However, there are pilot projects such as the 'Energy Observer' and a Norwegian ferry operator is developing a car ferry with a hybrid hydrogen/battery-electric propulsion system (Energy Observer, 2019; NCE Maritime CleanTech, 2018).

Since an internal combustion engine (ICE) configuration has low efficiency, Proton Exchange Membrane Fuel Cells (PEM FCs) with high efficiency are the preferred technology. PEM FCs with a capacity of 100 kW are available and the technology is scalable. For marine applications, testing and regulations are still required (DNV-GL, 2018).

The pressure of compressed hydrogen is typically 350 or 700 bar. This requires cylindric storage tanks typically made of composite. A 700 bar tank is approximately 20 times as heavy as the hydrogen it can store (Hexagon, 2019). Since high-pressure tanks require a minimum residual pressure that should be left in the tank. For tanks used in this study, this is 10 bar and approximately half the hydrogen should remain in the tank to keep this pressure (Abma, Atli-Veltin, & Verbeek, 2019b).

Liquid hydrogen (LH_2) is a cryogenic liquid stored at approximately 20 Kelvin or -253° Celsius. The tanks required to store LH_2 are lighter and less complex than for compressed hydrogen. However, up to 40 % of the energy is lost during processes including the liquefying process and boil-off (Züttel, Remhof, Borgschulte, & Friedrichs, 2010). To keep the tank cold, a minimum of approximately 20 % of the LH_2 should remain in the tank and 1 % of the total hydrogen is consumed by boil-off per day (Pratt & Klebanoff, 2016).

5.2.5 *Suggested innovation: methanol*

Methanol, which has the chemical structure CH_3OH, is an alcohol with the lowest carbon content and highest hydrogen content of all liquid fuels. It is widely used for products such as building materials, paints and packaging. As a fuel, it is used in auto racing.

Methanol as fuel is interesting for the marine industry because it is liquid at atmospheric pressure between -93 °C and +65 °C and has a relatively high energy density of 19,5 MJ/kg and 15,8 MJ/L (DNV-GL, 2018).

Currently, almost all methanol is produced with natural gas and coal. However, it is possible to produce 'green' methanol from hydrogen produced with electrolysis and CO_2. The latter can be captured from flue gasses from industry or from atmospheric air. A pilot production plant is currently operational on Iceland, which uses electricity from hydropower and CO_2 captured from industry (Goeppert, Olah, & Surya Prakash, 2017). Although CO_2 is emitted when methanol is converted into energy, it is argued to be zero-emission because the CO_2 would otherwise have entered the atmosphere directly. Capturing CO_2 from atmospheric air is less efficient and more expensive (SAPEA, 2018).

Currently, methanol is used as a fuel for MS Stena Germanica. The ICE configuration uses bio-methanol, which is cheaper than synthetic methanol, but not scalable and not completely zero-emission.

A demonstration project with fuel cells on MS Mariella is currently operational. However, these fuel cells do not deliver energy for propulsion and are relatively small (Maritiem Kennis Centrum, TNO, & TU Delft, 2018).
Because a large amount of energy is required for the production of green methanol, an energy converter with high efficiency is preferable. A Solid Oxide Fuel Cell (SOFC) has high efficiency and is seen as the most promising option for methanol (DNV-GL, 2018). However, these are still in an R&D phase and not yet market-ready. The ICE configuration is technically feasible, but not efficient.

5.2.6 *Suggested innovation: ammonia*

Ammonia, with the chemical structure NH_3 is widely used for the production of fertilizers and is the second-largest chemical produced over the world. As a fuel, it is interesting because it can be produced entirely renewable and has no carbon components (no PM or CO_2) and emits no SOx (Giddey et al., 2017). Ammonia can be transported as a liquid when fully pressurized with 10 bars at 20 °C. Other options are to cool ammonia to -34 °C at 1 bar, or use a semi pressurized/refrigerated option where the pressure needs to be higher than the vapour pressure. Ammonia is, just like methanol, interesting as a fuel because it can be produced with renewable hydrogen but has a higher volumetric energy density than hydrogen. Although most ammonia is currently produced with natural gas, it is possible to combine hydrogen with nitrogen from the air to produce green ammonia. The production of synthetic ammonia consumes less energy than the production of synthetic methanol.
Just like methanol, an efficient energy converter such as a SOFC is preferable since the production of ammonia consumes a lot of energy. Such a configuration is not feasible yet. An ICE configuration with a lower efficiency is technically feasible, although not yet demonstrated and all installations on a passenger vessel powered by ammonia are likely to require additional regulations.
One characteristic of ammonia is its toxicity. Although it is shipped on a large scale and regulations for safe handling are available, the use of highly toxic fuel on a passenger ferry in a sensitive environment will require additional regulations and safety measures.

5.2.7 *Status of suggested innovations*

In Figure 13, the current state of the suggested innovations is projected on an S-curve based on the curve of adopter distribution of Rogers (1995), shown in Figure 4. The status is based on known adaptions, pilot projects, and R&D projects of the technology, discussed in appendix I.
Although this is a projection for this moment, the horizontal time axis suggests that all innovations are moving over time.
Batteries are in a take-off phase, with a number of ferries adopting this technology since 2015. This is followed by hydrogen in the late predevelopment phase. Multiple small-scale pilot projects and the development of a ferry for 2021 support this.
Methanol and ammonia are still in a predevelopment phase, since the renewable and synthetic variants are only produced on a very small scale. The technology required for an efficient configuration, SOFCs, are not available yet. Therefore, methanol and ammonia with SOFC configurations are not technically feasible yet, but with the current developments, it is expected that SOFCs are available before all Wadden Sea ferries are replaced (Tronstad, Hogmoen Astrand, Petra Haugom, & Langfeldt, 2017).

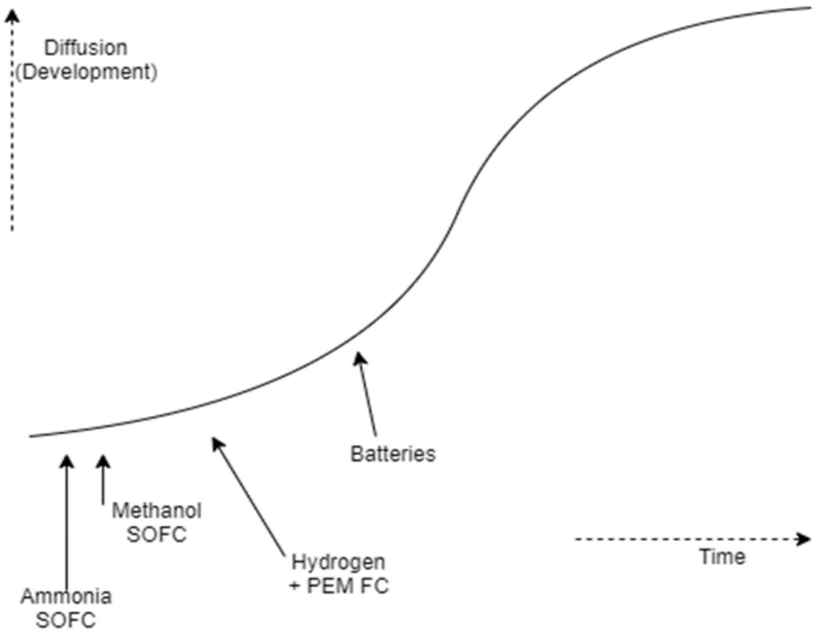


Figure 13; Suggested innovations projected on a diffusion curve based on Rogers (1995)

5.2.8 *Technical requirements*

As determined in section 5.1.2, the two criteria for the factor 'technical requirements' are:

- A limited additional weight of installation and fuel compared to diesel configuration (max + 20%)
- Charging or bunkering should have no effect on the time schedule

To calculate if the weight of the storage installations of each suggested innovation does not exceed the criteria, the energy demand and number of crossings for the three main areas are determined. These are based on machinery and speed of existing ferries, the length of the crossings and time schedules. The energy demand and the number of crossings for typical Wadden Sea ferries per area:

- Texel: 750 kWh per crossing, 32 crossings per day
- Western Wadden Sea: 4.200 kWh per crossing, 6 crossings per day
- Eastern Wadden Sea: 633 kWh per crossing, 14 crossings per day.

The calculations can be found in appendix II for Texel, appendix III for the western Wadden Sea and Appendix IV for the eastern Wadden Sea. The analysis has the following results:

Batteries, both fixed and mobile, are feasible for Texel and the eastern Wadden sea without additional weight when fully charged at the mainland harbour. Additional batteries for a limited DoD, a limited charging time without high C-rates and redundancy are included. The high number of crossings makes mobile batteries a labour-intensive method for Texel.
For the western Wadden Sea, the weight of the batteries only meets the criteria when charged at both harbours. Reinforcements of the electrical grid of the Wadden Islands might not be a feasible option.

Liquid hydrogen in a PEM FC configuration is a technically feasible option for all islands when a network of green hydrogen is established and regulations are available. Bunkering is required more frequently than with diesel, for most ferries multiple times a week. This does not affect the time schedule since it can be planned in the evening.
The installations for compressed hydrogen are large and heavy. For Texel, the installation required for one day of operation is not heavier than current fuel tanks. For the western and eastern Wadden Sea however, these installations are heavier than tanks on operational ferries. Bunkering of hydrogen during the day will affect the time schedule and does not meet the criteria of section 5.1.2. The use of mobile compressed hydrogen containers is an option which does not affect the time schedules.

The storage of methanol is no problem for Wadden Sea ferries. The technical requirements are met for all areas for both SOFCs with an efficiency of 60% and ICEs with an efficiency of 40%. Nevertheless, bunkering is required more frequently than with diesel.

For ammonia, the size and weight of tanks and installations are not a problem for operability. Nevertheless, because there is no experience with ammonia as fuel, the bunkering installations and procedures might be complex and bunkering time-consuming. However, bunkering is required once in a few days and can be executed in the evening when no passengers are on board.

5.2.9 *Overview of technical feasibility*

The results of this chapter are visualized in **Fout! Verwijzingsbron niet gevonden.**. The areas combined with suggested innovations that are coloured green are technically feasible within a short period (no longer than a standard designing and building period for a ferry).
The orange combinations are not yet feasible, or the feasibility is not known. For batteries in the western Wadden Sea, additional information about the reinforcement of the local grid on the Wadden Islands is required before it is clear if battery-electric ferries are technically feasible in this area.
The suggested innovations that are based on SOFC's and ammonia are not feasible within a short period, but this technology is likely to be feasible before all ferries are replaced (approximately 2050).

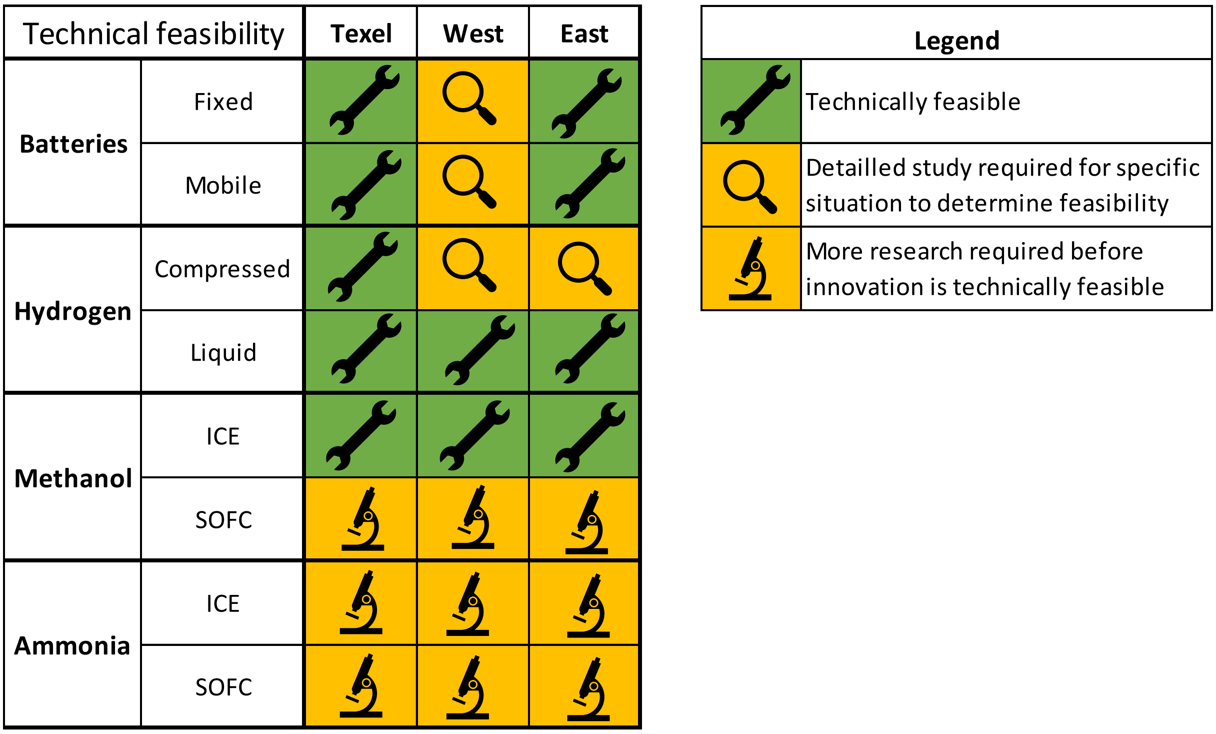


Figure 14; Overview of results of technical feasibility

5.3 Chapter conclusion

The sub-question this chapter answers is:

Which zero-emission alternatives are technically feasible for Wadden Sea ferries and how does the implementation affect the operation of these ferries?

All suggested innovations: batteries, hydrogen, methanol, and ammonia, are likely to be technically feasible before all Wadden Sea ferries are replaced. However, not all configurations are available for all ferries. The green options in **Fout! Verwijzingsbron niet gevonden.** are feasible at this moment or in the near future. For the western Wadden Sea, batteries are only feasible when charging infrastructure and grid reinforcements can be realized on the Wadden Islands. Fixed compressed hydrogen installations with a capacity for one day are heavier than the current installations for one week and are therefore not feasible. However, mobile compressed hydrogen containers can solve this. SOFC technology is not ready yet. However, developments are going fast and the potential for these fuel cells is high. An ICE configuration for methanol is technically feasible, but not efficient. An ICE configuration for ammonia is not yet used for marine applications and will require additional regulations. When demonstrated elsewhere, it can be technically feasible for Wadden Sea ferries. The implementation of zero-emission ferries affects the frequency of charging or bunkering. however, this does not affect the time schedule because it can be planned in the evening. Furthermore, for some alternatives land-based installations are required for charging or bunkering.

6 ECONOMICAL FEASIBILITY

In this chapter, the economic feasibility of zero-emission technologies for Wadden Sea ferries is discussed. First, the relevant factors according to the framework of Feitelson and Salomon are discussed. Then projections of future prices of electricity and diesel are described, since these will have large effects on the economic feasibility. The remainder of this chapter will discuss costs for the zero-emission alternatives of current technologies.

The sub-question this chapter will answer is:

What is the total cost of ownership of zero-emission alternatives compared to fossil fuel configurations?

6.1 Methodology

6.1.1 *Factors influencing the economic feasibility*

In the political economy model for transport innovations of Feitelson and Salomon (2004), the economic feasibility is described as one of the four feasibilities required for overall feasibility of an innovation. However, economic feasibility is not explicitly depicted in the framework. The economic feasibility is linked to social and technical feasibility. According to Feitelson and Salomon, an innovation is not likely to be seen as feasible unless it can pass a benefit-costs-analysis (Feitelson & Salomon, 2004). A detail of the relevant factors for economic feasibility is shown in Figure 15.

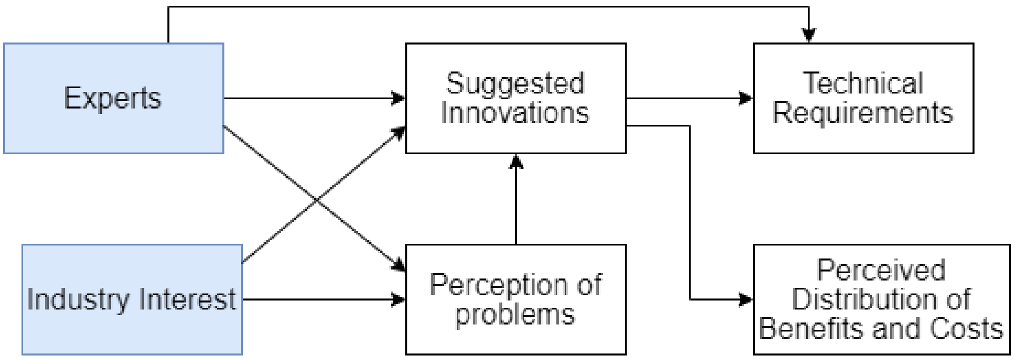


Figure 15; Detail of the economic feasibility part of the model of Feitelson and Salomon (2004)

For the factor 'perceived distribution of benefits and costs', the costs have to be known and therefore analysed in this chapter. The benefits and perceived distribution of both are social factors. Since the suggested innovations replace diesel, the 'costs' in this factor are additional costs above the existing costs of operating a diesel ferry. When the TCO of a suggested innovation is lower or similar to a fossil fuel-powered ferry, the ferry is economically feasible. When the alternative is more expensive, the perceived benefits should outweigh the costs, which is part of the social feasibility.

To determine the costs of the suggested innovations, the capital expenditures (CAPEX), which are based on the technical requirements, and the operational expenditures (OPEX) are analysed. The combination of CAPEX and OPEX, the total costs of ownership (TCO) of the suggested innovations are discussed and compared to a diesel configuration. The CAPEX are additional investments that are required compared to a diesel-powered reference ferry. The CAPEX of diesel is therefore used as a reference and will be zero.

6.1.2 *Selection of sources*

To determine the TCO for each suggested innovation, a number of calculations is performed. These calculations can be found in the appendix. The CAPEX calculations are based on the costs of the required installations on board. The capacity of the installations is based on the energy demand determined in chapter 5. CAPEX calculations for batteries can be found in Appendix V and are based on a study of Cole and Frazier (2019), who combined 25 studies to make a projection of li-ion battery prices. The costs of other installations required for charging are based on data from suppliers.
The CAPEX of liquid energy carriers is based on feasibility studies such as SF Breeze (Pratt and Klebanoff 2016) and Gouwenaar 2 (Abma et al. 2019b), and data from suppliers.
Operational expenditures are based on the energy demand of the typical ferries and the production costs of the energy that is converted. The electricity rate is the basis for all energy carriers and is discussed in the next section. Scientific sources that describe the production process and provide formulas for the distribution of costs are used to determine the prices. These are adjusted with the electricity rate of the next section. The calculations and sources for data can be found in Appendix V for batteries, appendix VI for hydrogen, appendix VII for methanol, and appendix VIII for ammonia.

6.1.3 *Projection of energy rates*

Because all four zero-emission alternatives discussed in this study are made from renewable, zero-emission electricity (see Figure 12), the OPEX largely depends on the rate of electricity.
The projected electricity rate that is used in this study is based on the projection of ECN for the Netherlands in 2030 and is € 57 per MWh (ECN, 2019).
Because the electricity that is retrieved from the grid is a mixture of renewable and fossil electricity, Guarantee of Origin (GO) certificates have to be bought to ensure that sufficient renewable electricity is produced. The price of these GO certificates is fluctuating and different for electricity sources and countries, despite being traded freely. For this study, the average GO rate for hydropower, wind power and solar power of the European Union in 2017 is used, this is an average of € 0,25 per MWh (Hulshof, Jepma, & Mulder, 2019). The electricity rate used for calculations is therefore € 57,25 per MWh.

Diesel is used as reference fuel to compare fossil fuels with the suggested innovations. Diesel prices can rise when the international price of crude oil rises or by policy measures. A short term projection is provided by Wagenborg for € 67,71 per MWh in 2020 (WPD, 2019). Although there are many different forecasts, most predict the price of crude oil will increase slightly. In this study, an increase of 8 % will be used for an average projected diesel price (Deloitte, 2019). The reference price therefore will be € 73,00 per MWh.

6.2 Results of analysis economic feasibility

In this paragraph, the results of the analysis of the economic feasibility are discussed. An in-depth analysis and the calculations can be found in appendix V, VI, VII, and VIII.

6.2.1 *Capital expenditures*

Off all suggested innovations, batteries have the highest capital expenditures (see appendix V). The limited lifetime of batteries contributes to this. The ferries have an expected lifetime of 30 years and the battery packs have an expected lifetime of 10 years and have to be replaced two times.
For marine applications, battery packs require expensive safety, cooling, and ventilation installations. Therefore, only 40% of the CAPEX of the battery pack consists of battery costs (MAN Energy Solutions, 2019). Since the costs for li-ion batteries will reduce, the second and third battery pack will cost less. The CAPEX of batteries is based on three batty packs, the first being purchased in 2025, the second in 2035 and the third in 2045, see Figure 16. The total costs for the lifetime of the ferries are € 1.389 per kWh. The projected battery costs are based on a study by Cole and Frazier (2019).
Fixed batteries require additional batteries on land and complex charging infrastructure. Mobile batteries require multiple battery packs and swap equipment.
The reinforcement of the local grid near the mooring bridge of the ferries is included in the CAPEX. However, the status of the electricity grid of each land harbour is different and a more radical reinforcement of the electric grid might be required. Because this is highly case-dependent, this is not included in this study.

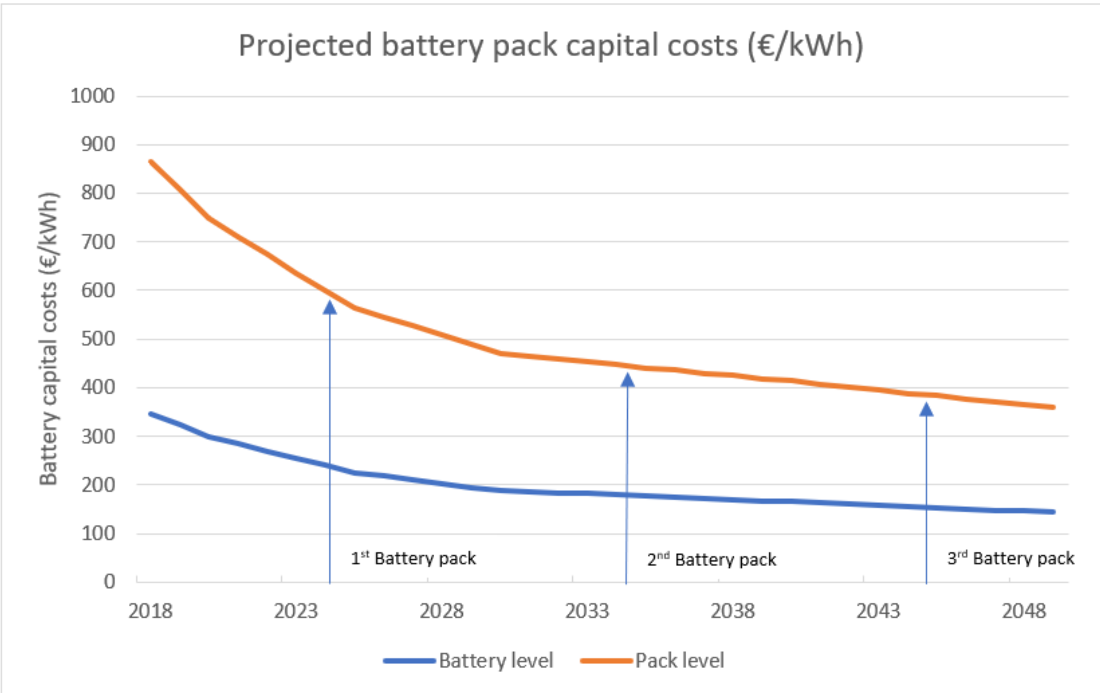


Figure 16; Battery capital costs based on Cole and Frazier (2019)

The capital costs of compressed hydrogen are mainly for the complex tanks and additional installations (see appendix VI). Storage costs for compressed hydrogen are € 550 per kg. Piping, bunkering, monitoring and safety equipment costs approximately an additional 50% of the storage costs.
Liquid hydrogen storage tanks costs are € 636 per kg of storage. Additional costs for required equipment are the same as for compressed hydrogen, which is 50 % of storage costs.

PEMFCs are very expensive at this moment. However, costs are expected to reduce when PEMFCs are produced on a larger scale. For this study, the expected price of 1000 dollar, or € 909 per kW is used. The hydrogen configurations include peak shaving batteries of 500 kWh.

For methanol, the CAPEX for an ICE configuration is only slightly larger than for diesel configurations (see appendix VII). The additional costs for engine modifications and bunkering installations are expected to be € 400.000.
SOFCs are not technically feasible yet. According to an analysis of manufacturing costs of fuel cell systems by Houchins (2019), the scale of production is the most important factor for the price of the fuel cells. According to James and DeSantis, the price difference between PEM FCs and SOFCs is small when produced on the same scale. Because the investments in PEM FCs are far ahead in comparison with SOFCs, the estimated costs for SOFCs in this study are 2 times the price of PEM FCs. This is € 1.800 per kW. However, this is not feasible until SOFCs are produced on a large scale.
For each route, a peak-shaving battery of 500 kWh is used.

Ammonia requires special tanks for 10 bar of pressure. Because this pressure is limited, the additional costs are relatively low (see appendix VIII). Because of the toxicity, ammonia requires additional installations for ventilation and safety. Additional costs for an ICE configuration are the same as for methanol. The SOFCs and peak shaving batteries are the same as the methanol SOFC configuration.

6.2.2 *Operational expenditures*

For batteries, the most important factor is the electricity rate. An efficiency rate of 90 % is used to cover losses during charging with a higher C-rate. Nevertheless, batteries are an alternative with very high efficiency compared to the other suggested innovations.

In this study, hydrogen production with electrolysis is expected to take place in the North of the Netherlands on a large scale. Recent large investments in the development of a green hydrogen network support this assumption (H2 Platform, 2019). Since electrolysis is a process which uses electricity and water to produce hydrogen and oxygen, the hydrogen price is based on the electricity price, see Figure 17 (Mulder, Perey, & Moraga, 2019). With an electricity rate of € 57,25 per MWh, the production of one kg of hydrogen costs € 3,35. Compression or cooling of hydrogen requires additional electricity and costs of these processes are also based on the electricity rate.
Since the production is assumed to be in the North of the Netherlands, the transportation costs are limited. These are estimated at € 0,50 per kg of hydrogen. This results in a price of € 4,48 per kg of LH2 and € 4,20 per kg of compressed hydrogen at 700 bars when the electricity rate is € 57,25 per MWh.

The production of methanol with hydrogen produced with electrolysis and CO2 captured from the atmosphere or flue gasses is based on costs for the installations and for electricity that is used for the production. The latter is approximately 70 % of the total costs (Atsonios, Panopoulos, & Kakaras, 2015). With a hydrogen price of € 3,35 per kg, the price of methanol is € 1.032 per ton methanol. A change in electricity rate will directly result in a change of the methanol rate.
For comparison, methanol produced with fossil fuels has a rate of € 280 per ton (Methanex, 2019).

Ammonia is produced with hydrogen and nitrogen. Just like methanol, the ammonia price therefore is a result of the costs of hydrogen, which is based on the electricity rate. The electricity required for the production and compression of ammonia is approximately 10,8 kWh per kg (Bennani et al., 2016). With an electricity rate of € 57,25 per MWh this is € 618 per ton ammonia. The average CAPEX of the production plant is € 44 per ton (Philibert, 2017) and the price of ammonia is thus € 662 per ton.

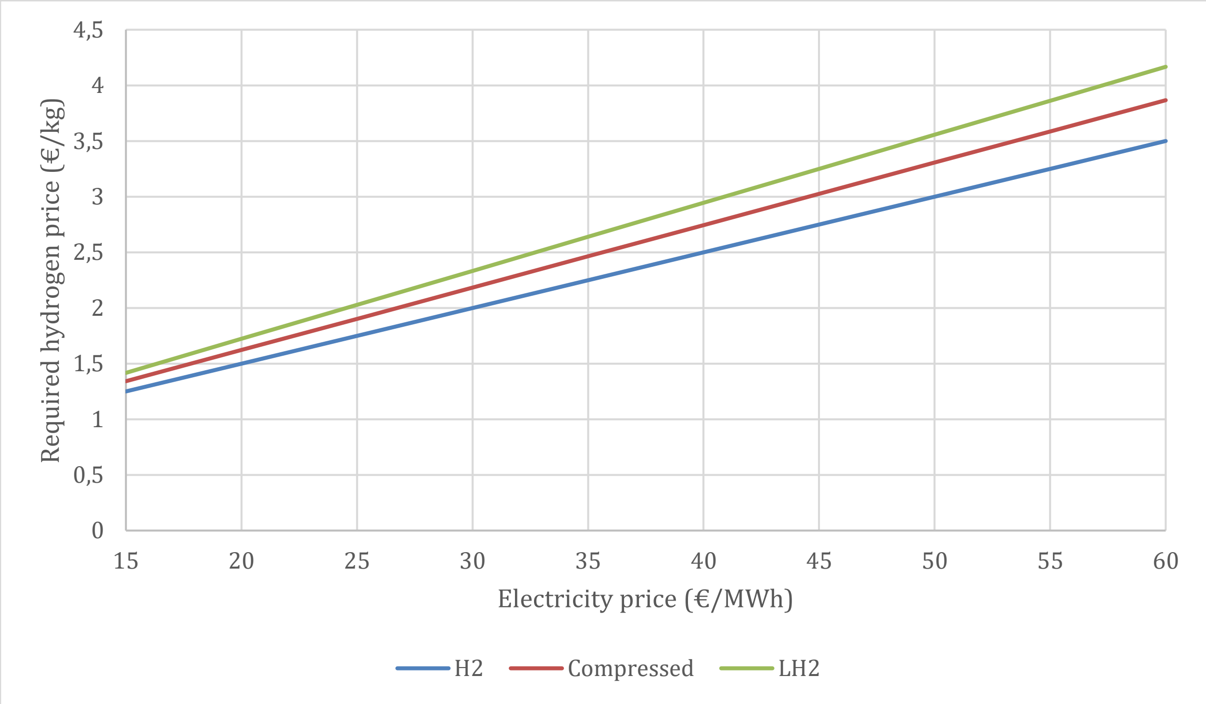


Figure 17; Required hydrogen price for electrolysis in relation to electricity rate (Mulder et al. 2019)

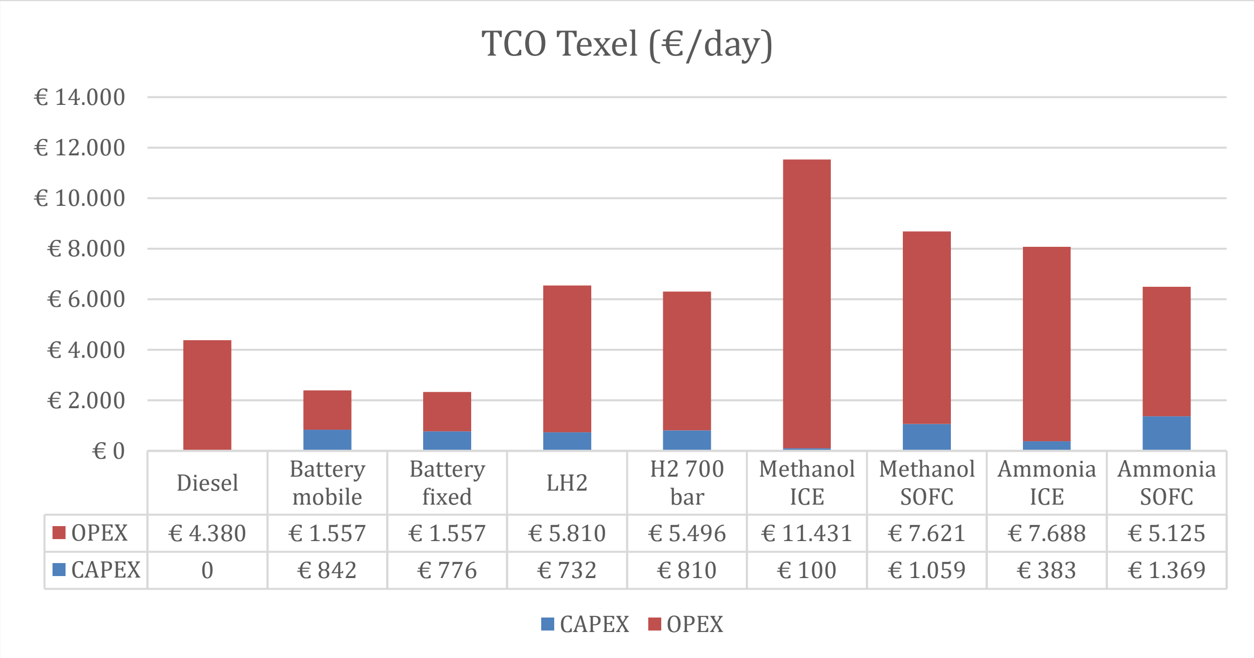
6.2.3 *Total costs of ownership*

The TCO is the combination of the CAPEX and OPEX per time unit. For this study, the TCO is shown per day. To calculate the CAPEX per day, the expected lifetime of 30 years is used. The OPEX is based on the time schedule of typical Wadden Sea ferries per area in summer. The TCOs of the suggested innovations are compared for typical ferries of the three main areas in the Wadden Sea: Texel, the western Wadden Sea and the eastern Wadden Sea. The results are shown in respectively Figure 18 Figure 19, and fFigure 20.

The CAPEX is coloured blue, the OPEX is red. As shown, the battery-electric configuration is the less costly and the only alternative that is cheaper than the diesel configuration. This is due to the high efficiency of battery-electric systems in comparison with liquid energy carriers. The price of electricity is also relatively low and the OPEX of battery-electric systems is the smallest.

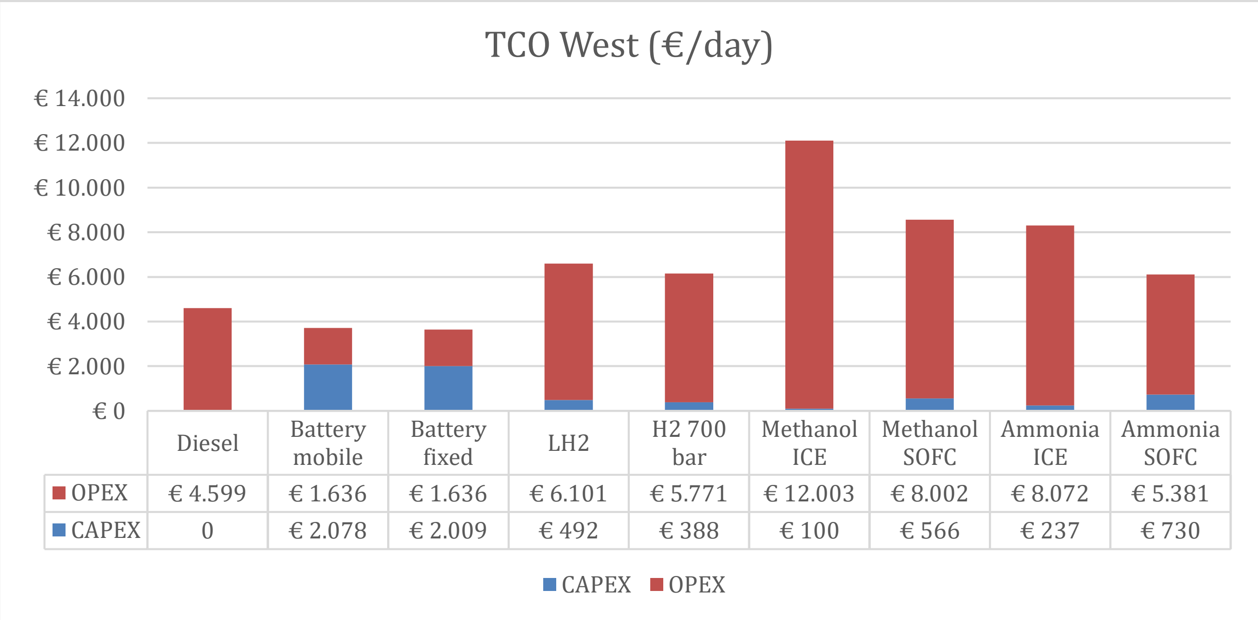
The relatively high OPEX of hydrogen and the hydrogen carriers methanol and ammonia are caused by the energy losses during the production process and the conversion of energy on board. The latter explains the difference between SOFCs and ICEs for methanol and ammonia.

The longer distances of the ferry routes on the western Wadden Sea result in relatively high CAPEX for batteries. Since the TCO for batteries is lower than for diesel, it is economically feasible according to the criteria of paragraph 6.1. The TCO of hydrogen is higher than diesel, but since the difference is small, the perceived distribution of benefits and these costs can be positive if the benefits are large enough. For methanol and ammonia with an ICE configuration, the costs are higher, which has negative effects on the perceived distribution of benefits and costs.



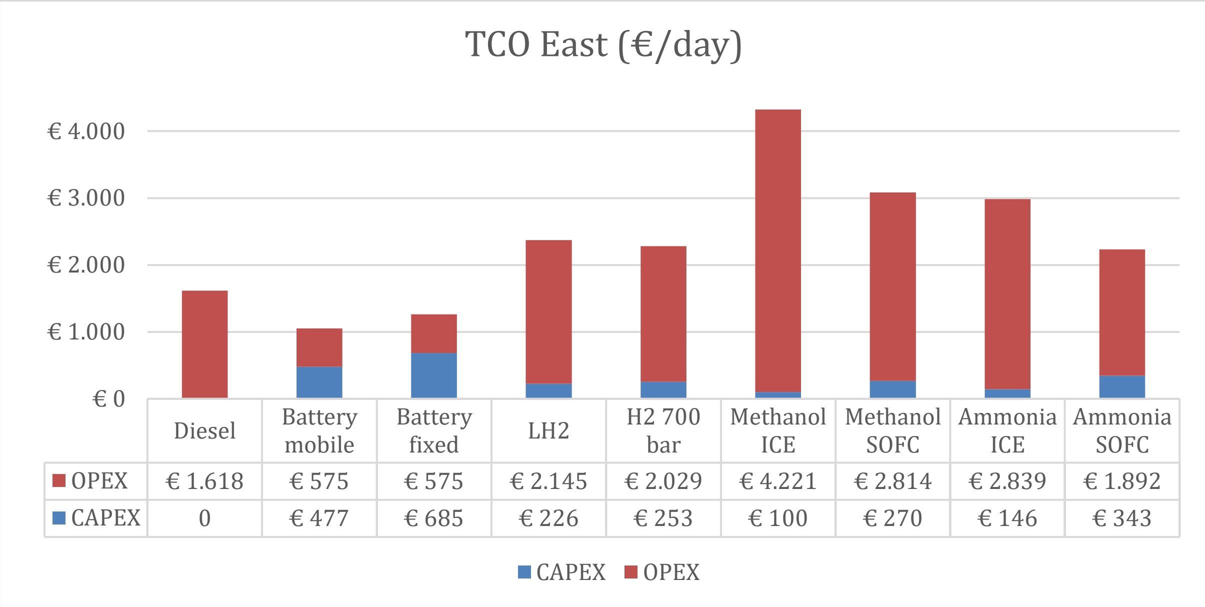
	Diesel	Battery mobile	Battery fixed	LH2	H2 700 bar	Methanol ICE	Methanol SOFC	Ammonia ICE	Ammonia SOFC
OPEX	€ 4.380	€ 1.557	€ 1.557	€ 5.810	€ 5.496	€ 11.431	€ 7.621	€ 7.688	€ 5.125
CAPEX	0	€ 842	€ 776	€ 732	€ 810	€ 100	€ 1.059	€ 383	€ 1.369

Figure 18; TCO of suggested innovations for Texel



	Diesel	Battery mobile	Battery fixed	LH2	H2 700 bar	Methanol ICE	Methanol SOFC	Ammonia ICE	Ammonia SOFC
OPEX	€ 4.599	€ 1.636	€ 1.636	€ 6.101	€ 5.771	€ 12.003	€ 8.002	€ 8.072	€ 5.381
CAPEX	0	€ 2.078	€ 2.009	€ 492	€ 388	€ 100	€ 566	€ 237	€ 730

Figure 19; TCO of suggested innovations for the western Wadden Sea



	Diesel	Battery mobile	Battery fixed	LH2	H2 700 bar	Methanol ICE	Methanol SOFC	Ammonia ICE	Ammonia SOFC
OPEX	€ 1.618	€ 575	€ 575	€ 2.145	€ 2.029	€ 4.221	€ 2.814	€ 2.839	€ 1.892
CAPEX	0	€ 477	€ 685	€ 226	€ 253	€ 100	€ 270	€ 146	€ 343

Figure 20; TCO of suggested innovations eastern Wadden Sea

6.2.4 *Sensitivity analysis*

The sensitivity of the CAPEX calculations for batteries is discussed below. The sensitivity of the CAPEX calculations of batteries is discussed in detail because the expected lifetime of batteries is limited and have to be replaced. The costs of the replacements are based on projections with a higher and a lower end. Furthermore, there are multiple configurations possible, for example with more batteries, or without the replacement of additional systems.

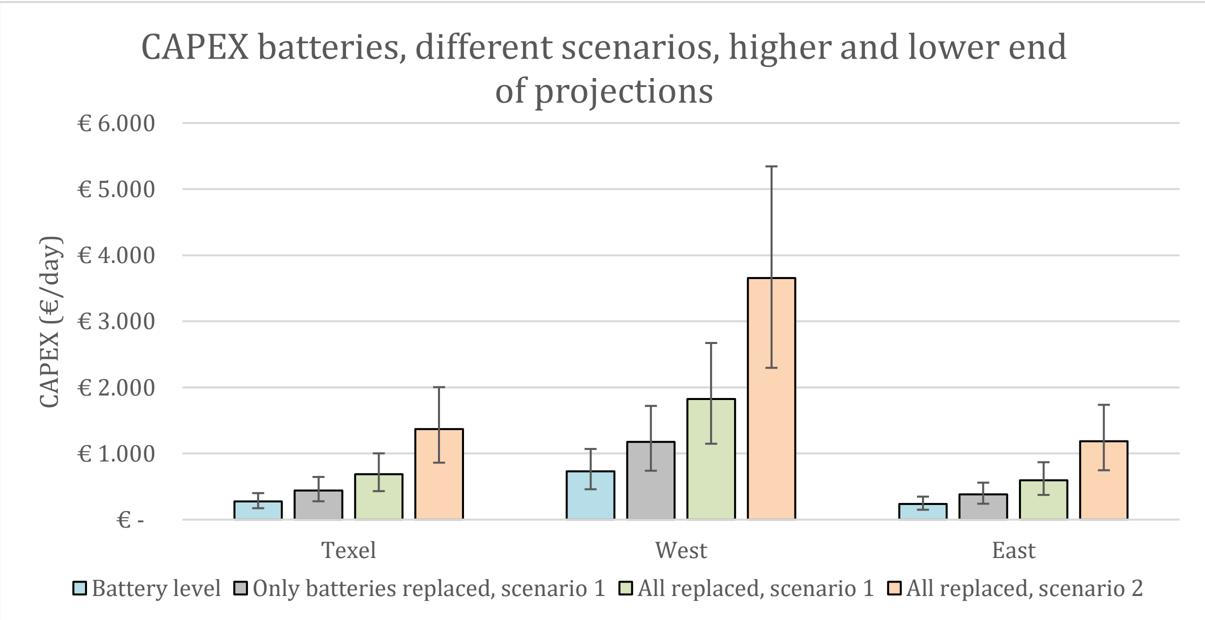


Figure 21; CAPEX batteries, different scenarios, higher and lower end of projections. Projections are based on Cole & Frazier, 2019

The CAPEX calculations of batteries based on the number of batteries that are required for one crossing The sensitivity of capital expenditures of other suggested innovations is not included, since the CAPEX is a relatively small part of the TCO for these technologies and because these technologies do not require replacements after a certain period. The battery costs are based on a study by Cole and Frazier (2019), which is discussed in detail in Appendix V.

(West) or two crossings (Texel and East). The calculations can be found in appendix I. The amount of batteries is based on a charging period of 15 minutes, a charging rate of 2 C and a depth of discharge of 50%. The calculations for fixed batteries include batteries that are placed on shore, these batteries are an additional 80% of the batteries that are required for the ferry (Appendix V).
As discussed in paragraph 6.1.2, the battery costs are only 40 % of the CAPEX costs of the battery pack level (see also Appendix V). The blue bars in Figure 21 show the costs on a battery level. Since the expected lifetime is approximately 10 years, this is based on two replacements. Additional costs are for safety, ventilation, and cooling systems. The grey bars in Figure 21 show the CAPEX of the battery packs when only the batteries are replaced. The green bars show the costs when all installations are replaced, this is used for the calculations in this study and results in Figure 18, Figure 19, and Figure 20. In a detailed study, it should be determined if the replacement of the additional systems is required when the batteries are replaced.
The amount of batteries is an optimum of weight, costs, capacity and life expectancy. This is different for each area and depends on the preference of the ferry operator.
Therefore, the orange bar in Figure 21 shows a different scenario (scenario 2), with the CAPEX of the batteries on a pack level when the whole system is replaced twice and with a DoD of 25% and a charging time of 15 minutes with 1C, or 7,5 minute with 2C. A lower C-rate and a lower DoD will increase the life expectancy of the batteries. However, this scenario will weigh more and might not be feasible for all options. For each new ferry, an optimum should be calculated, for example in cooperation with a battery supplier.

As described in paragraph 6.1.3, the projected electricity rate that is used for this study is for 2030 and is € 57,25 / MWh. This projection, made by Schoots et al. (2019), has a lower end of € 36,25 / MWh and a high end of € 80,25 / MWh. Since all alternatives are based on electricity, the influence of a lower or higher electricity rate is calculated for all alternatives and shown in Figure 22.
The low end of the diesel projection is based on the rate that Wagenborg uses for 2020, which is € 67,71 per MWh (WPD, 2019). The rate that is used for calculations (mid-level) is an increase of 8% (€ 73/MWh) and the high end that is used as an increase of 20 % (€ 81,25).

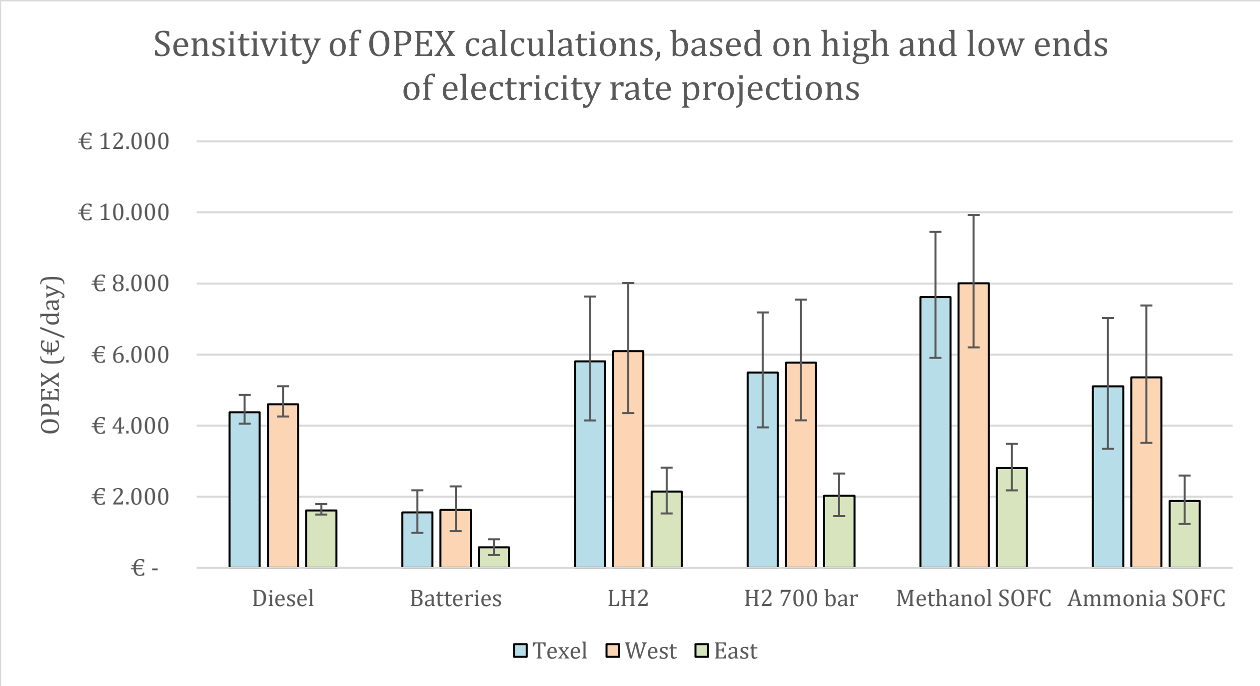


Figure 22; Sensitivity of OPEX calculations, based on high and low ends of energy projections (Schoots et al., 2019)

6.3 Chapter conclusion

The sub-question that this chapter answer is: *What is the total cost of ownership of zero-emission alternatives compared with fossil fuel configurations?*

A visualization of the TCOs for Texel, the western and eastern Wadden Sea can be found in respectively Figure 18, Figure 19, and Figure 20. The order of alternatives is roughly the same for all crossings, with minor differences between storage types. With the projections of the costs of lithium-ion batteries and electricity prices in the Netherlands, the battery-electric alternatives have the lowest TCO. Over a full lifetime of 30 years, the TCO of the battery-electric option is lower than the TCO of diesel. Therefore, for all ferry operators the battery-electric alternative is economically feasible.

For the liquid energy carriers, hydrogen has a slightly higher TCO than diesel, followed with respectively ammonia and methanol. Because these alternatives are more costly than the current configurations, the perceived distribution of benefits and costs is required to discuss the economic feasibility of these alternatives.

7 SOCIAL FEASIBILITY

In this chapter, the social feasibility of zero-emission technologies for Wadden Sea ferries is discussed. This will answer the first part of the sub-question:

What is the potential social and political feasibility of zero-emission ferries in the Wadden Sea?

The feasibility is determined by multiple factors discussed in the framework of Feitelson and Salomon. How these factors are influencing the feasibility of zero-emission technologies is analysed in this chapter. Additionally, characteristics of the alternative technologies that can negatively influence the social acceptability are discussed.

7.1 Methodology

7.1.1 *Factors influencing the social feasibility*

In the framework of Feitelson and Salomon (2004), social feasibility plays an important role since it is one of the three explicitly shown feasibilities in the political economy framework. However, the social feasibility influences the political feasibility instead of directly influencing the adoption of an innovation.

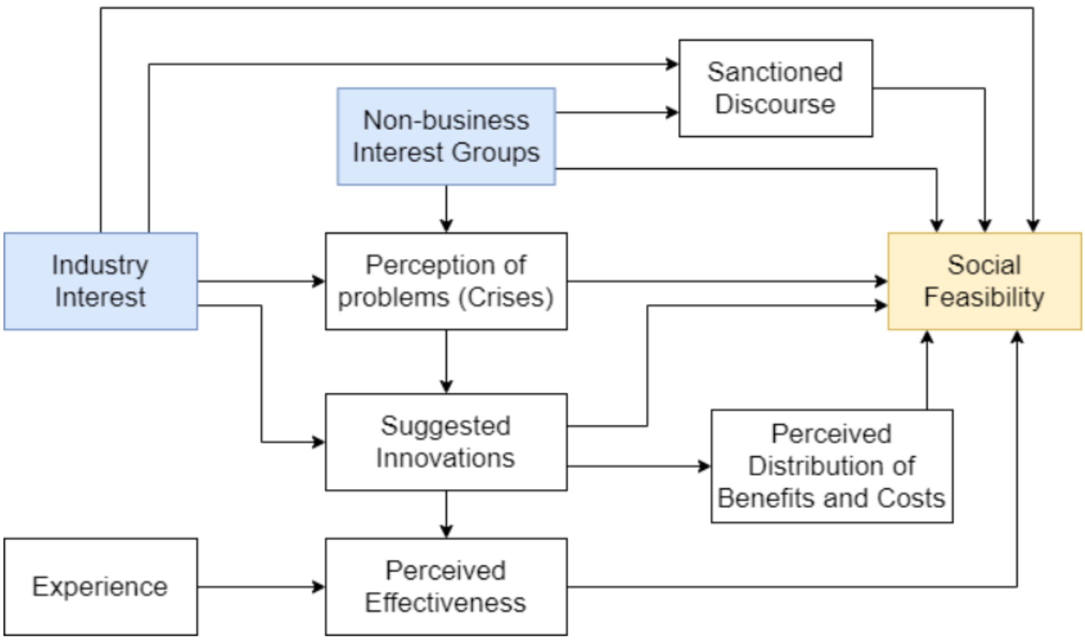


Figure 23; Detail of social feasibility part of the model of Feitelson and Salomon (2004)

Social feasibility is suggested to be a combination of the public perception of problems and the perceptions of the effectiveness of the suggested innovation in solving these problems (Rienstra et al., 1999).
However, Figure 23 shows that also the perceived distribution of benefits and costs and the sanctioned discourse influence the social feasibility.

This chapter discusses how the factors of Figure 23 influence social feasibility.
The perception of problems by industry is already discussed in 5.2.1, therefore the social and political perception of the problem is analysed in this chapter.
The sanctioned discourse provides outlines of the social and political demands for (future) ferries.
If the problem is defined as 'Wadden Sea ferries emit polluting emissions into the air', all suggested innovations are effective in solving this problem since they emit zero emissions. However, all suggested innovations have characteristics that can negatively influence social support. These are discussed in the analysis.
For the zero-emission alternatives that are more expensive than the current ferries, the perceived distribution of benefits and costs is discussed.

7.1.2 *Selection of sources*

The interviews that are conducted with a variety of actors are used for the analysis of the social feasibility. The interview protocol, which can be found in appendix IX, includes questions about the first factor, the perception of emissions as a problem and the requirement of zero-emission ferries in the Wadden Sea. For the factors 'sanctioned discourse' and 'perceived effectiveness', the semi-structured interviews proved to be an important source. Interviewees provided information of the sanctioned discourse, potential barriers for zero-emission ferries and potentially negative aspects of zero-emission technologies. Interviewees mentioned other sources such as policy papers. Further searches on Scopus on topics that interviewees mentioned provided scientific sources for further analysis.

When interviews are used as a source, the reference number is mentioned. Documentations of the interviews can be found in the appendix and an overview of the interviews can be found in Table 3.

7.2 Result of analysis of social feasibility

7.2.1 *Perception of problems*

Zero-emission ferries are a solution for the problem that can be defined as 'ferries in the Wadden Sea are emitting polluting emissions into the air'. Although the harmful effect of these emissions, especially the GHGs, has been a topic for NGO's and alarmist for years, the last years the priority of this topic has risen globally. For example, the Paris Climate agreement and more recent, the Dutch climate agreement show a wider political and societal interest in the reduction of emissions. The rise of zero-emission electric vehicles in the Netherlands shows that a growing number of customers is willing to invest in non-fossil fuel technologies.

Although there are many initiatives to reduce emissions, the motivation is not always the same. There is a difference between greenhouse gasses and emissions that are harmful to the local area. Reducing GHGs such as CO_2 are a main objective of the climate agreements, while local emissions such as PM, SOx and NOx are a health risk and are one of the objectives of the Norwegian government to introduce a zero-emission policy in certain fjords. This is due to the geographical characteristics of the fjords, where mountains nearby the fjords are blocking the exhaust gasses of ships and at certain locations smog is appearing (Launes, 2018). Local air quality improvement is also one of the reasons for cities to adopt zero-emission ferries.

At the Wadden Sea, exhaust gasses spread quickly into the air and the health risk of exhaust gasses is no more than other regions in the Netherlands. Public health risk caused by local emissions is therefore not a direct motivation for zero-emission ferries.
A reduction of GHGs is the main motivation for zero-emission ferries according to interviewees (1,5) Although GHGs are spreading globally and a reduction of GHGs in the Wadden Sea does not affect this area more than other areas, the Wadden Sea can be threatened directly by effects of global warming, such as sea level rising.

Since the Wadden Islands have a lot of nature and this nature is a reason that many tourists are crossing the Wadden Sea with a ferry, many interviewees believe that islands citizens and especially tourists are supporting innovations to reduce emissions in the Wadden Sea (interviews 1,2,4,5).

7.2.2 *Sanctioned discourse*

The importance of (changes in) the sanctioned discourse and relevant developments for the demands for ferries that affect the design are discussed in this paragraph.
Which changes to the current situation are socially and politically acceptable depends on the leading sanctioned discourse. Policy entrepreneurs and (environmental) interest groups can affect the public perceptions, which might alter the sanctioned discourse (Feitelson & Salomon, 2004).
Although the legal demands for ferry operators are part of the concessions, these demands are within the borders of the leading sanctioned discourse. Therefore, ferry operators are interested in the (future) sanctioned discourse, since it gives them the outlines of potential future concession demands. Zero-emission propulsion might be one of these demands.
Important documents where many relevant actors discuss their opinions on the future of the Wadden Sea are the 'Gebiedsagenda Wadden 2050' for all Wadden islands and the 'langetermijnvisie bereikbaarheid Ameland' specifically for Ameland (interview 3). These documents will be published in 2020.

Ferries as island's lifeline

Wadden Sea ferries are of great importance for the transportation of island citizen, the import of materials and food, and for the hundreds of thousands of tourists that are visiting the Wadden Islands every year. A reliable ferry with enough capacity is therefore very important for the local economy and overall quality of life of the Wadden Islands.
Because Wadden Sea ferries are designed for specific crossings, it can be difficult to find an alternative ferry when a ferry is out of service. Innovations that are not yet proven in similar situations might therefore be seen as a higher risk than traditional, proven technologies such as diesel-fuelled ferries by the public. Large scale tests, training, and clear communication can help to convince the public that new technology is reliable and safe.

Changes in transport demand for ferries

Wadden Sea ferries are purpose-built for the demand of the island that they are sailing to. The capacity of persons, freight, and cars of the ferries is based on the demand for transport. Since the demand is higher in summer and especially on specific moments (e.g. national holidays, Fridays and Sundays), the vessels are designed with a higher capacity than often required. For ferry operators, it is important to know what the demand will be for the lifetime of a ferry. For a new ferry, this will be approximately 30 years and a few additional years for designing and building of these ferries.
The demand for crossings for cars is important for new designs. Cars are relatively heavy and large and require specific places on a dedicated car deck. Interviewees suggest that the number of cars that make the crossing might be smaller in the future for Ameland and Terschelling This might be the case when

a car-sharing or car-renting infrastructure is developed on these islands. Because ferries have to be designed for a specific demand, such initiatives have the most effect when cooperated with ferry operators before new ferries are designed. For Schiermonnikoog and Vlieland it is not allowed for tourists to take a car to the island. For Texel, an increase of cars in expected (interview 6).
For Texel and the eastern Wadden Sea, freight is transported on the same ferry as persons. Ferry operators here argue that dedicated ferries for freights are not (cost) effective, it requires additional infrastructure or that more ferry movements are not desirable (interview 3). Therefore, freight is transported with the ferry. Wagenborg is studying alternatives for trucks to save weight.

Homeports
Most ferries have the island harbour as home port. This means that most ferries are moored at the island and that personnel that work on the ferry are living on the islands. For Texel, the Texelstroom is used to bring ambulances from Texel to the mainland approximately 150 nights per year (interview 6). When charging or bunkering installations are located at the mainland, this can influence the operation.
The operational speed of the ferries is important for the energy demand per crossing. The energy demand is higher when the speed demand increases. For Texel, the speed is determined for an hour schedule, where two crossings (including (un)loading) are made within one hour. The eastern Wadden Sea recently has some high-speed ferries (with limited capacity). When new ferries with higher operational speed are operational, the dedicated (low capacity) high-speed ferries are unnecessary (interview 3).

7.2.3 *Perceived effectiveness*
All four suggested innovations discussed in this study are effective in eliminating emissions emitted by the Wadden Sea ferries. However, there are characteristics of these technologies that can influence the social acceptability of these technologies. These will be discussed below.

Sustainability of batteries
Of all alternatives discussed in this study, batteries are the most energy-efficient (well-to-propeller) alternative and the GHG emissions of a battery-electric ferry are zero during operation. However, the lifetime of batteries is much lower than the lifetime of the ferries itself and the batteries have to be replaced multiple times during the operational life of the ferries. Research is conducted for the impact of the production of battery electric vehicles (BEV) and compared to the production of ICE vehicles, where is found that the battery production has a large environmental impact due to energy demand of raw material extraction, processing and production of batteries.
Furthermore, the production of batteries requires rare metals such as cobalt and lithium. The sustainability of using such rare earth elements on a large scale has been discussed in several studies (Klinger, 2018).
Cobalt is an essential component for lithium-ion batteries. Unfortunately, cobalt mining is associated with bad working conditions and health hazards. Over half of the cobalt comes from the Democratic Republic of Congo, where according to UNICEF an estimated 40.000 children work in dangerous mines. Tracing the origin of cobalt has been proved difficult and efforts to make the origin of cobalt more transparent failed according to Amnesty International (Dummett, 2017).

Since all FC alternatives use peak shaving batteries, the issues mentioned above are relevant for all alternatives, although on a smaller scale.
The production of large, complex installations such as hydrogen tanks is also energy-consuming. Especially the composite high-pressure hydrogen tanks required for the storage of hydrogen compressed to 700 bar.

Charging and bunkering procedures
The high energy density and ease of use of diesel makes that bunkering of diesel on conventional ferries is done with a relatively low frequency and with relative ease. For the alternatives, the bunkering process is more frequent and more complex.
For fixed batteries, complex and high-tech charging stations are designed and proven in Scandinavia. These systems include robotic arms to maximize charging time during (un)loading of the ferry and compensate ship motions from waves and current. Although these are expensive, no additional personnel is required.

For mobile battery packs, a crane to lift battery containers from the ferry is a possibility. However, since the ferries are designed as RoRo-ferries, a wheeled vehicle demands fewer investments and makes a crane unnecessary. For a zero-emission ferry, a zero-emission swapping system is preferred. An electric truck can be used, according to a recent study these trucks are economically feasible for short-range container moving in a few years (Van Sloten, Hoekstra, De Kerf, Hoogeveen, & Aldenkamp, 2019). However, because the distances required to swap containers are minimal, other solutions are possible. Experience with electric vehicles used for airfield ground handling can be used. For example, electric tractors used at airfields that are small and capable of towing large weights with precision. When a tractor-trailer solution is used, it is not necessary to leave the towing vehicle on the ferry, which reduces weight and volume requirement. The exact costs, time, manhour and expertise requirement is case dependent.

Hydrogen bunkering is more complex and time-consuming than diesel bunkering. For their newest ferries, bunkering of LNG is done once a week by Doeksen after their crossings (Rederij Doeksen, 2019). Bunkering during (un)loading or when passengers are on board is not desirable, especially when bunkering is complex and the fuel potentially dangerous. Bunkering during the day is therefore difficult and all fuel options that require bunkering multiple times a day are therefore not likely to be feasible. For complex bunkering processes such as with hydrogen and ammonia, additional training of personnel is required.

Inefficient use of renewable electricity
In 2018, 8 % of the total electricity in the Netherlands was generated by wind turbines and 3 % by solar panels (Meurink, Muller, & Segers, 2019).
Although the share of renewable electricity grows in the Netherlands, it is still limited. From a societal point of view, renewable electricity can be seen as a scarce good in the Netherlands. When ferries use liquid energy carriers, the amount of renewable electricity required for production is higher than when the electricity is directly used in batteries due to efficiency losses. Inefficient use of renewable electricity can be seen as undesirable by society.
In Scandinavia, where most of the existing zero-emission ferries are operating, the share of renewable electricity is much higher.

Health risk of ammonia
As mentioned in paragraph 5.9, ammonia is toxic. Although transported all over the world and procedures of (un)loading and handling of ammonia are available, it is not yet used as fuel for marine applications. Passenger ferries in a vulnerable environment might not be a good pilot for the use of ammonia from a societal and environmental point of view (interview 1). Even when theoretically safe to use, social acceptance is most likely to be higher when this technology is proven on other ships, for example on ammonia tankers.

Environmental impact of incidents
The Wadden Sea is a vulnerable environment and spills of oil or other chemicals can have large, long-term consequences for this area. The Wadden Association developed scenario's for oil spills as a result of a collision above the Wadden islands (Kuipers, Reinders, & Riesenkamp, 2012).
The loss of over 345 containers of container vessel MS Zoë above Terschelling in January 2019 and the resulting pollution of the Wadden Sea shows how large the impact of a single incident can be for the Wadden Sea (Waddenvereniging, 2019).
The phase-out of diesel and other fossil fuels from Wadden Sea ferries is for environmental organisations an opportunity to improve their situation and increase the chance of an environmental disaster. However, the potential dangers of alternatives must be investigated before it has the support of environmental organisations (interviews 1,5).

Although all alternatives are an improvement in the reduction of emissions, environmental organisations will also look at potential spills or other incidents. Social acceptance can be affected by the knowledge that new technology can be potentially dangerous or polluting. Environmental organisations may increase this factor and influence social acceptability.
Batteries are solid energy carriers and when fixed, this technology will only pollute the environment when the entire ferry sinks. Hydrogen is not liquid under atmospheric pressure and will not pollute when spilt. Methanol and ammonia are toxic for the environment and are therefore no improvement compared to diesel.

7.2.4 *Perceived distributions of benefits and costs*
Although the business cases of each ferry crossing depend on multiple factors and specific calculations for each crossing would be required for a ferry operator to decide what exact costs are feasible for their business case. In the calculations in chapter 6, resulting in the Total Cost of Ownership that can be found in figures 18, 19, and 20, diesel is used as a reference fuel. However, ferry operators believe that fossil fuels have no future (interviews 3,6) and that a change is necessary. In their opinion, the 'benefit' is a necessity when it is technically and economically possible.
In interviews, it was asked if passengers are willing to pay more for a ticket if the ferry emits no emissions. Although all interviewees agree that most passengers think that a reduction of emissions is important (interviews 1,2,3,4,5,6), the interviewees disagree about the willingness of passengers to pay more. That at least some passengers are willing to pay more is proved on the eastern Wadden Sea. There, the voluntary donation of € 0,50 per crossing that passengers can pay to compensate emissions is used by many passengers, according to WPD (interview 3).
TESO reduced the cost of a return ticket for a single passenger to € 2,50 and views affordability as one of their focus areas (interview 6).
Although affordability and investments in zero-emission sailing can be incompatible when the costs of zero-emission technologies are high, the investments of TESO and Doeksen in technologies to reduce emissions such as CNG and LNG show that the lowest costs are not deciding. Nevertheless, to avoid reducing the affordability of crossings, the alternatives with a low TCO are preferable from a societal point of view. Since the TCO of methanol is much higher than the alternatives, it is not likely to pass a cost-benefit analysis.

7.3 Chapter conclusion

The perception of the problem, defined as 'Wadden Sea ferries emitting polluting emissions' is recognized by all interviewees. However, this is mainly due to global GHGs. This is different than for the first zero-emission ferries in Norway, where local emissions were seen as the main problem. Interviewees agree that zero-emission ferries are socially desirable.

The sanctioned discourse shows the outline of possibilities. Since ferries are the lifeline for the Wadden Islands, reliability is very important. Changes in transport to the islands directly affect the requirements for the ferry and can affect the design and suitability of zero-emission systems for the ferries. Another social challenge might be that most ferries stay at night at the island port (for safety and crew), while the charging and bunkering installations will likely be located at the mainland port.

The suggested innovations are all effective to solve the problem, since no emissions are emitted when these technologies are used. Nevertheless, the alternatives have characteristics that can affect the social acceptance of such technologies. These negative characteristics must be justified when a suggested innovation is chosen. However, none of these characteristics conflicts with the ability to effectively solve the problem of emissions.

Interviewees agree that passengers think that sustainability is important and at least a part of the passengers is willing to pay a premium for sustainability. However, the affordability of ferries is also seen as an important factor and (high) increasements of ticket prices are socially undesirable. The alternatives with the lowest TCO are therefore more attractive.

It can be concluded that ferries that emit no harmful emissions are socially desirable. When negative aspects of batteries, hydrogen, and ammonia are justified, the suggested innovations are socially feasible. Methanol is not likely to pass the cost-benefit analysis since the TCO is much higher than the alternatives.

8 POLITICAL FEASIBILITY

The last feasibility that is analysed in this study is political feasibility. Although social feasibility is a large factor for political feasibility, it is not the only factor. This chapter focusses on the decision-making procedures, since there are multiple actors that have to make decisions relevant for potential implementation of zero-emission ferries separately and the decision-making procedures are very relevant for these decisions.

8.1 Methodology

To analyse the political feasibility of zero-emission ferries in the Wadden Sea, the relevant factors of the model of Feitelson and Salomon are discussed. The main source for this chapter are interviews.

8.1.1 *Factors influencing political feasibility*

As described in the previous chapter, the political feasibility is influenced by social feasibility. However, there is not a referendum that asks the general public whether Wadden Sea ferries should be zero-emission ferries or not. Therefore, social feasibility is not the only factor in the political feasibility. The model of Feitelson and Salomon (2004) is made for large infrastructural projects where politicians are responsible for large decisions. Although there are multiple governmental organisations such as multiple ministries and provinces involved with concessions where demands are set for ferry owners, there are more decision-makers involved. Ferry operators make the decision to invest in certain ferries and on which moment they do so. For Texel, there is no concession system and the role of governmental organisations is not as direct as for the other islands. Decision-making procedures and the role of multiple decision-makers is widely discussed in this chapter. Experience is another factor that affects the political feasibility. In this study, this exceeds the experience of decision-makers and is also the experience provided by existing zero-emission ferries.
The perception of problems and sanctioned discourse are discussed in the social feasibility chapter.

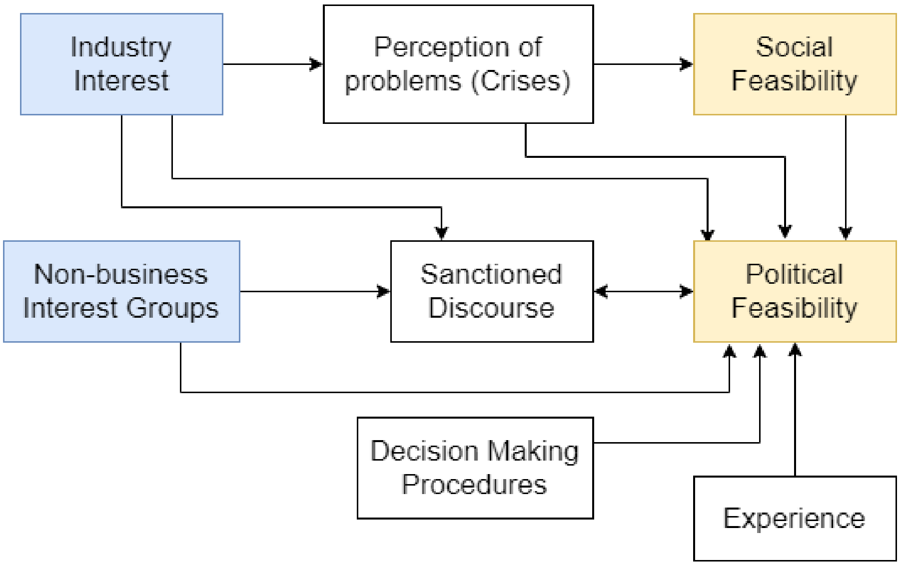


Figure 24; Detail of political feasibility part of the model of Feitelson and Salomon (2004)

8.1.2 *Selection of sources*

The decision-making procedures are based on the concession system. The documents describing this process and choices are publicly available (Ministerie van I&M, 2011a, 2011b). As part of the concession, the ferry operators publish a transport plan each year. When these documents are approved by the Ministry of I&W they are publicly available (Rederij Doeksen, 2019; WPD, 2019).
Nevertheless, the interviews are the main source of this chapter. Findings during these interviews provided context for the decision-making processes and potential windows of opportunities.

8.2 Results of analysis political feasibility

8.2.1 *Decision-making procedures*

The Wadden Sea ferry routes are crucial for the island citizens, the local economy and for the tourists that visit the Wadden Islands. Unlike other important infrastructure such as highways, the ferries are operated by private companies. TESO, the ferry operator to Texel, is a non-profit organisation with a lot of shareholders from the island. Doeksen and Wagenborg Passagiersdiensten are operating respectively the western Wadden Sea concession and the eastern Wadden Sea concession.
In the interviews which were conducted for this study, interviewees were asked who can make the decision whether a new ferry will be a zero-emission ferry. The overall answer was that the ferry operators make the decision to invest in new (zero-emission) ferries, based on the need of the passengers, especially island citizen, and to meet the criteria of the concession (interviews 1,2,3,4,5,6). Although TESO is not legally required to meet these criteria, they see these demands as a minimum standard they will deliver. Therefore, the concession criteria are also relevant for TESO (interview 6).

8.2.2 *Policy windows*

In his book Agendas, Alternatives and Public Policies, John Kingdon describes the Multiple Streams Framework (2011). When three streams come together, a window can open where changes can occur. This is related to the windows of opportunity, as described in chapter 2. A conceptual model can be found in figure 25.

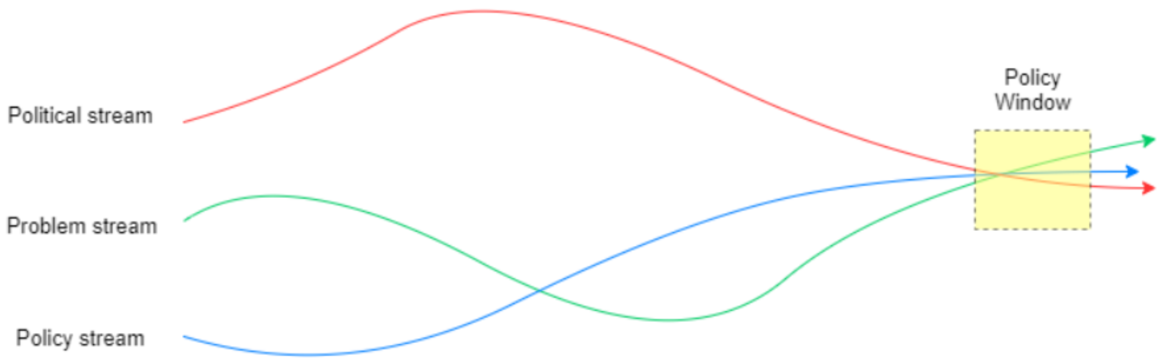


Figure 25; Multiple Streams Framework based on Kingdon (2011)

Problem stream

The problem stream is determined by the (public) perception of emissions as a problem. The actual amount of emissions emitted by ferries influences this, although this is not the only factor that affects the perception of the public.

Policy stream

Policies are solutions for the problem. In this study, the solutions are the suggested innovations. The policy stream is the availability of those alternatives, which are based on technical and economic feasibility. Since 2015, zero-emission ferries are in operation and make this availability more visible.

Political stream

The political stream provides the moment when decisions can be made and is often based on cycles such as elections or budgets. In the case of Wadden Sea ferries, the demand for a new ferry (when the operational ferry is at the end of its expected lifetime) determines the decision-moment.

The fact that both TESO as Doeksen invested in relatively sustainable systems (CNG and LNG) show that all streams came together, but the policy stream included only relatively sustainable systems. This was before zero-emission systems were (commercially) available.

Kingdon distinguishes two types of windows: predictable and unpredictable. For Wadden Sea ferries, the streams mentioned above are relatively predictable, although unpredictable events might alter the course of the streams.

The streams described above are visualized in Figure 26. The red line projects the cycle of the requirement of new ferries. Each ferry operator has at least one cycle here.

In Figure 26, at point 'A' the political and problem stream meet. This is a visualization of what happened during the designing process of the latest ferries of TESO and Doeksen, respectively the Texelstroom and Willem Barentsz. The emission problem was acknowledged, and new ferries were required. However, there were no zero-emission solutions available yet (the policy stream did not join) and CNG and LNG were chosen as a solution (interview 6).

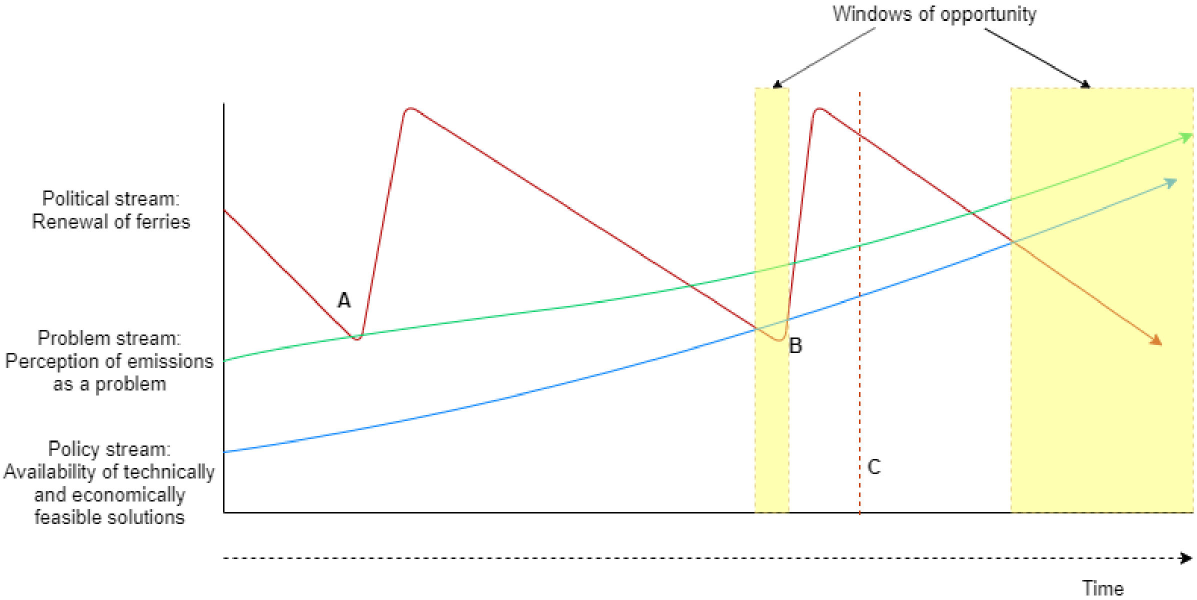


Figure 26; Multiple streams for window of opportunity for zero-emission Wadden Sea ferries. Based on kingdon (2011)

At point ‘B’ in Figure 26, also the policy stream joins, therefore all streams are coupled and a window of opportunity is opened.
Based on the technical developments of chapter 5, the economic projections of chapter 6 and interviews, this might be the case when Wagenborg requires new ferries within a few years (interview 3). The design criteria for such ferries must be known several years earlier.

After this moment, there is no need for new ferries for a time and the window of opportunity closes again. The cycle that determines the requirement of new ferries is not connected to the start of a new concession period, which is illustrated as the dotted line of point ‘C’ in Figure 26. If information about the criteria of the new concession is not available in the window of opportunity, the decision-maker can not include these criteria in the ferry design. The next concession starts in 2029 and Wagenborg will have to replace ferries before this, while the design criteria have to be known several years before this. Therefore, a situation as shown in Figure 26, where the decision has to be made without knowledge about the criteria of the concessions is possible.

When the technical and especially economic feasibility of zero-emission technologies increases together with the public perception of the emissions as a problem, a second window of opportunity can open before the existing ferries have to be replaced. An existing ferry is then refitted and machinery replaced. This is often an expensive operation, especially when the investments in the installed machinery is based on a longer period and are not yet fully paid off.

8.2.3 *Concession system*

The next concession for the western and eastern Wadden Sea will start in 2029 and will have a duration of 15 years, just like the current concessions that started in 2014. Although Doeksen and WPD are operating the ferry routes since respectively 1923 and 1919, the concession system makes it possible for other parties to challenge the ferry operators for the new concession in 2029. If this happens, this will have no consequences for the emissions of the ferries, since a potential new ferry operator is legally obligated to purchase the existing ferries from the current ferry operators (Ministerie van I&M, 2011a, 2011b).
Current concessions include sections about sustainability. This does not include the use of specific technologies but demands ‘a demonstrable effort to limit emissions such as CO_2, NOx, PM, and other harmful emissions’ (Ministerie van I&M, 2011a, 2011b).
All interviewees expect that the next concessions will include criteria for sustainability. However, it is not known if the next concession will include measurable demands for specific amounts of emissions (for example: zero emissions), will demand specific technologies or only demand ‘effort’ like the current concession.

8.2.4 *Influencing the streams*

All streams can be influenced by certain actors to couple the streams or to avoid this. The political stream is based on the replacement of ferries. A ferry operator can influence the purchasing of new ferries by carrying out refits instead of newbuilding (extending the lifetime of a ferry) or renew ferries earlier and sell their old ferries. However, these are often more expensive or provide less quality. In 2011, WPD extended the lifetime of MS Rottum with a refit (WPD, 2018).

The problem stream can be influenced by non-governmental organisations via (media) campaigns or other public performances. Although it is likely that effort is put in promoting zero-emission technologies, it is also possible that the problem stream is influenced in the other direction. For

example, when island citizen doubt that new technologies can provide the same reliability as the current technologies, the emission problem can be seen as less important. Because this is based on perceptions, the public opinion is not always based on facts and can be difficult to predict.
However, sustainability is already a widely discussed topic and an additional campaign might have limited effects of the problem stream.

The policy stream is based on solutions for the problem, in this study these solutions are zero-emission technologies. In reality, there is a stream for each of the four technologies discussed in this study. This stream can be influenced by investments in research in this technology, although the results can be difficult to predict and take a long time before resulting in higher feasibility. Direct funding, for example subsidies, can directly influence the policy stream. When otherwise not economically feasible, additional funding can help to couple the streams and make zero-emission ferries feasible. Interviewees agree that infrastructure or other capital investments are more suitable for additional funding than operational expenditures such as fuel (interviews 1,2,3). An increase in (energy) taxes, difficult (or incomplete) regulations or risks can influence the policy stream negatively.

When a window of opportunity for zero-emission ferries occur before the new concession of 2029, which is likely since WPD has intentions to replace ferries within a few years (interview 3), the influence of the criteria for the new concession can be limited. When concession criteria are only applied to new ferries, it can take many years before these criteria are applied. It is possible that no new ferries are built during the next concession period since Doeksen just added two new ferries to their fleet and WPD has intentions to build new ferries before the end of the current concession.

If the 2029 concession has criteria for emissions which are more demanding than operational ferries can deliver and apply these criteria on all operational ferries instead of only apply this on new build ferries, the operation ferries require a refit or have to be replaced. The consequences for this can be very large, both financially as for the operability of the ferry operators.

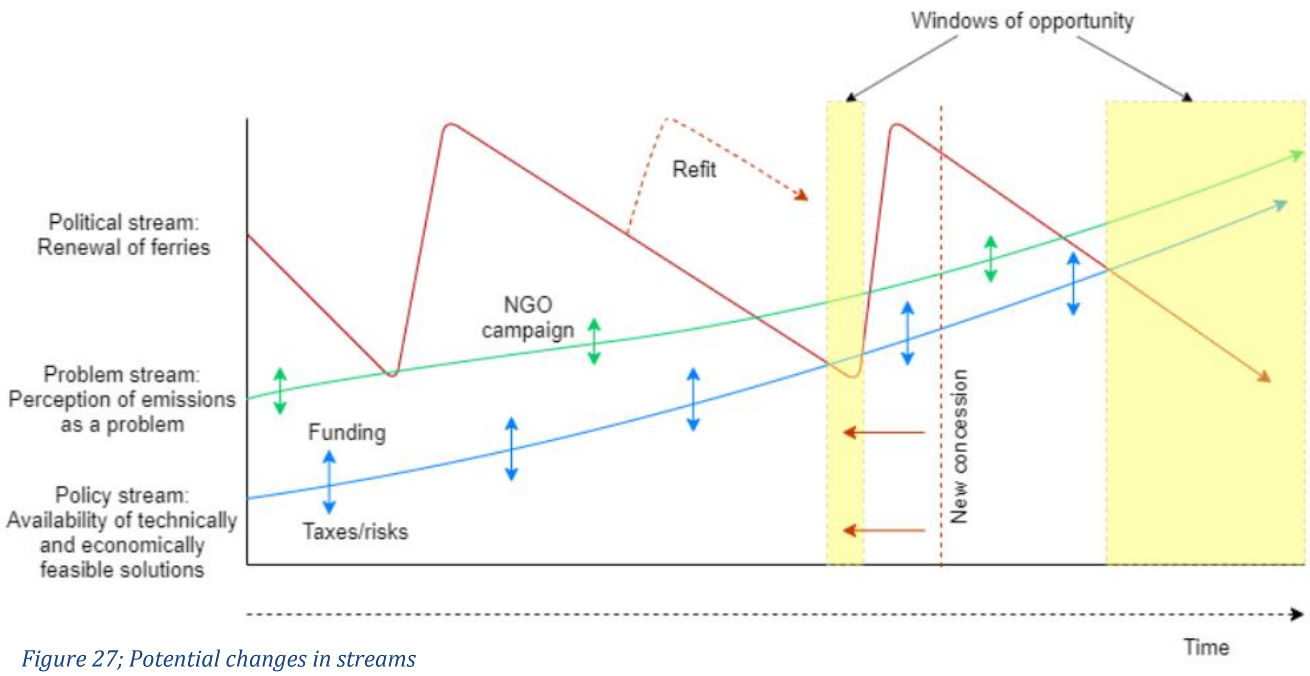


Figure 27; Potential changes in streams

Although determining new criteria for concessions is a complex, time-consuming process with many actors involved, the impact of any criteria for emissions is most likely larger when communicated with ferry operators before new ferries are designed and build. The arrows that place the dotted line of 'new concession' place into the window of opportunity in Figure 27 are based on information, not on the concessions themselves. A statement that concession criteria are based on certain policies or reports that are available before new ferries will be designed can be enough for ferry operators to invest in certain technologies. The 'Gebiedsagenda Wadden 2050' is an example of a policy paper that might be a basis for concession criteria and is available before new ferries will be designed.

For TESO, the moment that criteria for the 2029 concessions are published is less relevant since they are not legally involved with these concessions. However, the stakeholders of TESO (most of which are citizens of Texel) can be influenced by the criteria of the concessions. When there are criteria for sustainability for the concessions, TESO sees these as a minimum requirement.
Especially when other ferry operators are investing in zero-emission technologies, it is likely that stakeholders want similar developments for TESO. The next ferry will be the replacement of the Dr Wagemaker, which will be approximately in 2031 (interview 6).

8.3 UNESCO world heritage

The Dutch part of the Wadden Sea is a UNESCO World Heritage Site since 2008 and most parts of the German and Danish Wadden Sea became a UNESCO World Heritage Site in 2013 (UNESCO, 2018). Therefore, the Wadden Sea is recognized as an area of outstanding international value which is listed on the same footing as the Grand Canyon and the Great Barrier Reef.
Since the Wadden Sea is an extraordinary area, it is assigned with several protective regulations such as Natura2000, National Park and Ramsar. These designations have the intention to protect the special nature and ecosystems. However, when the Wadden Sea also became a UNESCO World Heritage Site, some island citizens were sceptical because it could bring additional regulations which could endanger their way of living or the local economy. Therefore, the UNESCO World Heritage designation is used to promote the uniqueness of the area, ensure that stakeholders understand the value of the Wadden Sea and to ensure that nature, tourism, and local communities benefit from the World Heritage Status, without a large number of additional regulations for local communities (interview 5). This is successful and the Wadden Sea is widely seen as a valuable, unique area. The Wadden Islands are known for their nature and are a popular holiday destination. Interviewees stated that the journey to the Wadden Islands over the Wadden Sea is for many tourists a part of their holiday (interview 5). The idea that the holiday starts at the mainland harbour and that the ferry crossing is part of the holiday itself can make a crossing a more unique experience. Also, the Wadden Sea ferries are very visible (interview 4).
For decision-makers, the fact that Wadden Sea ferries make crossings over a UNESCO world heritage site can be used to promote zero-emission technologies.
However, several interviewees mentioned that this also means that disturbing infrastructure or local electricity sources such as wind turbines are not desirable in the Wadden Sea (interview 1,4).

8.4 Chapter conclusion

In the previous chapter, it was found that zero-emission ferries are socially desirable (although there are consequences for each alternative). National and international initiatives to support sustainability such as the Dutch and international climate agreements and the green deals show the political will to support the reduction of emissions. Zero-emission ferries are therefore seen as politically desirable.
However, political feasibility depends on decision-making procedures. According to most interviewees, ferry operators make the decision to build new (zero-emission) ferries and the concessions include the minimum criteria for these ferries. Also TESO, which is not legally involved with the concessions, sees the concession criteria as a minimum.
Several interviewees say that the concessions are instruments where sustainability criteria can be made and most interviewees think that the concessions of 2029 will include more sustainability demands than the current concessions. However, the criteria are most likely only for new build ferries since conversions of existing ferries are expensive.

A version of Kingdon's three streams model Figure 26 shows that windows of opportunity are only open when ferries are at the end of their expected lifetime and have to be replaced. This theoretic model shows that previous actions such as the decision to sail with CNG by TESO, sail with LNG by Doeksen and to refit existing vessels by WPD can be explained that the three streams coupled, but the policy stream only included solutions based on relatively sustainable fuels such as LNG and CNG and the zero-emission solutions were not feasible yet.

The policy stream which includes zero-emission solutions can couple with the other streams for the next generation of ferries. Such a window can occur before the next concessions of 2029, since WPD is planning to design and build new ferries within a few years. When the criteria of the concessions are not known in this window, sustainability demands for new build ferries in the concession can be irrelevant because the ferries are already built. It is possible that during the whole concession period of 15 years, no new ferries will be built.

The problem stream can be influenced by NGO's with campaigning or by island citizen when they think that new technologies make ferries less reliable.
The policy stream is based on the technological and economic feasibility of solutions. Funding can close a gap when the economic feasibility does not yet reach the other streams. Risks or additional costs such as electricity taxes can make influence the stream negatively.

Decision-makers can use the UNESCO World Heritage recognition of the Wadden Sea to promote zero-emission technologies in this specific area.

Overall, it can be concluded that zero-emission ferries in the Wadden Sea are politically desirable and politically feasible in the long term. The political feasibility in the next decade depends on the decision-making procedures. The first windows of opportunity for zero-emission ferries might be missed when information about the next concessions is not available (on time) to the ferry operators who make the decision to build new ferries.

9 OVERVIEW OF RESULTS

In this chapter, an overview of the results of the technical, economic, social, and political feasibility studies for zero-emission ferries in the Wadden Sea are provided.

9.1 Overview of technical feasibility

In Figure 28, the technical, economic, and social feasibility of zero-emission ferries in the Wadden Sea is visualized. The configurations that are technically feasible do not affect the operations of the ferry and are feasible within the development period of a ferry (a few years). For batteries in the western Wadden Sea, charging is required after every crossing and the islands require a charging station. Because it is not known whether the local electricity grid of Vlieland and Terschelling can be reinforced or there can be local renewable electricity sources, this should be studied before the technical feasibility can be determined. For the storage of compressed hydrogen, the required storage tanks are heavy. In this study, it is assumed that bunkering is only possible after or before daily operations. However, the storage tanks for one day of operation are too heavy for both the western and the eastern Wadden Sea. When additional bunkering during the day is possible, the storage tank can be smaller and compressed hydrogen can be technically feasible. However, the possibility of bunkering during the day should be studied before.

SOFCs are not feasible yet since they are still in an R&D phase. However, it is expected that this technology is available before all ferries are replaced (< 30 years). For ammonia, additional regulations are required to ensure the safety of the use of ammonia on a passenger vessel in a vulnerable area. This can take many years and therefore this technology is not available yet.

9.2 Overview of economic feasibility

The economic feasibility is based on the TCO of each suggested innovation. Although the economic feasibility is a result of a cost-benefit analysis and therefore decision-makers should determine whether the benefit outweighs the costs. However, the TCO of the suggested innovations compared to the TCO of the reference fuel, which is diesel, can be used to determine whether it is likely that a suggested innovation will pass a cost-benefit analysis.

Batteries have a lower TCO than diesel and are therefore assumed to pass a cost-benefit analysis (since there are benefits and no costs). It should be noticed that this includes costs for batteries, land-based batteries and charging infrastructure, but no grid-reinforcements on land. For the other technologies, Figure 28 shows the costs in relation to a diesel configuration. The chance that a technology will pas a costs-benefit analysis increases when the costs are lower. Methanol in combination with an internal combustion engine is more than twice as expensive than diesel and of all innovations, this is the least likely to pass a cost-benefit analysis.

9.3 Overview of social feasibility

The interviews that are conducted for this study agree that emissions are a problem and that zero-emission ferries are desirable. The interviewees mentioned that a majority of the ferry users would agree with this. Combined with broader social attention to emission reduction, it is concluded that zero-emission ferries are socially desirable.

However, each suggested zero-emission innovation has adverse characteristics. The most important are shown in Figure 28. For Li-Ion batteries it is the use of rare earth metal and the limited expected lifetime that can have a negative effect on the perception of sustainability.

For hydrogen and the hydrogen-carriers methanol and ammonia, more renewable electricity is required due to energy losses during production, transportation and conversion on board. This inefficient use of renewable electricity is a negative aspect since only a small part of the Dutch electricity is renewable at this moment. The third negative aspect is for methanol and ammonia, which are polluting when spilt. Although there are multiple precautions to reduce the risk of spills, the results for the vulnerable Wadden Sea are large. Batteries and hydrogen are improvements compared to diesel because batteries are solid, and hydrogen will vaporize when spilt.
None of these adverse characteristics is directly threatening the feasibility of zero-emission ferries but can influence the choice for a certain zero-emission technology.
There are other factors that can lead to practical issues for all zero-emission technologies, for example the habit of ferry operators to leaving the ferry moored at the island harbour at night, which might make charging or bunkering in the evening more complicated.

9.4 Overview of political feasibility

The social feasibility is a major factor for political feasibility. Another factor is the decision-making procedure. For the western and eastern Wadden Sea this is based on the concession system Also for Texel, the ferry operator sees the concession criteria of the other areas as a minimum. Interviewees agree that zero-emission ferries are politically feasible. A reduction of emissions (or zero-emission) can become a criterion for new-build ferries for the next concession, which starts in 2029. Multiple interviewees see this as a policy method to realize sustainable ferries in the Wadden Sea. However, when ferries must be replaced before 2029 and the criteria are not published, the concession will not influence the decision-making. Since the expected lifetime of ferries can be 30 years, this will have consequences for a long time.
Wagenborg Passagiersdiensten has ambitions for zero-emission ferries on the eastern Wadden Sea and will replace ferries in the coming years. WPD will not wait for the next concession of 2029 and it is likely that WPD must make a decision for the criteria of the new ferries without knowing the criteria for the next concessions.
Doeksen has recently added two new ferries to their fleet for the western Wadden Sea and will most likely not add ferries to their fleet before the next concession.
TESO is planning to replace a ferry approximately in 2031. TESO does not depend on the concession criteria and has ambitions for zero-emission shipping.

Before new ferries can be designed, ferry operators have to determine design criteria (which might include zero-emission propulsion technology). Since the designing and building of ferries can take several years, this process starts soon for WPD and within a few years for TESO. To make the decision whether zero-emission propulsion is a criterium, a more detailed study for specific crossings is required.

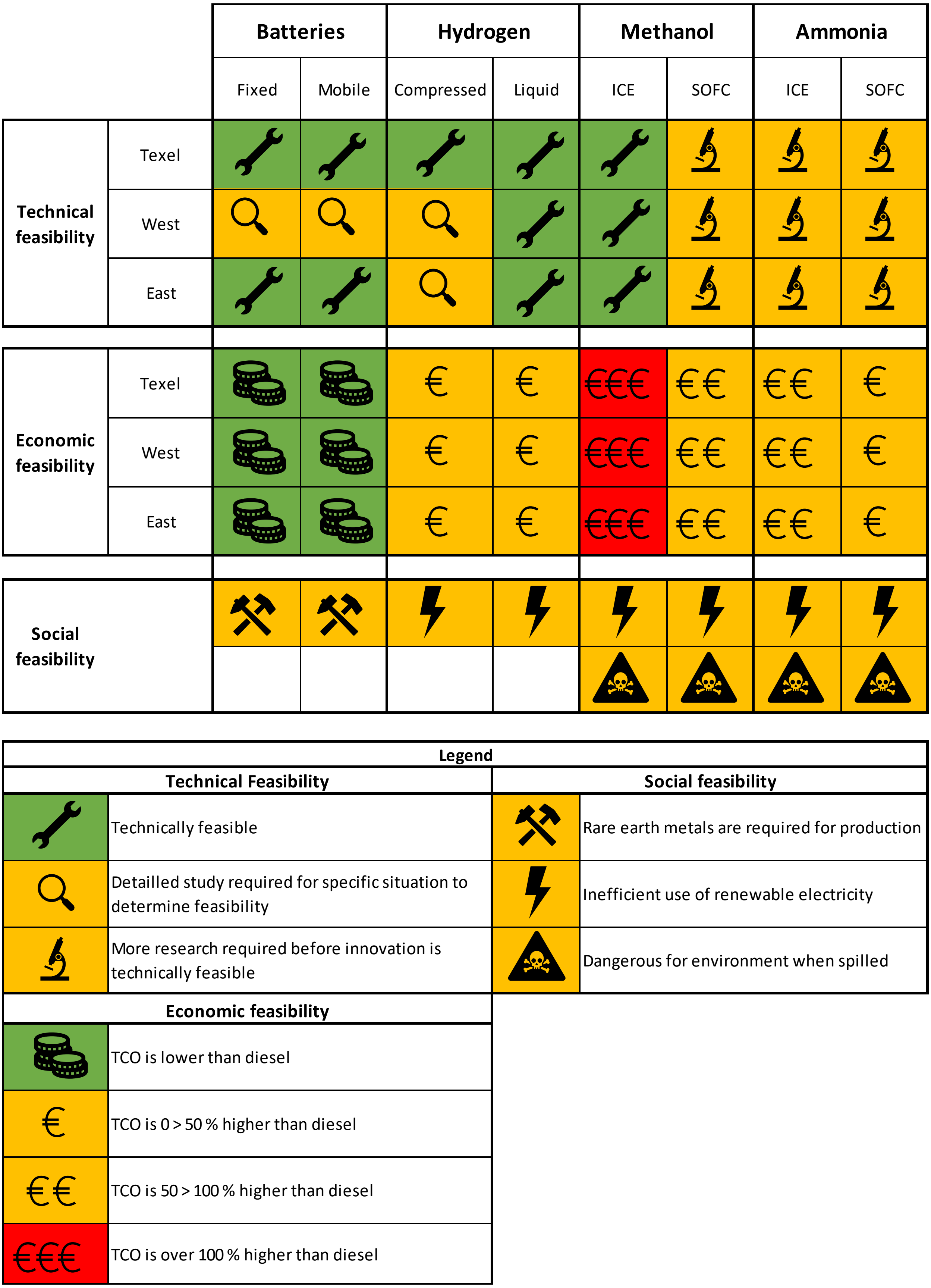


Figure 28; Overview of results

10 CONCLUSION AND DISCUSSION

10.1 Main findings

The research question that is answered in this study is:

"What is the potential technical, economic, social and political feasibility of zero-emission ferries in the Wadden Sea?"

Overall, the answer to this research question is that zero-emission ferries in the Wadden Sea are feasible in a technical, economic, social, and political perspective. However, there are specific demands for each area and not all zero-emission technologies are suitable for each area.

The fact that current Wadden Sea ferries are emitting emissions is seen as a problem and zero-emission ferries are seen as desirable by all interviewed actors.

Criteria are used to select innovations. This resulted in four suggested zero-emission innovations with in total eight configurations. Although all technologies and variations for storage or energy converters are likely to be feasible before 2050, not all technologies are ready in the near future. Some configurations require a more detailed study for some areas to determine the feasibility, this is especially relevant to the western Wadden Sea. Such studies can provide more information for the feasibility of charging infrastructure on the Wadden Islands and whether it is possible to bunker hydrogen during the day.
Nevertheless, for all areas there are zero-emission technologies feasible from a technical perspective. Therefore, zero-emission ferries are technically feasible.

The total costs of ownership of each zero-emission technology are calculated for the economic feasibility. According to these calculations, a battery-electric configuration as a lower TCO than a diesel configuration and are therefore economically feasible. The other suggested innovations have a higher TCO than diesel and the benefits (zero emissions) should outweigh the difference in TCO. For hydrogen the difference in TCO is limited and therefore it is likely that this technology will pass a cost-benefit analysis. For the methanol ICE configuration, the TCO is more than 100% higher than for diesel and this technology is therefore the least likely to pass a cost-benefit analysis.

Zero-emission Wadden Sea ferries are socially feasible since they provide an effective solution for a perceived problem, which is that ferries currently are emitting emissions. Nevertheless, each zero-emission technology has negative characteristics which have to be discussed for each area. Changes in the sanctioned discourse result in changes in the demand for ferries and can lead to practical issues for zero-emission ferries.

Social feasibility is an important factor for political feasibility. Zero-emission Wadden Sea ferries are also politically feasible. However, the concession system results in two major decision-makers: a government actor and a ferry operator. The ferry operator makes design criteria for ferries based on the concession criteria. However, it is possible that the ferry operator must make the decision before sustainability criteria are known and a window of opportunity for zero-emission ferries is missed.

10.2 Discussion

10.2.1 *Reflection of the research methods*

This research used a combination of literature and interviews. The amount of scientific literature on the subject was limited. Nevertheless, overview papers such as the zero-emission paper published by DNV-GL proved useful. For specific technologies and innovations, scientific literature was more numerous. Conversations with experts from C-Job proved very useful to select zero-emission innovations and make a visualization of the well-to-propeller process of these innovations.
With the current literature and with input from experts with the same expertise, another study with the same research question should have the same results for the technical and economic feasibility.

The interviews are conducted with actors found in the actor analysis. Not all actors that were approached (via e-mail) responded and the number of interviews is therefore lower than the number of approached actors. Nevertheless, the six interviews that were conducted included actors with different interests and a different perspective. This led to some contradictions for several questions in the interviews. The main actor groups (ferry operators, interest groups, facilitators, and government) are represented by the interviews that were conducted. The relatively low number of interviewees is also a result of the low number of relevant actors in this area.
The actors that did respond and agreed with an interview, provided useful information and seemed very interested in the topic. Since the interviewees represent all major perspectives on the feasibility of zero-emission ferries in the Wadden Sea, a similar study should result in the same outcome for social and political feasibility.

Unfortunately, the actor that is responsible for the next concession is not interviewed for this study. This is due to the fact that it is not yet clear which party will be responsible for this policy. A study by Muconsult (2019) recommended a transfer of responsibility from national to regional governments. The latter, in this case provinces, did not yet include this in their organisations.

10.2.2 *Reflection of the findings*

The technical feasibility is determined with certain criteria. Some of these criteria are specific for the Wadden Sea, such as a low weight to reduce the draught of the vessel. Calculations regarding this weight use a 'standard' diesel configuration as a reference. Calculations are focussed on the weight of the fuel and weight of the tanks or batteries. A weight-analysis of the total installation, with the specific weight of all the machinery required for the alternative compared to the machinery might result in slightly different numbers. This includes structural changes to the vessels, for example to support the tanks or machinery.
Electricity rates are the most important variable for the operational expenditures for all suggested innovations. Therefore, all operational calculations are performed with two rates: the projection that is used for policy and the high end of the projection.
Since OPEX is the largest contributor to the TCO, it is no surprise that technology with the highest efficiency and the lowest cost per MWh has also the lowest TCO. The gap in TCO between diesel and battery-powered ferries is remarkable but is explainable due to the decreasing CAPEX costs and high efficiency. Nevertheless, when the costs for reinforcing the local electricity grid increase, this gap will become smaller.
The social demand for a zero-emission ferry (or at least a less polluting ferry) was acknowledged by all parties. Nevertheless, the number of negative aspects of alternatives is relatively large. When one of the suggested innovations is used for a new ferry, this will be a topic of debate. This was one of the

only cases where the political economy model of Feitelson and Salomon (2004) was not complete. Therefore, the negative aspects of the suggested innovations were integrated into the factor 'perceived effectiveness'. Overall, the framework of Feitelson and Salomon proved very useful and complete.

The political feasibility showed the complex decision-making process. Since the interviewees did not agree about who will decide if the next ferries will be powered by zero-emission technologies, a model based on the multiple streams model of Kingdon (2011) was developed. This model shows that both the policymakers and the ferry operators decide whether the next ferries will be zero-emission ferries and that these decision-making moments are connected. Also, the windows of opportunity are identified in this model.

The different perspectives of the interviewees and a difference in their answers to the interview questions were an important source for this model.

10.2.3 *Theoretical reflection*

Some theories that are discussed in chapter 2 are used in the research methods. Other theories are not included in the research but are discussed below.

Socio-technical transitions

Multiple aspects of the multi-level perspective are identified in this study. It can be argued that the broad demand for a reduction of emissions in combination with technical feasibility is a change on the landscape level. This can lead to a transition on a meso level. However, it is not clear if ferries are part of the meso-level. It can be argued that Wadden Sea ferries are a niche because these ferries are purpose build with special demands from regulations and concessions. Also, it is not clear if zero-emission propulsion systems are a radical innovation, since the effect on operations can be limited.

It can be argued that zero-emission ferries in the Wadden Sea are niches and when these innovations are used for international commercial shipping, these innovations reach the meso level. Since the effects on operation for international commercial shipping would be much larger, this would likely be a radical innovation. However, this is not part of this study.

Lock-in

The change from diesel to CNG and LNG for Texel and Doeksen proves that there is no diesel lock-in for Wadden Sea ferries. However, the time schedule, speed and other aspects of the ferry operation are based on diesel-powered ferries. One of the criteria for technical feasibility in this study is a limited effect on operations (which are based on fossil fuel-powered ferries). Therefore, although active resistance from institutions or companies is not likely, the diesel standard is influencing the feasibility of zero-emission ferries.

Innovation in the maritime industry

The ambition of ferry operators (interviews 3,6) and multiple examples of innovation in the ferry industry suggests that there is not a lack of innovation for ferries. This supports the idea that ferries are often niches in the shipping industry.

Pre-diffusion phase

A projection of the current status of the four suggested innovations is projected in Figure 13. It is too early to distinguish any diffusion for zero-emission technologies as described by Ortt (2010). It can be argued that 'transition fuels' such as CNG and LNG have the same characteristics as innovations that do not reach the market stabilization phase and will be succeeded by zero-emission technologies. However, this is not included in the scope of this study.

10.2.4 *Scientific contributions*

Generalisability of results

The feasibility of zero-emission ferries is proved in several places with existing battery-electric ferries. This study stressed the feasibility of zero-emission ferries in a specific area: the Wadden Sea. This area has specific characteristics such as required capacity, range, frequency of crossings and limited water depth. Although these characteristics are specific for the three areas that are discussed, the results can be used for similar areas. In the international Wadden Sea, the crossings to the German Wadden Islands which are the closest to the Netherlands, such as Borkum, Juist, and Norderney, have similar characteristics as the crossings of the eastern Wadden Sea area. Nevertheless, the social and political situations in Germany and Denmark are not studied.
Most criteria that are used for the selection of the zero-emission alternatives, such as reliability, zero emissions during production, and scalability, are not specific for the Wadden Sea. The additional criteria that are specific, such as the weight limit due to the limited water depth, are stricter than for most areas. Therefore, the results of the technical feasibility are generalisable for other ferries with crossings with similar characteristics such as the length of the crossing and energy demand for ferries.

Since the operational expenditures of all alternatives are based on the Dutch projection of electricity rates, the TCOs cannot directly be used for other countries. However, since no other costs are specific for the Netherlands, the same calculations can be used for other electricity rates.

The demand for less polluting transport systems is international and not specifically for the Netherlands. Furthermore, international institutions such as the Common Wadden Sea Secretariat have ambitions for fewer emissions in the international Wadden Sea. The factors relevant to the social feasibility are not all specific for the Wadden Sea, although some are more relevant due to the sensitive environment. Nevertheless, the support for zero-emission ferries can vary per area and should be studied before the social feasibility can be generalized for other areas.

The political feasibility of the Wadden Sea ferries is not generalisable due to the concession system. This system is complex, with a variety of actors and demands without subsidies for the ferry operator. Since this system is different for most other ferries, the political feasibility is not generalisable. However, the model with multiple decision-makers and few windows of opportunity can be relevant for other situations.

For other ship types, the technical and economic feasibility are the most relevant. The social and political feasibility are linked to the large social function of ferries, especially for islands communities.

Enhancement to the political economy model for transport innovations

The political economy model for transport innovations (Feitelson and Salomon 2004) was generally found effective to identify factors and actors to determine the potential adaption of innovation. The paper of Feitelson and Salomon includes an analysis of three innovations: road pricing, (light) rail, and telecommuting centres. Although the perceived effectiveness of these innovations is discussed widely, it does not focus on negative aspects that do not influence effectiveness. The only negative aspect that is discussed is ‘costs’, in the factor ‘perceived distribution of benefits and costs’.
For sustainable systems such as zero-emission ferries negative aspects that do not influence the effectiveness can be a problem for the feasibility. For example, the toxicity of ammonia or the use of rare metals for batteries are issues that can influence the public view on these innovations, but do not directly influence the effectiveness of the ferry or the effectiveness to solve the emission problem.

Where traditionally the focus for innovation was on effectiveness and (cost)efficiency, sustainable innovations often have other priorities, such as the reduction of emissions or the phasing out of fossil fuels. These systems can have characteristics that have negative effects which are not directly affecting the effectivity. Although frameworks such as Technology Assessments do acknowledge this, it is not part of the economy model for transport innovations. This study used the factor 'perceived effectiveness' to discuss the adverse characteristics.
The model of Feitelson and Salomon is focusing on public transportation projects. This study showed that it is also applicable to transport that is owned by private companies with a public function.

Contribution of exploratory research
In a wider perspective, exploratory research such as this feasibility study can be a link between research and the application of technologies. Zero-emission propulsion for ships is a recent development which is only applied on a very small part of the total world fleet. The first zero-emission propulsion was applied on a niche, ferries with a small capacity and a relatively small range. This study shows that there are possibilities for another niche with other criteria, for example higher capacities and a focus on low weight. Exploratory studies like this can increase the diffusion of zero-emission ferries or provide opportunities for zero-emission technologies that are not yet applied on a commercial scale.

11 LIMITATIONS AND RECOMMENDATIONS

11.1.1 *Limitations*

The scope of this study is limited to the Dutch Wadden Sea. The technical, economic, social, and political feasibility for four alternative zero-emission technologies is studied with a total of eight configurations for three different areas in the Wadden Sea. With this method, the research question could be answered with details for which configurations are feasible for each area. However, it is not an in-depth analysis of one specific technology for one ferry.
The calculations are based on available information of existing 'typical' ferries. However, it is likely that there are changes for future ferries and other design criteria are used for new ferries. The machinery required for each configuration (including the existing diesel, LNG, and CNG powered ferries) is not calculated in detail. When a ferry operator wants to invest in a zero-emission ferry, a more detailed study will be required where more information is used to determine the consequences of new technologies for the design.
Since the feasibility is based on existing ferries, no radical changes are included in this study. The water depth problems in the eastern Wadden Sea might require more radical solutions. Also, the use of ferries with different capacity or size is not considered in this study.
The time scope of this study is relatively large (approximately 30 years) and some assumptions (based on literature) are for situations that are many years away. This includes projections for electricity prices and the development of technologies.

One of the results of this study is that battery-electric ferries are a cost-effective option for Texel and the eastern Wadden Sea. Here, a fixed number is used for charging infrastructure (1 million euros) per ferry. It is assumed that the electricity grid of the Wadden Sea is not capable of supporting this infrastructure. However, the strength of the electrical grid and the costs of potential reinforcements are not known and not part of the scope of this study.

Only new-build ferries are considered in this study. Conversions of existing ferries to zero-emission ferries might be feasible and can be a subject for another study.

11.1.2 *Practical recommendations*

The practical recommendations are general recommendations based on the findings of this study. These recommendations are not intended for one specific actor.

- More research is required to determine design criteria for new Wadden ferries and the consequences of zero-emission technology for machinery.

- When the ferries should be operational within 10 years, battery-electric or hydrogen are the most feasible option. However, studies are required to determine the impact of grid reinforcements and the development of green hydrogen production. When ferries can be designed later, ammonia and methanol with SOFC's should be investigated.

- Negative aspects and risks of innovations should be studies and justified when the innovations are implemented.

- For all zero-emission ferries, an improved ship-design will reduce energy demand. Especially a lower ship weight can reduce the required energy storage and reduce the additional weight required for storage of energy in batteries or heavy hydrogen tanks. The use and integration of secondary systems such as solar panels can also decrease the energy demand of the main power supplier on board.

11.1.3 *Policy recommendations*

- Communication between all actors is important. All actors that are interviewed in this study support zero-emission ferries in the Wadden Sea. However, the concession system results in multiple decision moments. This system can create the possibility that the concession criteria for emissions are published after new ferries are acquired by ferry operators. When these criteria or intentions are not communicated, the ferry operators must guess the intentions.

- The political feasibility that is studied in this thesis discussed the role of the concessions and a model showed that the concession cycle does not meet the cycle of the designing of new ships. The concession system for the eastern and western Wadden Sea does not involve government funding and since the ferries are designed for one specific route, any company that applies for the next concession is obligated to buy the ferries. However, unlike some German ferry operators, the ferry operators that are part of the concessions are not part of long-term planning programs. Since the design criteria for new ferries have consequences for 30 years, which is the same as two concession periods, cooperation between the ferry owner and governments in the designing process is recommended.

- There are multiple differences between the concessions where zero-emission ferries are introduced in Scandinavia and the concessions in the Wadden Sea. The concessions in the Wadden Sea does not include funding and the ferries are designed for one area so they cannot be used for other areas. Before criteria regarding emissions might be included in the 2029 concessions, it is recommended to study the concessions where zero-emission ferries are introduced and the differences with the Wadden Sea concessions.

- The UNESCO World Heritage status can be used to show the importance of sustainable sailing in this area. Since ferries are always present in the Wadden Sea and are visible, zero-emission ferries can be used to highlight that the Wadden Sea is a unique area that requires protection.

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List of Appendices

Appendix I: Analysis of Technical feasibility

Definition zero-emission technologies

This study is about zero-emission ferries. However, the 'zero-emission' is only about emissions that pollute the environment or the climate. This includes GHGs, NOx, SOx, and particle matters (PM) and does not include other non-polluting emissions such as water or oxygen.
The definition of zero-emission that will be used for this study is: 'a process or energy source that emits no waste products that pollute the environment or disrupt the climate'.

Other terms that are commonly used to indicate that effort is made concerning the reduction of emissions are 'sustainable' or 'green'. These terms can be used if a process or product is less polluting or uses fewer materials than previous or similar processes or products. However, these terms do not Therefore, it does not say anything about the extent of the measures and will not be used for this study.

Sustainable is often linked to 'renewable resources' and 'renewable energy'. Sustainable energy is defined as 'energy that meets the needs of the present without compromising the ability of future generations to meet their own needs' and renewable resources are defined as 'resources which are continually replenished by nature (Ellabban, Abu-Rub, & Blaabjerg, 2014). The ambition for renewable energy includes the phasing out of fossil fuels. Decarbonizing is also a term used to describe the phasing out of carbon-based fossil fuels.

Sustainable technologies that are not considered in this study

In the scope of this study not all sustainable propulsion technologies are included because the implementation in a Wadden Sea ferry is not realistic, the technology emits emissions, or it will affect the reliability of the ferries. The technologies that are not considered in this study are:

Nuclear power
Although no air pollution is resulting from this efficient energy source and there are multiple examples of ships with nuclear propulsion such as aircraft carriers, submarines and icebreakers, nuclear propulsion is not suited for smaller vessels. It is not commercially interesting, it produces radioactive waste and public opinion is likely against such technology in the Wadden Sea (Carlton, Smart, & Jenkins, 2011).

Wind energy
Wind was the primary energy source for ships for ages, when sails were used as primary propulsion technology. Still now, the Wadden Islands are a popular destination for hundreds of sailing boats. Modern wind power propulsion technology such as the Flettner rotor is available for ferries (Traut et al., 2014). However, the wind is an unreliable and inconsistent energy source and therefore, wind energy is not suited as an energy source. Wind assistance, where wind power is used as additional propulsion, is not included in this study because it still relies on a primary propulsion system (Lloyd's Register, 2017).

Solar energy

Although solar energy will become the primary source of renewable energy in the near future (MIT, 2015), for ships it is only suitable as a secondary energy source since the availability of sunlight is not consistent. Furthermore, the available surface on the upper deck of ferries is limited. For example, on the upper deck of the Texelstroom 700 m^2 of solar panels are placed, which saves 40.000 litres diesel per year. However, the diesel demand of TESO is 4,5 million litres (for two vessels, financial year 2016-2017)(TESO, 2019a).

Figure 29; Solar panels placed on top deck of MS Texelstroom (C-Job, 2019)

LNG & CNG

Natural gas is widely used in the Netherlands, for example for heating and cooking. However, natural gas has a low density at standard atmospheric pressure, and it is not suitable as fuel for ships because the required volume would be very large. To increase the density, natural gas can be compressed till 20-25 MPa and stored in special tanks, this is called CNG. Another method is to cool natural gas down to liquid form (LNG) at approximately –162 °C. Roughly, the volumetric energy density of CNG is 42 % that of LNG and 25% that of diesel fuel (Sinor, 1992). Both CNG and LNG are used for ferries in the Wadden Sea because it emits fewer emissions than diesel fuel and its availability. Especially NOx and SOx emissions are decreased by the use of CNG or LNG (DNV-GL, 2014). However, natural gas is a fossil fuel which emits emissions, especially CO_2 (Satish Kumar et al., 2011). Ship-owners see LNG and CNG as a transition fuel, that they use until a zero-emission propulsion system is available (Rederij Doeksen, 2019). CNG and LNG can be replaced with bio-CNG and bio-LNG, both created out of biogas. Although this decreased emissions, they are no zero-emission options and therefore (bio-)CNG and (bio-)LNG are not considered in this study.

Biofuels

Biofuels such as biodiesel and bioethanol are made from biomass such as palm oil, soy or oilseed rape. Biofuels can be a carbon-neutral fuel under certain circumstances because the crops used as biomass used CO_2 in the air to grow and therefore compensate for the CO_2 that is released by the combustion. This is only the case when the crops are planted on otherwise unused land, because otherwise indirect land-use change may occur (Fargione, Hill, Tilman, Polasky, & Hawthorne, 2008). This is for example the case when crops are planted on the agricultural ground, which often leads to deforestation because the land is required for food production. When the availability of unproductive land that can be used for biomass is limited and therefore the scalability of carbon-neutral biofuels is limited (GCB Bioenergy, 2014). Besides CO_2, biofuels emit other emissions such as particle matters and NOx. Therefore, biofuels will not be considered a zero-emission solution for this study.

Energy converters

Electronic motors

Conventional ships are equipped with an engine that transfers produced energy with a rotating shaft to the propeller, often with a gearbox. Although efficient for long journeys with limited variations in speed, this efficiency drops when high variations in energy demand are required, for example for manoeuvring.

Diesel-electric propulsion systems are widely used for vessels that have to be highly manoeuvrable or have variable sailing patters such as certain offshore vessels, cruise ships and ferries. A diesel-electric propulsion system has the possibility to optimize the loading of the diesel engines, since these can run on the most efficient rate.

Electronic motors convert electric energy (supplied by generators, batteries or fuel cells) into mechanical energy. Electronic motors have few moving parts and do not require much maintenance. The electromotors are often placed inside pods, directly connected to the propellers. These pods can turn 360 degrees and do not require a rudder. For this configuration, engines fuelled with renewable fuels can replace diesel engines. Batteries can be installed for peak-shaving or, in a battery-electric propulsion system, to provide all electricity for the electronic motors. Fuel cells can also supply these electronic motors.

Internal Combustion Engine

Internal Combustion Engines (ICE) are currently the most used energy converters onboard ships. These units are reliable and can be modified to be fuelled by renewable fuels including hydrogen, methanol, and ammonia (with a small amount of hydrogen). Investment costs for ICEs are relatively low and the technology is widely used and known.

An ICE transforms chemical energy into mechanical energy by the combustion of a fuel with an oxidizer in a combustion chamber. The mixture of the oxidizer (usually air) and the fuel can be ignited by compression or with a spark (Stapersma & Klein Woud, 2012).

During the combustion, temperatures are very high and molecular nitrogen (N_2) and oxygen (O_2), both present in the air, produce thermal NOx. The amount of NOx varies between engine types, but all ICEs emit NOx, which is a harmful emission.

It is possible to remove up to 99% of the NOx emissions with chemical reactions, with for example ammonia. The technology used for this process is called selective catalytic reduction (SCR). Installations that reduce NOx are also called DeNOx installations.

The efficiency of a diesel engine used for this study is 40 %, see appendix IV.

Fuel cells

A fuel cell is an electrochemical cell that converts chemical energy (from a fuel) into electricity through an electrochemical reaction with oxygen. This process does not include combustions and no NOx is produced. The direct convention from chemical energy into electricity enables electrical efficiencies of up to 60 per cent. Two of the most promising fuel cells for marine applications are Proton Exchange Membrane Fuel Cells (PEMFC) and Solid Oxide Fuel Cells (SOFC). Mass production is expected to occur beyond 2022, this should allow production costs to reach a competitive level (DNV-GL, 2018).

Although there are no commercial ships sailing with FCs as main power converter on this moment, there are pilot projects and PEMFCs are used for German submarines as an air-independent propulsion system (Sattler, 2000).

The technology for fuel cells is currently in development. Although not yet produced in large numbers for marine applications, the technology is scalable and materials required for fuel cells are available. PEMFCs are commercially available with a capacity of up to 100 kW. Both PEMFC and SOFCs can be

directly fuelled with hydrogen. Methanol and ammonia are hydrogen carriers and fuel reformers can be used to convert these fuels into hydrogen. SOFCs can also directly use methanol or ammonia as fuel, although this is still in an R&D stage (Fettah, 2009; van Biert, Godjevac, Visser, & Aravind, 2016).
Fuel cells have some advantages interesting for marine applications. For example, FCs do not produce vibrations or noise because there are no combustions. This is especially interesting for ferries because this improves comfort. Another advantage is that FCs are modular and the performance of a single cell is not different from a large stack. Therefore, power production can be distributed over the ship, improving the flexibility for a better ship design (van Biert et al., 2016).
The efficiency of a PEM FC that is used in this study is 55 % (DNV-GL 2018) and the efficiency of a SOFC is 60 % (DNV-GL 2018).

Batteries

Batteries are a widely used energy carrier, also in the marine sector. For example, in hybrid vessels and for peak shaving. Because a growing number of vessels has diesel-electric propulsion, often with azimuth-thrusters or other electric propulsion methods, the implementation of batteries instead of diesel engines does not affect the entire propulsion system. There are multiple types of batteries and new types are currently in development. Currently, the standard type is Lithium-Ion (Li-ion), used in hybrid vessels and existing zero-emission vessels. Also, this type of batteries used in zero-emission vehicles on a large scale.

Characteristics

Lithium is the third lightest element and has the highest oxidation potential of all known elements and therefore lithium batteries offer the best prospects for developing high energy and high-power batteries. Lithium-ion batteries hold the best short-to-medium term prospects (Thackeray, Wolverton, & Isaacs, 2012). Lithium-ion batteries can have a variety of positive and negative electrode materials and therefore the energy density and voltage can vary. Multiple characteristics are important for the choice between battery types, for example energy density, cost, safety, and expected lifetime.
For marine purposes, lithium nickel manganese cobalt oxide (NMC) are often used because of the small likelihood of fires or explosions. The energy density of such batteries is expected to increase in the future. The first full-electric ferry, MF Ampere, has two battery packs produced by Corvus with a combined capacity of 1.040 kWh, occupying 20 m^3. The specific energy of these batteries is 140 Wh/kg (0.506 MJ/kg) (Puchalski, 2015). The more recent MS Ellen uses lithium NMC batteries with a specific energy of 160 Wh/kg (0.576 MJ/kg) and an energy density of 336 Wh/litre (1.21 MJ/L) (Amanieu, 2016), this number is the current marine standard and will be used for battery calculations in this study.
Cylindric li-ion batteries such as typical 18650 cells, which are used in e.g. battery electric vehicles, have a volumetric energy density of up to 650 Wh/L (Thackeray et al., 2012). For lithium-ion batteries, 350 Wh/kg or 870 Wh/l is seen as a practical limit (Sujeet Kumar, 2016).

A new type of battery is lithium-sulphur (Li-S) batteries This technology is proven, although on a small scale. Li-S batteries are currently plagued by a decaying capacity due to the corrosion of the lithium anode. The theoretical specific energy of Li-S batteries is 2.567 Wh/kg (Lampic, Gotovac, Geaney, & O'Dwyer, 2016) and the practical specific energy is believed to be 800 Wh/kg (Zhang et al., 2017). Because of the low density (approximate 700 kg/m^3) the aerospace industry is interested in this technology.
The demonstrated energy density of Li-S batteries is 1.8 MJ/kg (1.26 MJ/l) under laboratory conditions. However, the technology is not yet commercially available with a higher energy density than Li-ion batteries (Zhang et al., 2017).

Another battery technology that promises a high energy density is Li-O_2. The theoretical energy density is 3.500 Wh/kg (Zhang et al., 2017) and a lot of research is conducted in the development of these batteries. The practical energy density is expected to reach 1700 kWh. However, Li-O_2 battery technology is not past its laboratory stage. This is a result of limited rechargeability of the batteries because of the degradation and passivation of the electrodes and electrolyte decomposition (Zhang et al., 2017).

Battery type	**Energy Density [MJ/L]**	**Specific Energy [MJ/kg]**
Li-Ion (current marine standard)	1.21	0.58
Li-Ion (practical, expected)	3.13	1.26
Li-S (demonstrated)	1.26	1.8
Li-S (practical, expected)	2	2.9
Li-S (theoretical)	6.44	9.2
Li-O_2 (practical, expected)	12.2	6.1
Li-O_2 (theoretical)	25.2	12.6

Battery Technology

There are multiple examples of vessels using batteries to power their propulsion systems. Because there is a lot of experience in the maritime industry with diesel-electric propulsion, the changes that are required to replace the diesel engine system with a battery system are relatively small for most short-range vessels. However, the charging of the batteries is a problem because the number of batteries is large, and the available charging time is limited.

The most used solution is to create an onshore charging station with battery packs similar to the battery packs used on the vessel. This results in the ability to charge the vessels battery fast without major changing the electricity infrastructure in the port. When the vessel is sailing, the liquid-cooled shore batteries are charged by the existing electrical infrastructure (Puchalski, 2015). To use the turnaround time in port efficiently, the charging systems are connecting to the vessel using a robotic system. For example, the system the electric ferry Tycho Brahe is using takes only 45 seconds to connect (Kane, 2019).

Charging from a battery pack to another battery pack can be done at 10 kV and 600 A, which translates to 6 MW, in the case of Tycho Brahe (Kane, 2019).

However, the number of charges in a lifetime of a battery is limited and often the lifetime of the batteries in ferries is smaller than the lifetime of the ferry itself. The battery pack of MS Ellen is tested for 8.000 cycles at 80 % depth of discharge (DoD) and has an expected calendar lifetime of 10 years (Amanieu, 2016). The Tycho Brahe, which is making a 2.5-mile crossing between Denmark and Sweden 46 times a day, is designed to keep the 4.1 MWh battery capacity charged between 40 % and 66 % and charges on both shore sides for relatively 5 and 9 minutes. The operational lifetime is expected to be 5 years before it has to be replaced (Kane, 2019).

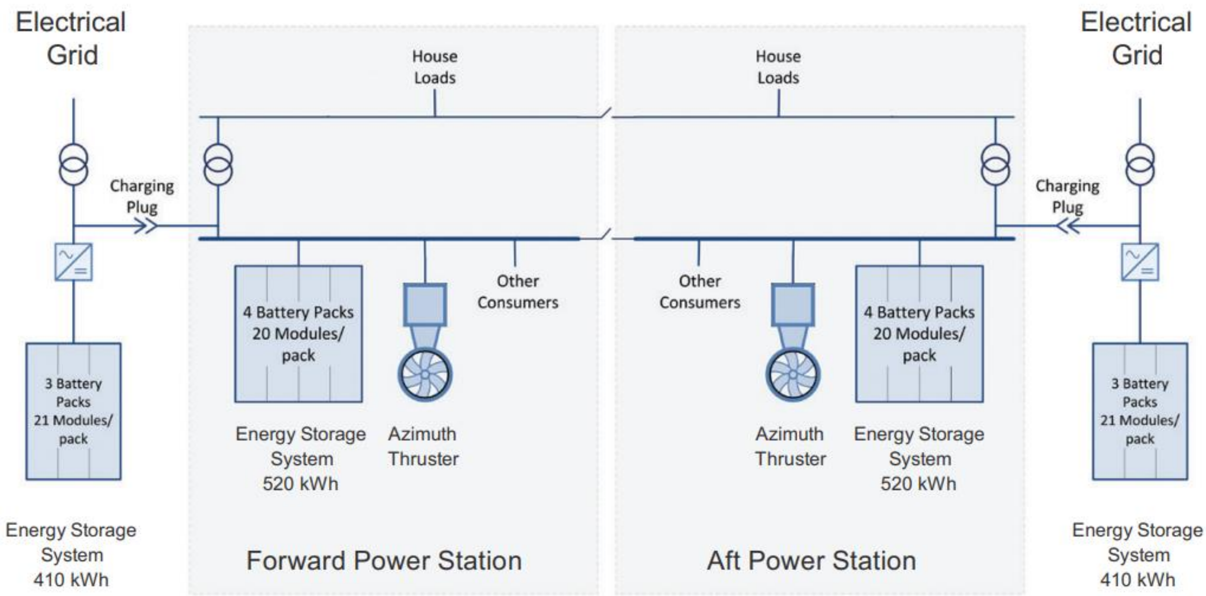


Figure 30; Single line diagram of MF Ampere (simplified) (Puchalski 2015)

Another method to ensure sufficient energy onboard is to switch battery packs. This method is not used on ferries yet, but trials are planned on inland barges in the Netherlands. Battery packs placed in containers are already used to convert diesel-electric ferries to battery-electric ferries such as the Tycho Brahe (Kane, 2019), although these containers are fixed and not replaceable. Battery packs are standardised in 20-foot containers, for example by the Dutch Start-up Skoon, with the initiative to create an operational battery network (Skoon, 2019). With standardisation multiple 'swapping' methods can be created, for example by using standardised container cranes or special trucks since Wadden ferries are already designed for trucks.

Technical consequences for design

There are a lot of ferries already sailing with a diesel-electric propulsion system. Switching from conventional fuel to batteries to supply the electric system has consequences for the design of the vessel. The energy density of batteries in combination with the minimum required range determines the required volume for batteries in the vessel. For diesel, the energy density is large and diesel-powered ferries do not require refuelling during the day because the range is sufficient for several crossings. For battery-electric ferries, the range is often limited to only one crossing for normal operations because the energy density is much lower for batteries. Because the specific energy of improving (MJ/kg) is much lower than that of conventional fuels, the weight of the batteries required for one crossing is very high. This weight is resulting in a higher displacement, which leads to a higher demand for energy to get the same vessel speed. Therefore, it is important to keep the weight of the vessel as low as possible (because fewer heavy batteries are required to compensate). Current battery-electric ferries have light, efficient designs that are less energy demanding than similar ferries. For example, aluminium is used as hull material instead of steel to reduce weight.

Most existing battery-electric ferries still have generators on board as a back-up. These generators are used when maintenance is required on the land-based charging infrastructure, when the ferry has to sail outside their normal operational waters for maintenance, or when more power is required because of weather circumstances such as storm or ice. However, MS Ellen does not have such a generator, because the battery packs are organised in such a way that they can be used as a back-up. A maintenance yard is located in the operational range and classification societies approved this layout.

For the land infrastructure, switching to battery-electric propulsion has more consequences. Because the electricity infrastructure is not intended for the demand of a fast-charging ferry, the electric grid is most likely to be reinforced. The consequences can be limited when a land-based battery pack is installed. The charging stations are often large investments, including high tech charging robots to increase charging time between crossings.

The amount of batteries required for a vessel depends on the depth of discharge (DoD) of the battery and the charging time that is possible. For Li-ion batteries, a DoD of up to 80% is allowed, although a smaller DoD is better for the lifetime of the battery. The best ratio between DoD and weight is different for each case and therefore a fixed DoD of 80% is taken as a maximum in this study. Fast charging can limit the lifetime of batteries. This is measured in (dis)charge rate, also called C-rate. Charging with a rate of 1C means that the battery is fully charged in one hour. Charging with 2C means that charging happens twice as fast, so a fully charged battery in half an hour. Because the charging time is limited by the time the ferry is in quay, a higher C-rate is desirable. However, a higher C-rate creates heat and cooling systems are required for higher C-rates. A higher C-rate also limits the lifetime of the batteries (Piernas Muñoz & Castillo Martínez, 2018). Typically, electric ferries have C-rates of 2C, for charging. Electric ferries have an overcapacity of batteries so the charging time can be limited with the same C-rate.

Safety

On October 10, 2019, a small fire was reported in the battery room of diesel-electric ferry M/F Ytteroyningen, the ferry could return to harbour under its own power. However, overnight a serious gas explosion rocked the battery room causing significant damage (Alvestad, 2019). Although this event occurred very recently and the root cause of the fire is still to be announced, the secondary explosion is likely a result of a buildup of flammable gasses from the batteries. Therefore, the industry is looking at ways to improve the safety of the thermal management systems (Perry & Brown, 2019).

Application on Wadden Sea ferries: Battery swapping

Weight is an important factor for ships overall and especially for Wadden Sea ferries. For the eastern Wadden Sea, the total weight of the ferries has to be kept low to minimalize the draught of the vessels (interview 3) and also for the western Wadden sea the weight influences the required power for the minimum speed that is important for these routes. Because the current marine standard batteries (Li-ion) are heavy, this limits the number of batteries that is acceptable onboard, which limits the range of operation.

For electric ferries, the combination of limited charging time and a limited C-rate makes that there is an overcapacity of batteries on board (the number of kWh required for fast charging is higher than the demand for powering of a ferry). This problem does not occur when mobile battery packs are used which are ‘swapped’ when empty and recharged onshore. When this method is used, the DoD becomes the limiting factor and the weight onboard can be limited.

Studies are conducted for inland barges, where containerized battery packs are swapped with cranes. For RoRo ferries, a wheeled version (a dedicated vehicle or a truck with a battery container) does not require a crane for swapping. With this method, the number of batteries onboard can be limited to, for example, enough for two crossings (a return crossing). In this study, the batteries are based on a C-rate of 2 C and a DoD of 50%. Multiple battery suppliers are developing standardized 20 ft containers (1 TEU) with batteries (Abma, Atli-Veltin, & Verbeek, 2019a).

All current Wadden ferries are designed to transport several trucks, the weight of these trucks is calculated as Truck equivalent (TE) and is approximately 10 tonnes for calculations. The consequences for weight and volume for the Wadden ferries are discussed below:

Texel

According to calculations described in appendix II, a passenger ferry for the Texel ferry route requires 750 kWh per crossing. This translates to a battery pack of 1.912 kWh and 11,9 tonnes for each return crossing. This is approximately 20 % more than a standard truck equivalent. The current ferry for Texel has a capacity for 34 trucks. This weight is lower than the fuel that is currently used per week and therefore feasible. The volume of the battery packs is relatively low (4,5 m^3) and no problem, although this might be higher when a mobile application is used. Because the reference ferry has a fuel-electric propulsion system, not all ICEs are running the entire time (see appendix II). For bad weather conditions, approximately 3.000 kWh is required for a return crossing, therefore one additional battery pack is required for these conditions, although not required for 80 % of operational time. more battery packs are required.

Western Wadden Sea

According to calculations described in appendix III, the required energy per crossing for the western Wadden Sea is 4.200 kWh. This number is relatively high because the distance is high and the speed of the ferries is higher than for Texel and the eastern Wadden Sea. A mobile battery pack should be switched after each crossing. The weight of a battery pack capable of supplying the ferry for one crossing (125% of required energy) is approximately 32 tonnes. This is less than a full tank of LNG, which is the current fuel.

Eastern Wadden Sea

As described in appendix IV the energy demand for a single crossing in the eastern Wadden Sea is approximately 633 kWh. The battery pack required for a return crossing weight approximately 10 tonnes. This is less than the weight of a weekly demand for diesel, the current fuel.
Because the time that is available to charge battery packs that are not in use when interchangeable batteries are used, the C-rates for charging can be lower and the infrastructure that is required on land to charge the batteries can be smaller and fewer reinforcements for the local grid are required than for fixed batteries.

Application on Wadden ferries: fixed batteries

Currently, all-electric ferries have fixed batteries that are charged with special infrastructure in port. The amount of batteries on board is higher than required for a single crossing to allow fast charging. The infrastructure on land consists of an additional battery pack that stores the energy, the charging can be done between the battery packs at high voltage. For the Tycho Brahe, the charging between these batteries is done with 10 kV (Kane, 2019). The current can therefore be limited to a lower C-rate. Commercial charging systems with a capacity of 4 MW are available, the e-ferry project, MV Ellen, has two of these charging systems to charge the two battery packs (Mobimar, 2019).

Texel

For a return crossing, approximately 1.530 kWh is used (appendix II). With 15 minutes available for charging, a charging system of approximately 6,1 MW is required. To charge with a C-rate of 2C, the battery pack has to be 3 MWh. The DoD would be approximately 50% and the weight 18,6 tonnes, this is less than the weight of the current weekly fuel consumption.

Western Wadden Sea

For the western Wadden Sea, a crossing consumes approximately 4280 kWh (appendix III). With 15 minutes available, the charging system with a capacity of 16 MW is required. To charge with a C-rate of 2C, the battery pack has to be 8 MWh, this would weight 50 tonnes. This would mean that the batteries required for one crossing with a charging period of 15 minutes would weight more than the current fuel for one-week weights. Because this would also require charging on the island, the grid on the island has to be reinforced.

Eastern Wadden Sea

The energy demand for a return crossing is approximately 1.290 kWh, as shown in (appendix III). With 15 minutes available for recharging the battery pack, the capacity of the charging system has to be 5,2 MW. With a C-rate of 2C, the battery pack should have a capacity of 2.600 kWh. The DoD would be approximately 50 % and the battery pack weight approximately 16,1 tonnes.

Green hydrogen

Characteristics

Hydrogen (H_2) is a colourless, odourless and non-toxic gas. It is seen as one of the main sustainable fuels that can be used for transport applications without emitting any emissions. One of the reasons for this is the high energy density of 120 MJ/kg. However, the density of H_2 is very low and for the use on ships, it has to be stored as a cryogenic liquid, as compressed gas, or chemically bound (DNV-GL, 2018).

To store hydrogen as a cryogenic liquid, it has to be cooled down to the boiling point at 20 Kelvin (-253 °C) at 1 bar. Liquid hydrogen, also called LH_2, has a higher energy density than compressed hydrogen (8,5 MJ/L). Despite this positive characteristic, there are several drawbacks of LH_2. Up to 40 % of the energy is lost during the liquefying process and boil-off imposes efficiency losses (Züttel et al., 2010).

Compression is the most mature technology and is typically done with pressures of 350 or 700 bar. However, with an energy density of 2,64 MJ/L for 350 bar and 4,5 MJ/L for 700 bar the volume required is relatively large.

Hydrogen can be chemically bound with CO_2 or N_2, to produce respectively green methanol (CH_3OH) or green ammonia (NH_3). These will be discussed in the next paragraphs.

Other chemical boundings, such as sodium borohydride ($NaBH_4$) are promising. However, since these are still in an early R&D stage, the characteristics of full-scale use are not yet clear and these methods are not included in this study.

There are multiple methods to produce hydrogen. Currently, almost all hydrogen is produced from natural gas (CH_4), which leads to emissions such as CO_2. Therefore, hydrogen produced from natural gas is not considered in this study. Another method is by electrolysis of water, which results in hydrogen and oxygen:

$$2\,H_2O \rightarrow 2\,H_2 + O_2$$

When renewable energy such as solar or wind energy is used, hydrogen produced by this method is considered a zero-emission alternative in this study. However, the energy required for the production of 'green' hydrogen is relatively large and currently the production of green hydrogen is very limited because it is not economically viable. This is discussed in more detail in chapter 6, economic feasibility.

Hydrogen can be produced from biomass, although this is not considered in this study for the same reasons as biofuels, see the beginning of this appendix.

Details of the characteristics of liquified and compressed hydrogen can be found below.

Hydrogen type	Specific Energy [MJ/kg]	Energy Densitiy [MJ/L]	Storage pressure [bar]	Storage temperature [°C]
Liquid (LH_2)	120	8.5	1	-253
Compressed 350 bar	120	2.64	350	20
Compressed 700 bar	120	4.5	700	20

Hydrogen technology

Because there is currently almost no demand for hydrogen fuel, there is no dedicated infrastructure for ships. Liquified hydrogen could be distributed in a similar manner as LNG (DNV-GL, 2018). Due to the very low boiling point of H_2, super-insulated pressure vessels are used for storage in liquid form. Boil-off is unavoidable, with a rate of 0,3 to 0,5 % per day, depending on technology, conditions, volume and tank surface. Since hydrogen production from electrolysis is a proven technology, it can be applied locally in ports when an adequate supply of electricity is available. This can be done when a surplus of renewable energy from, for example, (offshore) wind farms is available.

In August 2019, the North of the Netherlands received a subsidiary of 90 million euros to develop a green hydrogen network. To make use of surpluses of renewable energy, infrastructure is required from other regions such as Denmark and Germany (H2 Platform, 2019).

Hydrogen can be used in internal combustion engines, although hydrogen-fuelled internal combustion engines are less efficient than diesel engines. Fuel cells are a more efficient energy converter, although fuel cells for marine applications are still in development (DNV-GL, 2018).

Currently, there are many land-based pilot projects, for example for fuel-cell busses capable of driving on green hydrogen. In 2020, there will be 20 fuel cell buses and a refuelling station in Groningen in the North of the Netherlands (H2 Platform, 2019).
There are also marine pilot projects, the most famous being the 'Energy Observer', a French catamaran which generates its own hydrogen by solar and wind power and uses this hydrogen for propulsion. Currently this vessel is touring around the world with the ambition to visit 50 countries before 2022 to promote hydrogen technology (Energy Observer, 2019).
The Norwegian ferry operator Norled is developing a car ferry where a minimum of 50 % of the energy will be supplied by liquid hydrogen and the other half by batteries. This ferry will be in operation from April 2021 (NCE Maritime CleanTech, 2018).

Technical consequences for design

The first aspect which has consequences for ferry design is the safety of hydrogen. Hydrogen is a low-flashpoint fuel which makes it potentially dangerous. The flammability of hydrogen is perhaps best known by the Hindenburg disaster, when a 245-meter zeppelin filled with hydrogen burned away in seconds in 1937.
There are no regulations for hydrogen as a fuel for marine applications yet, although rules are under development. Until these regulations are published, an equivalent level of safety has to be demonstrated per case according to SOLAS (DNV-GL, 2018).
Fuel cells are considered a key technology for efficient use of hydrogen, this technology is not yet commercially available for marine applications. However, a lot of research is conducted, and smaller-scale fuel cells are being used at this moment. Because fuel cells produce electricity, this technology can be combined with batteries to add peak-shaving abilities.
Although there is not much experience with marine fuels of -253 °C, there are currently several ships with LNG as fuel, with a standard temperature of -162 °C. It is therefore expected that equipment and piping for hydrogen have similar characteristics and costs as for LNG. For compressed hydrogen it is the same: CNG is stored at a pressure of 250 bar, not as much as 350 or 700 required for hydrogen, but the marine industry has experience with fuels under high pressure.

Application on Wadden ferries: compressed hydrogen

Although hydrogen is relatively light per energy unit, the tanks that are required for pressurized hydrogen are relatively heavy. These tanks are typically made of composite and consist of cylindric tanks. According to manufacturer Hexagon, a 700 bar hydrogen tank has a weight ratio of approximately 5 wt% , thus an empty tank is 20 times as heavy as the hydrogen it can store (Hexagon, 2019). Storage can be done in cylindric tanks that are mounted in a rack. For this study, the type 4 cylindric storage tanks of Hexagon are used as a reference. These have a volumetric density of approximately 16,5 kg/m^3 (per square box) and weight efficiency of approximately 5 % (Hexagon, 2019). High-pressure tanks require a minimum residual pressure that should be left in the tank. For the tanks considered in this study, this is 10 bars. This results in the fact that an additional capacity of roughly the same amount of hydrogen is required to keep this pressure. The capacity of hydrogen tanks should therefore be roughly double the size of the required capacity (Abma et al., 2019b).

Texel

The required energy per crossing is 750 kWh. With an FC efficiency of 55 %, this is 1.364 kWh per crossing. For this study, bunkering once a day is used. The average daily consumption would be 1.31 tonnes of hydrogen. With an overcapacity of 25%, this would be 1.63 ton. The tank capacity should be double this amount, approximately 3,3 tonnes. The weight of the tanks would be approximately 66 tonnes.

The combined weight of tanks and hydrogen is 69,3 ton. The volume required for the tanks is 200 m^3, which is less than the fuel tanks on the current ferry operating at Texel.

Western Wadden Sea

As described in appendix III, the required energy per crossing at the western Wadden Sea is 4.200 kWh. With a converter efficiency of 55 % this is 7.636 kWh per crossing. For each crossing, 200 kg of hydrogen would be consumed. With an extra capacity of 25 % this would be 250 kg. To keep the residual pressure, the double capacity of 500 kg per crossing is required. For a return crossing, one ton of hydrogen should be stored in tanks, which weight approximately 20 tonnes and requires a volume of 61 m^3.

Although the hydrogen itself does not weight much (according to appendix III, the ferries consume approximately 10 tonnes per week), the storage tanks for compressed hydrogen are 20 times this number and for vessels where weight is an issue, this is a problem. For the western Wadden Sea, the weight of hydrogen storage tanks for one day would weight more than the current fuel demand for a week. Therefore, the hydrogen storage is calculated for 2 crossings (one return crossing) and bunkering is required three times a day. Because bunkering is time-consuming, mobile hydrogen tanks might be a more suitable option here.

Commercial 20 ft containers are available with a capacity of 415 kg hydrogen and a weight of 9 tonnes. These containers can be swapped, just like the mobile batteries described in the previous paragraph.

Figure 31; Mobile hydrogen container (Hexaconlincoln, 2019)

Eastern Wadden Sea

According to the calculations in appendix IV, a crossing at the eastern Wadden Sea consumes approximately 633 kWh. With an FC efficiency of 55%, 35 kg of hydrogen is required. For one day, this is 480 kg. With an extra capacity of 25 %, this is 600 kg. The tank capacity should be double this amount, approximately 1,2 tonnes.

The tanks required for 1,2 tonnes weight approximately 24 tonnes and have a volume of 73 m^3. Together, the tank and the hydrogen weight 25,2 tonnes. This is more than the weekly demand of diesel weights and therefore an additional bunkering moment per day might be added. Another option is to use mobile containers. When a mobile 20 ft container with a capacity of 415 kg is used, it should be swapped three times per day (it will provide enough hydrogen for approximate 5 of the 14 crossings).

When weight is a more critical factor than volume, a lower pressure can be used. When 250 bar cylindric tanks are used instead of 700 bar tanks, the weight ratio is 8% instead of 5%. The volume for a 250 bar tank is approximately twice as big as a 700 bar tank.

Application on Wadden ferries: Liquified hydrogen

For a feasibility study for a ferry in the San Fransisco area (SF Breeze) the characteristics of LH_2 tanks are studied. For one ton of LH_2, 200 kg of LH_2 should remain in the tank to keep the tank cold for refuelling. The empty mass of a tank that is capable of storing 1.200 kg LH_2 weights 10.440 kg, which is 8,7 times as much as the LH_2. The outer volume of this tank would be 29,76 m^3 (cylindric). An LH_2 tank requires boil-off to keep the temperature down. This boil-off will rise straight up when vented. This boil-off consumes up to 1 % of the total hydrogen per day (Pratt & Klebanoff, 2016).

Texel

As mentioned in the previous paragraph and in appendix II, the daily H_2 consumption for Texel is 1,31 ton, with an extra capacity of 25 % this is 1,63 ton. In LH_2 tanks, an additional 20% is required to keep the tank cool. The tank should therefore have at least a capacity of approximately 1,96 tonnes, when it is possible to bunker every day. The empty mass of this tank is 17 ton (a full tank weights 19 ton) and has a volume of approximately 48,6 m^3.

Western Wadden Sea
The reference ferry for the western Wadden Sea has a daily hydrogen consumption of 1,37 ton per day. With an additional 25% this would be 1.71 ton. An LH_2 tank with an additional 20 % should have a capacity of approximately 2,06 tonnes. The empty mass of this tank is 17,9 ton (a full tank weights 19,9 ton) and has a volume of approximately 51 m^3.

Eastern Wadden Sea
As described in the previous paragraph, the reference vessel for the eastern Wadden Sea consumes 480 of hydrogen per day. With an extra capacity of 25%, this is 600 kg. An LH_2 tank requires an additional 20% and therefore the required capacity per day is 720 kg. The empty mass of an LH_2 tank with a capacity of 720 kg is 6.26 ton and a full tank thus weight approximately 7 ton. The volume of this tank is 18 m^3.

The tank weights and sizes above are feasible for the reference vessels. However, there are currently no commercial ships which are powered by LH_2 and there is no demand for dedicated marine LH_2 tanks yet. The tanks described in the feasibility study of SF Breeze are placed in the open air and the boil-off installation is very limited. When an LH_2 tank is placed inside the ship, a more complex (and heavy) installation for the boil-off is required because leaked hydrogen is very dangerous. MAN designed a tank that can be placed inside the ship, see Figure 32.

Figure 32; LH2 storage tank (MAN 2019)

Green methanol

Characteristics

Methanol, with the chemical structure CH_3OH, is the simplest alcohol with the lowest carbon content and highest hydrogen content of any liquid fuel. It is widely used for the production of products such as building materials, paints and packaging. As a fuel, it is used in auto racing.
Methanol as fuel is interesting for the marine industry because it is liquid at atmospheric pressure between -93 °C and +65 °C and has a relatively high energy density of 19,5 MJ/kg and 15,8 MJ/L (DNV-GL, 2018). There are multiple ways to produce methanol. The cheapest and most used method nowadays is from fossil fuels, mainly natural gas and coal. Although this makes methanol as fuel affordable, it produces high amounts of GHG emissions. Another method is by using renewable resources like black liquor from pulp and paper mills and agricultural waste. This method is renewable but still emits emissions including NOx and PM and therefore will not be considered in this study. The only method that will be considered in this study is by combining green hydrogen with CO_2.

There are two ways to obtain CO_2 for methanol production: capture from flue gasses from industry and directly from atmospheric air. The first method, which is shown in Figure 33 is currently done in pilot projects, for example at a plant on Iceland which uses sustainable geothermal and hydropower as electricity sources (Goeppert et al., 2017). However, the CO_2 enters the atmosphere when the methanol is used for propulsion (SAPEA, 2018). It is argued to be a zero-emission method as long as the CO_2 that is used would otherwise directly enters the atmosphere. Because the concentration of CO_2 in flue gasses is much higher than in normal atmospheric conditions, the energy required to capture the CO_2 relatively low with this method (100 kWh per tonne CO_2 from natural gas and 65 kWh per tonne CO_2 for coal (SAPEA, 2018).

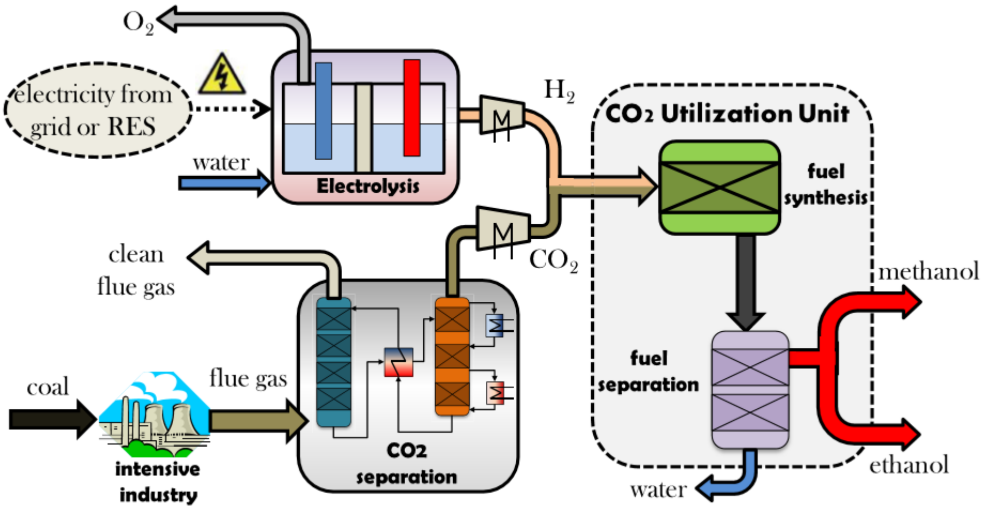


Figure 33; Synthetic methanol production with CO2 from flue gases (Atsonios et al, 2016)

The other method to capture CO_2 is directly from the atmospheric air, this is the only long-term zero-emission method because it does not depend on emissions from industry. It is expected that the costs of CO_2 captured from the atmosphere can drop to $ 94 per tonne under specific circumstances (Keith, Holmes, St. Angelo, & Heidel, 2018). Although the circumstances for the storage of methanol are less demanding than for hydrogen, the additional processes required for the production of methanol makes that the required energy to produce usable energy on the vessel (MJ/MJ) is higher and this method is less energy efficient. The renewable synthetic production costs of methanol are 2,6 MJ per MJ, compared to 1,8 for hydrogen (de Vries, 2019).

Methanol technology

There are two main options for using methanol as fuel in conventional ship engines: in a two-stroke diesel-cycle engine or in a four-stroke, lean-burn Otto-cycle engine. Currently, there are seven methanol tankers operational which are powered with special MAN two-stroke engines running on methanol and one passenger ferry, powered by Wartsila four-stroke engines is fuelled with methanol (DNV-GL, 2018). This ferry, the Stena Germanica, was converted from MGO-fuelled to methanol-fuelled in 2015. The engines are modified to obtain dual-fuel capabilities, so they can run on MGO as backup. Also smaller vessels such as car ferries and fishing vessels can be converted to use methanol as fuel.

In Germany, an inland ferry, MS Innogy, is converted into an electrical vessel using fuel cells on methanol. With this pilot project the intention is to test the use of sustainable produced methanol and the robustness of the system in a maritime environment (Maritiem Kennis Centrum et al., 2018).

Another demonstration project is on board of the Viking Line ferry MS Mariella, where a 90 kW system with liquid-cooled fuel cells have been installed to produce electricity for the ships hotel function (Maritiem Kennis Centrum et al., 2018).

Figure 34; Methanol-powered Ropax ferry MS Stena Germanica

Technical consequences for design

Since methanol is liquid under atmospheric circumstances, it can be stored in standard fuel tanks for liquid fuels, with certain modifications to accommodate its low-flashpoint properties. Furthermore, there are requirements currently under development at the IMO. The volume of the fuel tanks should be 2,5 times larger than for traditional fuel due to the lower energy density when the same range is required. This is much less than required for hydrogen or batteries.

Although methanol is in many ways similar to ethanol (drinking alcohol), it is highly toxic for humans. Although safer than gasoline, there are some fire safety issues with methanol. Methanol vapour is heavier than air and it will linger close to the ground unless there is good ventilation. This can be ignited by a spark and since a methanol fire releases its energy slowly and gives off very little light, it is hard to see the fire. Low-concentration methanol is biodegradable, which is an advantage in the case of a spill.

For land-based infrastructure, special fuelling stations are required. For the Stena Germanica, two bunkering stations and special safety measures on land are constructed.

Application on Wadden ferries

Because methanol is liquid under atmospheric pressure it can be used in similar tanks as current fuels. The energy density is lower than traditional fuels such as diesel, so a higher amount is required. The methanol tanks can be integrated into the construction of the vessel and therefore not calculated as extra weight.

As an energy converter for methanol, the solid oxygen fuel cell (SOFC) has much potential and expected efficiency of 60 %. These are not yet market-ready and therefore also the ICE alternative is taken into account in this study.

Texel

For a single crossing, a ferry for Texel with a SOFC powertrain would consume 231 kg methanol, see appendix II. For a week, this is approximately 52 tonnes, about 45 % more weight than the current weekly demand for diesel. The volume of this amount of methanol is approximately 64 tonnes, roughly 50 % more than the current diesel volume required for one week. For ferries on the Texel route, this extra weight would not be a problem.

When an ICE configuration is used, higher fuel capacity is required because the efficiency of ICEs is lower, approximately 40% instead of 60%. An additional 50% of methanol is required and more frequent bunkering might be considered by the ship-owner.

Western Wadden Sea

For a single crossing at the western Wadden Sea, 1,3 ton of methanol is required when a SOFC is used (appendix III). The weekly demand will be approximately 55 tonnes (67 m^3). The volume is less than the current fuel (LNG), in weight this is more than the current demand and more frequent fueling (e.g. two times a week) might be considered.

When methanol is used to fuel an ICE, the methanol consumption will be 50 % more.

Eastern Wadden Sea

As shown in appendix 4, the weekly demand for methanol when SOFCs are used is approximately 19,1 ton (23,6 m^3). This is approximately 45 % more (in weight) than the current weekly diesel demand.

When an ICE configuration is used, an additional 50% of methanol is required. Because weight is an issue at the eastern Wadden Sea, more frequent bunkering than once a week might be considered.

For all ships, more frequent bunkering than once a week might be considered to limit the tank sizes. Experience with bunkering for the Stena Germanica shows that bunkering is not a large issue and although additional safety measures are taken, the infrastructure requirements are limited.

Green ammonia

Characteristics
Ammonia, with the chemical structure NH_3 is widely used for the production of fertilizers and is the second-largest chemical produced over the world. As a fuel, it is interesting because it can be produced entirely renewable and has no carbon components (no PM or CO_2) and emits no SOx (Giddey et al., 2017). Ammonia can be transported in the liquid form either fully pressurized, 10 bar at 20 °C, fully refrigerated -34 °C at 1 bar, or semi pressurized/refrigerated were the pressure needs to be higher than the vapour pressure. For volumes less than 5.000 m^3, the storage of ammonia under pressure is the most cost-effective. The energy density of ammonia is 18,6 MJ/kg and the volumetric energy density is 12,7 MJ/L, which is much higher than for hydrogen and batteries (ISPT, 2017).
Ammonia is, just like methanol, interesting as a fuel because it can be produced with renewable hydrogen but has a higher volumetric energy density than hydrogen. Therefore, the practical storage conditions of ammonia are better than for hydrogen. The energy required for synthetic production of ammonia without emissions is lower than for methanol and comparable with hydrogen (the production requires more energy but the storage requires less energy).
Currently, the hydrogen used for ammonia production is in most cases produced from natural gas (methane, CH_4), which is not renewable and emits emissions. Only hydrogen produced without emissions (e.g. with electrolysis of water with renewable electricity) will be used in this study. The nitrogen used is obtained by air separation (dry atmospheric air contains 78 % nitrogen). Bounding hydrogen and nitrogen is done by the Haber-Bosch process:

$$N_2 + 3H_2 \rightarrow 2NH_3$$

Since the hydrogen is produced with water, green ammonia can be produced with renewable, zero-emission electricity, water and atmospheric air.

Technology
Ammonia can be used as a fuel in various ways, including internal combustion engines (ICE) and fuel cells. The ICE can be spark-ignited (SI) or compression ignited (CI), although it is for these options preferable to have a mixture of ammonia and hydrogen to increase efficiency. Although there are no ships that are using ammonia as fuel yet, the ICE is seen as the most feasible at this moment.
A Solid Oxigen Fuel Cell (SOFC) is more efficient and will probably be a better choice in the future, however this is only in an R&D stage and there are practical challenges with power density and load response capability (de Vries, 2019).
Ammonia is a flammable gas, although the flammability risk is relatively low. The flammability limits are more narrow than conventional fuels with a high lower limit. Also, the absolute minimum ignition energy temperature is higher than conventional fuels (ISPT, 2017).
However, ammonia is highly toxic. Under atmospheric conditions ammonia is a gas which can be lethal for humans when exposed for 10 minutes to 2.700 ppm. Adequate detection systems, safety measures and regulations are required for safe use of ammonia. Since ammonia is highly toxic, it has a large environmental impact when spilt.
Ammonia is part of the nitrogen cycle, so the environment can restore itself with low levels of ammonia over time. Nevertheless, ammonia spillage can have long-lasting effects on the environment.
Despite the toxicity, ammonia is shipped on a large scale overseas and overland with regulations for safe handling.

Technical consequences for design

There are no regulations yet for the use of ammonia as ships fuel. Nevertheless, there are some design consequences for ships that can be identified. A ship that uses ammonia as fuel will require separate spaces for the redundant fuel supply lines, when a mixture of ammonia and hydrogen is used this is especially complex and requires a lot of space. Safety measures such as a minimum distance from the side for routing, tanks and equipment will affect the design. Currently, there are no ships that use ammonia as fuel. A recent study suggests that the first vessels that are likely to use ammonia as fuel are ammonia carriers that use their own cargo as fuel, this will reduce the number of additional regulations required (de Vries, 2019).

Application on Wadden ferries

Because ammonia is not yet used as fuel for shipping, there are no dedicated ammonia tanks for marine applications. However, since ammonia is transported, standardized tanks for transport are available. The extra weight required for the cylindric tanks is calculated based on these tanks.
A standard tank fitted in the dimensions of a 20 ft container currently used to store ammonia has a capacity of 24,6 m^3 and weight 8 ton. The tank weight is approximately 50 % of the ammonia it can store.
As an energy converter for ammonia, the solid oxygen fuel cell has much potential and expected efficiency of 60 %. These are not yet market-ready and therefore also the ICE alternative is taken into account in this study.

Texel

When a SOFC is used, the daily demand for ammonia is 7,7 ton (11,4 m^3). The tank weight is approximately 50 % of the ammonia weight, which is 3,9 ton. A full tank of ammonia weights therefore 11.6 ton for each day. When similar tanks are used as in the current ferry, the amount of ammonia on board would be sufficient for several days.
When an ICE is used, 50% more ammonia is consumed, and bunkering is required more frequently.

Western Wadden Sea

At the western Wadden Sea, the daily amount of ammonia is 8.1 ton when a SOFC is used (appendix III). Including tank weight this is 12,1 ton. The required volume is 12 m^3. When similar weights are allowed as in the reference vessel, tanking twice a week is required. This is 50 % more when an ICE configuration is used.

Eastern Wadden Sea

As shown in appendix IV, the daily demand for ammonia when SOFCs are used is approximately 2,8 ton (4,2 m^3). Including tank weight this is 4,2 ton per day. When similar tanks as the reference vessel are available, bunkering twice a week is sufficient. When an ICE configuration is used, this is 50% more and more frequent bunkering should be considered by the ship-owner.

Appendix II: Tank calculations Texel

Energy requirements

For a typical ferry in this area, 80% of the sailing is done with one of the four engines running. The output of this engine is approximately 2.000 kW. 10 % sailing, two engines will be used, 8% of sailing, three engines will be used and 2 % of sailing, 4 engines will be used. The average output of the engines is therefore 2.640 kW.

$$0{,}8 \times 2000 + 0{,}1 \times 4000 + 0{,}08 \times 6000 + 0{,}02 \times 8000 = 2640\ kW$$

The sailing time for one crossing is 17 minutes. The average energy demand is therefore approximately 750 kWh (2640/60*17 = 748 ≈ 750).

Texel							
		Diesel ICE	Batteries	LH2 PEMFC	H2 700 bar PEMFC	Methanol SOFC	Ammonia SOFC
Required energy	[kWh]	750	750	750	750	750	750
Converter efficiency	[%]	40%	98%	55%	55%	60%	60%
Required energy before converting	[kWh]	1.875	765	1.364	1.364	1.250	1.250
Required energy before converting	[MJ]	6.750	2.755	4.909	4.909	4.500	4.500
Energy density	[MJ/kg]	42,9	0,58	120	120	19,5	18,6
Volumentric energy density	[MJ/L]	36	1,21	8,5	4,5	15,8	12,6
Required weight	[ton]	0,157	4,750	0,041	0,041	0,231	0,242
Required Volume	[m3]	0,188	2,277	0,578	1,091	0,285	0,357

Following the required weight and volume for each alternative is calculated for one crossing. For Texel, the ferries are required to perform 32 crossings a day.

A return crossing consists of 2 crossings (mainland – island and back). A week contains 224 crossings. Diesel is used as default fuel. Based on this default fuel, an increase of 20% in weight or volume for the required fuel is accepted. When more than 120% of the weight or volume of one week of diesel is required, the value in the table below is coloured red.

Because Li-ion batteries can be discharged at a maximum of 80%, an extra 25% is required onboard. The reference ferry for Texel has four engines with an output of 2.000 kW. Under normal circumstances only one is used. However, with bad weather conditions (headwind, current etc.) 3 engines with a total output of 6.000 kW are required. This is included in the average energy demand, but for batteries this is important because these are only providing enough energy for two crossings. For normal conditions this is 1.530 kWh, however with bad conditions, one of the two crossing requires 1.700 kWh (6000/60*17). Because the ferry turns around 180 degrees and the headwind and current are not likely to switch 180 degrees with full speed this fast, the other crossing is assumed to be an average 750 kWh. The total bad weather requirement for a return crossing is therefore 2.450 kWh.

Fuels that are compressed or liquified require special tanks that require more volume because of their shape (e.g. cylindric.)

		Diesel ICE	Batteries	LH2 PEMFC	H2 700 bar PEMFC	Methanol SOFC	Ammonia SOFC
Single crossing weight	[ton]	0,16	4,75	0,04	0,04	0,23	0,24
Single crossing volume	[m3]	0,19	2,28	0,58	1,09	0,28	0,36
Return crossing weight	[ton]	0,31	9,50	0,08	0,08	0,46	0,48
Return crossing volume	[m3]	0,38	4,55	1,16	2,18	0,57	0,71
Day weight	[ton]	5,03	152	1,31	1,31	7,38	7,74
Day volume	[m3]	6,00	72,9	18,48	34,91	9,11	11,43
Week weight	[ton]	35,2	1064	9,2	9,2	51,7	54,2
Week volume	[m3]	42,0	510	129,4	244,4	63,8	80,0

Appendix III: Tank calculations western Wadden Sea

Required energy

Minimal capacity is based on the current ferries designed for this route: LNG powered catamarans with a capacity of 600 PAX.
These catamaran ferries have two LNG tanks of 46 m3. Combined the capacity is 92 m3 LNG. The ferry will take new fuel once a week.
The energy density of LNG is 53,6 MJ/kg and 22,2 MJ/L. The tanks of the ferries thus have a capacity of 2.042 GJ.
The vessels have two engines of 1.500 kW, thus a total of 3.000 kW.
The fuel consumption of these engines is 9.561 kJ/kWh.
For this calculation, it is assumed that the engines will operate at 80 % MCR and produce 2.400 kW/h with an LNG consumption of 22.946 MJ. This means an efficiency of 38% (22.946/3,6 = 6.374, 2.400/6.374=0,38).
The cruising speed of these ferries is 14 knots, the distance is 22 nm, the travel time of one crossing will take approximately 1 hour and 45 minutes, including manoeuvring.
The energy requirement of one crossing is approximately 4.200 kWh, based on an average of 80% MCR for 1 hour and 45 minutes (2.400*1,75).

Western Wadden Sea (Vlieland and Terschelling)								
		Diesel ICE	Batteries	LH2 PEMFC	H2 700 bar PEMFC	Methanol SOFC	Ammonia SOFC	LNG ICE
Required energy	[kWh]	4.200	4.200	4.200	4.200	4.200	4.200	4.200
Converter efficiency	[%]	40%	98%	55%	55%	60%	60%	38%
Required energy before converting	[kWh]	10.500	4.286	7.636	7.636	7.000	7.000	11.053
Required energy before converting	[MJ]	37.800	15.429	27.491	27.491	25.200	25.200	39.789
Energy density	[MJ/kg]	42,9	0,58	120	120	19,5	18,6	53,6
Volumentric energy density	[MJ/L]	36	1,21	8,5	4,5	15,8	12,6	22,2
Required weight	[ton]	0,9	26,6	0,2	0,2	1,3	1,4	0,7
Required Volume	[m3]	1,1	12,8	3,2	6,1	1,6	2,0	1,8

Following the required weight and volume for each alternative is calculated for one crossing. For the western Wadden Sea, the ferries are required to perform 6 crossings a day.
A return crossing consists of 2 crossings (mainland – island and back). A week contains 42 crossings.
LNG is used as default fuel. Based on the reference vessel, an increase of 20% in weight or volume for the required fuel is accepted. When more than 120% of the weight or volume of one week of diesel is required, the value in the table below is coloured red.

		Diesel ICE	Batteries	LH2 PEMFC	H2 700 bar PEMFC	Methanol SOFC	Ammonia SOFC	LNG ICE
Single crossing weight	[ton]	0,88	26,60	0,23	0,23	1,29	1,35	0,88
Single crossing volume	[m3]	1,05	12,75	3,23	6,11	1,59	2,00	1,05
Return crossing weight	[ton]	1,76	53,20	0,46	0,46	2,58	2,71	1,76
Return crossing volume	[m3]	2,10	25,50	6,47	12,22	3,19	4,00	2,10
Day weight	[ton]	5,29	159,61	1,37	1,37	7,75	8,13	5,29
Day volume	[m3]	6,30	76,51	19,41	36,65	9,57	12,00	6,30
Week weight	[ton]	37,01	1.117,24	9,62	9,62	54,28	56,90	37,01
Week volume	[m3]	44,10	535,54	135,84	256,58	66,99	84,00	44,10

Appendix IV: Tank calculations eastern Wadden Sea

Efficiency current engines

According to the engine manufacturer (Mitsubishi, 2019), the 470 kW S6R-(Z3)MPTAW high speed engine consumes 80,5 liter diesel per hour. This is according to the ISO 8178 E3 calculation which takes 0,6875 of MCR according to the following formula:

$$0{,}2 * 1 + 0{,}5 * 0{,}75 + 0{,}15 * 0{,}5 + 0{,}15 * 0{,}25 = 0{,}6875$$

In this formula, the fuel consumption per power output is weighted by a factor (100 % power weighted by factor 0,2 etc.). From this calculation can be concluded that for an engine with a MCR of 470 kW, 80,5 liter diesel is consumed for 323 kWh (0,6875 x 470). This is an efficiency rate of 40 %, according to the following calculation:

- Energy density diesel: 36 MJ/L
- 80,5 liter diesel for 323 kWh (1.163 MJ): Approximately 14,4 MJ/L

$$Efficiency\colon \frac{14{,}4}{36} = 0{,}4$$

Required energy

According to WPD, m.s. Rottum consumes 190 liter diesel per hour (WPD, 2019). With an average efficiency of 40%, this would correspondent with 760 kWh (190 x 36 x 0,40 / 3,6).

The crossing between Ameland and Holwerd takes 50 minutes for 6.9 miles. The crossing between Schiermonnikoog and Lauwersoog takes 45 minutes for 5.9 miles. The top speed of m.s. Rottum is 10.8 knots. For this study, an average of these two routes will be taken as ‘Eastern Wadden Sea’, where the average energy required for a crossing of a ferry with similar size and capacity of m.s. Rottum require 633 kWh (760/60*50).

This number will be used to calculate volumes of multiple alternative fuels and technologies. First, the required volumes and weight for alternatives will be calculated and secondly the frequency of bunkering will be calculated.

Following the required weight and volume for each alternative is calculated for one crossing. For the eastern Wadden Sea, the ferries are required to perform 14 crossings a day (WPD, 2019).

Eastern Wadden Sea (Ameland and Schiermonnikoog)							
		Diesel ICE	Batteries	LH2 PEMFC	H2 700 bar PEMFC	Methanol SOFC	Ammonia SOFC
Required energy	[kWh]	633	633	633	633	633	633
Converter efficiency	[%]	40%	98%	55%	55%	60%	60%
Required energy before converting	[kWh]	1.583	646	1.151	1.151	1.055	1.055
Required energy before converting	[MJ]	5.697	2.325	4.143	4.143	3.798	3.798
Energy density	[MJ/kg]	42,9	0,58	120	120	19,5	18,6
Volumentric energy density	[MJ/L]	36	1,21	8,5	4,5	15,8	12,6
Required weight	[ton]	0,133	4	0,035	0,035	0,195	0,204
Required Volume	[m3]	0,158	1,9	0,487	0,921	0,240	0,301

A return crossing consists of 2 crossings (mainland – island and back). A week contains 98 crossings. Diesel is used as default fuel. Based on the reference vessel, an increase of 20% in weight or volume for the required fuel is accepted. When more than 120% of the weight or volume of one week of diesel is required, the value in the table below is coloured red.

		Diesel ICE	Batteries	LH2 PEMFC	H2 700 bar PEMFC	Methanol SOFC	Ammonia SOFC
Single crossing weight	[ton]	0,13	4,01	0,03	0,03	0,19	0,20
Single crossing volume	[m3]	0,16	1,92	0,49	0,92	0,24	0,30
Return crossing weight	[ton]	0,27	8,02	0,07	0,07	0,39	0,41
Return crossing volume	[m3]	0,32	3,84	0,97	1,84	0,48	0,60
Day weight	[ton]	1,86	56,13	0,48	0,48	2,73	2,86
Day volume	[m3]	2,22	26,90	6,82	12,89	3,37	4,22
Week weight	[ton]	13,0	392,9	3,4	3,4	19,1	20,0
Week volume	[m3]	15,5	188,3	47,8	90,2	23,6	29,5

Appendix V: Cost calculations batteries

Batteries

As energy carriers, batteries are capital intensive systems. However, because of the lower operational costs of electricity and low maintenance costs of electronic systems in comparison with fuel systems, electronic ferries are profitable for certain ferry routes. A study by Siemens concluded that 70% of the coastal ferries of Denmark are more profitable when powered by a battery-electric configuration. This study included the costs of batteries, expanding the electricity grid and the costs of charging stations. Typically, the ferries that are profitable have an energy consumption of less than 2.000 kWh per trip and a crossing time of less than one hour (Siemens, 2016).

CAPEX Batteries

For this study, the CAPEX will be compared to a standard ferry with a generator set connected with an electromotor. Therefore, the costs of the electromotor are not taken into account. When a battery-electric system is used, there is no ICE installed. However, additional installations such as converters and transformers are required. Because the exact costs vary for each case, the costs of an ICE is estimated to be the same as the electric installation required for a battery-electric system.

An electromotor is cheaper than an ICE and a battery system has a higher efficiency than fuel systems. However, the batteries itself are relatively expensive per kWh. In a recent study, Cole and Frazier combined 25 studies to analyse the cost reduction for lithium-ion batteries for the next decades (Cole & Frazier, 2019). The results are shown in Figure 35 (the rates are converted to euros with the rate of 1,1 $ to 1 €). For this study, the mid-level projections will be used.

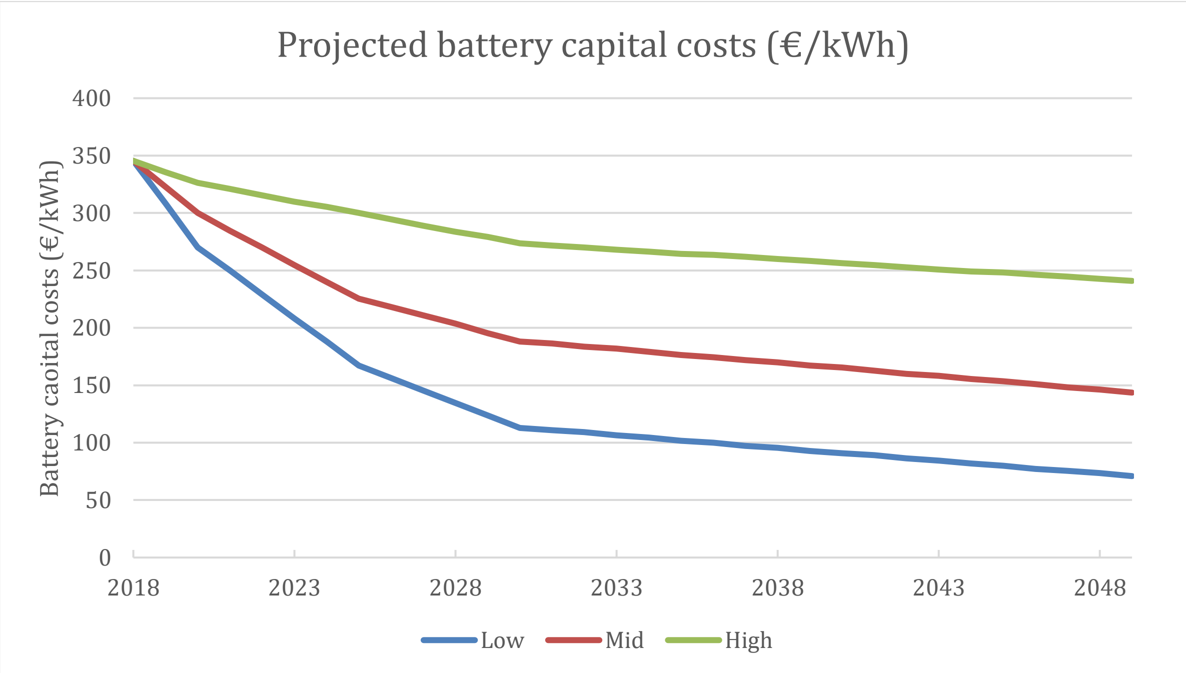
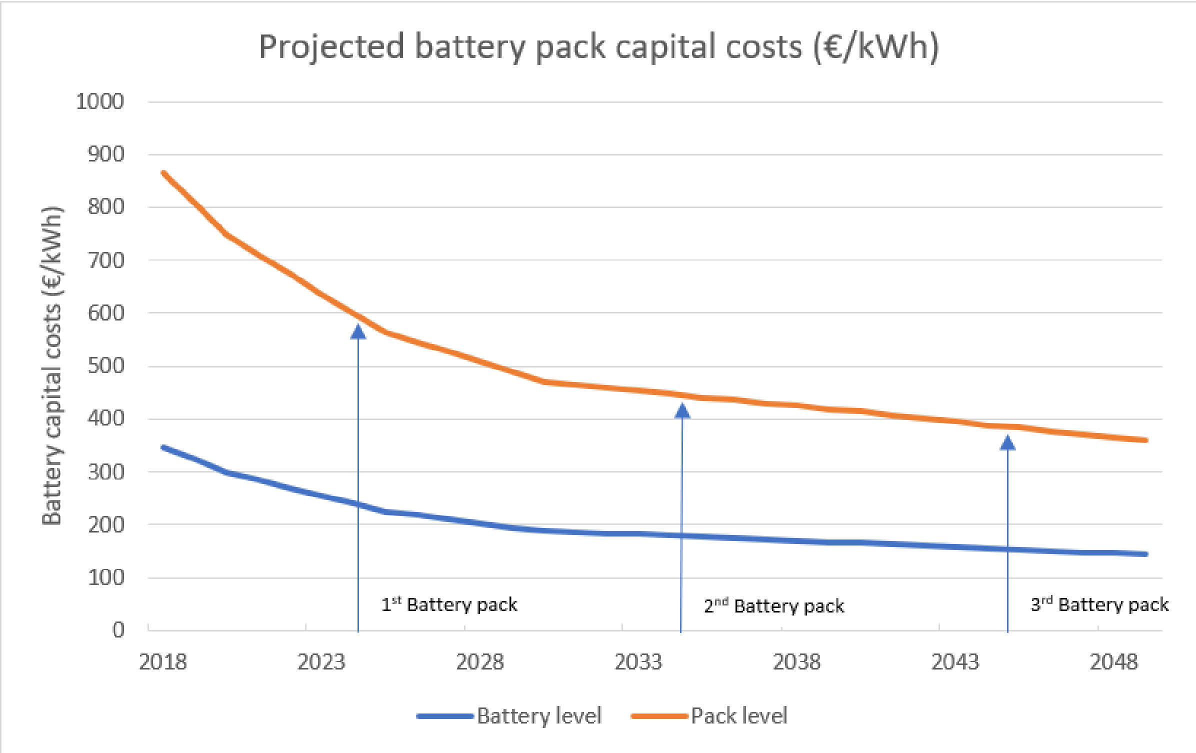


Figure 35; Projected battery capital costs, rates converted from dollar to euro with a rate of 1.1$=1€ (Cole & Frazier, 2019)

The expected lifetime used for this calculation is 10 years and the first battery pack is purchased in 2025. This means that the second battery pack is purchased in 2035 and the third in 2045. The prices in today's euros would be respectively € 564, € 441 and € 384 per kWh of battery storage capacity.



Source: Cole & Frazier, 2019. Converted from dollars to euros with a rate of 1.1 (November 2019).

For mobile battery packs that are swapped between the ferry and a charging station, multiple battery packs are required. For Texel and the eastern Wadden Sea, the packs are swapped every return crossing at the mainland and 2 mobile battery packs are required. For the western Wadden Sea, the battery pack have to be swapped after each crossing and 3 mobile battery packs are required.
The calculations are shown below

Mobile batteries	Battery pack	Costs 1st	Costs 2nd	Costs 3rd	Total	CAPEX costs per day
		2025	2035	2045		
	kWh	€ 564	€ 441	€ 384	€ 1.389	
Texel	1912	€ 1.078.368	€ 843.192	€ 734.208	€ 2.655.768	
# of packs	3	3	3	3	6	
Total	**5736**	**€ 3.235.104**	**€ 2.529.576**	**€ 2.202.624**	**€ 7.967.304**	**€ 728**
West	5040	€ 2.842.560	€ 2.222.640	€ 1.935.360	€ 7.000.560	
# of packs	3	3	3	3	9	
Total	**15120**	**€ 8.527.680**	**€ 6.667.920**	**€ 5.806.080**	**€ 21.001.680**	**€ 1.918**
East	1520	€ 857.280	€ 670.320	€ 583.680	€ 2.111.280	
# of packs	2	2	2	2	6	
Total	**3040**	**€ 1.714.560**	**€ 1.340.640**	**€ 1.167.360**	**€ 4.222.560**	**€ 386**

The average CAPEX costs for the battery packs per day are € 728 for Texel, € 1.918 for the western

Wadden Sea and € 386 for the eastern Wadden Sea.
To swap the battery packs, cranes or (electric) vehicles are required. The distance the packs have to cross is limited (less than 50 meters per swap), but the batteries are heavy and because of the tidal difference, there is a variable height difference between the ferry and the mainland. The costs are estimated to be € 250.000 for each battery pack with a lifetime of 30 years. This means that for Texel and the western Wadden Sea, this is an additional € 750.000 for 30 years, or € 70 per day. For the eastern Wadden Sea, this is an additional € 500.000, or € 47 per day.
The charging station and grid reinforcement is less demanding than for fixed batteries and the charging installations and electrical grid reinforcement, without any energy storage systems, is estimated on € 500.000 and be enough for 30 years. For the western Wadden Sea, this investment is required for both ends of the crossing and one million euros is required.

CAPEX	Texel	West	East
Batteries	€ 7.967.304	€ 21.001.680	€ 4.222.560
Swap equipment	€ 750.000	€ 750.000	€ 500.000
Charging/grid	€ 500.000	€ 1.000.000	€ 500.000
Total	€ 9.217.304	€ 22.751.680	€ 5.222.560
Total/day	€ 842	€ 2.078	€ 477

For fixed batteries on board, more batteries are required to limit the C-rate. Because the charging time is limited to the (un)loading time of the ferry, additional batteries are required to store the energy on land. For this study, the same layout as the land infrastructure of MS Ampere is used. This means that the capacity of the batteries on land is 80% of the batteries on board of the ferry. These batteries have the same lifetime as the batteries on board of the ferry, which is 10 years.
The calculations of the fixed batteries are shown below:

Ferry route	Battery pack	Costs 1st	Costs 2nd	Costs 3rd	Total	CAPEX costs per day
		2025	2035	2045		
	kWh	€ 564	€ 441	€ 384	€ 1.389	
Texel	3000	€ 1.692.000	€ 1.323.000	€ 1.152.000	€ 4.167.000	
Land	2400	€ 1.353.600	€ 1.058.400	€ 921.600	€ 3.333.600	
Total	**5400**	**€ 3.045.600**	**€ 2.381.400**	**€ 2.073.600**	**€ 7.500.600**	**€ 685**
West	8000	€ 4.512.000	€ 3.528.000	€ 3.072.000	€ 11.112.000	
Land	6400	€ 3.609.600	€ 2.822.400	€ 2.457.600	€ 8.889.600	
Total	**14400**	**€ 8.121.600**	**€ 6.350.400**	**€ 5.529.600**	**€ 20.001.600**	**€ 1.827**
East	2600	€ 1.466.400	€ 1.146.600	€ 998.400	€ 3.611.400	
Land	2080	€ 1.173.120	€ 917.280	€ 798.720	€ 2.889.120	
Total	**4680**	**€ 2.639.520**	**€ 2.063.880**	**€ 1.797.120**	**€ 6.500.520**	**€ 594**

Although no swapping equipment is required, the charging systems are more complex for fixed batteries. These have a lot of moving parts, must compensate (limited) ship motions and are automated to make optimal use of the limited time. These systems are commercially available. For this study, the costs of the system and reinforcement of the electrical grid are estimated to be one million euros. Because two of these systems are required for the western Wadden Sea, the costs will be twice this amount.

CAPEX	Texel	West	East
Batteries	€ 7.500.600	€ 20.001.600	€ 6.500.520
Charging/grid	€ 1.000.000	€ 2.000.000	€ 1.000.000
Total	€ 8.500.600	€ 22.001.600	€ 7.500.520
Total/day	€ 776	€ 2.009	€ 685

OPEX batteries

The required energy for Texel, the western Wadden Sea and the eastern Wadden Sea can be found in respectively appendix 2,3, and 4. The electricity rate that is used is € 57,25 per MWh, as found in paragraph 6.1.3. The OPEX calculations can be found below. The efficiency rate of 90% is due to the loss of energy while charging. When charged with a high C-rate, the energy loss is due heat generation.

OPEX		Texel	West	East
Consumption/crossing	MWh	0,765	4,286	0,646
Efficiency rate	%	90%	90%	90%
Required/crossing	MWh	0,85	4,762	0,718
Crossings/day	#	32	6	14
Consumption/day	MWh	27,2	28,6	10,0
Electricity rate	€/MWh	€ 57,25	€ 57,25	€ 57,25
Electricity cost/day	€	€ 1.557	€ 1.636	€ 575
OPEX/day	€	€ 1.557	€ 1.636	€ 575
OPEX/year	€	€ 568.378	€ 597.076	€ 209.984

TCO Mobile batteries	Texel	West	East
CAPEX/day	€ 842	€ 2.078	€ 477
OPEX/day	€ 1.557	€ 1.636	€ 575
Total/day	**€ 2.399**	**€ 3.714**	**€ 1.052**

TCO Fixed batteries	Texel	West	East
CAPEX/day	€ 776	€ 2.009	€ 685
OPEX/day	€ 1.557	€ 1.636	€ 575
Total/day	**€ 2.334**	**€ 3.645**	**€ 1.260**

Appendix VI: Cost calculations hydrogen

CAPEX hydrogen

Storage costs H2 700 bar

For compressed hydrogen, multiple relatively small cylindric tanks are used. These are type 4 composite tanks for hydrogen storage at a pressure of 700 bar. The costs of such tanks, which are also used for heavy automobile purposes such as trucks, is approximately 14 USD/kWh. This is approximately 466 USD/kg storage (H2 has an energy density of 120 MJ/kg (33,33 kWh/kg)). With a currency rate of 1,1 this is € 425 per kg storage. For the system level with several tanks, an additional 30 % is estimated for the rack, connections and safety systems. The storage price is therefore approximately € 550 per kg of storage capacity.

Additional piping, equipment for safety, bunkering, monitoring and managing hydrogen levels are estimated to costs an additional 50% of the tank costs.

H2 700 bar	Texel	West	East
Tank capacity (kg)	3300	1000	1200
Tank costs	€ 1.815.000	€ 550.000	€ 660.000
Equipment	€ 907.500	€ 275.000	€ 330.000
Total	€ 2.722.500	€ 825.000	€ 990.000

Storage cost liquid hydrogen

For liquid hydrogen, the storage costs are approximately 700 dollar per kg. This is calculated for SF Breeze (Pratt & Klebanoff, 2016). With the currency rate of 1,1 (November 2019), this is € 636 per kg of storage.

Additional piping, equipment for safety, bunkering, monitoring and managing hydrogen levels are estimated to costs an additional 50% of the tank costs.

LH2	Texel	West	East
Tank capacity (kg)	1960	2060	720
Tank costs	€ 1.247.273	€ 1.310.909	€ 458.182
Equipment	€ 623.636	€ 655.455	€ 229.091
Total	€ 1.870.909	€ 1.966.364	€ 687.273

Fuel cell cost

Of all fuel cells, PEM FCs is the cheapest because the automobile industry has invested on a large scale in this technology. Current research and development work aims to make maritime fuel cell systems marketable and scalable from 2022. Although current systems are 3.000 USD/kW, the aim is to reduce this to 1.000 USD/kW by 2022. This is still much higher than the automotive PEM FCs, of which the costs are expected to become 280 USD/kW when manufactured at mass (DNV-GL, 2018). In this study, 1.000 USD/kW or € 909/ kW is used. For calculations, the same installed power is used as the reference vessels have, which are 6 MW for Texel (without one back-up engine of 2 MW), 3 MW for the western Wadden Sea and 1,2 MW for the eastern Wadden Sea.

PEM FC	Texel	West	East
Installed power (kW)	6000	3000	1200
Costs	€ 5.454.545	€ 2.727.273	€ 1.090.909

Peak shaving batteries
To protect the FCs from heavy peaks loads which reduce the expected lifetime, peak-shaving batteries are often used in proposed hydrogen FC configurations. For this study, 500 kWh batteries are used. When the same characteristics are used as in paragraph 6.3, the expected costs are € 1.389 per kWh for 30 years of service. For a 500 kWh battery this is € 694.500.

All these components combined are the CAPEX for a hydrogen system. This can be found below. For some configurations the land infrastructure is also part of the CAPEX, for example when a dedicated electrifier is owned by the ship-owner. For this study, developed hydrogen infrastructure is assumed where it is possible to bunker from trucks with high pressure (or cooled) hoses directly from these trucks. The costs for these operations are part of the OPEX.

CAPEX H2 700 bar	Texel	West	East
Tank	€ 1.815.000	€ 550.000	€ 660.000
Equipment	€ 907.500	€ 275.000	€ 330.000
PEM FC	€ 5.454.545	€ 2.727.273	€ 1.090.909
Battery	€ 694.500	€ 694.500	€ 694.500
CAPEX	€ 8.871.545	€ 4.246.773	€ 2.775.409
CAPEX/day	€ 810	€ 388	€ 253

CAPEX LH2	Texel	West	East
Tank	€ 1.247.273	€ 1.310.909	€ 458.182
Equipment	€ 623.636	€ 655.455	€ 229.091
PEM FC	€ 5.454.545	€ 2.727.273	€ 1.090.909
Battery	€ 694.500	€ 694.500	€ 694.500
CAPEX	€ 8.019.955	€ 5.388.136	€ 2.472.682
CAPEX/day	€ 732	€ 492	€ 226

OPEX hydrogen
For this study, it is assumed that large scale hydrogen production by electrolysis takes place in the North of the Netherlands. Recent large investments in the development of a green hydrogen network support this assumption (H2 Platform, 2019). The required hydrogen price for electrolysis plants is a linearly increasing function of the electricity price, see the calculations below.
The long term electricity price used in this study, as described in paragraph 6,2, is € 57,25 per MWh. The hydrogen price when an electrolysis plant is used is € 3,35 /kg hydrogen.

However, the produced hydrogen is not yet suitable for transport or bunkering. For liquefaction of hydrogen, 40 MJ/kg H_2 is required (Bossel & Eliasson, 2003). With an electricity price of € 57,25 per MWh, this is an additional € 0,63 per kg LH2.

For the compression of hydrogen to 700 bar, 22 MJ/kg is required. With an electricity price of € 57,25 per MWh, this is an additional € 0,35 per kg of compressed hydrogen.

The transportation costs depend on volume, type of transportation and range. Because it is not yet known where the production will take place and on what scale hydrogen will be transported in the future in the Netherlands, an estimation is used for this study of € 0,50 per kg of hydrogen. The transportation is done with trucks by a dedicated transport company.
The price for liquid hydrogen that will be used in this study including transport is € 4,48 per kg and the price that will be used for hydrogen compressed to 700 bar is € 4,20.

OPEX LH2		**Texel**	**West**	**East**
Consumption/crossing	MWh	0,75	4,2	0,633
Efficiency rate	%	55%	55%	55%
Required/crossing	MWh	1,36	7,636	1,151
Required/crossing	kg	41	229	35
Crossings/day	#	32	6	14
Consumption/day	kg	1.309,1	1.375	483
After blow off (99%)	kg	1.296,0	1.360,8	478,5
LH2 price	€/kg	€ 4,48	€ 4,48	€ 4,48
H2 cost/day	€	€ 5.810	€ 6.101	€ 2.145
OPEX/day	**€**	€ 5.810	€ 6.101	€ 2.145
OPEX/year	**€**	€ 2.120.796	€ 2.226.836	€ 783.104

OPEX H2 700 bar		**Texel**	**West**	**East**
Consumption/crossing	MWh	0,75	4,2	0,633
Efficiency rate	%	55%	55%	55%
Required/crossing	MWh	1,36	7,6	1,15
Required/crossing	kg	41	229	35
Crossings/day	#	32	6	14
Consumption/day	kg	1.309,1	1.375	483
After blow off	kg	1.296,0	1.360,8	478,5
LH2 price	€/kg	€ 4,20	€ 4,20	€ 4,20
H2 cost/day	€	€ 5.496	€ 5.771	€ 2.029
OPEX/day	**€**	€ 5.496	€ 5.771	€ 2.029
OPEX/year	**€**	€ 2.006.040	€ 2.106.342	€ 740.730

TCO Hydrogen

A combination of the CAPEX and OPEX for liquid hydrogen gives the total cost of ownership shown in table 15. For hydrogen compressed to 700 bar, the TCO is shown in table 16. The difference in TCO between LH_2 and compressed H_2 is not very large, with a higher CAPEX and lower OPEX for compressed H_2 compared to LH_2. The costs are in euros per day.

TCO LH2	Texel	West	East
CAPEX/day	€ 732	€ 492	€ 226
OPEX/day	€ 5.810	€ 6.101	€ 2.145
Total/day	**€ 6.543**	**€ 6.593**	**€ 2.371**

TCO H2 700 bar	Texel	West	East
CAPEX/day	€ 810	€ 388	€ 253
OPEX/day	€ 5.496	€ 5.771	€ 2.029
Total/day	**€ 6.306**	**€ 6.159**	**€ 2.283**

Appendix VII: Cost calculations methanol

CAPEX methanol

Methanol is liquid under atmospheric pressure and does not require special storage tanks. However, as the pilot project Stena Germanica shows, additional infrastructure for bunkering is required. When methanol is used in an ICE configuration, additional investments for the engines are required. For this study, a CAPEX of € 400.000 is used for an ICE configuration for each route.
For methanol, a SOFC has the largest potential as an energy converter. These are still in an R&D phase and are not yet market-ready. According to an analysis of manufacturing costs of fuel cell systems by Houchins (2019), the scale of production is the most important factor for the price of the FCs. According to James and DeSantis, the price difference between PEM FCs and SOFCs is small when produced on the same scale. Because the investments in PEM FCs are far ahead in comparison with SOFCs, the estimated costs for SOFCs in this study are 2 times the price of PEM FCs. This is € 1800 per kW. However, this is not feasible until SOFCs are produced on a large scale.
For each route, a peak-shaving battery of 500 kW is used, with a total cost of € 694.000.

CAPEX ICE	
Engine conversion and bunker station	€ 400.000
Peak shaving batteries	€ 694.000
CAPEX life (30 years)	€ 1.094.000
CAPEX/day	€ 100

CAPEX SOFC		**Texel**	**West**	**East**
Power	kW	6.000	3.000	1.200
SOFC		€ 10.800.000	€ 5.400.000	€ 2.160.000
Peak shaving batteries		€ 694.000	€ 694.000	€ 694.000
Bunker station		€ 100.000	€ 100.000	€ 100.000
Costs/day		€ 1.059	€ 566	€ 270

OPEX methanol

The price per ton methanol depends on the production method. There are multiple methods to produce methanol. In this study, only methanol produced from 'green' hydrogen and CO2 from air or captured from flue gases is used. Methanol from biomass is cheaper, but not used in this study for the same reason that biodiesel is not used, see appendix I.

The green hydrogen production dominates the methanol production costs. The costs of electricity for hydrogen and the electrolyser costs are approximately 70 % of the total costs for methanol production. The CO_2 capture and utilization (CCU) installations and electricity demand are the other costs (Atsonios et al., 2015). Atsonios et al. (2015) calculated the price for green methanol at € 955 per ton. However, the hydrogen production costs are not in the scope of the study of Atsonios and were assumed equal to € 3 per kg. Because this study uses a higher hydrogen price of € 3,35 per kg (see the previous paragraph), the price that is used is € 1.032 per ton methanol. Conventional methanol has a price of € 280 per ton (Methanex, 2019).

OPEX ICE Configuration		Texel	West	East
Consumption/crossing	MWh	0,75	4,2	0,633
Efficiency rate	%	40%	40%	40%
Required/crossing	MWh	1,88	10,5	1,58
Required/crossing	kg	346	1.938	292
Crossings/day	#	32	6	14
Consumption/day	kg	11.076,9	11.631	4.090
Methanol price	€/kg	€ 1,03	€ 1,03	€ 1,03
Methanol cost/day	€	€ 11.431	€ 12.003	€ 4.221
OPEX/day	€	€ 11.431	€ 12.003	€ 4.221
OPEX/year	€	€ 4.172.455	€ 4.381.078	€ 1.540.679

OPEX SOFC configuration		Texel	West	East
Consumption/crossing	MWh	0,75	4,2	0,633
Efficiency rate	%	60%	60%	60%
Required/crossing	MWh	1,25	7,0	1,06
Required/crossing	kg	231	1292	195
Crossings/day	#	32	6	14
Consumption/day	kg	7.384,6	7.754	2.727
Methanol price	€/kg	€ 1,03	€ 1,03	€ 1,03
Methanol cost/day	€	€ 7.621	€ 8.002	€ 2.814
OPEX/day	€	€ 7.621	€ 8.002	€ 2.814
OPEX/year	€	€ 2.781.637	€ 2.920.719	€ 1.027.119

TCO methanol

The total costs of ownership for a ferry powered by green methanol, configurations for ICE and SOFC installations are calculated. These are shown below.

TCO ICE configuration	Texel	West	East
CAPEX/day	€ 100	€ 100	€ 100
OPEX/day	€ 11.431	€ 12.003	€ 4.221
Total/day	**€ 11.531**	**€ 12.103**	**€ 4.321**

TCO SOFC configuration	Texel	West	East
CAPEX/day	€ 1.059	€ 566	€ 270
OPEX/day	€ 7.621	€ 8.002	€ 2.814
Total/day	**€ 8.680**	**€ 8.568**	**€ 3.084**

Appendix VIII: Cost calculations ammonia

CAPEX ammonia

Ammonia has to be stored at 10 bar of pressure, therefore special tanks are required. However, because the pressure is limited, the additional costs are relatively low. Because of the toxicity of ammonia, additional safety systems and ventilation is required. Piping and bunkering systems require additional costs to ensure no toxic ammonia can be released into the air during operation or bunkering. The SOFCs are assumed to cost € 1.800 per kW and both the ICE as the SOFC configurations have peak shaving batteries of 500 kW, which cost € 694.000.

CAPEX ICE		Texel	West	East
Power	kW	6.000	3.000	1.200
Equipment		€ 400.000	€ 300.000	€ 200.000
Storage		€ 3.000.000	€ 1.500.000	€ 600.000
Peak shaving batteries		€ 694.000	€ 694.000	€ 694.000
Bunker station		€ 100.000	€ 100.000	€ 100.000
Costs/day		€ 383	€ 237	€ 146

CAPEX SOFC		Texel	West	East
Power	kW	6.000	3.000	1.200
SOFC		€ 10.800.000	€ 5.400.000	€ 2.160.000
Equipment		€ 400.000	€ 300.000	€ 200.000
Storage		€ 3.000.000	€ 1.500.000	€ 600.000
Peak shaving batteries		€ 694.000	€ 694.000	€ 694.000
Bunker station		€ 100.000	€ 100.000	€ 100.000
Costs/day		€ 1.369	€ 730	€ 343

OPEX ammonia

Since ammonia is produced with the Haber-Bosch process from hydrogen and nitrogen, the price is highly depending on the price of hydrogen, which is highly depending on the electricity price. The production of ammonia required approximately 10,4 kWh/kg electricity (Bennani et al., 2016). A further 0,4 kWh is required to pressurize the ammonia. The electricity required per kg of ammonia is therefore 10,8 kWh, with an electricity price of € 57 per MWh, this is € 615 per ton ammonia.
The capital costs for ammonia production plants is estimated to be € 44 per produced ton. This is an average, since the costs per produced ton depend on utility rate and scale of the production plant (Philbert 2017). The price per ton ammonia used for this study is € 660 per ton.

OPEX ICE		Texel	West	East
Consumption/crossing	MWh	0,75	4,2	0,633
Efficiency rate	%	40%	40%	40%
Required/crossing	MWh	1,88	10,5	1,58
Required/crossing	kg	363	2032	306
Crossings/day	#	32	6	14
Consumption/day	kg	11.613	12.194	4.288
Methanol price	€/kg	0,662	0,662	0,662
Methanol cost/day		€ 7.688	€ 8.072	€ 2.839
OPEX/day		€ 7.688	€ 8.072	€ 2.839
OPEX/year		€ 2.806.026	€ 2.946.327	€ 1.036.125

OPEX SOFC		Texel	West	East
Consumption/crossing	MWh	0,75	4,2	0,633
Efficiency rate	%	60%	60%	60%
Required/crossing	MWh	1,25	7,000	1,055
Required/crossing	kg	242	1355	204
Crossings/day	#	32	6	14
Consumption/day	kg	7.741,9	8.129	2.859
Methanol price	€/kg	€ 0,66	€ 0,66	€ 0,66
Methanol cost/day		€ 5.125	€ 5.381	€ 1.892
OPEX/day		€ 5.125	€ 5.381	€ 1.892
OPEX/year		€ 1.870.684	€ 1.964.218	€ 690.750

TCO Ammonia

The calculations for the total cost of ownership for ammonia can be found in appendix 8. The summary of the TCO can be found in table 19 of the ICE configuration and in table 20 for the SOFC configuration.

TCO ICE configuration	Texel	West	East
CAPEX/day	€ 383	€ 237	€ 146
OPEX/day	€ 7.688	€ 8.072	€ 2.839
Total/day	**€ 8.071**	**€ 8.309**	**€ 2.984**

TCO SOFC configuration	Texel	West	East
CAPEX/day	€ 1.369	€ 730	€ 343
OPEX/day	€ 5.125	€ 5.381	€ 1.892
Total/day	**€ 6.494**	**€ 6.111**	**€ 2.235**

Appendix IX Interview protocol

Because all interviewees are interviewed in Dutch, the questions are stated in Dutch.
Naam: …………………………………………..
Functie: ………………………………………..
Organisatie: …………………………………..
Datum: …………………………………………..

Introductie

- Kennismaking: voorstellen, achtergrond en context
- Tijd van interview: 45 minuten
- Opname van het interview, goedkeuring.
- Introductie van het onderzoek: MoT vanuit TU Delft en achtergrond C-Job (ervaring Texelstroom en onderzoek alternatieve brandstoffen)
- Opzet interview, brede haalbaarheid (eerst algemene vragen dan vragen per feasibility: technisch, economisch, sociaal en politiek)

Algemene vragen

1. Kunt u iets meer over uzelf en uw rol bij uw organisatie vertellen?
2. Is het voor uw organisatie een doelstelling om volledig emissieloze veerboten te realiseren in het Waddengebied (indien positief, op welke termijn? Indien negatief, waarom niet?)
3. Wat is volgens u de belangrijkste motivatie om te verduurzamen of volledig emissieloos te varen? Wat bepaald hierin het tempo?
4. Denkt u dat de Waddenzee een geschikt gebied is voor emissieloze veerboten?
5. Wie zijn volgens u de belangrijkste belanghebbenden die de keuze bepalen over duurzaamheidseisen aan nieuwe veerboten?
6. Wat zijn volgens u de belangrijkste (ontwerp)eisen voor veerboten in de Waddenzee?

Technische haalbaarheid

Presenteren 4 emissieloze mogelijkheden volgens onderzoek

7. Naar aanleiding van de vier getoonde alternatieven, ziet u al deze vier als mogelijkheden voor emissieloos varen? Zijn er nog alternatieven die u meeneemt welke niet getoond zijn?
8. Is er een van technieken die uw voorkeur heeft? Zijn er technieken die u niet of zeer moeilijk haalbaar acht?
9. Voor de optie batterijen: deze hebben een laadstation nodig in minimaal één haven inclusief versterkingen van het elektriciteitsnet. Denkt u dat dit haalbaar is (op de waddeneilanden)?
10. Is langer in de haven liggen om batterijen op te laden een mogelijkheid? Of bijvoorbeeld meerdere kleine boten met langere laadmogelijkheden?
11. Ziet u het als een mogelijkheid om de veerboten klaar te maken voor volledig emissieloze energie, maar op ‘grijze’ of ‘blauwe’ energie te varen zolang de prijs van ‘groene’ energie hoger is?

12. Theoretisch kunnen alle vier de alternatieven lokaal worden opgewekt (benodigheden zijn groene stroom, water en eventueel lucht (stikstof/co2). Ziet u dit als wenselijk en indien dit zo is, als haalbaar?

Economische haalbaarheid

13. Hoe kijkt u tegen de business case van emissieloze veerboten aan?
14. Indien uit onderzoek blijkt dat het niet rendabel is om volledig emissieloze veerboten te gebruiken, denkt u dat er dan subsidiemogelijkheden bestaan?

Sociale haalbaarheid

15. Denkt u dat er onder het groter publiek een vraag naar volledig duurzame veerboten in de Waddenzee is? Denkt u dat passagiers van de veerdiensten eventueel bereid zijn om meer te betalen?
16. Sneldiensten: Er is een trend in het Waddengebied dat er naast de normale veerdiensten ook meer gebruik wordt gemaakt van sneldiensten, welke relatief veel brandstof verbruiken. Denkt u dat de ontwikkeling van duurzame veerboten samen kan gaan met deze ontwikkeling?

Politieke haalbaarheid

17. Concessiesysteem: Geeft dit systeem kansen voor het ontwikkelen van emissieloos varen of juist beperkingen?
18. Denkt u dat emissieloos varen of verminderen van emissies een eis kan worden vanuit de concessieverlener?
19. Heeft u verder nog aanvullingen die nog niet besproken zijn in dit interview?

#	Interviewee	Position	Organisation
1	Bas Bijl	Physical geographer	De Waddenvereniging
2	Paul Pot	Director	Port of Harlingen
3	Ger van Langen	Director	Wagenborg Passagiersdiensten
4	Rick Timmerman	Project Manager	Programma naar een rijke Waddenzee/ Rijkswaterstaat
5	Bernhard Baerends	Executive Sectretary	Common Wadden Sea Secretariat
6	Cees de Waal	Director	TESO

Interview 1

Naam: Bas Bijl
Functie: Fysisch geograaf, projectleider Lauwerskust
Organisatie: Waddenvereniging
Datum: 11-11-2019, Harlingen

Algemene vragen

1. Kunt u iets meer over uzelf en uw rol bij uw organisatie vertellen?

- *Fysisch geograaf, bezig met dynamiek van Waddenzee en Waddeneilanden, specifiek voor Lauwersoog/Lauwersmeer met het project project Lauwerskust.*

2. Is het voor uw organisatie een doelstelling om volledig emissieloze veerboten te realiseren in het Waddengebied

- *Alle ontwikkelingen die duurzaamheid in UNESCO werelderfgoed Waddenzee bevorderen zijn goed. Waddenvereniging is gericht op het verminderen van de belasting op dit gebied zodat deze zo natuurlijk mogelijk kan blijven bestaan.*

3. Wat is volgens u de belangrijkste motivatie om te verduurzamen of volledig emissieloos te varen?

- *Vooral klimaat, we zullen allemaal moeten verduurzamen, dus ook de waddenveren.*

4. Wie zijn volgens u de belangrijkste belanghebbenden die de keuze bepalen over duurzaamheidseisen aan nieuwe veerboten?

- *Reders bepalen uiteindelijk wat voor boten ze kopen. Regelgeving (concessies) bepalen wat hiervoor de eisen zijn. Uiteindelijk zullen vooral klanten en omwonenden de input zijn voor die concessies. Deze regelgeving zal duurzaamheid moeten afdwingen.*

5. Wat zijn volgens u de belangrijkste (ontwerp)eisen voor veerboten in de Waddenzee?

- *Vooral in het Oostelijke Waddengebied is diepgang een belangrijke eis. Doordat de geulen ondieper worden moet er meer gebaggerd worden, dit kost miljoenen en verstoord de natuurlijke dynamiek van het wad.*
- *Liever gescheiden vervoer, passagiersschepen kunnen dan met minder diepgang ontworpen worden en vracht kan met de vloed mee varen, zodat er minder gebaggerd hoeft te worden.*
- *In de toekomst zou het mooi zijn als er minder toeristen met de auto de oversteek maken, bijvoorbeeld door (elektrische) huurauto's aan te bieden op de eilanden. De veren kunnen dan ontworpen worden voor minder/geen auto's.*

Technische haalbaarheid

6. Is er een van technieken die uw voorkeur heeft? Zijn er technieken die u niet of zeer moeilijk haalbaar acht?

- *De schadelijkheid van niewe technieken (zoals batterijen en ammoniak) is een mogelijk probleem, als dit in het water terecht komt heeft het grote gevolgen voor het kwetsbare Waddengebied. Hier zou dus eerst heel goed naar gekeken moeten worden.*

7. Voor de optie batterijen: deze hebben een laadstation nodig in minimaal één haven inclusief versterkingen van het elektriciteitsnet. Denkt u dat dit haalbaar is (op de waddeneilanden)?

- *In bepaalde havens zou dit mogelijk kunnen zijn, dus lokale of regionale opwekking van duurzame energie als bron. Met de kanttekening dat de Waddenvereniging tegenstander is van windmolens in en nabij het Waddengebied. Dit verstoord het landschap en is gevaarlijk voor de vele vogels in het gebied.*

8. Is langer in de haven liggen om batterijen op te laden een mogelijkheid? Of bijvoorbeeld meerdere kleine boten met langere laadmogelijkheden?

- *Waarschijnlijk hebben veel toeristen die naar de Waddeneilanden gaan hier wel begrip voor.*

9. Ziet u het als een mogelijkheid om de veerboten klaar te maken voor volledig emissieloze energie, maar op ‘grijze’ of ‘blauwe’ energie te varen zolang de prijs van ‘groene’ energie hoger is?

- *Als beperkte overgangsperiode kan dit, maar er moet wel een moment zijn dat dit volledig groen wordt.*

10. Theoretisch kunnen alle vier de alternatieven lokaal worden opgewekt (benodigheden zijn groene stroom, water en eventueel lucht (stikstof/co2). Ziet u dit als wenselijk en indien dit zo is, als haalbaar?

- *Ja, hoewel dit qua stroom niet overal kan.*

Economische haalbaarheid

11. Indien uit onderzoek blijkt dat het niet rendabel is om volledig emissieloze veerboten te gebruiken, denkt u dat er dan subsidiemogelijkheden bestaan?

- *Dit behoort tot de mogelijkheden, vooral voor pilot projecten.*

Sociale haalbaarheid

12. Sneldiensten: Er is een trend in het Waddengebied dat er naast de normale veerdiensten ook meer gebruik wordt gemaakt van sneldiensten, welke relatief veel brandstof verbruiken. Denkt u dat de ontwikkeling van duurzame veerboten samen kan gaan met deze ontwikkeling?

- *Dit hoeft niet slecht te zijn, snellere boten kunnen ook kleiner zijn, waarvoor minder gebaggerd hoeft te worden. Zolang duurzaam kan het zonder probleem snel zijn. Maar fauna op de Waddenzee moet er niet onder lijden, dus snelvaren tot op zekere hoogte.*

Politieke haalbaarheid

13. Concessiesysteem: Geeft dit systeem kansen voor het ontwikkelen van emissieloos varen of juist beperkingen?

- *Concessiesysteem biedt kansen. Hoewel er niet veel veranderd zal worden voor de volgende concessie in gang gezet wordt hebben de partijen nu voldoende tijd om zich voor te bereiden op de volgende concessie.*

14. Denkt u dat emissieloos varen of verminderen van emissies een eis kan worden vanuit de concessieverlener?

- *Dit zal waarschijnlijk de manier worden.*

15. Heeft u verder nog aanvullingen die nog niet besproken zijn in dit interview?

- *Constatering: rond het oostelijk waddengebied meer initiatieven, zoals bijvoorbeeld rond waterstof in Lauwersoog.*

Interview 2

Naam: Paul Pot
Functie: Directeur
Organisatie: Port of Harlingen
Datum: 11-11-2019, Harlingen

Algemene vragen

1. Kunt u iets meer over uzelf en uw rol bij uw organisatie vertellen?

- *NV Port of Harlingen is 2 jaar oud, sinds februari ben ik directeur. Organisatie is 100 % eigendom van gemeente Harlingen. Hiervoor is ook een havenvisie opgesteld. Mijn achtergrond is in een ander havenbedrijf, namelijk die van Amsterdam, waar ik 15 jaar gewerkt heb.*

2. Is het voor uw organisatie een doelstelling om volledig emissieloze veerboten te realiseren in het Waddengebied

- *Als havenautoriteit hebben we hier niet veel invloed op. De veerboten die in Harlingen komen zijn van Doeksen en de eisen vanuit het rijk worden strenger en daardoor worden de schepen schoner. De overige schepen die lading transporteren is dat anders. Er komen ook oudere schepen en die kunnen we niet uitsluiten.*
- *Eventueel zouden we kortingen kunnen geven op schonere schepen of walstroom faciliteren.*

3. Denkt u dat de Waddenzee een geschikt gebied is voor emissieloze veerboten?

- *Voor de veerboten wel, afstanden zijn te overzien. Veerboten zijn grootverbruikers in het Waddengebied.*

4. Wie zijn volgens u de belangrijkste belanghebbenden die de keuze bepalen over duurzaamheidseisen aan nieuwe veerboten?

- *Concessieverlener, maar ook klanten.*

5. Wat zijn volgens u de belangrijkste (ontwerp)eisen voor veerboten in de Waddenzee?

- *Diepgang, maar ook zuinigheid. Er wordt tegenwoordig gekozen voor catamarans van aluminium. Dat scheelt een hoop brandstof. Daarnaast varen ze op LNG.*

Technische haalbaarheid

6. Voor de optie batterijen: deze hebben een laadstation nodig in minimaal één haven inclusief versterkingen van het elektriciteitsnet. Denkt u dat dit haalbaar is (op de waddeneilanden)?

- *Investeringen zijn heel hoog. Zie bijvoorbeeld walstroom voor cruiseschepen, dat gebeurt al heel weinig. Dit kost heel veel geld omdat het bestaande net vaak niet te upgraden is.*
- *Op de Waddeneilanden is dit nog een groter probleem, grote kans dat dit niet haalbaar is (met de huidige kabels onder die onder water lopen).*

7. Is langer in de haven liggen om batterijen op te laden een mogelijkheid? Of bijvoorbeeld meerdere kleine boten met langere laadmogelijkheden?

- *Er is een behoorlijk strak schema, 's nachts kan het natuurlijk wel.*

8. Theoretisch kunnen alle vier de alternatieven lokaal worden opgewekt (benodigheden zijn groene stroom, water en eventueel lucht (stikstof/co2). Ziet u dit als wenselijk en indien dit zo is, als haalbaar?

- *Zeker, dit staat ook in de havenvisie. Dit is ook te combineren met brandstoffen voor andere scheepsvaart in de haven van Harlingen. Dit gaat dan vooral om waterstof.*

Economische haalbaarheid

9. Indien uit onderzoek blijkt dat het niet rendabel is om volledig emissieloze veerboten te gebruiken, denkt u dat er dan subsidiemogelijkheden bestaan?

- *Zeker, niet voor goedkopere stroom maar wel voor investeringen, vooral als het pilot projecten zijn.*

Sociale haalbaarheid

10. Denkt u dat er onder het groter publiek een vraag naar volledig duurzame veerboten in de Waddenzee is? Denkt u dat passagiers van de veerdiensten eventueel bereid zijn om meer te betalen?

- *Een grote groep toeristen is waarschijnlijk wel bereid iets extra's te betalen.*

11. Snelldiensten: Er is een trend in het Waddengebied dat er naast de normale veerdiensten ook meer gebruik wordt gemaakt van sneldiensten, welke relatief veel brandstof verbruiken. Denkt u dat de ontwikkeling van duurzame veerboten samen kan gaan met deze ontwikkeling?

- *Als de brandstof schoon is, zou dit geen probleem hoeven te zijn.*

Politieke haalbaarheid

- <u>Concessiesysteem: Geeft dit systeem kansen voor het ontwikkelen van emissieloos varen of juist beperkingen?</u>
- *Waarschijnlijk wel kansen. Het kan wel lastig zijn voor het bepalen van het bouwen van nieuwe boten.*

12. <u>Denkt u dat emissieloos varen of verminderen van emissies een eis kan worden vanuit de concessieverlener?</u>

- *Ja. Dit doen ze ook bij andere grote aanbestedingen zoals infrastructuurprojecten (onderhoud van de afsluitdijk), hier staat duurzaamheid steeds hoger op de agenda.*
-

13. <u>Heeft u verder nog aanvullingen die nog niet besproken zijn in dit interview?</u>

- *Veiligheid kan wel een grote rol gaan spelen, zeker als de haven in dichtbevolkt gebied ligt zoals Harlingen.*

Interview 3

Naam: Ger van Langen
Functie: Directeur
Organisatie: Wagenborg passagiersdiensten
Datum: 12-11-2019, Holwerd

Algemene vragen

1. Kunt u iets meer over uzelf en uw rol bij uw organisatie vertellen?

- *Achtergrond: zeevaartschool, stuurman op grote vaart. Hierna bedrijfskunde gestudeerd en directeur geworden bij WPD, inmiddels 22 jaar in deze functie.*
- *Wagenborg heeft 7 divisies, waarvan 1 B2C, namelijk WPD. Deze verzorgt het vervoer naar de eilanden Ameland en Schiermonnikoog met veerboten, watertaxi's en sneldiensten, ook de parkeerdiensten, Retail en horeca vallen onder WPD.*

2. Is het voor uw organisatie een doelstelling om volledig emissie loze veerboten te realiseren in het Waddengebied?

- *Huidige concessie loopt tot 1 april 2029. Mijn ambitie is om nieuwe veerboten te bouwen op de korte termijn. Hiervoor zijn wel een aantal piketpalen nodig om de randvoorwaarden te bepalen. Deze worden onder andere vastgelegd in de gebiedsagenda 2050, welke in maart aangeboden wordt aan de tweede kamer. Als hier bijvoorbeeld in komt te staan dat natuurbelang vóór maatschappelijk en economisch belang komt te staan, dan zal dit gevolgen hebben voor de veerboten en een uitdaging zijn.*
- *De Oostelijke Waddenzee heeft te maken met verdroging, de bodemstijging gaat harder dan ze zeespiegelstijging. De oorzaken zijn onderzocht door Deltares, dit komt vooral door menselijk ingrijpen zoals het afsluiten van voormalige 'spoelmeren' Zuiderzee en Lauwerszee, het aanleggen van 'zandmotor' 2e Maasvlakte. Ook is de zuidkant van de Waddeneilanden gefixeerd met kunstwerken (dijken) en 'wandelt' de noordkant door natuurlijke oorzaken. Om dit te borgen vindt er zandsuppletie plaats, waarbij veel zand verloren gaat, wat terecht komt in de Waddenzee. Dit gaat sneller aan de oostkant dan aan de westkant van het waddengebied.*
- *Andere piketpaal is de lange termijnvisie die de minister heeft gevraagd voor de bereikbaarheid van Ameland. De huidige vaargeul ligt op het wantij, waar de verdroging nog sneller gaat. De drie mogelijkheden zullen worden, handhaven zoals de huidige situatie, het verplaatsen van de haven naar Ferwerd of een tunnel. Al deze mogelijkheden zijn ingrijpend en zullen gevolgen hebben. Voor de eerste twee opties zal op termijn op het tij gevaren moeten worden, bijvoorbeeld 3 uur voor en 3 uur na hoog water.*
- *Op dit moment doen we samen met de Rijksuniversiteit Groningen een socio-maatschappelijke mobiliteitsanalyse. Dit om te kijken naar wat mobiliteit voor de gemeenschap gaat betekenen. Hierbij wordt ook gekeken naar de rol van auto's op de eilanden (en dus het vervoer van auto's op de veerboten).*

- *Wij hebben zeker de ambitie om emissievrij te varen. Dit hebben we al onderzocht in 2011 met een industrieel onderzoek voor eventuele vervanging van de Rottum en de Monnik. Hieruit bleek dat het bedrijfseconomisch toen niet haalbaar was. Toen hebben we de Rottum gerefit zodat deze de concessie uit kon varen en we tegen die tijd met een nieuw vervoersconcept kunnen komen. Hierbij kijken we naar lichtgewicht rompen van bijvoorbeeld composieten, emissievrij varen en voorbereiding op autonoom varen.*

3. Denkt u dat de Waddenzee een geschikt gebied is voor emissie loze veerboten?

- *Technisch: de Waddenzee wordt in Nederland als binnenvaartwater gezien, anders dan in Denemarken en Duitsland. Dit geeft ruimte voor het ontwerpen, zoals bijvoorbeeld lichtere boten met minder weerstand.*

4. Wat zijn volgens u de belangrijkste (ontwerp)eisen voor veerboten in de Waddenzee?

- *Onze ambitie: Emissievrij, autonoom en circulair, de mogelijkheden hierin zijn afhankelijk van de piketpalen die duidelijk zullen worden in o.a. de gebiedsagenda.*
- *Praktisch gezien: we moeten de continuïteit waarborgen, de garantie van een prijsniveau en een vooraf afgesproken hoeveelheid brandstof.*
- *Gewicht: door de beperkte diepte van het vaarwater moeten we erg op het gewicht gaan letten, in het ontwerp, maar ook in het vervoer. Bijvoorbeeld vrachtvervoer, we kijken of dat slimmer kan dan met vrachtwagens, zoals het nu gaat.*
- *Volume: om het aantal schepen beperkt te houden moet er voldoende capaciteit zijn per schip. In de krappe geulen wil je zo min mogelijk bewegingen hebben, daarnaast zit je met turnaround tijd en haveninfrastructuur. De hoeveelheid schepen moet daarom zo klein mogelijk zijn en de capaciteit hoog.*

Technische haalbaarheid

5. Naar aanleiding van de vier getoonde alternatieven, ziet u al deze vier als mogelijkheden voor emissie loos varen? Zijn er nog alternatieven die u meeneemt welke niet getoond zijn?

- *In de toekomst: Thorium, als dit op kleine schaal kan dan moet dit een serieuze optie blijven. Dit is nu nog ver weg, maar in de toekomst zeker interessant.*
- *Zaken als zonnepanelen voor verlichting etc. kunnen de totale energiebehoefte omlaag brengen, dit is echter niet relevant voor de hoofdvoortstuwing.*

6. Is er een van technieken die uw voorkeur heeft? Zijn er technieken die u niet of zeer moeilijk haalbaar acht?

- *Diepgang is voor ons erg belangrijk. Daardoor mag de brandstof niet te veel wegen, een belangrijk issue met batterijen. Ammonia is te ver weg voor de schepen die wij willen ontwerpen in de komende paar jaar.*
- *Wagenborg (ook zeevaart) ziet momenteel het meest in waterstof en methanol*

7. Theoretisch kunnen alle vier de alternatieven lokaal worden opgewekt (benodigdheden zijn groene stroom, water en eventueel lucht (stikstof/co2). Ziet u dit als wenselijk en indien dit zo is, als haalbaar?

- *De hoeveelheid die je nodig hebt, maakt dat de impact groot is. Bijvoorbeeld elektriciteitsopwekking via zonnepanelen of windmolens is lastig, omdat je veel nodig hebt. Een mogelijkheid is waterstofproductie uit getijdenstroom.*

Economische haalbaarheid

8. Als uit onderzoek blijkt dat het niet rendabel is om volledig emissie loze veerboten te gebruiken, denkt u dat er dan subsidiemogelijkheden bestaan?

- *Zeker, bijvoorbeeld via het waddenfonds of vanuit de Europese Unie.*

Sociale haalbaarheid

9. Denkt u dat er onder het groter publiek een vraag naar volledig duurzame veerboten in de Waddenzee is? Denkt u dat passagiers van de veerdiensten eventueel bereid zijn om meer te betalen?

- *Er is zeker een grote vraag, we zijn daarom ook overgestapt naar een nieuwe brandstof om de vervuiling te beperken. Ook zijn we bezig met het reduceren van plastic aan boord om aan de maatschappelijke vraag te voldoen.*

- *Passagiers willen in principe niet meer betalen. Hoewel blijkt uit het CO2 compensatiefonds wat WPD nu heeft dat er wel passagiers zijn die dit belangrijk vinden en bereid zijn hiervoor te betalen.*

10. Sneldiensten: Er is een trend in het Waddengebied dat er naast de normale veerdiensten ook meer gebruik wordt gemaakt van sneldiensten, welke relatief veel brandstof verbruiken. Denkt u dat de ontwikkeling van duurzame veerboten samen kan gaan met deze ontwikkeling?

- *Door de 'normale' schepen lichter te maken, kunnen we de oversteektijd verkorten en is een sneldienst niet meer nodig.*

Politieke haalbaarheid

11. Concessiesysteem: Geeft dit systeem kansen voor het ontwikkelen van emissie loos varen of juist beperkingen?

- *Beperkingen, ik ben voorstander van een liberaal systeem: laat het aan de markt. Door dit systeem worden wij niet betrokken bij hele belangrijke zaken zoals de langetermijnvisie.*

- *Het concessiesysteem staat los van de vlootontwikkeling. In dit systeem zouden wij kunnen zeggen, we varen de schepen op en doen niet mee met de nieuwe concessie, de ontwikkeling van nieuwe schepen duurt 5 jaar, dit zou betekenen dat de eilanden 5 jaar lang een enorm* *probleem hebben. Wij gaan dus zeker niet wachten op een nieuwe concessie maar gaan eerder nieuwe schepen ontwikkelen.*

- *We hebben in de afgelopen 100 jaar altijd bovenwettelijk gewerkt, wij willen verder gaan dan de eisen, kijk bijvoorbeeld naar de milieuprijs die we hebben gekregen voor de Sier en de Oerd.*

12. Denkt u dat emissieloos varen of verminderen van emissies een eis kan worden vanuit de concessieverlener?

- *Wij willen de nieuwe schepen operationeel hebben voor er een nieuwe concessie komt. De concessie is dus voor ons van minder belang, wij stellen over het algemeen strengere eisen aan onszelf dan van ons gevraagd wordt van een concessieverlener. De gebiedsagenda 2050 en langetermijnplanning zijn van groter belang.*

13. Heeft u verder nog aanvullingen die nog niet besproken zijn in dit interview?

- *Vrachtvervoer en personenvervoer moet je niet willen scheiden, hier zijn nog meer schepen voor nodig, dus kapitaalintensiever. Er zijn meer bewegingen, wat in de smalle geulen tot problemen leidt en dit ook gevaarlijker maakt. Zeker als er op termijn op het tij gevaren moet worden, dan heb je nog meer bewegingen in minder tijd.*
- *Wij willen graag op termijn meer onderzoek doen samen met de TU Delft om meer ontwikkelingen te onderzoeken, juist ook om breder te kijken en nieuwe input te krijgen.*

Interview 4

Naam: Rick Timmerman
Functie: Proces- en projectmanager
Organisatie: Programma naar een Rijke Waddenzee/Rijkswaterstaat
Datum: 20-11-2019, Leeuwarden

Algemene vragen

1. Kunt u iets meer over uzelf en uw rol bij uw organisatie vertellen?

- *In dienst bij RWS, en sinds 1 maart 'uitgeleend' aan PRW. PRW is een tijdelijke programmaorganisatie met als doel om de Waddenzee rijker te maken voor natuur én mens. Wij doen integrale projecten waar de afzonderlijke moederorganisaties niet aan toe komen of niet van zijn. Deze hebben vaak een groot maatschappelijk belang, vaak niet één duidelijke verantwoordelijke, zijn vaak gericht op innovaties of transities innovatief en hebben de horizon vaak verder weg liggen.*

2. Is het voor uw organisatie een doelstelling om volledig emissieloze veerboten te realiseren in het Waddengebied?

- *In ieder geval wel een ambitie; een ultiem duurzame mobiliteit in het waddengebied. Wij kijken naar de langere termijn, zeg 2050. Het besef is er zeker dat de veerboten door een UNESCO werelderfgoed varen. Ook bij RWS zijn we hier mee bezig, deze heeft als doelstelling om in 2030 emissieloze netwerken te hebben.*
- *Wij zijn naast alleen de veerboten vooral ook aan het kijken naar het hele systeem. Bijvoorbeeld de waterwegen in stand houden met baggeren. Wij willen niet dat de veerboten wel emmisie vrij zijn, maar er constant een baggerboot nodig is die niet emissievrij is.*
- *Vorig jaar hebben we een 'hackaton' gehouden, 3 dagen lang met 30 mensen in een loods op Terschelling. Doelstelling was hiervan om na te denken over nieuwe systemen die mogelijk zijn bij weinig water en niet baggeren (in 2050). Voor het bereiken van een duurzame mobiliteit wordt nu ingezet op 2 strategieen. Een eerste (voor de korte en middellange termijn) is doorgaan met het verder verduurzamen van het huidige systeem. Een 2e strategie voor de echt lange termijn is is het verkennen van een transitie naar een ultiem duurzaam mobiliteitssysteem, met zo min mogelijk ingrijpen door de mens (bijv. Baggeren). Voor het ontwerpen van een dergelijk transitieproces zijn we o.a. bezig met transitiebureau's.*

3. Denkt u dat de Waddenzee een geschikt gebied is voor emissieloze veerboten?

- *In de Waddenzee is de (door eb en vloed veranderende) diepgang van cruciaal belang. Het volume van de huidige veren is mogelijk niet houdbaar (te zwaar en te diep). Vooral het oostelijk Waddengebied is hierin beperkt en mogelijk moeten de veerboten kleinschaliger om met minder diepgang te kunnen blijven varen.*

- *Voorbeeld is de Seabubble, een frans ontwerp van een 'pod' met drie draagvleugelprofielen, die vrijwel geen diepgang nodig heeft en volledig elektrisch vaart met een capaciteit van enkele personen.*

4. Wie zijn volgens u de belangrijkste belanghebbenden die de keuze bepalen over duurzaamheidseisen aan nieuwe veerboten?

- *De uiteindelijke wensen/eisen m.b.t. de duurzaamheid van nieuwe veerboten zullen door beleidsmakers moeten worden geformuleerd en zullen uiteindelijk opgenomen kunnen worden in de concessie die in 2029 opnieuw verleent gaat worden. M.b.t. beleidsvorming wordt momenteel de Agenda voor de Wadden (opvolger van de Structuurvisie Wadden) opgesteld, waarin voor diverse thema's richtingen worden geformuleerd over waar het naar toe moet in de wadden richting 2050. Duurzame mobiliteit is een van de onderwerpen.De input hiervoor komt ook vanuit inwoners, ondernemers, toeristen etc. De concessie is een draaiknop om het beleid waar te maken.*

5. Wat zijn volgens u de belangrijkste (ontwerp)eisen voor veerboten in de Waddenzee?

- *Door de bepertke diepgang kom je al snel aan scheepsbouwtechnische eisen als gewicht, voortstuwing- en rompoptimalisatie. Met emissie loze voortstuwing. Richtinggevend voor de dimensies van de vaartuigen begint natuurlijk bij de vraag naar mobiliteit (wat moet er wanneer naar de andere kant en waarom)), en de keuzes die daarin te maken zijn (wel/geen auto's naar overkant, etc).*

Technische haalbaarheid

6. Is er een van technieken die uw voorkeur heeft? Zijn er technieken die u niet of zeer moeilijk haalbaar acht?

- *Geen voorkeur voor welke techniek dan ook, mits duurzaam/emissieloos. Voor batterijen en waterstof zijn de toepassingen duidelijk en is ook wat meer ervaring.*

7. Voor de optie batterijen: deze hebben een laadstation nodig in minimaal één haven inclusief versterkingen van het elektriciteitsnet. Denkt u dat dit haalbaar is (op de waddeneilanden)?

- *Als Noord Nederland zich wil profileren als voorloper op het gebied van waterstof en andere groene innovaties zal hier zeker steun voor zijn. Als de laadstations groots en meeslepend moeten zijn, lijkt me dat persoonlijk op de eilanden minder wenselijk en maatschappelijk lastiger (visueel niet passend bij werelderfgoed, hoe krijg je de energie die nodig is voor het opladen naar een eiland (aparte infra?), ect?*

8. Is langer in de haven liggen om batterijen op te laden een mogelijkheid?

- *Met de huidige concessie en dienstregeling niet. Dat op de eilanden 's nachts minimaal één boot ligt kan het lastiger maken voor infrastructuur. Maar dit moeten oplossingen voor de toekomst niet in de weg staan. Het huidige systeem hoeft/moet een toekomstig (beter) systeem dat de bereikbaarheid garandeert niet in de weg te staan.*

9. Theoretisch kunnen alle vier de alternatieven lokaal worden opgewekt (benodigheden zijn groene stroom, water en eventueel lucht (stikstof/co2). Ziet u dit als wenselijk en indien dit zo is, als haalbaar?

- *Niet zozeer lokaal, maar regionaal (Noord Nederland) past het heel goed.*

Economische haalbaarheid

10. Indien uit onderzoek blijkt dat het niet rendabel is om volledig emissieloze veerboten te gebruiken, denkt u dat er dan subsidiemogelijkheden bestaan?

- *Ik zit niet zo in de subsidiewereld. Ik vind/denk wel dat , als de gemeenschap een uitdrukkelijke wens heeft voor duurzame mobiliteit in de wadden, er ook ook een financieel verhaal bij hoort. Als de business case van een reder (een eerste periode) dan niet dekkend kan zijn, kunnen andere betrokkenen (financieel) helpen om de wens te vervullen.*

Sociale haalbaarheid

11. Denkt u dat er onder het groter publiek een vraag naar volledig duurzame veerboten in de Waddenzee is? Denkt u dat passagiers van de veerdiensten eventueel bereid zijn om meer te betalen?

- *De meeste bezoekers van de eilanden waarderen de natuur erg. De optie bij rederij Doeksen om ter compensatie van de CO2-uitstoor 0,50 eurocent meer te betalen, wordt veel gebruikt, wat dit beeld ook bevestigd. Ook een bredere maatschappelijke beweging richting duurzaamheid is groeiende. De reders zijn zich ook bewust van gebied waarin ze varen, en zijn volop met verduurzaming bezig.*

12. Sneldiensten: Er is een trend in het Waddengebied dat er naast de normale veerdiensten ook meer gebruik wordt gemaakt van sneldiensten, welke relatief veel brandstof verbruiken. Denkt u dat de ontwikkeling van duurzame veerboten samen kan gaan met deze ontwikkeling?

- *Ook voor de snellere veerverbindingen geldt de uitdaging/ambitie om duurzaam te worden. Juist innovatieve ideeën kunnen hierin een oplossing zijn. Een duurzame oplossing hoeft niet langzaam te zijn. Zie bijvoorbeeld de Sea Bubble.*

Politieke haalbaarheid

13. Concessiesysteem: Geeft dit systeem kansen voor het ontwikkelen van emissieloos varen of juist beperkingen?

- *Kansen. Je kan het zien als een draaiknop waarmee sturing gegeven kan worden. De volgende concessie (2029) is hierbij interessanter dan de huidige omdat deze openbaar wordt aanbesteed in tegenstelling tot de huidige die onderhands is aanbesteed. Duurzaamheid zal zeker een item gaan worden. De pakweg 5 jaar ervoor zullen deze eisen langzaam duidelijk worden en kunnen reders ook nadenken over hun ontwerpen.*

14. Denkt u dat emissieloos varen of verminderen van emissies een eis kan worden vanuit de concessieverlener?

- *Wat we wel/niet willen wordt uiteindelijk in beleid vervat. Hangt mede af van welke ambities/doelstelling de samenleving en overheid heeft, ook om te voldoen aan internationale afspraken die daarover zin gemaakt. Wat meespeelt is de enorme zichtbaarheid van de veerboten.*

15. Heeft u verder nog aanvullingen die nog niet besproken zijn in dit interview?

- *Goed dat er naar het brede geheel gekeken wordt. Het is niet alleen technisch, maar bijvoorbeeld ook sociaal en gaat over de leefbaarheid van de eilanden. De demografie van de eilanden zal ook erg mee gaan spelen.*
- *Wij vinden de visuele impact van vooral land installaties belangrijk.*

Interview 5

Naam: Bernard Baerends
Functie: Executive Secretary, head of the secretariat
Organisatie: Common Wadden Sea Secretariat
Datum: 22-12-2019, Groningen

Algemene vragen

1. Kunt u iets meer over uzelf en uw rol bij uw organisatie vertellen?

- *De drie waddenzee landen werken al meer dan 40 jaar samen op het gebied van bescherming en duurzame ontwikkeling. Ter ondersteuning van de besluiten die zijn genomen tussen de drie landen is het secretariaat opgericht. Sinds half september 2019 ben ik daar uitvoerende secretaris van dit secretariaat. Hiervoor zat ik bij het ministerie van LNV. Hier hield ik me ook al bezig met de trilaterale samenwerking, het ministerie van LNV is het verantwoordelijke ministerie voor de trilaterale samenwerking vanuit Nederland.*

2. Is het voor uw organisatie een doelstelling om volledig emissieloze veerboten te realiseren in het Waddengebied

- *De drie landen hebben in 2010 afgesproken om tot een CO2 neutrale regio te komen in 2030. Dit liep ver vooruit op het klimaatakkoord van Parijs. In die zin past duurzaam transport in de Waddenzee zeker in het streven. Dus emissie neutrale veerboten is geen expliciete doelstelling, maar past wel in de bredere doelstellingen van een duurzame regio.*

3. Wat is volgens u de belangrijkste motivatie om te verduurzamen of volledig emissieloos te varen? Wat bepaalt hierin het tempo?

- *Verschillend lijnen: de politieke lijn zegt dat de Waddenzee een regio moet zijn die voorop loopt op het gebied van duurzaamheid*
- *Het past ook goed in het concept van het werelderfgoed en duurzaam toerisme.*

4. Denkt u dat de Waddenzee een geschikt gebied is voor emissieloze veerboten?

- *Nationale overheden willen graag regionaal stimuleren*
- *Interessant is dat Hamburg ook onderdeel is van de Waddenzee.*

5. Wie zijn volgens u de belangrijkste belanghebbenden die de keuze bepalen over duurzaamheidseisen aan nieuwe veerboten?

- *Formeel de concessieverleners. Uiteindelijk de gemeenschappen en maatschappij*
- *Een duurzame veerboot helpt om een regio te profileren als voorloper op het gebied van duurzaamheid*

- *Interessant: in Duitsland zijn de rederijen 'partners' in de nationaal parken. Dit zorgt ervoor dat ze duidelijk maken dat ze onderdeel zijn van het gebied.*

Technische haalbaarheid

6. Is er een van technieken die uw voorkeur heeft? Zijn er technieken die u niet of zeer moeilijk haalbaar acht?

- *Noord-Nederland wil zich profileren als voorloper op waterstof.*
- *We kijken in de Waddenzee erg naar vervuiling. Risico op milieurampen, maar ook landschapvervuiling en extra transport nodig voor aanvoer van de brandstoffen*

7. Theoretisch kunnen alle vier de alternatieven lokaal worden opgewekt (benodigheden zijn groene stroom, water en eventueel lucht (stikstof/CO2). Ziet u dit als wenselijk en indien dit zo is, als haalbaar?

- *Wenselijk wel, maar je zit wel met de inpasbaarheid. Er zou gepraat kunnen worden met de eilanden.*
- *Het is wenselijk als de eilanden onderling samenwerken en afstemmen op het gebied van deze ontwikkelingen*
- *Pilots van getijdenstroom kunnen botsen met de waarden van de waddenzee en is misschien niet wenselijk. Als het bewezen is en geen schade geeft is er waarschijnlijk meer draagkracht*

Economische haalbaarheid

8. Hoe kijkt u tegen de business case van emissieloze veerboten aan?

- *Omdat het onderdeel uitmaakt van een groter geheel, verantwoord duurzaam werelderfgoed toerisme, is de business case van alleen de veerboot eigenlijk minder belangrijk dan de business case van het grote concept. Dus samen met de eilanden en samen met de regio bekijken en niet geïsoleerd*

Sociale haalbaarheid

9. Denkt u dat er onder het groter publiek een vraag naar volledig duurzame veerboten in de Waddenzee is? Denkt u dat passagiers van de veerdiensten eventueel bereid zijn om meer te betalen?

- *De trilaterale waddenzee is één van de best bestudeerde en een van de best beschermde wetlands ter wereld. Wij willen laten zien waarom dit gebied zo bijzonder is. Het grote publiek ziet dit ook in, maar het is niet zo duidelijk als bijvoorbeeld andere UNESCO gebieden als de Grand Canyon. Uitleggen waarom dit gebied zo bijzonder is zou samen kunnen gaan met duurzame veerboten.*
- *Dit begint al bij de boeking van de boot. Het totale plaatje moet hierin kloppen.*

10. Sneldiensten: Er is een trend in het Waddengebied dat er naast de normale veerdiensten ook meer gebruik wordt gemaakt van sneldiensten, welke relatief veel brandstof verbruiken. Denkt u dat de ontwikkeling van duurzame veerboten samen kan gaan met deze ontwikkeling?

- *Los van de snelheid van de boten, het gaat vooral over mentaliteit en de beleving van de wadden.*
- *Er zouden eerst ook powerboat races gehouden worden in de waddenzee, dit staat haaks op de waarden van de waddenzee. Het past niet in het het grotere concept van de waddenzee. Deze gedachtegang zou ook voor watertaxi's en snelboten kunnen gelden. Een publiek bewustzijn dat dit niet de duurzaamste manier is en samenwerkingen met partners om zo tot gemeenschappelijke overeenkomsten komen kunnen er dan toe leiden dat dit soort ontwikkelingen wordt tegen gegaan.*

Politieke haalbaarheid

11. Concessiesysteem: Geeft dit systeem kansen voor het ontwikkelen van emissieloos varen of juist beperkingen

- *Kansen. Je kan hierbij met elkaar afspreken wat je doelen zijn voor de waddenzee en in deze lijn de concessies invullen*

12. Denkt u dat emissieloos varen of verminderen van emissies een eis kan worden vanuit de concessieverlener?

- *Gezien de maatschappelijke ontwikkelingen en politieke draagvlak en het bewustzijn van dat er goed op het waddengebied gepast moet worden lijkt het dat er een meerstap gezet gaat worden in de volgende concessie.*
- *Vanuit de trilaterale samenwerking: reders kunnen elkaar hierin inspireren.*

13. Heeft u verder nog aanvullingen die nog niet besproken zijn in dit interview?

- *Voor de UNESCO status is uitgegaan van bestaande regelgeving. Het proces hiervoor heeft 20 jaar geduurd. De laatste 5 jaar van het nominatieproces was er weerstand, omdat er al veel stempels op het gebied lagen. Er was angst voor beperkingen. Er is hierna vastgelegd dat er geen additionele regelgeving zou komen door de aanwijzing als UNESCO werelderfgoed. De laatste jaren is er een kentering en worden de kansen en het onderscheidende van de aanwijzing meer gezien en benut. Er wordt meer gekeken naar meer exclusief, duurzaam toerisme. Het totaalplaatje moet dan kloppen en duurzame veerboten zouden hier heel goed in passen. De integratie van duurzame systemen (elektrische bus/trein op duurzame veerboot naar bijvoorbeeld elektrische auto) is hierin van belang en de schakel van een duurzame veerboot mag dan niet missen.*
- *De Nedersaksische eilanden lijken erg op de Nederlandse Waddeneilanden. Bij Hamburg heb je minder eilanden. Naar het noorden heb je ook andere manieren om naar de eilanden te gaan, zoals trekkers en treintjes en dergelijke.*
- *Voor Nederland en Duitsland is de Waddenzee unieker dan voor Denemarken, waar de Waddenzee slechts zo'n 3% van hun kustlijn is.*

Interview 6

Naam: Cees de Waal
Functie: Directeur
Organisatie: TESO
Datum: 06-12-2019, Den Helder

Algemene vragen

1. <u>Kunt u iets meer over uzelf en uw rol bij uw organisatie vertellen?</u>

- *Cees de Waal, geboren en getogen Texelaar. Vanaf 17e wereld over geweest en verschillende banen gehad. Sinds 2008 directeur van TESO en weer woonachtig op Texel.*
- *TESO heeft geen winstoogmerk. Als wij winst maken stoppen we dit in een verbetering van onze vervoersprestatie en/of het verlagen van de prijs van het bootkaartje.*
- *TESO is eigendom van ruim 3.100 aandeelhouders die voornamelijk op het eiland wonen*
- *Driekwart van de personen die wij vervoeren zijn mensen die niet op Texel woonachtig zijn.*

2. <u>Is het voor uw organisatie een doelstelling om volledig emissieloze veerboten te realiseren in het Waddengebied?</u>

- *Toen ik directeur werd waren er drie kernwaarden voor TESO:*
  - *Veiligheid*
  - *Continuïteit*
  - *Kwaliteit*
- *Hier hebben we aan toegevoegd:*
  - *Betaalbaarheid voor reiziger*
  - *Duurzaamheid*
- *Betaalbaarheid is tot op heden goed gelukt. We hebben de prijs voor een retour passagierskaartje een paar geleden van 3 euro naar 2,50 gebracht. We willen dan ook stimuleren dat mensen uit de auto stappen, met het OV naar Den Helder reizen en een aantrekkelijk geprijsd voetgangerskaartje kopen. Het OV kan helaas nog niet goed concurreren met de auto voor het reizen van en naar Texel, qua prijs (relatief duur, zeker in geval van een groepsomvang van vier personen) en de reistijden zijn nog niet goed genoeg.*
- *Samen met C-Job hebben we de Texelstroom ontwikkeld. Deze heeft onder andere de Shippax award 2016 gewonnen. Duurzaamheid was hierin voor TESO een belangrijke eis, wat heeft geresulteerd in een aantal innovaties zoals de CNG installatie waar nog geen wet en regelgeving voor was. TESO heeft hier haar nek uitgestoken in de overtuiging dat dit op een veilige, verantwoorde en milieuvriendelijke wijze toegepast zou kunnen worden. Door te investeren in reductie van het energieverbruik en in duurzame alternatieven wordt je minder afhankelijk, dan het geval is indien je één type fossiele brandstof gebruikt en daardoor wordt je minder gevoelig voor prijsstijgingen van fossiele brandstoffen.*
- *Kortom: We willen voor de volgende boot zeker emissie vrij varen en hopen dat dan te kunnen*

doen op basis van 100% groene stroom. Wet en regelgeving kan nog wel een probleem worden, maar het nieuwe schip komt pas in de vaart in 2031 en tegen die tijd hopen wij dat de techniek al erg ver doorontwikkeld is en wet- en regelgeving voorhanden is. Onze ambitie is dat we de beste veerdienst ter wereld willen zijn op basis van onze 5 kernwaarden, waaronder dus duurzaamheid.

3. Wat is volgens u de belangrijkste motivatie om te verduurzamen of volledig emissieloos te varen? Wat bepaalt hierin het tempo?

- *Investeren in duurzaamheid is noodzakelijk voor de continuïteit van elke organisatie. Een organisatie die hier niet serieus werk van maakt is m.i. op termijn niet levensvatbaar.*
- *Dit inzicht komt gelukkig bij steeds meer bedrijven, maar sommige bedrijven zullen te laat of niet flexibel genoeg zijn om te kunnen ombuigen.*
- *We bestaan nu 112 jaar. We willen over 200 jaar nog als eigen veerdienst van Texel bestaan en kijken dus echt op de lange termijn.*

4. Denkt u dat de Waddenzee een geschikt gebied is voor emissieloze veerboten?

- *Ik denk dat alle korte routes met vaste havens op termijn geschikt zijn voor zero emission.*
- *Waddenveren zijn volgens de regelgeving binnenvaart. We hebben ruim 20 jaar geleden wel op initiatief van de Zoute Veren reders een initiatief ontplooit dat heeft geresulteerd in een bijlage in de regelgeving gezet met extra eisen voor compartimenten, vrijboord en andere scheepsbouwkundige zaken. Dit omdat we geen concessies willen doen aan veiligheid, dat is onze belangrijkste kernwaarde.*

5. Wie zijn volgens u de belangrijkste belanghebbenden die de keuze bepalen over duurzaamheidseisen aan nieuwe veerboten?

- *Primair de rederijen. De drijfveren van de rederijen is het belangrijkste. Anders zullen ze zich 'slechts' conformeren aan de eisen die van overheidswege worden gesteld. Als partijen in de omgeving het niet snel genoeg vinden gaan kunnen deze ook druk uitoefenen.*

6. Wat zijn volgens u de belangrijkste (ontwerp)eisen voor veerboten in de Waddenzee?

- *Voor TESO: kunnen blijven varen binnen een uurdienst, dus heen en weer binnen een uur. Telkens 10 minuten laden/lossen, 20 minuten varen. Redundancy is voor ons belangrijk omdat we normaal met één schip varen. Het schip is zo ingericht dat het door kan varen in geval van een single failure. We moeten tijdens de vaart een machine kunnen repareren.*

Technische haalbaarheid

7. Naar aanleiding van de vier getoonde alternatieven, ziet u al deze vier als mogelijkheden voor emissieloos varen? Zijn er nog alternatieven die u meeneemt welke niet getoond zijn?

- *Er is nog een manier van waterstof opslag: natriumboor hybride in combinatie met ultrapuur water. We kijken ook naar deze ontwikkelingen, ondanks dat ze nog in de kinderschoenen staan.*
- *Op Texel zou een bio(gras)vergister kunnen staan, dit zou kunnen via biomassa van het eiland kunnen.*
- *Wij kijken naar de hele keten. We willen dan ook geen grijze stroom gebruiken voor onze energie.*

8. Voor de optie batterijen: deze hebben een laadstation nodig in minimaal één haven inclusief versterkingen van het elektriciteitsnet. Denkt u dat dit haalbaar is (op de waddeneilanden)?

- *Het lokale netwerk is er nu niet klaar voor. We hebben een dochterbedrijf van Aliander om een ontwerpvoorstel gevraagd van eventuele aanpassingen in combinatie met een lokaal grid zodat deze het wel aan zou kunnen.*

9. Theoretisch kunnen alle vier de alternatieven lokaal worden opgewekt (benodigheden zijn groene stroom, water en eventueel lucht (stikstof/co2). Ziet u dit als wenselijk en indien dit zo is, als haalbaar?

- *We gebruiken momenteel zonnepanelen voor lokale energieopwekking. We kijken ook naar getijdenstroom. Persoonlijk is mijn mening voor windmolens: niet in mooie natuurgebieden plaatsen, maar eerst zoveel mogelijk in industriegebieden.*

Economische haalbaarheid

10. Hoe kijkt u tegen de business case van emissieloze veerboten aan?

- *We weten niet wat diesel of gas kost over een aantal jaar ook de prijs van alternatieve technieken en de betrouwbaarheid van dergelijke technieken en de leverbaarheid van alternatieve brandstoffen zijn nog onzeker. Het is dus niet een doorzichtig verhaal. Uitgangspunt voor TESO is dat we in beginsel willen laten zien dat je kunt verduurzamen zonder dat daar subsidie voor nodig is, terwijl de betaalbaarheid van de boottickets gehandhaafd kan blijven.*

Sociale haalbaarheid

11. Sneldiensten: Er is een trend in het Waddengebied dat er naast de normale veerdiensten ook meer gebruik wordt gemaakt van sneldiensten, welke relatief veel brandstof verbruiken. Denkt u dat de ontwikkeling van duurzame veerboten samen kan gaan met deze ontwikkeling?

- *Door de frequentie van afvaarten en relatief korte afstand is dit voor Texel niet aan de orde. We hebben gekeken naar een apart schip voor de ongeveer 150 nachtelijke ambulance afvaarten die we per jaar hebben. Maar dat bleek in meerdere opzichten suboptimaal, niet in de laatste plaats voor de kwaliteit van het ziekenvervoer.*

Politieke haalbaarheid

12. Concessiesysteem: Geeft dit systeem kansen voor het ontwikkelen van emissieloos varen of juist beperkingen?

- *TESO heeft geen concessie, maar we willen de beste veerdienst zijn en kijken dus wel naar de inhoud van de concessies en hanteren zaken hierin als een soort van ondergrens.*
- *We zijn blij met de unieke positie zonder concessie op basis van het vertrouwen dat we van de overheid hebben gekregen, dat wij "voor onze reizigers een betere uitkomst opleveren dan de overheid via een systeem van aanbesteden zou kunnen organiseren".*

13. Heeft u verder nog aanvullingen die nog niet besproken zijn in dit interview?

- *Het echte laagseizoen bestaat eigenlijk niet meer. Dit is goed voor Texel (geen seizoenswerkeloosheid meer), maar vormt in toenemende mate een uitdaging voor het onderhoud van de schepen dat traditioneel in het laagseizoen wordt uitgevoerd.*
- *Regelgeving voor land is vaak totaal anders dan regelgeving voor (Wadden)zee, terwijl het dezelfde technische toepassing betreft. Dit hebben we ondervonden bij de installatie van het CNG vulstation. Er was al veel ervaring met laadstations op het land en het gebruik van CNG in bijvoorbeeld stadsbussen, maar dit had slechts beperkt voordeel voor de ontwikkeling van het systeem voor de Texelstroom.*
- *We hebben de Schulpengat laten slopen in Gent, bij een van de duurzaamste sloperijen ter wereld. Dit kostte ons weliswaar geld, maar wij willen als maatschappelijke onderneming graag onze verantwoordelijkheid nemen en dus niet naar een minder duurzaam bedrijf of zoals nog steeds veel gebeurd: een sloopstrand in Azië.*