Masteroppgave

NTNU
Norges teknisk-naturvitenskapelige universitet
Fakultet for ingeniørvitenskap
Institutt for energi- og prosessteknikk

Maria Kristine Saksvik Munkvold

Comparative Life Cycle Assessment of a hydrogen fuel cell and diesel-powered high-speed passenger catamaran

Masteroppgave i Energi og Miljø
Veileder: Anders Hammer Strømman

Juni 2020

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The maritime sector is working to reduce its GHG and other emissions. If measures are not taken, it is expected that global CO2 emissions from the maritime sector will continue to grow strongly and could be as much as 2.5 times higher by 2050. Different technologies are being explored in order to facilitate the desired reduction. Commonly discussed options include ammonia, biofuels and hydrogen. Lessons from life cycle assessments of different options in the land transport sector has demonstrated the importance of the inclusion of all life cycle stages to ensure consistent and robust comparisons of alternatives for reducing emissions. High speed passenger ferries can have a cruise speed between 25 and 45 knots, i.e. up to 83 kilometers an hour. Hydrogen fuels cells have been identified as a contender for powering such vessels, as they could indeed provide power enough for the vessel to cruise at such high speeds, whilst typically carrying 100 to 300 passengers. Fuel cells have lower operational emissions than the usual combustion engines. Hydrogen fuel cells emit only water, avoiding direct emissions of CO2 and related air. However upstream emissions need to be considered, from production to distribution and storage to dispensing systems and fuel cells.

Main objective of the thesis is assessing the comparative life cycle environmental footprint of a hydrogen fuel cell powered high speed passenger catamaran, versus a conventional diesel powered one.

Key tasks include:

1) Collection of data vessel characteristics and fuel cells.
2) Development of an LCI model for a high-speed passenger catamaran.
3) Integrated assessment applying the LCA, with a comparative analysis of the results.

Supervisor

Anders Hammer Strømman

Co-supervisors

Helene Muri, Lorenzo Usai.

The student will have licensed access to the following for the duration of the work:

i) the LCA software ARDA including the Ecoinvent database for the duration of the thesis work.

The student has no right to further use or distribution of this software and data.
Upon completion of the work, the software and data must be uninstalled from the computer used.

Abstract

Big cuts are necessary to overcome expected growth in the shipping industry. The CO_2 emissions from this sector could be as much as 2.5 times higher by 2050 if measures are not taken(Smith et al. 2015). Different technologies have been explored to facilitate the desired reduction. One of the options being discussed is hydrogen. Hydrogen Fuel cells(FC) have been identified as a contender for powering high speed passenger ferries, as they can provide power enough for the vessels to cruise at the required high speeds. FCs have lower operational emissions than usual combustion engines. However upstream emissions need to be considered.

This thesis presents a comparative Life Cycle Assessment(LCA) of a hydrogen fuel cell(FC) and diesel-powered high speed passenger catamaran. LCA is a method to assess environmental impacts associated with all the stages of a product's life from raw material extraction, through the processing of the material, the distribution, transport, and manufacture, use, disposal, or recycling of the product. The whole chain. The two boats that are compared are both carbon fiber sandwich catamarans. The model of the diesel boat is based on MS Terningen and MS Tyrhaug, these boats operate the route from Trondheim to Kristiansund. The hydrogen FC boat is based upon a case study, where the boat Aero42H2, a battery and hydrogen powered fast ferry, was dimensioned to operate the same route.

This thesis quantifies the comparative life cycle environmental footprint of a hydrogen FC powered high speed passenger catamaran, versus a conventional diesel powered one. Processes accounted for are the production phase; Hull production, interior, and exterior; paint, windows, seating, electronics. Production of FC, batteries, and engines, and also Hydrogen storage in terms of a Hydrogen tank. In addition direct- and- indirect emissions in terms of use phase are included with the combustion and production of Diesel, and production of Hydrogen by electrolysis. End of life is omitted in this study. Furthermore, a sensitivity analysis in terms of the electricity for Hydrogen production, the lifetime of FCs, batteries, and Engines and of Engine efficiency/fuel use has been conducted.

This thesis reveals that in terms of a Norwegian setting with Norwegian electricity mix, the Hydrogen FC HSC beats the Conventional Diesel HSC, with the total emissions of 657 kg CO2-eq/crossing compared to the Conventional Diesel HSC which emits 5396 kg CO2-eq/crossing. However, For the upstream emissions, the Hydrogen FC HSC has the largest emissions (50 kg CO2-eq/crossing) this is due to the hydrogen tank and the production of

battery and FCs. In the end, to reduce impacts for the Hydrogen FC HSC, the production and storage of Hydrogen are still the most pressing issues, for the Conventional Diesel HSC, the nerve is impacts associated with fossil fuel extraction and production. For both catamarans, the Carbon sandwich hull showed big emissions in the production phase, here a consideration of the material used could be examined.

Sammendrag

Store utslipps kutt er nødvendig for å overvinne forventet vekst i skipsfartsindustrien. CO_2-utslippene fra denne sektoren kan være så mye som 2,5 ganger høyere innen 2050 hvis ikke tiltak blir satt igang (Smith et al. 2015). Ulike teknologier har blitt utforsket for å oppnå ønsket reduksjon. Et av alternativene som blir diskutert er Hydrogen. Hydrogen brenselceller er blitt identifisert som en utfordrer for å drive hurtigbåter, da de kan gi kraft nok til at fartøyene kan kjøre med de nødvendige høye hastighetene. Brenselceller har lavere driftsutslipp enn vanlig forbrenningsmotor. Imidlertid må oppstrøms utslipp vurderes.

Denne Masteroppgaven er en sammenlignende livsløps analyse av en Hydrogen Brenselcelle- og en dieseldrevet høyhastighets passasjer katamaran.

De to båtene som blir sammenlignet er begge karbonfiber sandwich-katamaraner. Modellen av dieselbåten er basert på MS Terningen og MS Tyrhaug, disse båtene drifter ruten fra Trondheim til Kristiansund. Hydrogen-båten er basert på en casestudie, der båten Aero42H2 ble dimensjonert for å drifte samme rute.

LCA er en metode for å vurdere miljøpåvirkninger forbundet med alle faser i et produkts levetid. Fra utvinning av råvarer, gjennom prosessering av materialet, distribusjon, transport og produksjon, bruk, avhending eller gjenvinning av produktet. Hele kjeden.

Denne Masteroppgaven kvantifiserer det sammenlignende LCA fotavtrykket til en hydrogenbrenselcelle-drevet høyhastighets passasjer katamaran, kontra en konvensjonell dieseldrevet en. Prosesser som er moddelert er produksjonsfasen; Produksjon av skrog, interiør og eksteriør; maling, vinduer, sitteplasser, elektronikk. Produksjon av brenselceller, batterier og motorer, samt Hydrogen lagring i form av Hydrogen-tank. I tillegg inngår direkte- og indirekte utslipp i form av bruksfase med forbrenning og produksjon av Diesel, og produksjon av Hydrogen ved elektrolyse. End-of-life er utelatt i denne studien. Videre er det utført en sensitivitetsanalyse av elektrisitet til Hydrogen produksjon, levetid på brenselceller, batterier og motorer og motoreffektivitet / drivstofforbruk.

Denne Masteroppgaven avslører at når det kommer til en norsk setting med norsk elektrisitetsmiks, slår Hydrogen brenselcelle hurtigbåten den konvensjonelle Diesel hurtigbåten. Hydrogenbåten har totalt utslipp på 657 kg CO2-ekv./Kryssing til sammenligning med den konvensjonelle Diesel Hurtigbåten som avgir 5396 kg CO2-ekv. /kryssing. For oppstrøms utslipp har imidler-

tid Hydrogen Brenselcelle Hurtigbåten størst utslipp (50 kg CO2-ekvivalent / kryssing) dette skyldes hydrogentanken samt produksjonen av batteri og brenselceller.

Til slutt viser det seg at fokusområder for å redusere miljøpåvirkningene for Hydrogen hurtigbåten er å se på produksjon og lagring av Hydrogen. For den konvensjonelle diesel Hurtigbåten burde man fokusere på områder forbundet med utvinning og produksjon av fossilt brensel for å redusere utslipp. For begge båtene viser Carbon sandwich skroget store utslipp i produskjonsfase, her kan det gjøres en vurdering i form av materialbruk.

Acknowledgement

This master's thesis is the culmination of my years at the Master's program Energy and Environmental Engineering at the Norwegian University of Science and Technology (NTNU). The report is the result of the work done in the course TEP4935 - Energy Planning and Environmental Analysis Master's Thesis, spring semester 2020.

My motivation for starting my degree at NTNU was the wish to be able to contribute to solve or be a part of solving environmental problems. I have always felt the urge to do more when learning and hearing about climate change, sustainability, and the famous ”føre-var prinsippet”, or The precautionary principle in English. And it is a constant eye-opener to learn that we in 2020, still have not solved a lot of the problems I strongly had an interest in as a kid!

I want to thank my supervisor Anders Hammer Strømman, and my co-supervisors Helene Muri and Lorenzo Usai for great guidance both through my project thesis during the autumn 2019 and for my master thesis. Thank you for believing in me and trusting me with this extremely interesting topic.

Thank you for helping me in the right direction when I have used to much time on specific details, that I have found interesting, but have not had that great importance for the big picture. For giving me motivation and specific literature that I have enjoyed going through. Working with you and being a part of the work you do at Industrial Ecology has been a great inspiration, and I have really enjoyed getting a glimpse of what is happening in the field. I really believe that what you do is of great importance!

This spring has been interesting not just in light of the sudden pandemic and the need for another work structure due to the home office, and the need for electronic guidance sessions. I have also enjoyed working on a bigger scale with my masters. To be allowed to go more into detail and to get educated on such a topic as a master's thesis do, I have appreciated it.

Although the home office has at times been a challenge; Dealing with roommates, bad internet access, and completing the Life cycle assessment(LCA) through Microsoft-remote desktop, which has been a hassle. And, not to mention, time-consuming. The whole master's experience has been nice.

In the end, I will give a special thank you to family and friends for support during this time. You guys believing in me have meant more than you know!

”You will come to know that what appears today to be a sacrifice will prove instead to be the greatest investment that you will ever make.”

Gordon B Hinckley

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Acronyms

- BPA - Bisphenol A.
- BEV - Battery Electric Vehicle.
- BoP - Balance of Plant.
- CCS - Carbondioxide Capture and Storage.
- CF - Carbon fiber.
- CH - China.
- CO2 - Carbon dioxide.
- CPU -Central Processing Unit.
- DC - Direct Current.
- EV - Electric Vehicle.
- FC - Fuel Cell.
- FCV - Fuel Cell Vehicles.
- FU - Functional Unit.
- GF - Glass Fiber.
- GPU - Graphic graphic Processing Unit.
- GWP - Global Warming Potential.
- EPD - Environmental Product Declaration.
- EV - Electric Vehicle.
- GDP - Gross Domestic Product.
- GHG - Greenhouse gas.
- GLO - Global
- HSC - High Speed Craft.
- HOR - Hydrogen Oxidation Reaction.
- ICEV - internal combustion engine vehicle.
- IMO - International Maritime Organization.
- H2 - Hydrogen gas.

- H2O - Water.
- IndEcol - Industrial Ecology.
- IPCC - Intergovernmental Panel on Climate change.
- LCA - Life Cycle Assessment.
- LCI - Life Cycle Inventory.
- LH2 - Liquidized Hydrogen.
- LNG -liquefied natural gas.
- MDO - Marine Diesel oil.
- MGO -Marine Gas Oil.
- MJP - Marine Jet Power.
- NTNU - The Norwegian University of Science and Technology.
- NG - Natural Gas.
- NO - Norway
- NO_x - Oxides of Nitrogen
- NORDEL - Nordic electricity market.
- PAX - Passenger.
- PEM - Proton Exchange Membrane
- PEMFC - Proton Exchange Membrane Fuel Cell.
- RER - Europe.
- ROW - Rest of the World.
- SO_X - Sulfur oxides: SO_2 is the most common.
- UCTE - Union for the Coordination of the Transmission of Electricity
- VER - Vinyl Ester Resins.

Contents

1 Introduction

Considering the big challenge we are facing today with the climate changes, and the importance of everybody taking their share in this work. It is extremely important to address measures in every sector so we can secure the reduction of the emitting of greenhouse gases(GHG). Internationally, most countries have agreed to keep the temperature rise, compared to pre-industrial levels, below 2°C. This is called the two-degree target. Through the Paris agreement, the pledging countries have agreed to further limit the temperature increase to 1.5°C(Schleussner et al. 2016; FN Sambandet 2018). The only way to slow down climate change is to emit less GHG than we do today. It is also necessary to find good ways to remove carbon-dioxide (CO_2) from the atmosphere(Qin et al. 2013). GHG emitted today have century-long consequences on the climate, we already see some of these today in the form of bigger storms, unusual flooding, etc. (Cherubini et al. 2016) Therefore, climate mitigation is one of the most urgent environmental problems. Global GHG emissions have to decrease to net-zero and even further to negative values across all sectors(Smith et al. 2015). The decarbonization level required by each of the sectors is dependent on the widespread adoption of negative emissions technologies and measures, such as bioenergy with carbon dioxide capture and storage(CCS) and afforestation(Lawrence et al. n.d.). Despite the current hope of a promising technology blooming in this field, deployment of negative emissions technologies is seemingly not happening at the required scale or the pace that we are dependent on. Although the temptation of keeping the business as usual in the promise of a save later, all sectors need to decarbonize on the premise that negative emissions technologies might not work at scale(Bouman et al. 2017; Fuss et al. 2018; Pehl et al. 2017; Brahim, Wiese, and Münster 2019). Negative emissions should not work as a resting argument. The transport sector emitted 7 Gt CO2 direct emissions in 2010, about 9% of these emissions came from international and coastal shipping. Without the implementation of substantial mitigation policies, Qin et al. 2013 states that transport emissions will increase at a faster rate than emissions from any other sector and reach around 12 Gt CO_2-eq./yr by 2050. The CO_2 emissions from this sector could be as much as 2.5 times higher by 2050 if measures are not taken(Smith et al. 2015).

Over the past 40 years, maritime transport has increased by 250%, following the same growth rate as global Gross Domestic Product (GDP), and growing faster than energy consumption (170%) and global population (90%)(Bouman et al. 2017). International shipping emitted 796 million tonnes of CO_2 in 2012. This accounts for about 2.2% of the total emission volume for that year. Considering that shipping is the main carrier of world trade handling more than 80% of the global trade. And also taking into account that shipping is probably the most effective and cost-effective method for international transport for most gods(Smith et al. 2015). There is significant potential in reducing these numbers.

From a global freight transport perspective, shipping is recognized as an energy-efficient means of transportation compared to road and air transport, because of its large carrying capacity and low fuel consumption per ton transported(Pratt and Klebanoff 2018). On the background of the Paris agreement and the international maritime organization's (IMO) target for a 50% reduction in CO2 emissions from shipping, there is an increasing need for zero-emission solutions for all vessel segments.

Sustainability has become trendy. However, we need to know what measures actually have an effect. That fixing this problem will not lead to a bigger or more urgent environmental issue. It is no point in greenwashing the maritime sector if we just move the problem elsewhere. To make sure that problem shifting does not happen. Life cycle assessment (LCA) is a tool for quantifying various aspects of the environmental consequences of a system. In the maritime sector, different technologies are being explored to facilitate the desired reduction. This is because the cost of utilizing traditional marine fossil fuels is expected to increase rapidly due to impending regulation, and also because changes need to come in a big scale (Pratt and Klebanoff 2018).

1.1 Background: High Speed Crafts

The need for maritime passenger transport is a big part of global transportation needs. The breakthrough for high speed ferries came in the 70's. The change from the previous generation of ferries led to much shorter travel times, often halving the travel time between different traffic hubs. High speed ferries, from now on referred to as high speed crafts (HSC), are primarily intended for passenger transport, but several HSCs have also been built to carry a certain amount of cargo. There has been significant technology development, with the use of lighter designs, better propulsion systems and more efficient engines. This development has led to reduction in fuel consumption(Sandmyr et al. 2018).

Generally, HSC consume a great amount of energy relative to slow-moving vessels. Modern HSCs are built from lightweight materials and can reach speeds up to 45 knots. Materials in carbon is common to minimize the weight of the vessel. Fast ferries tend to have a hull design that allows the boat to deadrise to minimize water resistance. This is positive for reducing energy demand at high speeds, but factors such as air and wave resistance plays a greater role in energy consumption. Even though the fuel consumption of many HSCs has been reduced significantly in recent years, especially when using lighter construction materials, HSCs remains one of the most energy-intensive transportation means per passenger-km(C. Ianssen, E. Ianssen, and Sandblost 2017).

A rapport by Sandmyr et al. 2018 presented the total GHG emissions for Norwegian HSCs in 2016 as approximately 149.5 tonnes CO2/year. The analysis included 82 HSCs, which could be identified and analyzed. this study pointed out a new direction for how to measure emissions due to operation of different vessel types. Indicating that the use of AIS systems leads to a more stringent measurement of emissions than the previous method used by, among others,(C. Ianssen, E. Ianssen, and Sandblost 2017). In 2016, there were no county municipal HSC that used LNG, biofuels or power from land. In 2016, the HSC used marine gas oil (MGO) as fuel.

HSCs can have a cruise speed between 25 and 45 knots, i.e. up to 83 kilometers an hour. Hydrogen Fuel cells (FC) have been identified as a contender for powering such vessels, as they could provide power enough for the vessel to cruise at such high speeds, whilst typically carrying 100 to 300 passengers. FCs have lower operational emissions than the usual combustion engines. Hydrogen FCs emit only water, avoiding direct emissions of CO2 and related air. International shipping now points to hydrogen as one of the most realistic zero-emission fuels for larger ships and longer distances (Launes 2019; Notter et al. 2015; Tronstad et al. 2017; Biert et al. 2016; Jafarzadeh and Schjølberg 2017)

1.2 Life Cycle Assessment on High Speed Ferries

The large potential of hydrogen FC driven propulsion has led to an increasing interest in the technology. FCs are a promising technology in the context of clean power sustainability and alternative fuels for shipping. Different specific developments on FC are available today, with research and pilot projects under evaluation that have revealed strong potential for further scaled up implementation. Several studies have addressed the feasibility (Pratt and Klebanoff 2016; Pratt and Klebanoff 2018; Tronstad et al. 2017; Berti 2019), cost (Aarskog et al. 2020), design (Strømgren et al. 2017; Fabricius 2019; Hirth et al. 2017; Evenstad 2017) and potential/efficiency (C. Ianssen, E. Ianssen, and Sandblost 2017; Godø and Kramer 2019) of introducing Hydrogen FC systems into maritime transportation. The studies mentioned here are just some of them. In general, these studies conclude that hydrogen FC systems can be a cost-efficient competitor to conventional diesel propulsion systems. Although this technology is associated with a higher initial cost than today's diesel system. This cost is related to the immaturity of the technology as well as the lack of infrastructure and market for the fuel value chain.

However these studies do not take into account the system as a whole, but often look at a limited part of the system, often the use phase. LCA is a tool for quantifying various aspects of the environmental consequences of a system. Lessons from the LCA of different options in the land transport sector has demonstrated the importance of the inclusion of all life cycle stages to ensure consistent and robust comparisons of alternatives for reducing emissions.

A study by Evangelisti et al. 2017 showed that the production process of the FC vehicle (FCV) showed a higher environmental impact compared to the production of the other two vehicles power sources (battery electric vehicles (BEVs) and conventional internal combustion engine vehicles (ICEVs)). This was mainly due to the hydrogen tank and the fuel cell stack. Simons and Bauer 2015 show inconclusive environmental benefits for using FCVs instead of modern ICEV. Concluding that a substantial reduction of GHG emissions can only be achieved using hydrogen produced with non-fossil energy resources.

Several LCAs has focused on models single components such as, battery or FC models for Vehicles (Hawkins et al. 2013; Ellingsen et al. 2014; Usai 2018; Simons and Bauer 2015; Evangelisti et al. 2017; Correa 2013). These studies has, as the previous mentioned, shown the importance of upstream emissions due to production of batteries, FCs, hydrogen and/or storage systems.

Similar findings has been found in the LCA of maritime applications. Kullmann 2016 did a Comparative Life Cycle Assessment of conventional and all-electric Car ferries in 2016. This master thesis quantifies the environmental impacts of four ferry alternatives using the method of LCA. An all-electric lightweight catamaran in aluminium was compared to a conventional diesel powered monohull in steel. In addition, two theoretical cases were included where the design was the same as the all-electric ferry but the energy carrier was changed to liquefied natural gas (LNG) and marine diesel oil (MDO). In this study, impacts were divided into the processes battery/engine, hull and operation. The all-electric ferry was run on the average Norwegian electricity supply mix. The model does not reflect the entire ferries but some of the components and parts of the operation of them. Material for hull and engines, battery production and some operational inputs were included in the analysis.

The analysis by Kullmann 2016 identifies that using all-electric ferries gives a problem shift with reducing impacts in categories linked to combustive stressors and fossil fuels and increasing impacts in toxicity. Similar tendencies have been presented in studies on electrical cars.

The focus on production of hydrogen has been highlighted in several studies (Øgård 2017; Jokela et al. 2018; NCE maritime CleanTech 2019; Launes 2019; Kullmann 2016). The overall conclusion from these is that Produced from green energy, hydrogen is a clean and green option.

However, as adressed by Kullmann 2016, further studies should include more complete parts of the ferries, being their components, production, operation and end of life. Several LCA has focused on models single components such as, battery (Hawkins et al. 2013; Ellingsen et al. 2014), Fuel Cells (Munkvold 2019; Usai 2018; Correa 2013; Windsheimer 2016), Hydrogen production (Launes 2019; NEEDS 2008; NCE maritime CleanTech 2019) and Hydrogen storage (Moradi and Groth 2019; Biert et al. 2016; NCE maritime CleanTech 2019; Stoystown n.d.; the Linde group n.d.; Viswanathan 2017). There are few complete LCAs on HSCs. In this thesis, the upstream emissions and operational emissions have been considered, from the production of the boat, fuel cells, battery, hydrogen tank, the production of the hydrogen and diesel. A comparison of the most relevant part of the system gives a better understanding of what the technology can provide. A transparent inventory is provided for most of the system.

1.3 Objective and Scope

The insight from literature points to a potential for reduction of emissions for HSC propelled by hydrogen FCs. The reductions that is seen are case-dependent. This study looks upon a HSC catamaran in a Norwegian setting, with Norwegian electricity mix.

This thesis is a comparative LCA of a hydrogen FC and diesel-powered high HSC. The two HSCs that are compared are both carbon fiber sandwich catamarans. The model of the diesel catamaran is based on MS Terningen and MS Tyrhaug, these boats operate the route from Trondheim to Kristiansund. The hydrogen FC catamaran is based upon a case study, where the boat Aero42H2 was dimensioned to operate this exact route.

This thesis is aiming to include the most relevant parts of a high-speed passenger catamaran in an LCA to compare environmental effects.

2 Case and method description

Energy consumption and diesel consumption for the HSCs MS Terningen and MS Tyrhaug is based upon numbers from Fabricius 2019. The information on crossings each year are from Øgård 2017. The numbers are presented in section 2.2 and 2.1.

This thesis will be based on the this data. Including data by Strømgren et al. 2017 for the Aero42H2 concept. Further explained in section 2.3.

2.1 Trondheim-Kristiansund

The route (800) between Trondheim and Kristiansund has a distance of about 95 nautical miles (nm) and takes approximately 3.5 hours. Today the route is operated by 3 boats. The two main boats are MS Tyrhaug and MS Terningen. They were added to the route in April and November 2014. The vessels were to replace MS Ladejarl at that time. The latter operates the route if there is any service that needs to be done. The route is illustrated in figure 1.

In 2014, the replacement meant a reduction of emissions of about 40%. Much due to a lightweight hull and the change to a new diesel engine(Stensvold 2014). Additional information by Oppheim 2015 adds that NOx emissions were halved, and CO2 emissions were reduced by 6400 tonnes in total. Each of the old boats built in 2002 emitted 7956 tonnes of CO2 a year. The new ones emitted 4773 tonnes of CO2 a year(Oppheim 2015).

According to Øgård 2017, the route (800) operates, in total, 32 crossings per week and 1632 crossings per year.

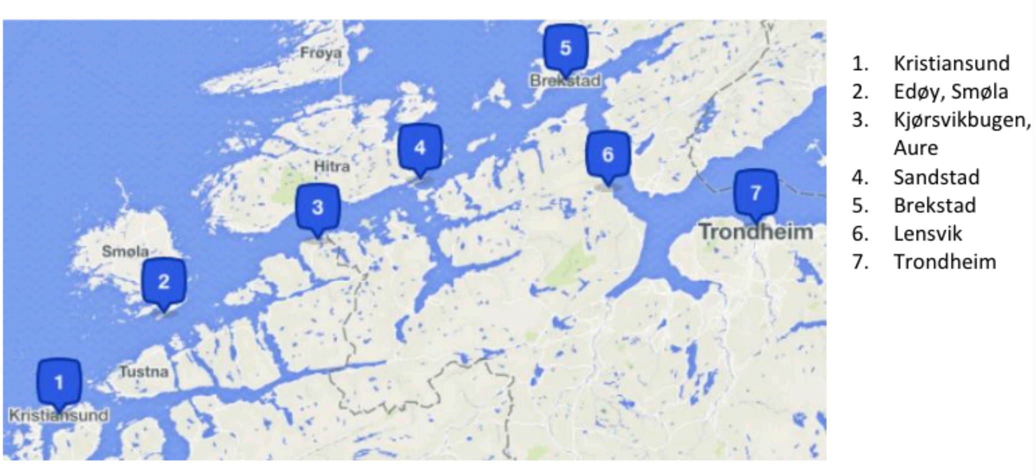


Figure 1: Route 800 from Trondheim-Kristiansund (Fabricius 2019)

2.2 MS Terningen/MS Tyrhaug

M/S Terningen and MS Tyrhaug are two 275 pax carbon fiber catamarans delivered in 2014 to the Norwegian operator Kystekspressen ANS. They are powered by 2 x MTU 16V2000 M72, equipped with waterjets from Marine Jet Power (MJP), and designed for a service speed of 34 knots. Tyrhaug is the sister ship of M/S Terningen. The Key data for MS Terningen and MS Tyrhaug is shown in table 1(Brodrene Aa n.d.).

Table 1: Key Data: MS Terningen and MS Tyrhaug(Brodrene Aa n.d.)

	MS Terningen/ MS Tyrhaug
Construction #	274
Year	2014
Pax	275
Materials	Carbon fibre sandwich / vinylester
L/W/GRT	40,8m / 10,8m / 492 GRT
Service speed	34 Knots
Main engine	2x MTU 16V2000 M72
Propulsion	ZF type 4550 / MJP 650
Fuel	Diesel(MGO)

According to Fabricius 2019, each of the vessels have a total consumption of approximately 1700 liters of diesel per crossing (table 2). It is added to this point that the vessel consumes 630 liters of diesel per hour at 35 knots, while this long route has 5 stops en route with periods of slower speed and quai stops. With the density of Diesel at 0.84 kg/liter. It gives that 1700 liters are equivalent to 1428 kg of diesel. An HSC diesel engine has a specific consumption of 0.210 kg / kWh. The power output of the vessel will then be 6800 kWh per crossing (3.5 hours) Per passenger kilometer this gives approximately 0.14 kWh per pax-km (if the boat is full and sails at 35 knots).

Table 2: Fuel Consumption: MS Terningen and MS Tyrhaug (Fabricius 2019)

	MS Terningen/ MS Tyrhaug
Diesel Consumption(liter)	1700 liter
Diesel Consumption(kg)	1428 kg

Figure 2: Tyrhaug(Brodrene AA 2014)

2.3 Aero42H2

In 2017, Trøndelag and 10 other county municipalities challenged Norwegian and international industry to develop the world's first emission-free HSC for speeds over 30 knots. The following year, five groups, comprising 19 companies, were awarded a contract to develop and demonstrate that zero emissions are possible(Miljødirektoratet 2017; Solvang 2019).

Aero42 is the result for the Trondheim-Kristiansund route, for one of these five groups, found in "Utviklingskontrakt utslippsfri hurtigbåt, Brødrene Aa", (Strømgren et al. 2017).

The Aa brothers consortium has optimized a hydrogen-based energy system for HSCs with high energy consumption. The system designed is called the Aero 42H2 vessel type, and is a battery and hydrogen powered fast ferry. The vessel has storage capacity for 612 kg of hydrogen. With an optimized driveline for speeds of 33.4 knots. This is enough energy to sail Trondheim-Kristiansund with today's route speed and with a good margin on energy storage. The vessel is equipped for 277 passengers(pax). Strømgren et al. 2017

The installed energy system for Aero42H2 is 2x1300 kW, an FC system with 2x7 x 200kW-modules, and a battery pack of 672 kWh. Key features for Aero42H2 can be found in table 3.

At short stops at the quay, the FCs will keep running and charge the batteries. For longer stays, the batteries will be charged with shore power(Strømgren et al. 2017).

Another aspect that is worth mentioning is that the vessel will be optimized for minimal energy consumption. This is done by a focus on low weight, and by that the hull structure is optimized for speed, weight, and gravity.

Table 3: Key Data Aero42H2

	Aero42H2
Pax	277
Materials	carbon fibre sandwich
Service speed	33,4
installed power	2600 kW
Battery capacity	672 kWh
Fuel Cell system	2800 kW

Figure 3: Aero42H2 (Strømgren et al. 2017)

Terningen / Tyrhaug and Aero42H2 are different in the form of energy carriers. Tyrhaug/Terningen is operated by a diesel system, while Aero42H2 is hydrogen FC system based, as well as a battery. The brothers Aa are responsible for the construction of all three boats. And although much may have happened in regards to boat building in 6 years (2014-2020). Terningen/Tyrhaug and Aero42H2 are all of the carbon sandwich types.

The HSCs have several other systems and components where they differ, but the energy providing systems are principally different.

There will be a need for infrastructure for a docking system for the bunkering of hydrogen and charging of the battery pack. The Docking station is not a part of the scope in this thesis, and will not be discussed further.

3 Method

This section is a description of the life cycle assessment(LCA)method. LCA has been used to assess the environmental impact of the diesel and hydrogen catamarans modeled for this thesis. There are different software for modeling and assessment of inventories. For this thesis, the ARDA tool developed at the Norwegian University of Science and Technology(NTNU) is used.

Some of this material describing the LCA-method is based on the researcher's project thesis "Life Cycle Assessment of a Hydrogen Fuel Cell Propulsion System for Maritime Applications"(Munkvold 2019).

3.1 Life cycle Assessment

LCA is a method to assess the environmental impacts associated with all the stages of a product's life. From raw material extraction, through the processing of the material, the distribution, transport and manufacture, use, disposal, or recycling of the product. The whole value chain. LCA use a "cradle to gate" way of thinking and look at every stage of the product to say something about its complete footprint(ISO 2007). By doing this, an holistic view of the product is obtained. This way problem shifting can be avoided.

Problem shifting is an important issue when it comes to climate change mitigation, and LCA's are a tool which can be used to better understand a system/product, by addressing how the different stages of a products production, use or end of life turns out in terms of environmental footprints. Problem shifting means solving an environmental problem by defining it outside the system, or by creating a new problem by fixing the first. An example of problem shifting is saying that "hydrogen FC ships have zero emission". As an example: Hydrogen from LNG reduces CO_2 emissions but increases CH_4 emissions (Hammer Strømman 2010; Brahim, Wiese, and Münster 2019). The examples above, are all information known because it is revealed by the results of performing LCAs.

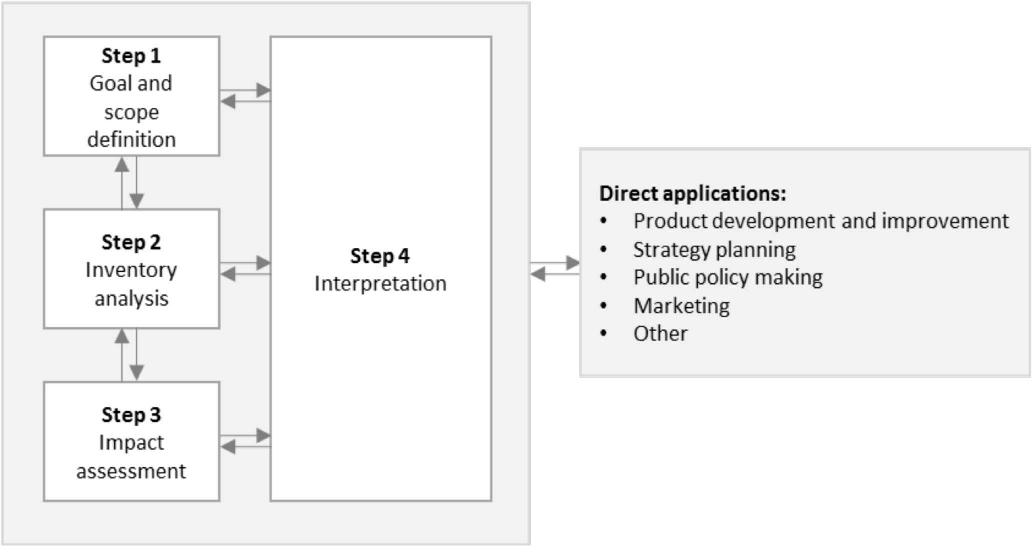


Figure 4: The four phases of an LCA (ISO 2007)

Traditionally LCA is divided into four phases, as shown in figure 4. These phases are the goal and scope definition, inventory analysis, impact assessment, and interpretation. Sub-section 3.1.1 to 3.1.4 go through each phase.

3.1.1 Goal and Scope definition

In the first step, assessing of the goal and scope definition find place. The goal definition is defining the objective of the study, the audience, and the actors. The most important part is stating why the analysis is performed. The intended use of the results. Who should be involved and who will have an interest in the results are questions that should be asked before starting.

The Scope definition is where the methodological choices are set. A big part of LCA is choosing a good functional unit (FU). The FU is a quantitative measure of the function the system is meant to deliver. The focus on function rather than any other physical property of the system allows for consistency across products with varying characteristics. It is also important to define the system boundaries. Choosing which impacts categories shall be used, which databases to collect the data from is also a part of the scope definition.

Functional Unit

In this thesis, two high speed catamarans have been modeled. The FU is set to one crossing, i.e. The boats traveling from Trondheim-Kristiansund (95nm). It is assumed that each boat in total has, 32 crossings per week and 1632 crossings per year. With the lifetime of the HSCs set to 15 years.

The catamarans MS Terningen/MS Tyrhaug and Aero42H2 have been modeled individually from construction to use phase. The FU, system boundaries and reference flows are presented in Figure 5 and 6.

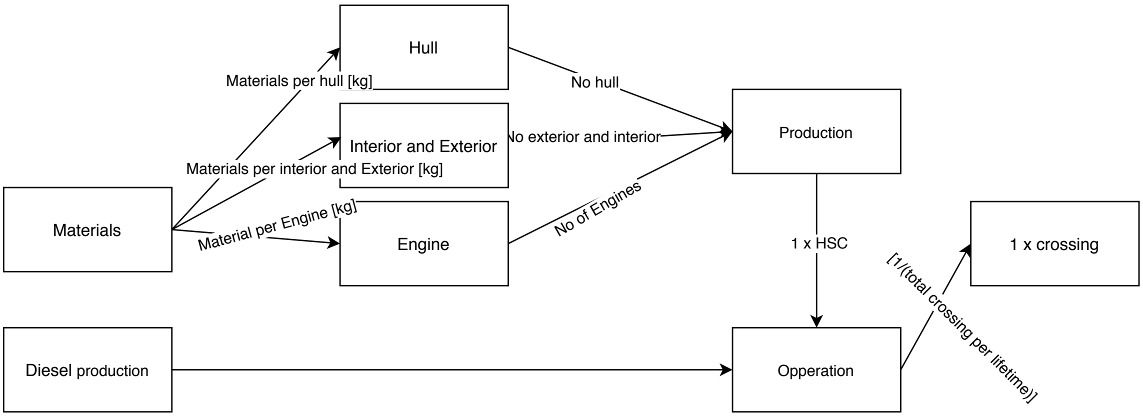


Figure 5: Flowchart: Modeling of Conventional Diesel HSC

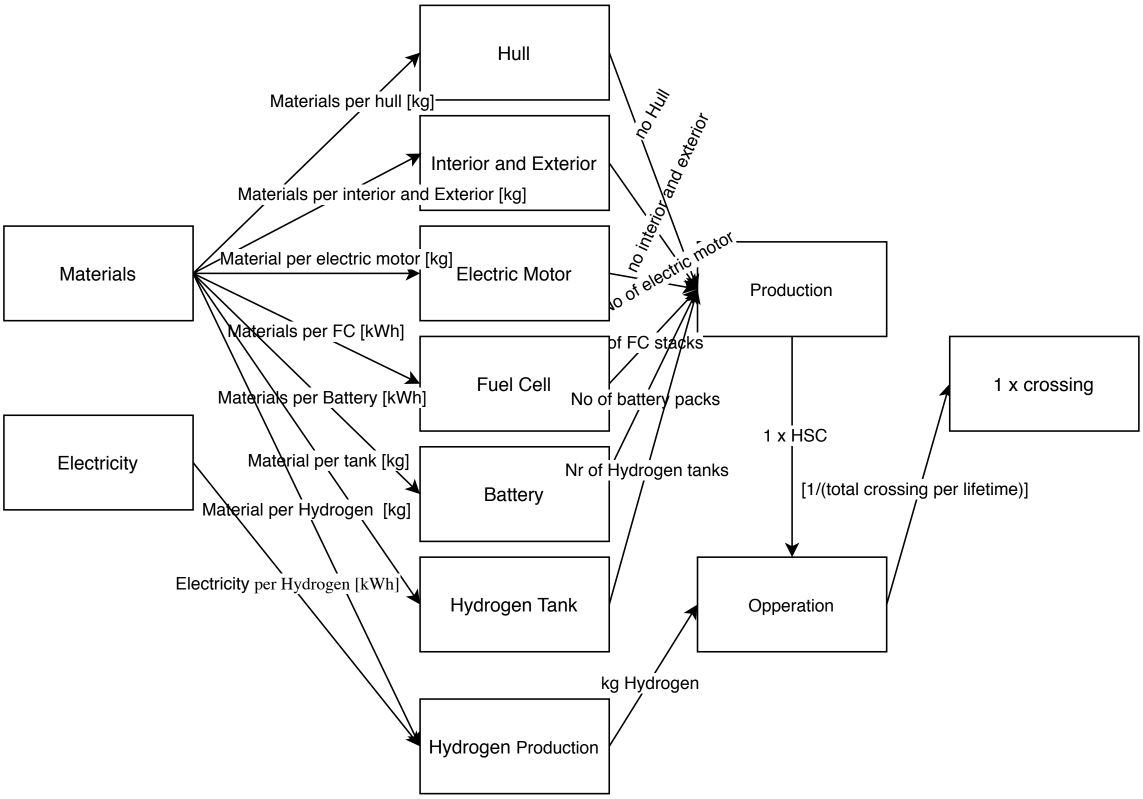


Figure 6: Flowchart: Modeling of Hydrogen FC HSC

3.1.2 Inventory analysis

LCA Stage two is called inventory analysis/modeling. In this step, the construction of the flowchart describing the system and collection of data for input and outputs for each of the processes are done. There are many ways on collecting data. Either on-site, from the manufacturer, from literature, databases, expert estimates, life cycle inventory(LCI) data from previous LCA studies, etc. In this thesis, most of the data are collected from literature and databases. Ecoinvent is the database used for the processes in this thesis.

From these data, the calculation of the environmental stressors can be done. The LCA builds upon a mathematical framework. For the most part, it is dealt with linear systems in LCA. In particular matrix algebra. The researcher can perform these calculations by hand, but when the data sets get big, it is more convenient to use a tool performing it for. As stated earlier different software can be used for modeling and assessment of inventories. For this thesis, the ARDA tool developed at NTNU is used.

When compiling the LCI in the second step in the LCA, information about the material and energy flows necessary are needed to fulfill the desired function. A production system consists of different production nodes, the coefficients of requirements a_{ij}, and the external demand of products y_j. The coefficients of requirement a_{ij} denote the amount required by process i per unit output of process j.

For each process, the collection of information on the requirements of inputs to production is needed. Having identified the recipe for all the production nodes, one can establish a matrix containing all recipes. This matrix is called the requirements matrix, A.

The A-matrix is divided between a foreground and a background system. Usually, the foreground system is defined by the one doing the LCA with data from different sources, while the background system usually is build up by information from databases for the different processes related directly or indirectly to the foreground system. The A-matrix can be used to identify the activity generated in all nodes as the result of the demand for the FU.

When connected to system output, the total amount required from each process can be determined.

$$x = Ax + y \tag{1}$$

The x-vector is the total output of the system that is needed to satisfy the final demand. Equation 1 gives the x-vector. The total output from the system is the sum of the intermediate and final demand.

The y-vector is the final demand vector, also called external demand. It is the requirement of products that the network has to deliver. The y-vector is typically the FU.

Performing the mathematics of the LCA one operates with something that is called the open Leontief model. For this, the Leontief inverse matrix, L, is needed. The coefficients in the L matrix, l_{ij}, represent the amount of output of process i that is required per unit of final delivery of process j.

From equation 1 the requirements matrix, A, and the FU, y is found. To get the Leontief inverse matrix, a rearrangement of equation 1 and solving for the unknowns is needed. This yields

$$(I - A)x = y \Leftrightarrow x = (I - A)^{-1}y \tag{2}$$

Where I is the identity matrix. This matrix has the same dimensions as the A matrix, but with ones on the main diagonal and zeros as the other elements.

From this the Leontief inverse matrix, L, is obtained:

$$L = (I - A)^{-1} \Rightarrow x = Ly \tag{3}$$

Having established the central elements in the open Leontief model, one are soon able to calculate the total emission and environmental loads in general, for a given external demand. This is called the contribution analysis.

Outputs from processes that do not contribute to the value-adding of the supply chain must also be accounted for. These flows are called stressors. The stressors refer to environmental pressures such as emissions and land use and are collected in the stressor intensity matrix, S. The stressor matrix S, contains the environmental stressors associated with the output of each process. A given column of S contains the vector of stressors for one unit of output of that particular process.

Stressors are used as more general terminology than emissions. A process can have other environmental loads than just those associated with what is traditionally thought of when using the term emissions. A given column of S contains the vector of stressors for one unit of output of that particular process. Stressor data must be collected analogously to the requirements coefficients in the A matrix. The number of individual stressors that are included, varies depending on the study. It can be anywhere from a handful of stressors up to thousands as in the case of the more comprehensive LCA databases.

$$e = Sx = SLy \tag{4}$$

The e-vector contains the total stressors associated with the external demand given by the y vector. It is now achieved what was set out to do. That is, to find the total emissions generated in a production network as a result of a given external demand.

3.1.3 Impact assessment

The third stage is the impact assessment. Here one group stressors into impact categories and do the characterization. This means converting stressors into impact units(equivalents). Characterization factors allow us to convert emissions of different substances with the same type of environmental impact into equivalents. Having determined the total amount of stressors, the final step in the quantification is to convert the long list of stressors into a manageable number of environmental impacts. This is a two-stage procedure consisting of classification and characterization ISO 2007. To calculate total impacts, one must classify which stressors contribute to which impacts and by how much.

After classification is completed for all impact categories, characterizing can be done, i.e. calculating the environmental impacts of the investigated system,

$$d = CSLy \tag{5}$$

3.1.4 Interpretation

The fourth stage of an LCA is the analysis and interpretation. It is divided into two steps; analysis and presentation of the results where one identifies the significant contributions from emissions and processes and evaluating the results where you establish confidence; a sensitivity analysis. In other words; how will the conclusion change concerning assumptions made. If the results depend on uncertain data, it is also here one can do an uncertainty analysis.

Although the four steps are presented in sequential order, LCA is in practice an iterative process. As seen in figure 4, the four steps are interrelated. The iterative nature of the LCA procedure allows for adaption and adjustments of earlier steps due to findings in later phases of the study. For example, if one finds in the final step (interpretation) that the defined FU was unsatisfactory, one may go back to step one (goal and scope definition) and define a new FU. In this example, it follows that step two to four must also be repeated. Several iterations may be required in the course of an LCA study.

3.2 Life cycle phases

The emissions and impacts associated with the construction and demolition, need to be attributed to per unit product output in operation. As an example, how should the environmental load associated with the construction of the boat factory be attributed to boat production.

In LCA the environmental loads associated with the construction of a given factory are distributed linearly to each unit output. This is done by dividing the total load from construction by the total number of units produced throughout the lifetime of the factory. Demolition is treated completely analogously. We formally then have that

$$a_{C_iO_i} = a_{D_iO_i} = \frac{1}{total\,production\,over\,lifetime} = \frac{1}{\dot{m}_{year}\tau_{life}} \qquad (6)$$

In equation 6, the coefficients, $a_{C_iO_i}$ and $a_{D_iO_i}$, represent the amount of construction and demolition required per unit output of process i.
$\dot{m}_{year}$ is annual production volume and τ_{life} is the lifetime of the facility.

For our system, the system's lifetime is set to 15 years. In other words, the HSCs have a lifetime set to 15 years.

As the FU is set to one crossing, i.e. The boats traveling from Trondheim-Kristiansund (95nm). It is assumed that each boat in total has, 32 crossings per week and 1632 crossings per year. With the lifetime of the HSCs set to 15 years. All components in the production phase are distributed linearly over these 15 years.

In the next section, the system description for this thesis is presented.

4 Life Cycle Assessment Model

4.1 System Description

The optimal solution would be to include all aspects of production, operation, and end of life for the HSC. Access or research on all this data is however not feasible. It was therefore looked into what parts of the life cycle that would have the largest impact on the analysis.

The operational phase is pointed out as the most important part of the life of most ferries (Kullmann 2016). It is expected a similar trend as with FC cars on the Hydrogen HSC, that the production is increasingly important as the operational emissions are reduced for some impact categories(Hawkins et al. 2013).

The motivation for this model was to include as much of the HSCs as possible, starting with the biggest components. The aspects that are attempted to include in the analysis are items that are principally different for the two catamarans, for example, the FCs, Hydrogen tank, the batteries, and the engines. In addition to this, the hull, electronics, and some interior and exterior are taken into account. As a cut-off criterion, there was not modeled for a docking or charging system for the HSC.

4.2 Life Cycle Inventory

This LCI model consists of two parts. The production phase and the use phase. In the production phase: production of the boat, interior and exterior, electronics, engine production, FC- and battery production was modeled for. The production phase is presented in section 4.3 For the use phase, indirect and direct emissions were accounted for. The Diesel fuel production and the direct emissions concerning propulsion were taken into account for the Conventional Diesel HSC. For the Hydrogen FC HSC; The production of Hydrogen with electrolysis was modeled as a part of the indirect emissions for the use phase. The Production of Hydrogen and Diesel fuel is carried out in section 4.4 and handled in section 4.5.

End of life emissions were not modeled for but are shortly discussed in section 4.6. The dismantling of carbon-fiber and the end-of-life treatment of the different components of the HSCs is a large field and could have been a study in itself.

This thesis focus on LCA of the production and operation of the HSCs. The next section goes through the modeling of the production of the HSCs, followed by the modeling of the use phase before the end of life is discussed; Section 4.3, 4.5, and 4.6. The full inventory for most of the system is found in Appendix A Note that all stages are modeled in terms of the FU. The FU was presented in section 3.1.1.

4.3 Production Phase

The production phase has been seen in the literature as an important source of emissions. In this section, the model of production of the HSCs based on Terningen/Tyrhaug and Aero42H2 is carried out. Processes accounted for are hull production, interior, and exterior; paint, windows, seating, electronics. Production of FC, batteries, and engines, and also Hydrogen storage in terms of a Hydrogen tank.

4.3.1 Hull production

The traditional hull material for ships is steel, but for HSCs lightweight is essential to achieve the desired speed. For that reason, other lightweight materials, such as aluminum and plastic composites, are used. Aluminum is traditionally the most used hull material for HSCs. Plastic composite has in Norway, in the form of a carbon sandwich taken over a large proportion of the market, mostly due to weight optimization potential. (Evenstad 2017)

Separating two materials with a lightweight core material increases the structure's stiffness and strength. Modern, advanced composite materials give a strong and robust structure which reduces overall vessel weight. Reduction in weight translates directly into greater payload, range and speed(Advance Composite Manufacturing Sdn Bhd — 2020).

Additional benefits of composite sandwich hulls are increased thermal and acoustic insulation with significantly less impact from machinery vibration. Corrosion resistance allowing for longer service life between maintenance is also presented as some of the benefits.(Advance Composite Manufacturing Sdn Bhd — 2020)

As weight is a critical issue for any high speed vessel. The material and design of the hull are of critical matter. A sandwich structure consists of two high strength skins separated by a core material. By Inserting a core into the laminate you increase the thickness of the material without incurring the weight penalty that comes from adding extra laminate layers(Gurit n.d.). Single skin laminates, made from glass, carbon, aramid, or other fibers may be strong, but they can lack stiffness due to their relatively low thickness. A sandwich-structure solves this problem. Traditionally the stiffness of these panels was increased by the addition of multiple frames and stiffeners, adding weight and construction complexity(Gurit n.d.).

The Aero42H2 is a carbon fiber sandwich catamaran. Anstein Aa, the technical manager at Brødrene AA, estimated 40000 kg carbon-sandwich material in an HSC of the size of Aero42H2. For the model, it is assumed that this yields for both vessels.

For greater detail aspects regarding the modeling of carbon sandwich structure, one could have assumed that MS Terningen/ MS Tyrhaug and Aero42H2 were built with different materials due to the years between the building of the boats. For simplicity and for the sake of not comparing "old technology" with new, the same hull materials are assumed.

There are modeled for two types of the hull. One with glass fiber(GF) and waste polystyrene. The other with carbon fiber(CF) and bisphenol A (BPA) epoxy Vinyl Ester Resins (VER). The CF hull is the base case, as this is the material used for Aero42H2 and Terningen/Tyrhaug. in addition, GF has been modeled as a part of the sensitivity analysis, section 5.2.

It is used a ratio of 40/60%. 40 % GF and 60% polystyrene. And 40% CF and 60% BPA.

The modeling of the hull consists of the Ecoinvent processes shown in table

5 and 6. CFis modeled as done by Usai 2018 and Munkvold 2019, and is shown in table 4

Table 4: Modeling of Carbon Fiber

Background name(Ecoinvent)	Geography	Unit
electricity, low voltage/market group for electricity	RER	kWh
heat, district or industrial, natural gas/market for heat	Europe without Switzerland	MJ
heat, central or small-scale, natural gas/heat production	Europe without Switzerland	MJ
acrylonitrile/market for acrylonitrile	GLO	kg
methyl acrylate/market for methyl acrylate	GLO	kg

Table 5: Modeling of CF sandwich hull

Background name(Ecoinvent)	Geography	Unit
bisphenol A epoxy based vinyl ester resin production	RoW	kg
CF as modeled in table 4		

Table 6: Modeling of GF sandwich hull

Background name(Ecoinvent)	Geography	Unit
glass fibre/glass fibre production	GLO	kg
waste polystyrene/market for waste polystyrene	GLO	kg

4.3.2 Interior and Exterior

To have a more complete LCA of the HSCs, some of the interior and exterior parts have been modeled. This includes paint, windows, and seating for the two vessels. Paint and seating are adjusted according to the independent boats, while the amount of glass material for the windows is assumed the same.

Windows

There is done a simplified analysis of the windows. It was assumed a range of average window sizes. The weight of the total glass material used was estimated as seen in table 7. The different window types are shown in Appendix B. The Ecoinvent process used for the glass material is shown in table 8

Table 7: Key data: Modeling of windows

	Type A	Type B	Type C	Type D
Amount	8	12	3	2
Density kg/mˆ3	2579	2579	2579	2579
Length m	8	1	0,5	10
Height m	1	1	0,5	0,5
Area mˆ2	8	1	0,25	5
Thickness m	0,01	0,01	0,01	0,01
Weight kg	206	26	6	129
			Sum	368 kg

Table 8: Modeling of Windows

Background name(Ecoinvent)	Geography	Unit
Flat glass, coated/flat glass production, coated	RER	kg

Paint

Paint is important in terms of the maintenance of boats. Bottom paint (anti-fouling paint) is a paint or coating designed to discourage weeds, barnacles, and other aquatic organisms from attaching themselves to the underwater portion of the hull(BoatUS n.d.). The fuel use can according to Stensvold 2020increase by 10-20% due to marine growth that adheres to ship hulls.

To calculate how much paint in kg, that is needed, a simplified analysis is assumed where the area of each boat has been used. It is assumed four strokes of paint. Table 9, 10 gives the values that is used to calculate the amount of paint needed.

Table 9: Key data: Paint

liter paint/m^2(Biltema n.d.)	0,087	l/m^2
Density alkyd paint(Biltema 2017)	1361	kg/m^3

To model the paint Ecoinvent is used, the process is found in table 11.

Table 10: Key data: Amount of Paint

	Terningen/Tyrhaug	Aero42H2	
Area (one side of the boat)	440,6	451,4	m^2
Paint for one side in liter	38,3	39,3	liter
Paint one side in kg	52,2	53,4	kg
Paint in kg, both sides	130,4	133,6	kg
Four strokes	521,5	534,3	kg

Table 11: Modeling of Paint

Background name(Ecoinvent)	Geography	Unit
alkyd paint, white, without solvent, in 60% solutionstate	RER	kg

Seating

To model for seating, there was used an environmental product declaration (EPD) of a "Transit 24 three-seat sofa"(The Norwegian EPD Foundation 2017). This Product is a three-seat sofa, upholstered with base in aluminum. The EPD contained information about the product's lifetime, complete material use, and the marked area was set to worldwide. Due to this, it was decided to use this declaration for the seating although the seating used for Tyrhaug/Terningen was delivered by another company, West Mekan, and was of type "WM 1000". Since each chair is a tiny fraction of the boats' total footprint to use the material from the EPD was considered an OK estimation. The total weight of the system was adjusted according to the weight of the original system.

There is assumed a total weight of 2104kg and 2200kg for the seating alone on Terningen/Tyrhaug and Aero42H2. This is calculated with the weight of one chair being 8kg. And a total seating of 263 and 275 for each vessel. The fraction of the materials for the chairs is assumed as in The Norwegian EPD Foundation 2017 and can be found in Appendix B. The Ecoinvent processes used are shown in table 12.

Table 12: Modeling of Seating

Background name(Ecoinvent)	Geography	Unit
metal working, avg for aluminium product manufacturing	GLO	kg
scrap aluminium/market for scrap aluminium	GLO	kg
metal working, avg for steel product manufacturing	RER	kg
polyethylene terephthalate, granulate, amorphous	RER	kg
synthetic rubber/production	RER	kg
sawnwood, hardwood, market for sawnwood	RoW	m3

4.3.3 Electronics

The main features of the energy and propulsion system for Aero42H2 consist of two parallel systems. Each system has separate fuel cell and battery packs, DC boards, control, monitoring, and engine. This provides the necessary redundancy, security, and reliability for optimal operation. The DC boards supply energy to each AC board for hotels, instruments, and consumer loads. Both auxiliary systems (navigation, security systems, hotels, etc.) will be secured energy supply from one FC/battery system(Strømgren et al. 2017). The model for the FC and the battery production is explained in section 4.3.4 4.3.6.

For simplicity, the electronics in this thesis are assumed an equivalent of 10 desktop computers. The Ecoinvent process that is used can be seen in table 13.

Table 13: Modeling of Electronics

Background name(Ecoinvent)	Geography	Unit
computer, desktop, without screen/market for computer	GLO	unit

4.3.4 Fuel Cell Production

The FC system is assumed to be a substantial part of the impacts associated with a Hydrogen based energy system. The Aero42H2 has a capacity of 2800 kW FC installed. Key features for the FC system is given in table 14. Parts of the coming Paragraphs are from the researcher's project thesis (Munkvold 2019).

FCs are different from most batteries in requiring a continuous source of fuel and oxygen to sustain the chemical reaction, whereas in a battery the chemical energy usually comes from metals and their ions or oxides that are commonly already present in the battery. FCs can produce electricity continuously for as long as fuel and oxygen are supplied. In addition, FCs have a very high density which makes them very attractive for electric mobility. These factors combined are what makes fuel cells such a promising technology both in maritime applications and for transportation generally(Notter et al. 2015; Tronstad et al. 2017; Biert et al. 2016; Jafarzadeh and Schjølberg 2017).

According to Strømgren et al. 2017, the FC system in table 14 is specially developed for Norled's Hjelmeland ferry, scheduled for operation in 2021. The modules consist of stacks from Ballard's proven technology. The fuel cell modules will be water-cooled and provide high-quality heat that can be used for heating the vessel

Hydrogen pressure will be reduced outside the tank and lead to the fuel cell compartment by approximately 8 bars pressure and flow of a total of 60 grams/ second. The value applies to all module assemblies. The fuel cell modules will individually supply power to the DC bus, via its own DC / DC converter in the board room. In addition to the physical foundations and power delivery, the cooling water system, a common filter air intake, and the Hydrogen ventilation system are the most important interfaces between fuel cells and ships. (Strømgren et al. 2017)

Table 14: Key Data Fuel Cells

Producer	Ballard
Number of modules	14
Capacity	200 kW
Total Capacity	2800 kW
L x B x H	2,0 x 1,8 x 0,8 m
Efficiency	58 %
Lifetime	3000-5000 Operating hours

A Hydrogen fuel cell is a fuel cell that uses Hydrogen as fuel and oxygen as oxidant. An FC power pack consists of a fuel and gas processing system and a stack of fuel cells that convert the chemical energy of the fuel to electric power through electrochemical reactions(Tronstad et al. 2017).

The PEM fuel cell consists of

- Bipolar plates(BPP),

- Electrodes,
- Catalyst,
- membrane,
- The necessary hardware such as current collectors and gaskets, and
- The FC Auxiliaries/Balance of plant(BoP).

The overall system is shown as a flowchart in figure 7. To get the voltage to a higher level, many separate FCs are combined to form an FC stack. The functional unit for this model is chosen as a 2800 kW PEMFC unit. This system consists of 14 FC stacks/modules. Each of the FC stacks of 200kW.

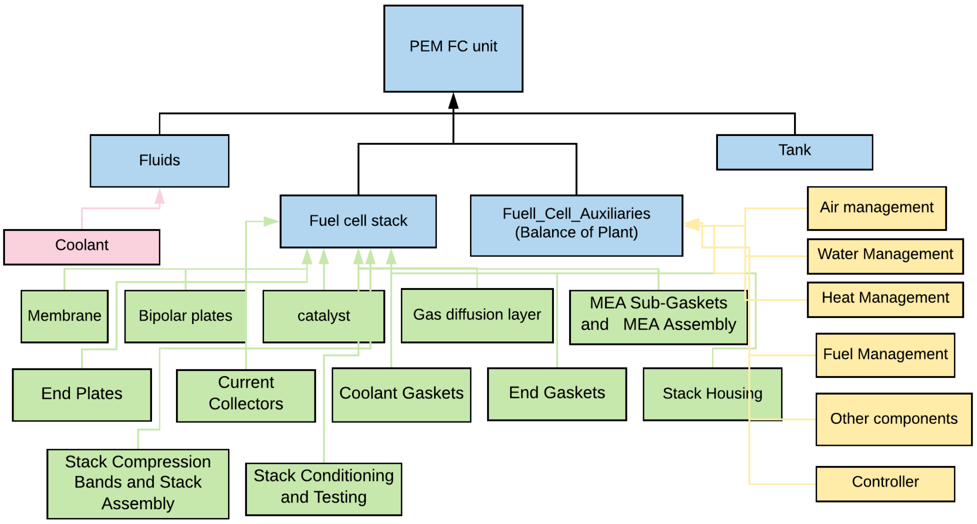


Figure 7: Flowchart: Fuel Cell System (Munkvold 2019)

Industrial ecology (IndEcol) at NTNU has been developing an inventory for a Proton-exchange membrane (PEM) FC for Electric Vehicles(EV). As there has not been done so many LCA on FC systems for maritime applications, this inventory was further developed for the project thesis of the researcher, Munkvold 2019. The same model is used for this master thesis. As this model is based upon a PEM FC for electric vehicles, and not the exact FC that is chosen for AERO42H2 this might give some errors due to the result. However, the model from IndEcol is based on the most recent literature in the field and is therefore considered robust.

Table 15: Key Data: FC system

Number of modules	14	p
Module	200	kW
FC system	2800	kW
L x W x H	2,0 x 1,8 x 0,8	m
Efficiency	58	%
Lifetime	3000-5000	Operational hours
Power of system	200	kW

The model used as a baseline for the scaled inventory of the FC system is a cradle-to-grave LCA. The inventory for the FC system was developed by Correa 2013, it has been updated by Windsheimer 2016 and re-modeled and updated by Usai 2018. According to Usai 2018, Windsheimer 2016 adjusted some input requirements to the system, taking as benchmark other studies in the literature. At that point, the inputs to the FC system modeled were all scaled per net power output (kW) of the system, and throughout the update, linearity was assumed between power and size. Thus, changing the power output of the system, the entire inventory was scaled accordingly.

After this Usai has been developing it further and today's inventory is not considered linear. There are two key components that the system is changing in alliance with. These are the Catalyst performance based on the Platinum loading with a starting point of 0.32mg/cm^2. Further, the inventory is scaled by the net power of the system. For this system, the net power was set to 200kW.

It was not possible to scale the FC auxiliaries/Balance of Plant (BoP) properly according to different assumptions. The auxiliaries(BoP) are composed of many different sub-components. However, this section of the inventory, modeled previously by Correa 2013 is based on Cooper 2004, presents the bill of materials necessary for all the auxiliaries without a distinction of the single components(Usai 2018). With lack of information from the shipping industry on BoP, and since the report used for scaling the parameters for this inventory did not include adequate information about the BoP, it is assumed that the assumptions and data used are still well aligned with the literature regarding FC, and it can, therefore, be considered robust.

Something that can be seen upon as a tiny error for this model is that when the FC system becomes more powerful, more coolant is needed to maintain the system below the maximal operating temperature. Therefore, the fluid is scaled linearly according to the net power output of the system. One needs to have in mind that this model originally is made for sizes suited for vehicles.

Furthermore, at the moment, due to the low number of Hydrogen ships produced, although there are many test projects, there is no data from the manufacturers. Therefore, this inventory, as all the inventories for FC systems in the literature, is based on assumptions. This is a major limitation of the study, but the assumptions and data used for this inventory are well aligned with the literature, and therefore can be considered robust.

The FCs are assumed to have a life of 30000-50000 operating hours under the described load profiles. This corresponds to 4-6 years for the Hydrogen FC HSC in the Trondheim-Kristiansund route. In this model, it is assumed one set of FC for the base case. The replacement of FCs due to lifetime is a part of the sensitivity analysis and is further discussed in section 5.

The former model was based upon an 80KW FC, the starting point of the project thesis systems fuel cell was 240kW. For the purpose of this thesis, the system was scaled to a 200kW and the result multiplied by the number of modules (14). Although it is a big difference in how much energy the system delivers, the basic components of the fuel cell are still the same. In addition to up-scaling the previous system from 80kW to 2800kW, there has been modeled for storage of Hydrogen in terms of a Hydrogen tank made of CF, this is discussed further in section 4.3.5.

For the base case, it is assumed one set of FC during the lifetime of the HSC set to 15 years. A sensitivity analysis due to lifetime of batteries, FC and engines is conducted, see section 5

Due to confidentiality reasons, the inventory for the FC cannot be shared.

4.3.5 Hydrogen tank

The Hydrogen tank represents the biggest part of the total weight for a Hydrogen based energy system. The system becomes bigger than it is for a traditional propulsion system with Diesel motors, but is not critical for either speed or total weight for a high-speed passenger catamaran(Strømgren et al. 2017)

Among all introduced green alternatives, Hydrogen, due to its abundance and diverse production sources is becoming an increasingly viable clean and green option for transportation and energy storage.(Moradi and Groth 2019; Pivovar, Rustagi, and Satyapal 2018; Tronstad et al. 2017). Most studies still reveal that the technology that is holding FC back is the Hydrogen storage (Niaz, Manzoor, and Pandith 2015; Andersson and Grönkvist 2019). However, according to (Strømgren et al. 2017) one can save up to 30-35% of the weight by choosing tanks for liquid Hydrogen in comparison with tanks for pressurized Hydrogen.

Brødrene Aa has chosen hexagon's Hydrogen tanks. The tanks are made of CF.

The biggest tanks from Hexagon has a capacity of 153kg and a weight of 2400kg. This tank is chosen for Aero42H2 for the route Trondheim-Kristiansund. As shown in table 16, the boat will have installed four of these tanks with a total capacity of 612kg Hydrogen.

Table 16: Key Data Hydrogen tank

Tank material	Carbon fiber
Amount of tanks	4
Type	Hexagon Titan XL38ft
Producer	Hexagon
Capacity	612 kg Hydrogen
Pressure	250 bar
Wight(one tank)	2400 kg
Volume	85000 m^3
L/kg	55,6
H2 capacity	152,88 kg
System weight	7064 kg

In this model, the tanks are modeled as 4*2400kg= 9600 kg CF. The CF is modeled by the same Ecoinvent processes as the hull, shown in table 4.

4.3.6 Battery production

To get to the right amount of efficiency and to help the hybrid system a battery is a part of Aero42H2. The energy requirement is the gross value of the supplied energy, ie. the sum of the energy content of the bunkered amount of Hydrogen and electrical energy supplied to the batteries when charging from the land.

The batteries are assumed to be a substantial part of the impacts associated with a Hydrogen based energy system. Aero42H2 has a battery capacity of

672 kWh installed onboard.

Industrial ecology (IndEcol) at NTNU has been developing an inventory for a Lithium-ion battery for EVs. The inventory is based on Lithium-ion battery data from the study by Ellingsen et al. 2014: Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack. The model has the modeling option of a range from 1 to 100kWh. To get emission information for a battery with a size of 672 kWh, calculations for a battery of 72 kWh and 100 kWh was conducted and added to the right amount of kWh.

To secure the lifetime of the batteries, Strømgren et al. 2017 has pointed out that in the scenario modeled the charge state of the batteries is kept relatively high, which results in a small reduction in capacity over the life of the batteries. The battery is sized to provide enough capacity to receive energy from the fuel cell while stopping along the route without taking down the load from the cells. For optimum service life, fuel cells should be operated with the most constant power possible(Strømgren et al. 2017). The battery pack of 672 kWh gives the Aero 42H2 the range at a minimum of 20 nautical miles with a speed of eight-knot. This range is sufficient for the vessel from any position on the route to reach different ports with a good margin if there is a functional failure in the Hydrogen-based energy system. This is according to Strømgren et al. 2017 an important feature of the chosen solution.

For the base case, it is assumed one battery during the lifetime of the HSC set to 15 years. A sensitivity analysis due to lifetime of batteries, FC and engines is conducted, see section 5

Due to confidentiality reasons, as for the FC, the inventory for the battery cannot be shared.

4.3.7 Engine production

Electric motor: Hydrogen FC HSC

With the use of FC, the Hydrogen is converted into electrical energy that can propel a propeller via an electric motor.

The Aero42H2 is said to have an electrical motor of 2x1300 kW. The engine type or model was not stated. By looking at vessels needing the same amount of motor capacity, the Marelli MJR450L generator from Scandinavian Electric System was found.

The electrical motor is modeled based on the weight of Marelli MJB450 electric motor, with a weight of 3600 kg (MarelliMotori 2018).

Diesel motor: Conventional Diesel HSC

MS Tyrhaug and MS Terningen has 2xMTU 16V 2000 M72 of 1440 kW as main engine, this engine has a weight of 2400kg(NOGVA 2014).

The modeling of engines for each HSC type is shown in table17.

Assuming only one engine used over the HSC lifetime may underestimate the impacts as engines have extensive maintenance every 1200h run, where multiple parts are changed. Fast-running Diesel engines are according to Strømgren et al. 2017, usually replaced after 3-5 years of operation.

A sensitivity analysis has been conducted taking into account the engines lifetime, section 5.3.

Table 17: Modeling of Engines

Background name(Ecoinvent)	Geography	Unit
Internal combustion engine, for passenger car, production	GLO	kg
Electric motor, vehicle, production	RER	kg

4.4 Fuel Chain

4.4.1 Production of Hydrogen

Over 95 % of the current Hydrogen production is fossil-fuel based, using oil, coal, or gas as the energy source. Reforming natural gas is the most dominant production form and most cost- and energy-efficient. About 4 % is produced by electrolysis where electricity is used to split water into Hydrogen and oxygen(NCE maritime CleanTech 2019).

Norway has according to NCE maritime CleanTech 2019 large amounts of both natural gas, 121 billion Sm^3 in 2018, and about 10 TWh of surplus hydropower in 2018. Thus, from an energy perspective, Norway is well suited to produce Hydrogen from both gas reformation with CCS and electrolysis.

Electrolysis is the technology chosen for the modeling of Hydrogen production in this thesis. The model of electrolysis is by Lundberg 2019. The model was adjusted according to the FU(361 kg Hydrogen). which is the Hydrogen needed for one crossing.

The complete life cycle of an electrolyzer includes, according to Lundberg 2019, four phases, plus the transports added between these phases. The four life cycle phases are; producing the raw materials, manufacturing of components and the electrolyzer, producing the Hydrogen, and finally waste handling.

The study by Lundberg 2019 includes the three first main steps; raw material extraction, manufacturing of the electrolyzer, and production of the Hydrogen. Figure 8 shows the system boundary set by Lundberg 2019. This thesis follows the same modeling.

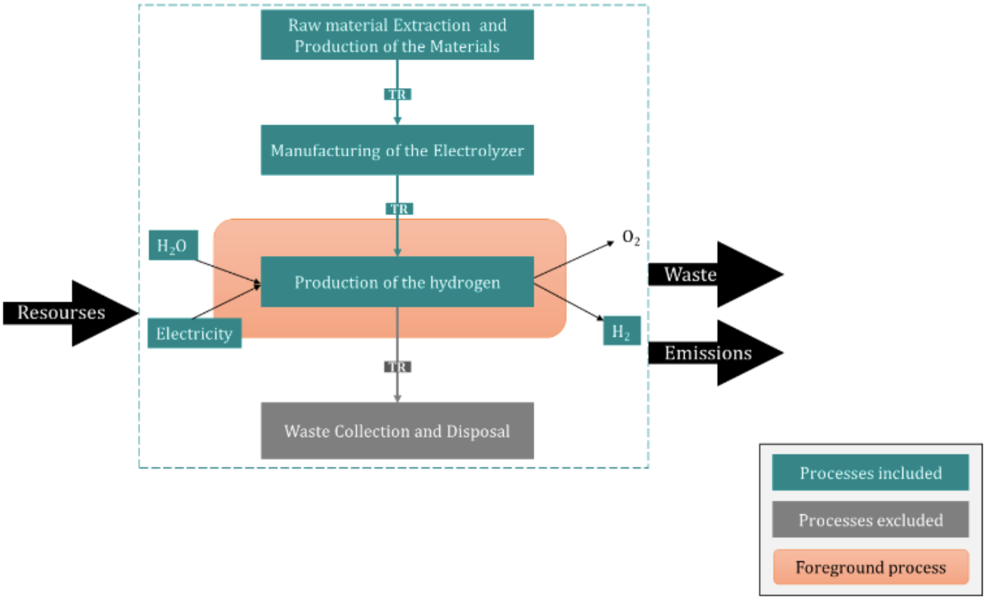


Figure 8: System boundary of the LCA for the electrolysis (Lundberg 2019)

The processes used for this thesis are from Ecoinvent and are presented in table 18. There are done some minor changes to the model, where some of the processes had to be adjusted to similar Ecoinvent processes. Lundberg 2019 original inventory is found in Appendix C.

4.5 Use Phase

The use phase is divided into two groups. Direct- and indirect emissions.

Table 18: Electrolysis

Background name (Ecoinvent)	Geography	Unit
PEM-Electrolysis production		
titanium, primary/titanium production, primary	GLO	kg
aluminium, primary, ingot/aluminium production, primary	EU27, EFTA	kg
selective coat, stainless steel sheet, black chrome/market for selective coat	GLO	m^2
sheet rolling, copper/sheet rolling, copper	RER	kg
polyethylene, high density, granulate/market for polyethylene	GLO	kg
spent activated carbon with mercury/market for spent activated carbon with mercury	GLO	kg
platinum/market for platinum	GLO	kg
transport, freight, lorry 16-32 metric ton, EURO5	RER	tkm
electricity, high voltage/market group for electricity, high voltage	RER	kWh
PEM-Electrolysis Hydrogen production		
water, deionised, from tap water, at user/market for water	GLO	kg
transport, freight, lorry 16-32 metric ton, EURO5	RER	tkm
PEM-Electrolysis Hydrogen electricity		
electricity, high voltage/market group for electricity, high voltage	RER	kWh

Direct emissions are the emissions that are often most focused upon. It is often the use phase that is used as an argument to change to Hydrogen FC propelled systems. This is because FCs have zero direct emissions during the operational phase. However, it is important to not forget the indirect emissions. Indirect emissions consist of fuel production. This represents the production of Diesel for the Conventional Diesel HSC and the production of Hydrogen for the Hydrogen FC HSC.

The FU is one crossing, meaning the distance of Trondheim-Kristiansund. It is stated by Fabricius and Fylkeskommune 2018 that MS Terningen/ MS Tyrhaug uses 1700 liters of Diesel per crossing. This equals 1428 kg Diesel.

Consumption of Hydrogen by normal operating pattern (stretch Trondheim-Kristiansund) is 361 kg Hydrogen for Aero42H2(Strømgren et al. 2017).

Indierct emissions: Production of the fuel

In this model, the indirect emissions due to the production of 361 kg Hydrogen is accounted for. This is the amount of Hydrogen needed for one crossing of the route Trondheim-Kristiansund. In this thesis production of Hydrogen through electrolysis was chosen, see section 4.4.1. The Diesel propulsion system is accounted for by taking into account both the production and combustion of Diesel. It is assumed that MS Terningen/MS Tyrhaug uses 1428 kg of Diesel for one crossing. It is assumed low-sulfur Diesel.

The indirect emission of Diesel is modeled with the Ecoinvent process shown in table 19.

Table 19: Diesel Process

Background name(Ecoinvent)	Geography	Unit
market for Diesel, low-sulfur	Europe without Switzerland	kg

Direct emissions: Operation of the HSC

To calculate the direct emissions due to combustion the emission factors from C. Ianssen, E. Ianssen, and Sandblost 2017 was used, table 20. CO2, NOx, and SO2 are the emissions accounted for.

Table 20: Emission factors

Gas	Factor	Ratio
CO2	3,17	ton/tonne
SO2	1,054	kg/tonne
NOx	35	kg/tonne

4.6 End of Life

As stated at the beginning of this section, the End of life emissions were not modeled for in this thesis. The dismantling of carbon-fiber and the end-of-life treatment of the different components of the HSCs is a large field and could have been a study in itself.

There has in recent years been shown a bigger interest in what happens to ships after their useful life. Such vessels can lead to pollution, navigational hazards, and removal costs for marinas, ports, and recreational craft owners(RYA 2014).

Recreational crafts that are at the end of their useful life need to be disposed of in a safe and environmentally responsible manner(RYA 2014).

Norway has played a key role in the development of a binding international ship dismantling regulations, and as the first country addressed the problem of unsustainable conditions in the ship dismantling industry in the United Nations Maritime Organization IMO in 1999 (Sjøfartsdirektoratet 2015).

In addition to the dismantling of ship hulls, recycling of FCs and batteries are important aspects of a ship's lifetime. And could show interesting results in terms of an LCA.

End of life is not discussed further in this thesis as the thesis focus on the LCA of the production and operation phase of the HSCs.

5 Sensitivity analysis

A sensitivity analysis of important parameters was performed to investigate the dependency between input and results. Electricity mix for Hydrogen production, the material used for carbon-sandwich hull, battery-, FC- and engine life were the parameters varied.

5.1 Hydrogen production: Electricity Mix

The base case in this model is Hydrogen produced by the Norwegian electricity mix.

Various literature has pointed out the importance of how the Hydrogen is produced, but also what type of electricity that is used has been shown to be of great importance.

The aim of the sensitivity analysis was to evaluate the change in the Hydrogen production environmental impact by comparing electricity mixes used during Hydrogen production. Previous studies have concluded the large impact of the energy source. Amongst them are Lundberg 2019 and NEEDS 2008.

As previously stated, electricity is added in the manufacturing of the electrolyzer and to Hydrogen production, section 4.4.1. In the sensitivity analysis, the electricity mix is changed during the Hydrogen production phase. Hydrogen production is a large electricity consumer in the life cycle perspective and, therefore, potential changes might contribute much to the overall result (Lundberg 2019).

This sensitivity analysis was conducted in two steps. First, the potential environmental impact from supplying the electrolyzers with Norwegian Electricity mix was compared to supplying them with other electricity mixes: European average(RER el-mix), UCTE el-mix, NORDEL el-mix and as an extreme the Chinese el-mix. This was chosen since the available energy supply differs dramatically among regions and countries. Norwegian electricity mix has, for example, a large amount of renewable energy, whereas China has more energy sourced from fossil resources.

The Norwegian supply mix consists of 98% hydropower, making it one of the electricity mixes with the largest proportion of renewable energy. The NORDEL production mix is the product mix of the countries Denmark, Norway, Sweden, and Finland. The UCTE (Union for the Coordination of the Transmission of Electricity) consists of many countries in the continental Europe(Kullmann 2016).

The second step of the sensitivity analysis was to compare different electricity sources from Norway. This to evaluate and to recommend the best energy source to power the electrolyzer with. The chosen energy sources for the comparison were the wind, oil, and natural gas.

Results in terms of GWP are shown and discussed in section 6.3.1, while results in terms of all impact categories can be found in Appendix D.

5.2 Hull Material

As stated in section 4.3.1, There are modeled for two types of the hull. One with glass fiber(GF) and waste polystyrene. The other with carbon fiber(CF) and bisphenol A (BPA) epoxy Vinyl Ester Resins (VER). The CF sandwich is the base case for this thesis.

As stated in section 4.3.1, Aero42H2 is a CF sandwich catamaran. The development of lighter hull material has been of great importance for HSCs.

GF was the most common composite option for HSC for a long period, but with quality improvement by vacuum injection and reduced CF prices, CF has taken over carbon sandwich (Evenstad 2017). In this connection, it is modeled for two types of the hull. CF sandwich hull and FG sandwich hull.

The result is presented in section 6.3.2.

5.3 Lifetime: Baterry, Fuel Cell, Engine

Various manufacturers state fuel cells (FC) for Hydrogen to have a service life of 30000-50000 hours of operation before planned replacement. This requires smooth operation on the fuel cells, which in turn necessitates battery packs on board to take load variationsStrømgren et al. 2017. This corresponds to 4-6 years of FC lifetime for the vessel in the Trondheim-Kristiansund route. Fast-running Diesel engines are according to Strømgren et al. 2017, usually replaced after 3-5 years of operation

Due to this, it is conducted a sensitivity analysis that takes into account the lifetime of FCs, batteries, and Diesel-engine.

The analysis looks at the impacts due to the maintenance and shifting of these components. The results are shown in section 6.3.

5.4 Efficiency/Fuel Use

Energy consumption and Diesel consumption for the HSCs MS Terningen and MS Tyrhaug is based upon numbers from Fabricius 2019. Several studies have looked upon the route from Trondheim-Kristiansund. Some of these studies give different numbers for fuel use regarding Terningen/Tyrhaug.

- Base case: 17,9 liter/nm (Fabricius and Fylkeskommune 2018)
- 17-19 liter/nm (Strømgren et al. 2017)
- 26 liter/nm (Hirth et al. 2017)

To take these errors into account there has been conducted a sensitivity analysis.

An assumption was the efficiency of an HSC engine. An HSC Diesel engine has a specific consumption of 0.210 kg / kWh. The power output of the vessel will then be 6800 kWh per crossing (3.5 hours). The sensitivity analysis has taken into account an increase/decrease in the efficiency of this motor by 10%.

Results from these sensitivity analyses can be found in section 6.3.

In the next section, the results are presented.

6 Results

In this chapter the results from the Previously discussed LCA model is provided. All emissions are in terms of the FU. The FU is set to one crossing, meaning the boats traveling the distance from Trondheim to Kristiansund. The HSCs Aero42H2 and Terningen/Tyrhaug are referred to as "Hydrogen FC HSC" and "Conventional Diesel HSC". Note that the Aero42H2 system is a battery and hydrogen powered fast ferry, but is referred to as Hydrogen FC HSC.

The results are first presented with focus on global warming potential (GWP) in section 6.1, before the impact for each HSC is presented in terms of all impact categories in section 6.2. In the end a sensitivity analysis is conducted. The result of the sensitivity analysis is presented in section 6.3.

6.1 Global Warming Potential

6.1.1 Total Emissions

The total emissions in term of the FU for the two HSCs can be seen in figure 9. The total emission is divided in three categories; production of HSC, Fuel production and operation of HSC.

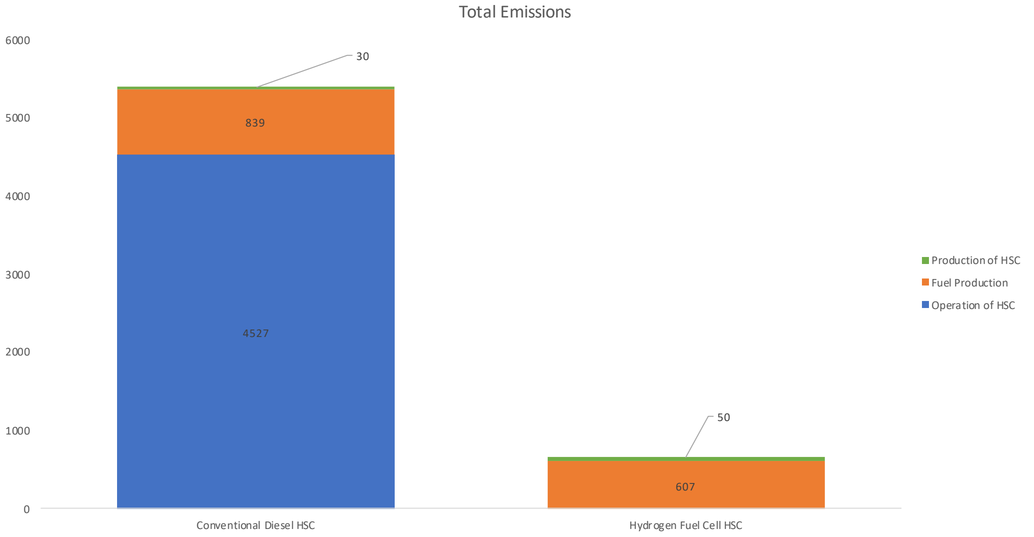


Figure 9: Comparison of total emissions for the HSCs [kg CO2 eq/crossing].

The Conventional Diesel HSC dominates the emissions. The overall total emissions are 5396 kg CO2-eq/crossing for the Conventional Diesel HSC,4527kg

CO2-eq/crossing for operation, 839 kg CO2/crossing for Diesel production and 30 kg CO2-eq/crossing for the production of the Conventional Diesel HSC. The Hydrogen FC HSC emit only 657 kg CO2-eq/crossing. With 607 kg CO2-eq/crossing linked to the Hydrogen production and 50 kg CO2-eq/crossing due to production of the Hydrogen FC HSC. This yields that the Diesel HSC emits 88% more CO2-eq/crossing than the Hydrogen FC HSC.

Operation of the Conventional Diesel HSC has the largest contribution to emissions with 84% of the emissions. The impacts due to production of the Diesel fuel is a small percentage of the total Diesel HSC emissions, however when compared to the Hydrogen FC HSC is still bigger than the total emissions of the Hydrogen FC HSC. For the Diesel HSC, production of the boat only yields 0.6% of the total emissions.

Use phase is the largest contributor to emissions for both vessels. For the Hydrogen FC HSC indirect emissions linked to Hydrogen production stands for 92% of the total emissions. This leaves the production of the boat with 8% of the total emissions.

6.1.2 Use Phase

Use phase is divided into two groups. Direct- and indirect emissions.

The direct emissions are the emissions that is often most focused upon. Its often the use phase that is used as an argument to change to Hydrogen FC propelled systems. This is because FC have zero direct emissions during the operational phase. However, it is important to not forget the indirect emissions. The indirect emissions consist of fuel production. This represents the production of Diesel fuel for the Conventional Diesel HSC, and the production of Hydrogen for the Hydrogen FC HSC.

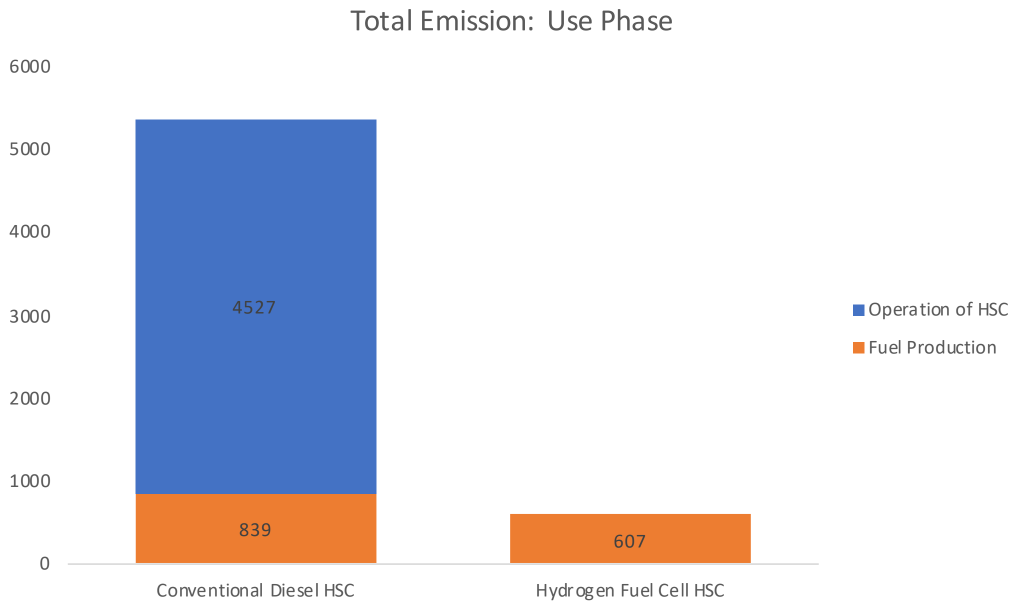


Figure 10: Comparison of total emissions for the HSCs: Use phase [kg CO2 eq]

Diesel fuel production is explained in section 4.5. The Diesel fuel process data is from Ecoinvent and consists of “Transportation of product from the refinery to the end user. Operation of storage tanks and petrol stations. Emissions from evaporation and treatment of effluents. Excluding emissions from car-washing at petrol stations.» In addition, there is energy associated with removing sulfur from the Diesel. Which makes the emissions somewhat higher for low sulfur Diesel for GWP100 compared to regular Diesel. Diesel production contributes with 839 kg Co2-eq/crossing.

One of the main focuses when it comes to Hydrogen FC technology is that FC have no emissions during the use phase. As mentioned earlier, and shown in figure 10, the Hydrogen HSC has emissions in use phase in terms of indirect emissions . The indirect emissions are linked to the production of the Hydrogen and is 607 CO2-eq/crossing.

Hydrogen production contains of the the processes PEM-Electrolysis production, PEM-Electrolysis Hydrogen production and PEM-Electrolysis Hydrogen electricity and are presented in section 4.4.1. It is the electricity required that is the most essential process in terms of emissions for Hydrogen production. This was first presented in section 4.4 and is further discussed in the presentation and results of the sensitivity analysis, section 5 and 6.3.1.

Emissions due to the combustion of fuel is also considered. These are the direct emissions. As seen from figure 10 and discussed in the previous section, the operational phase dominates the emissions for the Conventional Diesel HSC with 4527kg CO2-eq/crossing.

6.1.3 Production Phase

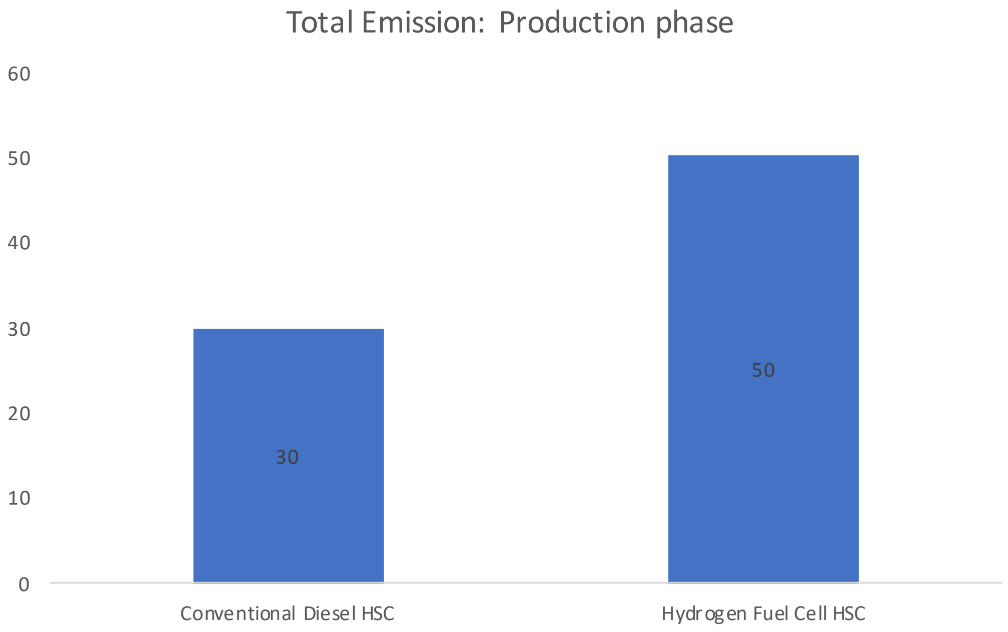


Figure 11: Comparison of total emissions for the HSCs: Production phase [kg CO2-eq/crossing]

Figure 11 gives the total emissions due to production phase in terms of kg CO2-eq/crossing.

The literature has requested a fulfilling model that look at the upstream emissions. It is clear from the previous section, that Hydrogen FC system is feasible and can match and even conquer a Conventional Diesel propelled system in terms of emissions, if the Hydrogen is produced by green options.

It is known that FC systems need to take into account the emissions in terms of FC an battery production, including the Hydrogen tank.

By looking at the production phase separately, this concern is warranted. It is seen that the Hydrogen vessel has the highest emissions due to production.

A closer look at the numbers shows that in total, the production of the Hydrogen FC HSC emits 50 kg CO2-eq/crossing, while the production Conventional Diesel vessel emits 30 kg CO2-eq/crossing. The Hydrogen FC HSC has bigger emissions linked to the production phase than the Conventional one. In this thesis the Hydrogen FC HSC emits 67% more in the production phase than the Conventional Diesel one.

If we compare this to the overall emissions, the production phase does not seem to matter that much, as long as the Hydrogen is produced by a viable and clean option.

Table 21: Total Emissions by component [kg CO2-eq]

	Hydrogen Fuel Cell HSC	Conventional Diesel HSC
Hull Glassfiber sandwich	1,1	1,1
Hull Carbon fibre sandwich	26,7	26,7
Engine production	1,4	2,8
Electronics	0,2	0,2
Windows	0,02	0,02
Chairs	0,4	0,3
paint	0,1	0,1
Battery	4,2	
Fuel Cell	4,9	
Hydrogen Tank	12,5	

The marine society has for a longer time worked on design of HSC with Hydrogen FC system to ease the weights of the components.

Table 21 shows the emissions due to climate change for each of the components modeled for each of the HSCs. For results due to all impact categories, see section 6.2.

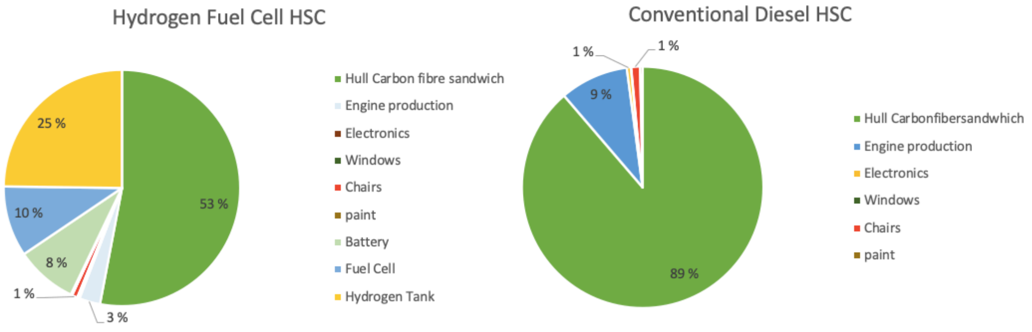
As explained in section 4. The hull, electronics and windows have the same input values. This means that the emissions from these components does not participate in separating which system is the best. They give a impression of which components are the most emission intensive.

For the Hydrogen HSC the hull is 53% of the emissions in production phase. For the Conventional Diesel HSC the hull contribute to 79% of the emission due to production. The Hydrogen tank is ranked number two for the Hydrogen HSC with 23% of the emissions. Both hull and Hydrogen tank is modeled with CF. CF is a material with extremely high emissions/kg produced. The material emit 41 kg co2-eq/kg CF produced. This is because CF need a lot of energy to be produced. You need 118 MJ of heat (30 kWh) and almost 40 kWh per kg of CF (James et al. 2016).

It is mainly due to the Hydrogen tank, FC and battery that the Hydrogen HSC has the highest production emissions. Of these the Hydrogen tank dominates. The literature has focused a lot on trying to reduce the weight of the tanks for storage of Hydrogen. While CF is a light material in terms of weight, it is carbon intensive. See discussion, section 7

The big picture tells us that it is the production of the hull and the Hydrogen tank that dominates the emissions in the production phase.

Figure 12 gives the distribution of the production emissions for the both HSCs; Aero42H2 To the left and Terningen/Tyrhaug to the right.


Hydrogen Fuel Cell HSC

Conventional Diesel HSC

Figure 12: Component Share of Emissions: Production of Hydrogen FC HSC to the left and Conventional Diesel HSC to the right

The left graph in figure 12 show the percentage share of each component for the production of the Hydrogen FC HSC; The carbon fibre hull has the largest share of emissions with 53%, followed by the Hydrogen tank with 25%. The FC and battery contributes to 10%, 8% of the emissions. For the Conventional Diesel HSC to the right, the hull is responsible for 89% of the emissions. The engines, paint and chairs contributes by 9%, 1% and 1%.

6.2 ReCiPe midpoint indicators

In this section, the 18 midpoint impact categories calculated in ReCiPe are reported. The results are both presented quantitative in table and graphically as bar charts. First a 100% bar chart demostrating the comparison between the two vessels are presented in figure 13. Then there are individual tables and charts for each of the vessels. Emissions due to the Conventional Diesel HSC is presented in table 22, and figure 14, while emissions for the Hydrogen FC HSC is presented in table 23 and figure 15. This is done to give a clearer picture of where the focus area should be. Lessons from LCA has shown the importance of looking at a system with a holistic view. The different impact categories are not studied in detail, but rather reviewed for their overall significance.

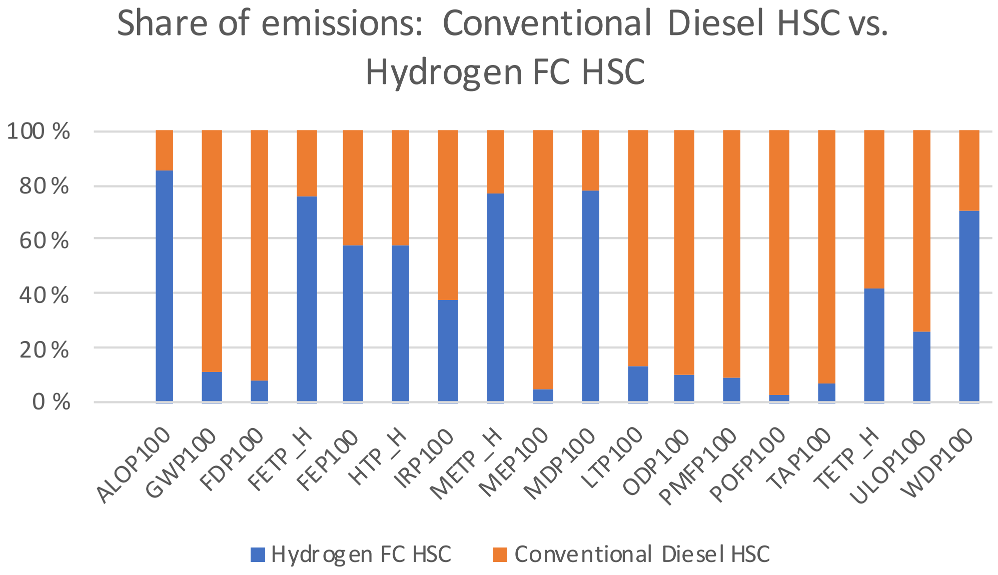


Figure 13: All impact categories:Bar Chart-Comparison between the Conventional Diesel HSC and the Hydrogen FC HSC

In figure 13 it shows that the Conventional Diesel HSC dominates most of the impact categories with 11/18. The Hydrogen FC HSC dominates 7/18 impact categories.

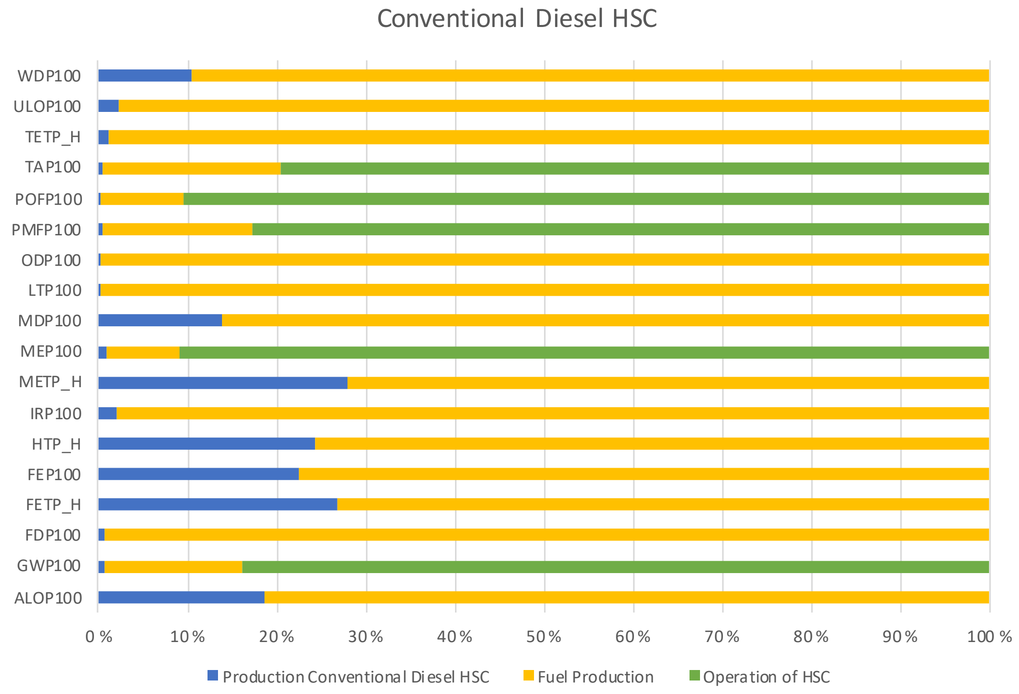


Figure 14: Component Share of Emissions in all impact categories for the Conventional Diesel HSC.

The Conventional Diesel HSC is presented in table 22, and figure 14. For the Conventional Diesel HSC we see that it is emissions from the use phase that dominates. Emissions from either Diesel production or operation of the HSC dominates all impact categories.

Table 22: Characterisation factors for all impact categories for the Conventional Diesel HSC.

Impact Id	Unit	Production Conventional Diesel HSC	Fuel Production	Operation of HSC
ALOP100	m2a	4,75E+00	2,06E+01	0,00E+00
GWP100	kg CO2 eq	3,36E+01	8,39E+02	4,53E+03
FDP100	kg oil eq	1,12E+01	1,85E+03	0,00E+00
FETP_H	kg 1,4-DB eq	2,28E+00	6,27E+00	0,00E+00
FEP100	kg P eq	3,51E-02	1,20E-01	0,00E+00
HTP_H	kg 1,4-DB eq	4,44E+01	1,38E+02	0,00E+00
IRP100	kg U235 eq	7,45E+00	3,72E+02	0,00E+00
METP_H	kg 1,4-DB eq	2,03E+00	5,25E+00	0,00E+00
MEP100	kg N eq	2,00E-02	1,73E-01	1,95E+00
MDP100	kg Fe eq	4,67E+00	2,92E+01	0,00E+00
LTP100	m2	3,04E-03	1,87E+00	0,00E+00
ODP100	kg CFC-11 eq	2,89E-06	9,91E-04	0,00E+00
PMFP100	kg PM10 eq	6,23E-02	2,30E+00	1,13E+01
POFP100	kg NMVOC	9,65E-02	5,15E+00	5,01E+01
TAP100	kg SO2 eq	1,52E-01	7,48E+00	2,95E+01
TETP_H	kg 1,4-DB eq	4,72E-03	3,90E-01	0,00E+00
ULOP100	m2a	2,61E-01	1,18E+01	0,00E+00
WDP100	m3	3,36E+00	2,87E+01	0,00E+00

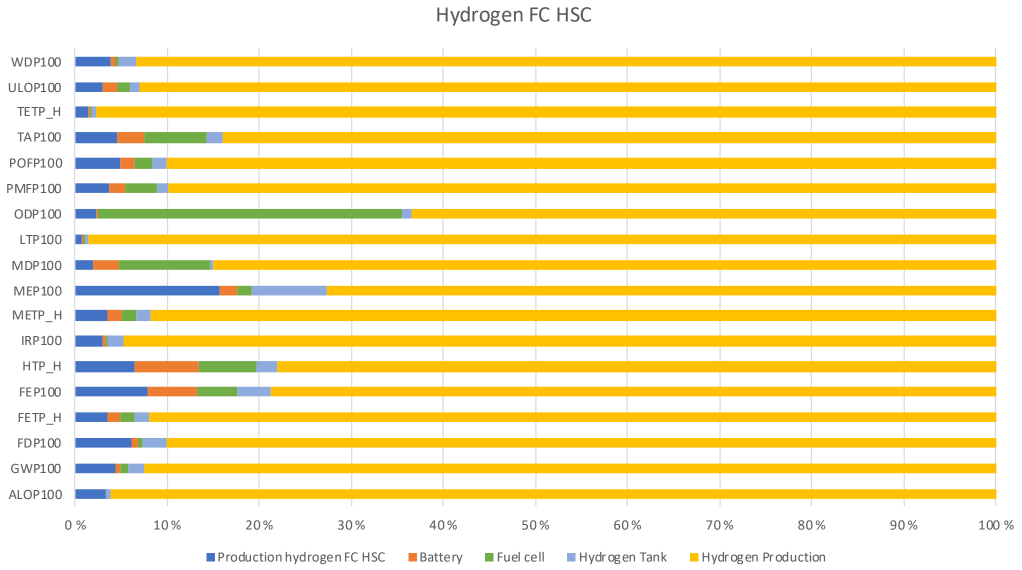


Figure 15: Component Share of Emissions in all impact categories for the Hydrogen FC HSC.

For the Hydrogen FC HSC table 23 and figure 15, it is the Hydrogen production that dominates the impact categories. Among these categories we see a bigger share of toxicity impacts. Figure 15 show that it is mainly the production of Hydrogen that dominate every impact category.

Table 23: Characterisation factors for all impact categories for the Hydrogen FC HSC.

impact Id	Unit	Production Hydrogen FC HSC	Battery	Fuel cell	Hydrogen Tank	Hydrogen Production
ALOP100	m2a	4,69E+00	1,21E-01	9,93E-02	7,47E-01	1,38E+02
GWP100	kg CO2 eq	2,88E+01	4,24E+00	4,87E+00	1,25E+01	6,14E+02
FDP100	kg oil eq	9,91E+00	1,12E+00	1,02E+00	4,20E+00	1,48E+02
FETP_H	kg 1,4-DB eq	9,25E-01	3,86E-01	4,10E-01	4,18E-01	2,47E+01
FEP100	kg P eq	1,67E-02	1,14E-02	9,52E-03	7,52E-03	1,68E-01
HTP_H	kg 1,4-DB eq	1,59E+01	1,73E+01	1,55E+01	5,41E+00	1,92E+02
IRP100	kg U235 eq	6,86E+00	8,62E-01	2,44E-01	3,98E+00	2,19E+02
METP_H	kg 1,4-DB eq	8,39E-01	3,57E-01	3,77E-01	3,75E-01	2,19E+01
MEP100	kg N eq	1,82E-02	2,11E-03	1,79E-03	9,53E-03	8,42E-02
MDP100	kg Fe eq	2,30E+00	3,43E+00	1,23E+01	2,79E-01	1,04E+02
LTP100	m2	2,24E-03	5,52E-04	3,57E-04	1,03E-03	2,94E-01
ODP100	kg CFC-11 eq	2,49E-06	2,83E-07	3,70E-05	1,33E-06	7,11E-05
PMFP100	kg PM10 eq	4,76E-02	2,37E-02	4,56E-02	1,54E-02	1,18E+00
POFP100	kg NMVOC	7,60E-02	2,23E-02	2,92E-02	2,42E-02	1,38E+00
TAP100	kg SO2 eq	1,26E-01	8,08E-02	1,86E-01	4,85E-02	2,30E+00
TETP_H	kg 1,4-DB eq	4,08E-03	5,28E-04	3,09E-04	1,78E-03	2,77E-01
ULOP100	m2a	1,24E-01	6,98E-02	5,42E-02	4,59E-02	3,90E+00
WDP100	m3	3,03E+00	3,73E-01	2,46E-01	1,52E+00	7,31E+01

6.3 Sensitivity Analysis

In this section the results from the sensitivity analysis is presented and partly discussed. There has been done sensitivity analysis due to modeling choices of the carbon fiber sandwich hull, battery-, FC- and engine lifetime, Engine effieciency and fuel use for the Diesel HSC. There is also an analysis due to the production of Hydrogen.

6.3.1 Sensitivity: Hydrogen Production

The assumption regarding the electricity source for Hydrogen production has been tested in a sensitivity analysis. The energy source for the base case is Norwegian electricity mix, the result has been compared towards a variation of countries electricity mixes plus energy sources origin in Norway. The result is presented as GWP(kg CO2-eq/crossing), figure 16. The results for the other categories are presented in Appendix D.

In the process of production of Hydrogen, electricity consumption is the most crucial in terms of emissions. Electricity is a process of emissions depending on the production method. This is illustrated in section 4.4. The sensitivity analysis of the choice of energy mix shows that electrolysis for Hydrogen production is very sensitive to the electricity used.

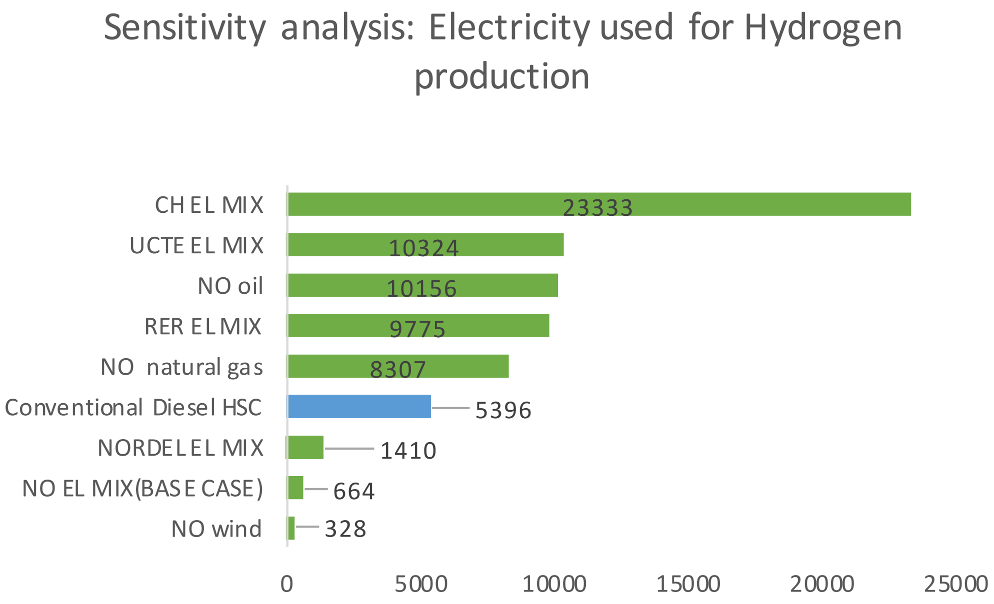


Figure 16: Sensitivity analysis: Electricity mix for Hydrogen production

A simple analysis shows that only Norwegian wind power, Norwegian electricity mix and NORDEL electricity mix make the Hydrogen FC HSC more attractive than the Conventional Diesel HSC (Shown as blue in figure 16). With increased power trade with the Nordic countries or Europe, the Hydrogen will soon have a bigger amount of energy from non-renewable sources than desired. We see that a shift towards European energy mix does not agree with the footprint of the Hydrogen FC HSC. The worst case scenario is set as production of Hydrogen by Chinese electricity mix. This scenario doubles the emissions in comparison with the UCTE electricity mix. The importance of electricity from renewable sources is the main take away.

This is illustrated by previous literature that the footprint of Hydrogen is highly dependent on the mode of production. The choice of modeling method here in terms of production by electrolysis and a setting with Norwegian electricity mix, clearly has a large impact for the results.

The energy source impacts the Hydrogen production life cycle performance dramatically and the result derives highly on the amounts of fossil vs. renewable energy sources. China's electricity mix is contributing to the highest values of CO2 equivalents. China's electricity mix consists of 75% coal and therefore has the greatest contribution to the Hydrogen production (23333 kg CO2-eq/crossing.), while Norwegian wind has the lowest(328 kg CO2-eq/crossing.). Norwegian wind- and electricity mix together with the NORDEL el-mix contributes to the lowest amounts. Note that these emissions are also taking into account the production of the rest of the HSCs, not just the Hydrogen production.

However, the results for the other impact categories indicates equal pattern to GWP, except abiotic depletion where Norwegian wind- and electricity mix contributes much, see Appendix D. The reason to the big impact on abiotic depletion is the large amount of non-renewable resources, deriving from the power plant constructions. We also see that the different el-mixes contributes in different categories. This has not been studied further. As this has been done by Lundberg 2019.

6.3.2 Sensitivity: Hull

The hull contributes by 53% and 89% of the emissions due to the production of the Hydrogen HSC and the Conventional Diesel HSC, respectively. The choice of producing the hull with CF is the main reason for these high emissions. A sensitivity analysis conducted by changing the CF hull with GF hull shows that the modeling choice is of importance. The CF hull gives 24%

more emissions than the GF hull. Figure 17 shows the total impact on the different modeling options in terms of kg CO2-eq/crossing. This is further discussed in section 5.2.

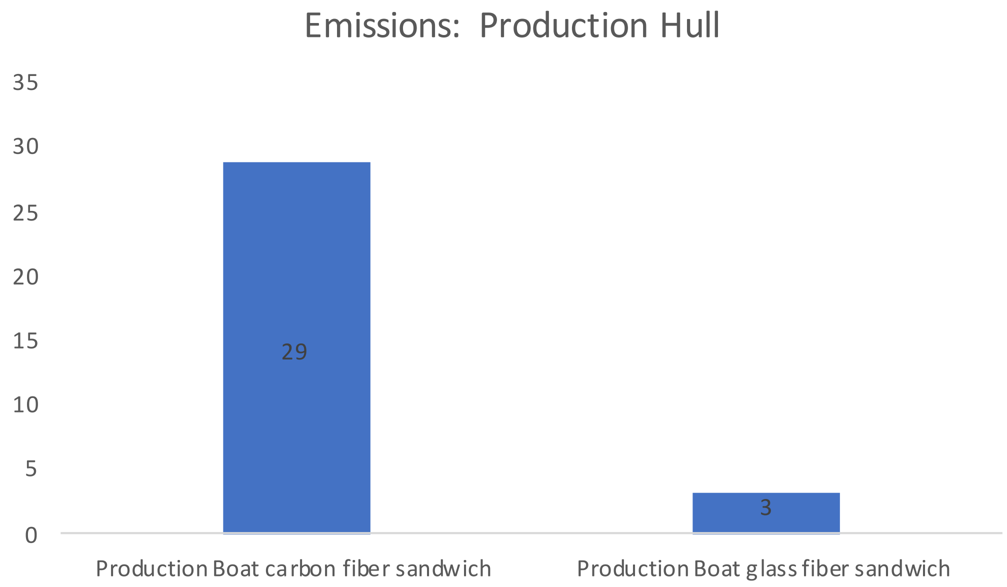


Figure 17: Sensitivity analysis: Hull material [kg CO2 eq]

CF is a material with extremely high emissions/kg produced. The material emits 41 kg co2-eq/kg CF produced. This is because CF needs a lot of energy to be produced. You need 118 MJ of heat (30 kWh) and almost 40 kWh per kg of CF (James et al. 2016). There is no doubt that CF costs a ton of energy to produce. According to Jennings 2015 it is about 14 times as energy-intensive as producing steel, and the creation process spews out a significant amount of GHG. On the other hand, CF does not corrode, degrade, rust, or fatigue. Which can give the material a much longer life cycle than other conventional hull materials (steel, aluminum, tree). This meaning it is potentially only produced once where a steel part would have to be replaced multiple times (Jennings 2015). Results for GF shows great mechanical strength but is not that robust compared to CF. The CF gives high emissions for both the hull and the Hydrogen tank. But gives savings in terms of weight which again translates to fuel saving. According to Toray group n.d. one can see that When the body structure of a car is made 30% lighter using carbon fiber, 50 tons of CO2 will be reduced per 1 ton of carbon fiber over a life cycle of 10 years; when the fuselage structure of aircraft is made 20% lighter using carbon fiber, on the other hand, 1400 tons of CO2 will be reduced under the same condition. The same rapport claims that "If passenger cars (42 million vehicles owned, excluding light automobiles) and passenger aircraft (430 planes owned) in Japan adopt carbon fiber to reduce weight and therefore improve fuel economy, 22 million tons of CO2 will be saved.". If this is true, and GF does not have the qualities needed, CF is maybe ok in reducing CO2 and contributing to the global environment(Toray group n.d.).

6.3.3 Sensitivity: Lifetime for Battery, Fuel Cell and Engine

As mentioned, FC and battery account for 10% and 8% of production emissions for the Hydrogen FC HSC. A sensitivity analysis was conducted to consider what happens if you include battery- and FC lifetime. A battery/FC lifetime of 15, 7.5, and 5 years is assumed, to give an insight into what this will mean for the total emissions.

In addition, it is also included impacts due to Diesel engine maintenance/replacement. As mentioned in section 4.3.7, Diesel engines are usually changed every 5 years. Here, as for battery and FC, the lifetime is chosen as 15, 7.5, and 5 years.

Battery lifetime
Figure 18 shows an increase in emissions due to different battery lifetime, while figure 19 gives the overall emissions for the Hydrogen FC HSC due to this, in comparison to the Conventional Diesel HSC.

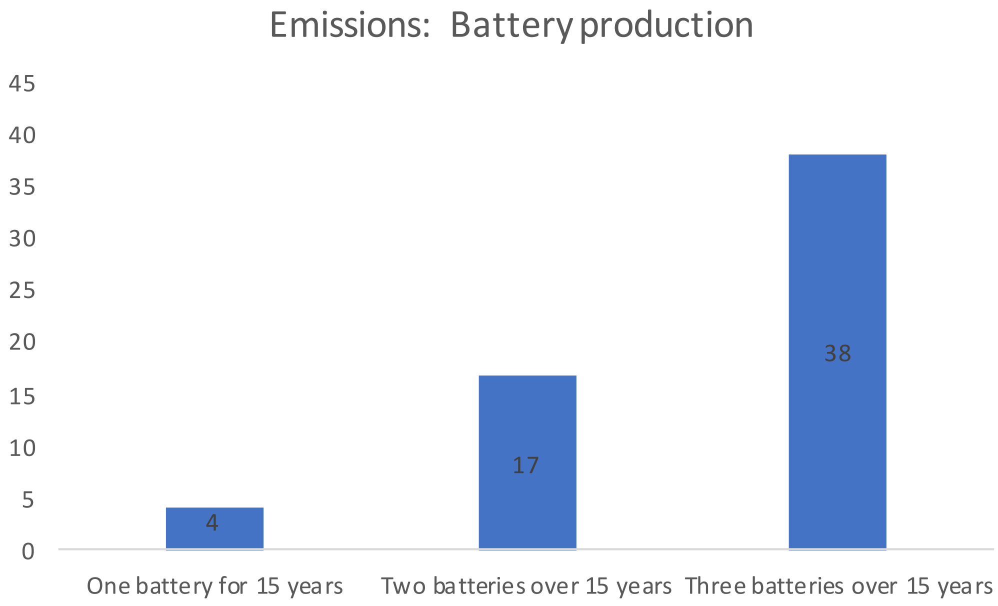


Figure 18: Sensitivity analysis: Battery lifetime

As seen in figure 19, although we need to take into account maintenance and replacement of batteries and FC, These additional emissions do not compare to the overall emissions by the Conventional Diesel HSC.

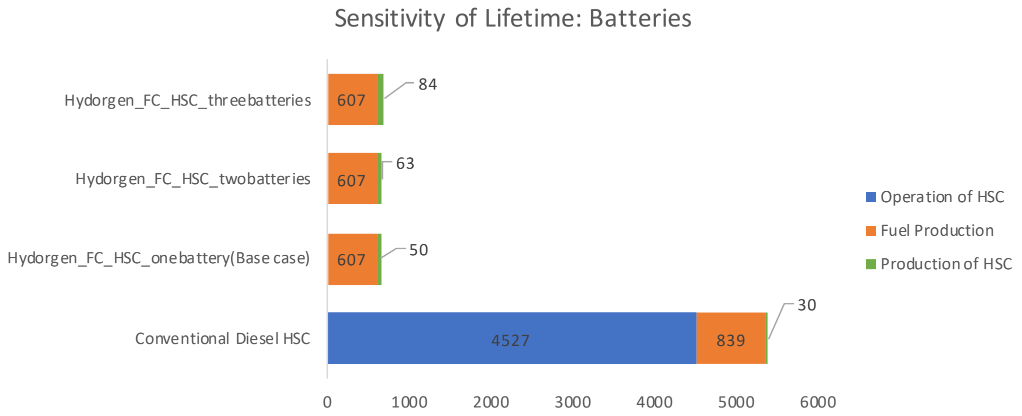


Figure 19: Sensitivity analysis: Battery lifetime for Hydrogen FC HSC in comparison with the Conventional Diesel HSC.

Battery, FC and Engine lifetime

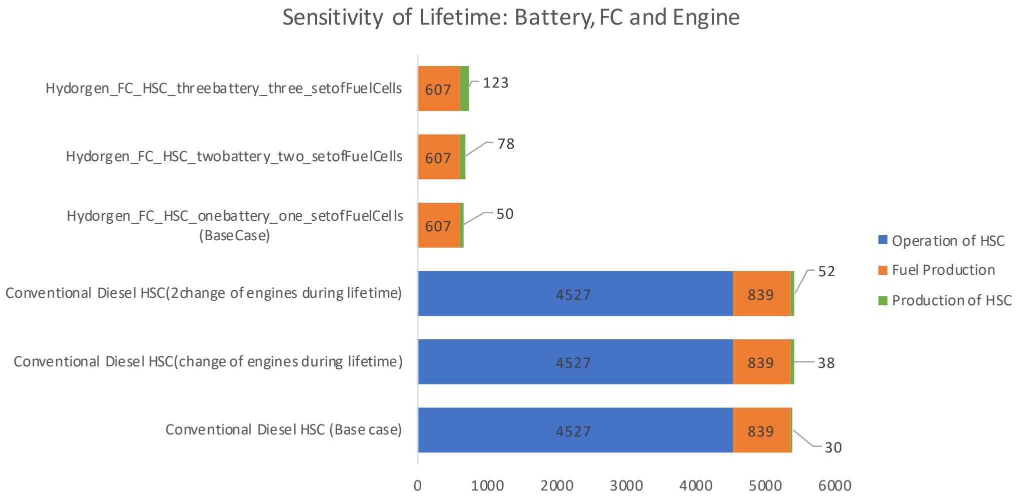


Figure 20: Sensitivity analysis: Battery, FC and Engine lifetime

Figure20 shows the overall emissions due to the replacement of batteries, FC, and engines in comparison. The main take away from this sensitivity analysis is that the assumption about not taking into account the lifetime of these components does not conflict with the overall result.

6.3.4 Sensitivity: Efficiency/Fuel Use

Energy consumption and Diesel consumption for the HSCs MS Terningen and MS Tyrhaug is based upon numbers from Fabricius 2019. Several studies have looked upon the route from Trondheim-Kristiansund. Some of these studies give different numbers for fuel use regarding Terningen/Tyrhaug.

- Base case: 17,9 liter/nm (Fabricius and Fylkeskommune 2018)
- 17-19 liter/nm (Strømgren et al. 2017)
- 26 liter/nm (Hirth et al. 2017)

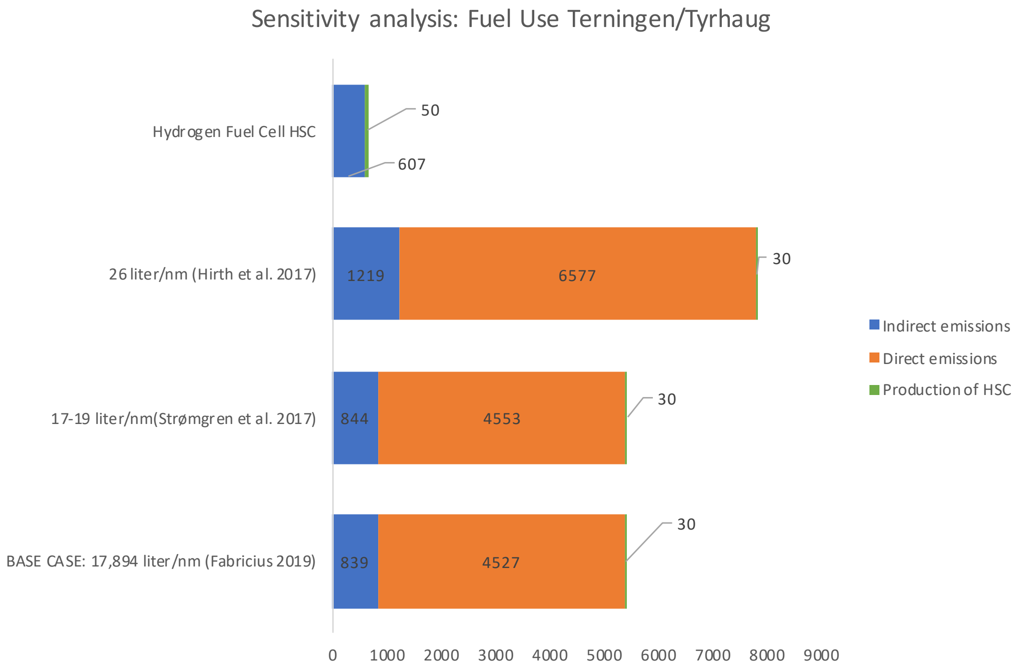


Figure 21: Sensitivity analysis: Diesel HSC Fuel Use

The outcome for different benchmarks in the literature is shown in figure 21. The base case gives the smallest amount of emissions. This means that the Diesel HSC may have much larger emissions than what is assumed in this report. This is important. Especially to have a fair comparison with the Hydrogen FC HSC and the importance of the way Hydrogen is produced.

An assumption was the efficiency of an HSC engine. An HSC Diesel engine has a specific consumption of 0.210 kg / kWh. The power output of the vessel will then be 6800 kWh per crossing (3.5 hours). The sensitivity analysis has taken into account an increase/decrease in the efficiency of this motor by 10%. The results are shown in figure 22.

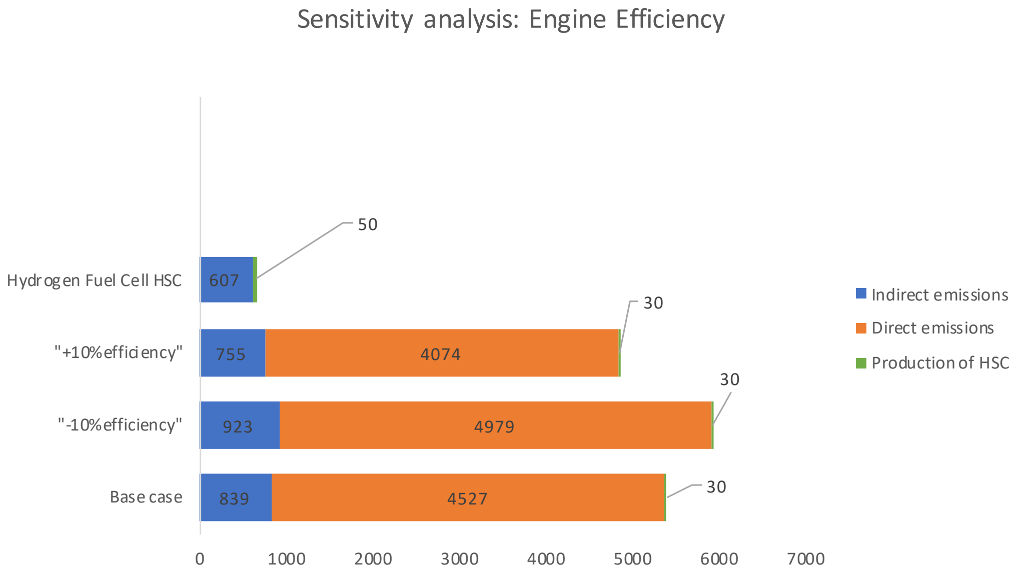


Figure 22: Sensitivity analysis: Diesel HSC Engine Efficiency

Here we have researched the impacts of an increase/decrease of 10% efficiency for the HSC motor, the results are compared with the total emissions from the Hydrogen FC HSC.

7 Discussion

This thesis presents a comparative LCA of a Hydrogen FC and Diesel-powered HSC. The emissions are presented in full detail in terms of the impact category climate change (global warming potential) and shortly reviewed in terms of all impact categories in ReCiPe. The results give a holistic evaluation of the environmental impacts of a Hydrogen FC HSC in comparison to a Conventional Diesel HSC. In this section, the main results will be discussed. In subsection 7.1, the modeling choices are reviewed, in subsection 7.2 the data quality is critically discussed, and in subsection 7.3 the main take away points of this work is presented in the context of previous studies within the field. Lastly, some suggestions for further work are stated in subsection 7.4.

The main findings from the model's results were: The use phase has the largest contribution in terms of all impact categories. For the Conventional Diesel HSC, the operation emission due to both indirect- and direct emissions dominates. While for the Hydrogen FC HSC it is the production of Hydrogen that has the largest impacts in all categories. In the production of the HSCs, the CF sandwich hull gives the biggest impacts. The CF sandwich hull is responsible for 53% and 89% of the emissions for the Hydrogen FC HSC and the Conventional Diesel HSC, respectively.

7.1 Modeling Choices

Due to the complexity of the model, some assumptions and choices regarding the scope of the component parts had to be made. The CF sandwich hull turned out to be one of the biggest components in the production phase. In this thesis, the hull was modeled with carbon fiber(CF) and bisphenol A (BPA) epoxy Vinyl Ester Resins (VER). There was assumed a fraction of 40% CF and 60% BPA. That being said, it is not modeled with a core, as weight is a critical issue for any HSC. The material and design of the hull are of critical matter. A sandwich structure consists of two high strength skins separated by a core material. By Inserting a core into the laminate you increase the thickness of the material without incurring the weight penalty that comes from adding extra laminate layers(Gurit n.d.). One can argue, that by not taking into account the core of the carbon fiber sandwich the emissions for the CF sandwich hull is probably higher than it would be with a core. This is because the core material would have taken more of the share of the total weight of the hull. The emissions in terms of the hull would still be high, but it could be that one could see a smaller share of the overall emissions due to less fraction of the CF material in favor of the core material. As CF is a quite carbon-intensive material. However, this does not matter to the overall result as both the Hydrogen FC HSC and the Conventional Diesel HSC are modeled with the same core.

Another aspect that is pointed out several times during this study is that it is not modeled for a docking system or a charging port for the refueling of Hydrogen and charging of the batteries. These elements would give the Hydrogen FC HSC system higher emissions. Hirth et al. 2017 and Strømgren et al. 2017 has looked upon options for these types of infrastructure. One can argue that the Diesel system benefits from the already established fuel value chain and that for a Hydrogen fuel value chain to be implemented, we need the initial cost and emissions implementation of such systems do require, which future Hydrogen system will benefit of. These are though emissions that need to be considered when swhiching to a Hydrogen FC system.

The overall take away from the study is that the use phase in terms of direct- and indirect emissions dominates all impact categories for each HSC. As stated, it is the operational phase for the Convectional Diesel HSC that emits the most for the overall system, these emissions are calculated in terms of the emission factors by C. Ianssen, E. Ianssen, and Sandblost 2017. The Diesel that has been modeled for is the low-sulfur Diesel. The direct emissions in the operational phase are generated by the combustion of the fuel. The exhaust emissions of diesel engines primarily include carbon dioxide (CO2), carbon monoxide (CO), sulfur oxides (SOx), nitrogen oxides (NOx), hydrocarbons (HC) and particulate matters (PM). CO, NOx, and PM originate from engine technology whereas CO2, SOx, heavy metals and further PM (sulfur compounds) come from fuel property. Because of this, the sustainability of shipping can according to Durmaz, Kalender, and Ergin 2017 be improved by utilizing the ultra-low sulfur diesel fuel for the propulsion. The emissions in terms of GWP for the low-sulfur Diesel in Ecoinvent do emit more than the process for regular diesel. This is not taken into account in this thesis.

For the Hydrogen FC HSC, it turned out to be the production of Hydrogen that is the pressing issue. The assumption regarding the electricity source for Hydrogen production was tested in a sensitivity analysis, section6.3.1. The energy source for the base case is the Norwegian electricity mix, the result was then compared towards a variation of countries electricity mixes plus energy sources origin in Norway. In the process of production of Hydrogen, electricity consumption is the most crucial in terms of emissions. Electricity is a process of emissions depending on the production method. This is illustrated in section 4.4. A sensitivity analysis of the choice of energy mix shows that electrolysis for Hydrogen production is very sensitive to the electricity used. As this model has a base case in terms of a Norwegian setting with the Norwegian electricity mix, this is in quite a favor for the Hydrogen FC HSC.

7.2 Data Quality

Data estimation, collection, and structuring were described in section 4. Several methods of acquiring data have been used and they, therefore, may be different in terms of quality.

Consultation of experts, data estimation, literature, generic databases, and a combination of these have been used to estimate the inputs to the analysis.

Experts have contributed with the amount of hull material, guidance in terms of scaling battery- and FC data. Some estimations have been carried out by the researcher, examples: estimation of paint and kg glass for windows, and most values obtained were used as the amount of a certain process in the Ecoinvent database.

It has been attempted to have the same data quality on the systems that were compared, but some exceptions have been made.

These are the level of detail in the data for the battery and FC compared to e.g. the engines and electronics. This can however be justified by the level of impact the parameters have on the results. It can also be argued that the modeling of CF has had a large impact on the result. The emissions due to the modeling of CF is aligned with the literature and is therefore considered robust. Specific data have been used to estimate the production impacts of the batteries and the FC. However, for the engines, scaling was done by the weight of the specific motor model and the Ecoinvent process for the engine and electric motor was used. The same applies to electronics. This can give errors due to the level of detail, but as the impacts for the engines and electronics are limited it is considered negligible.

The modeling of the electrolysis and the production of Hydrogen was based on a model of a PEM-electrolyzer by Lundberg 2019. The original model was in terms of a FU of Producing 100 kg of Hydrogen. The model was then modified in terms of the FU for this thesis, the production of 361 kg of Hydrogen. According to Lundberg 2019, the results are based on available data where the quantity and quality of this data vary among the technologies. The results are in relation to the FU of the study. Possible impacts on the results can have occurred, if the available data does not transparently document all information about important life cycle steps, such as detailed information regarding the manufacturing. In addition, the information regarding the electrolyzers was gathered from more than four, distinct sourcesLundberg 2019. While the result in this thesis matches the results from Lundberg 2019 one must keep in mind that minor changes due to material choices in Ecoinvent were done, and this could have an impact on the overall results. These errors are though seen as minor, and the model in this thesis is therefore considered robust.

7.3 Comparison to Studies within the Field

The production of the Hydrogen is stated as the most important take away key emission process for the Hydrogen FC HSC. previous studies has indicated the importance of hydrogen production from renewable sources(Lundberg 2019; Øgård 2017; Liebig-Larsen and Skiaker 2017; Correa 2013; NCE maritime CleanTech 2019). The sensitivity analysis in this thesis confirms this. A simple analysis showed that only Norwegian wind power, Norwegian electricity mix and NORDEL electricity mix make the Hydrogen FC HSC more attractive than the Conventional Diesel HSC (Shown in figure 16). With increased power trade with the Nordic countries or Europe, the Hydrogen could soon have a bigger amount of energy from non-renewable sources than desired. We see that a shift towards European energy mix does not agree with the footprint of the Hydrogen FC HSC. The worst case scenario is set as production of Hydrogen by Chinese electricity mix. This scenario doubles the emissions in comparison with the UCTE electricity mix. The importance of electricity from renewable sources is the main take away.

However, the results for the other impact categories indicates equal pattern to GWP, except abiotic depletion where Norwegian wind- and electricity mix contributes much, see Appendix D. The reason to the big impact on abiotic depletion is the large amount of non-renewable resources, deriving from the power plant constructions. We also see that the different el-mixes contributes in different categories. This has not been studied further. This was indicated by Lundberg 2019 and similar trends are shown in this system.

This thesis has focused on overall emissions. By looking at the whole HSC, the perspective to which impacts seem most pressing changes. Previous studies have highlighted a problem shift from GWP to Toxicity categories. The results show that the Hydrogen FC HSC dominates 7/18 impact categories. Among these categories, we see a bigger share of toxicity impacts. In a study by Jokela et al. 2018 the result showed that the hydrogen-electric ferry turned out worse than the Conventional Diesel Ferry in five out of ten impact categories. The categories of the impact that the hydrogen-electric ferries came out poorer were related to toxicity, on land, and at sea. It also turned out worst on abiotic depletion. These are tapping resources in the non-living environment of the ecosystem. There is particularly aquatic marine toxicity potential and aquatic freshwater toxicity potential where the hydrogen-electric ferry stands out with very high numbers. This may be because the hydrogen system and the electrical system in the hydrogen-electric ferry have several components made of minerals and raw materials, which have a great toxicity effect on the environments of water in extraction and waste management. The same was highlighted by Kullmann 2016. The latter addressed a problem shift from the reduction of impacts in categories linked to fossil fuels and increases in many categories regarding toxicity. Mark that the study by Kullmann 2016 looked at an all-electric ferry and not an FC one. Nevertheless, In a study by Correa 2013, the comparison of the different vehicle technologies (BEV, ICEV, and FCV) plead in favor of the fuel cell vehicles, not only as a mean to achieve reductions on climate change impacts, but also because they over-perform EVs in critical impact categories such as human toxicology, and freshwater ecotoxicology and eutrophication. The study by Correa 2013 concludes with the same as the results for this thesis; For the different components, in all vehicle technologies, the climate change impacts are dominated by the fuel.

Keeping this in mind, the overall result for this thesis are well aligned with the literature. The literature has asked for a holistic approach looking at the whole system. This thesis shows that a Hydrogen FC HSC has lower GHG emissions, for the Norwegian electricity mix than the Conventional Diesel HSC.

This implies that the measures to reduce impacts from Hydrogen FC HSC and conventional Diesel HSCs are different. To reduce impacts for the Hydrogen FC HSC the production and storage of the Hydrogen are still pressing issues.

For the Conventional Diesel HSC, impacts associated with fossil fuel extraction and production can reduce impacts.

For the production phase, impacts from the CF sandwich hull had the most emissions. This is something that should be further looked upon.

7.4 Further work

For suppliers in this market, the present study and future studies can give some insight into what components that pose the largest environmental impact. It has earlier been stressed the need for looking at upstream emissions. Component studies with a focus on batteries and FCs have shown the need for taking into account the production phase.

In this analysis, it is shown that the use phase has the largest contribution for all impact categories. In the production phase, we see that the CF sandwich hull shows great impacts. The CF sandwich hull is responsible for 53% and 89% of the emissions for the Hydrogen FC HSC and the Conventional Diesel HSC, respectively. The Hydrogen tank has 25 % of the emissions, beating the FCs and battery that contributes to 10% and 8%, respectively for the Hydrogen FC HSC. Which shows the importance of the material choices for these components, see section 6.3.2.

End of life is omitted in the present study, and future studies should strive to include this in the analysis. This is suspected to influence the results of the Hydrogen FC HSC more than the Conventional Diesel HSC due to the recycling of batteries and FCs. But it is also interesting to see how the maintenance and recycling of the CF sandwich hull would impact the overall result.

The model does not reflect the entire HSC but some of the components and parts of the operation of them. The aspects that were attempted to include in the analysis were items that are principally different for the two catamarans, for example, the FC, Hydrogen tank, the batteries, and the engines. In addition to this, the hull, electronics, some interior and exterior, and some operational inputs such as Hydrogen and Diesel production and operation of the Diesel HSC are included in the analysis.

This model reflects a more holistic approach to an HSC than has been conducted before. By taking into account the upstream emissions we see which components have a larger contribution to the whole system.

This can have a large impact on HSC cases in impact categories where the total impacts are small and increases in impacts can have large effects. An example here was the choice of CF as material for the hull and Hydrogen tank. We also see that the production of the Hydrogen FC HSC has a larger contribution to climate change than the Conventional Diesel HSC. But that in the overall picture the thing that matters the most for this to happen is the production of Hydrogen.

This analysis has not included modeling of docking system for refueling Hydrogen and charging of batteries or emission-reducing technologies such as scrubbers or catalysts. Future studies should attempt to include such measures.

8 Conclusion

A simplified comparative LCA of conventional and HSC has been carried out. The environmental benefits and burdens associated with a hydrogen HSC have been compared to an HSC run on fossil fuels. A transparent inventory for most of the system is provided for future studies.

This thesis reveals that in terms of total emissions the Hydrogen FC HSC comes out as the best option with a total of 657 kg CO2-eq/crossing compared to the Conventional Diesel HSC which emits 5396 kg CO2-eq/crossing.

For the overall emissions, the use phase has the largest contribution in terms of all impact categories. For the Conventional Diesel HSC, the operation emission due to both indirect- (839 kg CO2/crossing) and direct emissions(4527kg CO2-eq/crossing) dominates. The combustion of Diesel fuel has the largest contribution. While the Hydrogen production (607 kg CO2-eq/crossing) contributes to the most to the potential environmental impact emissions in terms of electricity supply for the Hydrogen FC HSC, with less influence from the components. The reasons are the electricity source and the great amount of electricity required in the current Hydrogen gas production processes.

For the production phase the Hydrogen FC HSC proves the highest emissions (50 kg CO2-eq/crossing), the Conventional Diesel HSC only emits 30 kg CO2-eq/crossing for the production phase. The bigger amount of emission in this phase for the Hydrogen FC HSC is because of the Hydrogen tank, production of FCs, and batteries. The CF sandwich hull and the CF Hydrogen tank contribute the most to the overall emissions in terms of the production phase.

In spite of this, the overall total emissions show that the Conventional Diesel HSC dominates the use phase and looses towards the Hydrogen FC system.

The sensitivity analysis proves the importance of Hydrogen production with an emphasis on renewable energy sources. The Hydrogen FC HSC is dependent on green energy sources to keep the emissions low.

Regardless, the Hydrogen FC HSC, has lower GHG emissions with respect to the average Norwegian electricity mix, than the Conventional Diesel HSC.

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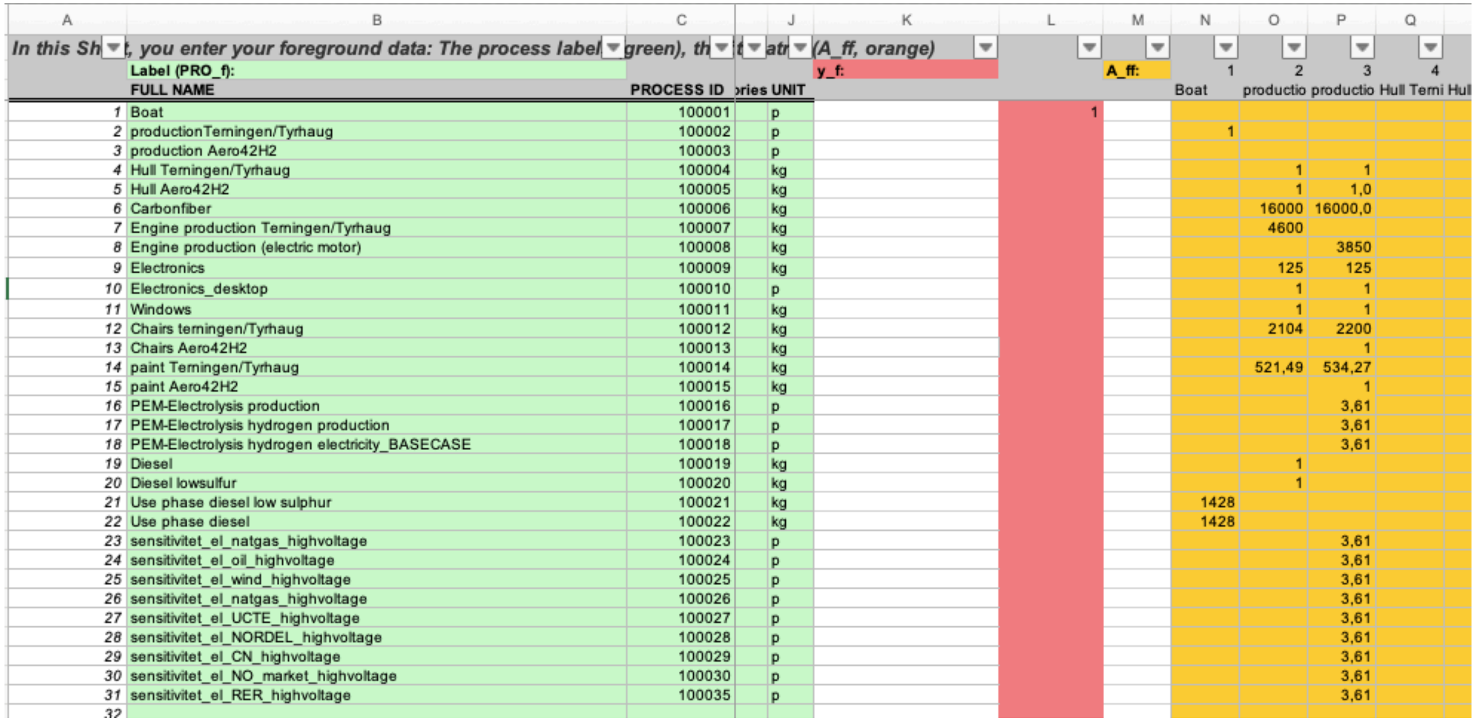
Appendices

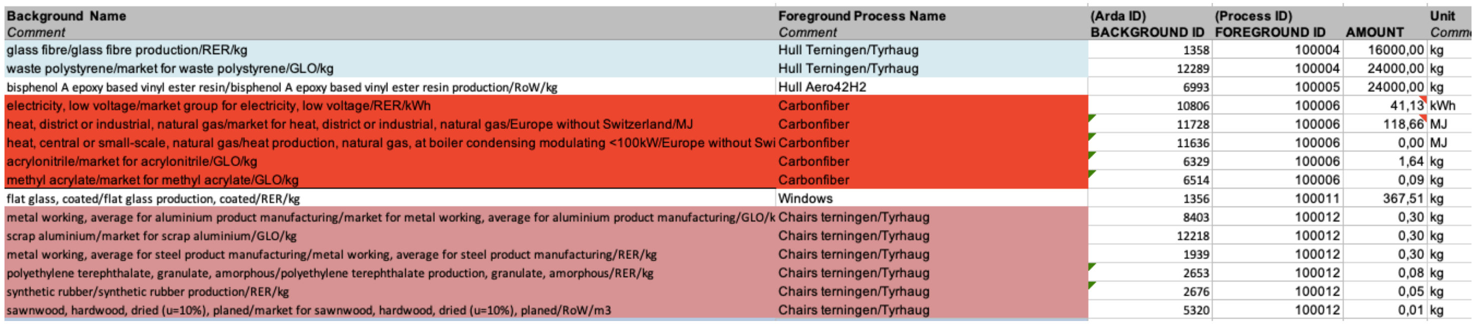
A Inventory Aero42H2 and Terningen/Tyrhaug

The Arda-template used for the modeling of the HSCs are shown below. This inventory does not include the battery and FC production, as these cannot be shown due to confidentiality reasons.



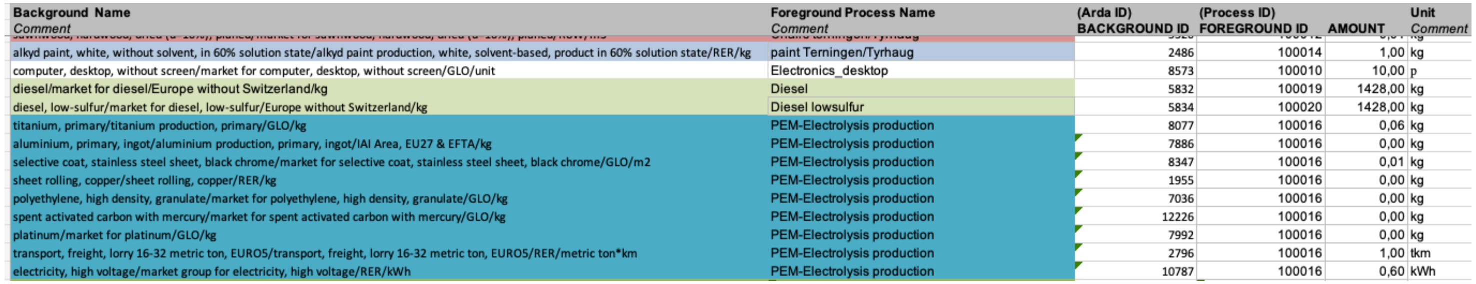
A	B	C		J	K	L	M	N	O	P	Q	
In this Sh	t, you enter your foreground data: The process label	green), th	t	atr	(A_ff, orange)							
	Label (PRO_f):				y_f:		A_ff:	1	2	3	4	
	FULL NAME	PROCESS ID	ories	UNIT				Boat	productio	productio	Hull Terni	Hull
1	Boat	100001		p		1						
2	productionTerningen/Tyrhaug	100002		p				1				
3	production Aero42H2	100003		p								
4	Hull Terningen/Tyrhaug	100004		kg					1	1		
5	Hull Aero42H2	100005		kg					1	1,0		
6	Carbonfiber	100006		kg					16000	16000,0		
7	Engine production Terningen/Tyrhaug	100007		kg					4600			
8	Engine production (electric motor)	100008		kg						3850		
9	Electronics	100009		kg					125	125		
10	Electronics_desktop	100010		p					1	1		
11	Windows	100011		kg					1	1		
12	Chairs terningen/Tyrhaug	100012		kg					2104	2200		
13	Chairs Aero42H2	100013		kg						1		
14	paint Terningen/Tyrhaug	100014		kg					521,49	534,27		
15	paint Aero42H2	100015		kg						1		
16	PEM-Electrolysis production	100016		p						3,61		
17	PEM-Electrolysis hydrogen production	100017		p						3,61		
18	PEM-Electrolysis hydrogen electricity_BASECASE	100018		p						3,61		
19	Diesel	100019		kg					1			
20	Diesel lowsulfur	100020		kg					1			
21	Use phase diesel low sulphur	100021		kg				1428				
22	Use phase diesel	100022		kg				1428				
23	sensitivitet_el_natgas_highvoltage	100023		p						3,61		
24	sensitivitet_el_oil_highvoltage	100024		p						3,61		
25	sensitivitet_el_wind_highvoltage	100025		p						3,61		
26	sensitivitet_el_natgas_highvoltage	100026		p						3,61		
27	sensitivitet_el_UCTE_highvoltage	100027		p						3,61		
28	sensitivitet_el_NORDEL_highvoltage	100028		p						3,61		
29	sensitivitet_el_CN_highvoltage	100029		p						3,61		
30	sensitivitet_el_NO_market_highvoltage	100030		p						3,61		
31	sensitivitet_el_RER_highvoltage	100035		p						3,61		
32												

Figure A.1: Inventory for Aero42H2/Terningen/Tyrhaug



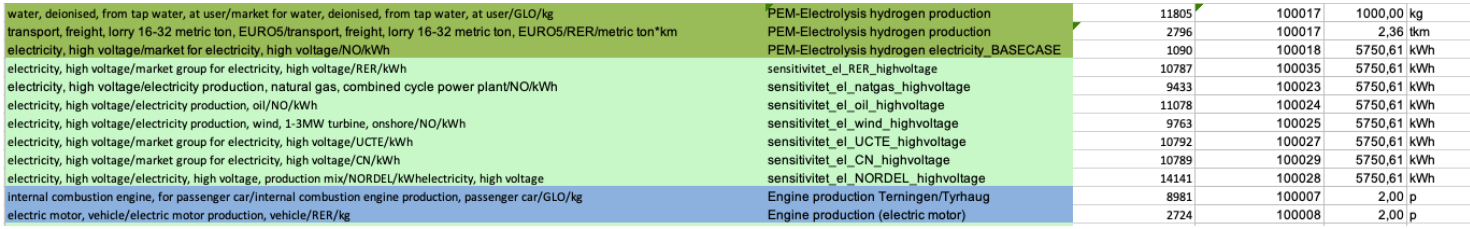
Background Name *Comment*	Foreground Process Name *Comment*	(Arda ID) BACKGROUND ID	(Process ID) FOREGROUND ID	AMOUNT	Unit *Comm*
glass fibre/glass fibre production/RER/kg	Hull Terningen/Tyrhaug	1358	100004	16000,00	kg
waste polystyrene/market for waste polystyrene/GLO/kg	Hull Terningen/Tyrhaug	12289	100004	24000,00	kg
bisphenol A epoxy based vinyl ester resin/bisphenol A epoxy based vinyl ester resin production/RoW/kg	Hull Aero42H2	6993	100005	24000,00	kg
electricity, low voltage/market group for electricity, low voltage/RER/kWh	Carbonfiber	10806	100006	41,13	kWh
heat, district or industrial, natural gas/market for heat, district or industrial, natural gas/Europe without Switzerland/MJ	Carbonfiber	11728	100006	118,66	MJ
heat, central or small-scale, natural gas/heat production, natural gas, at boiler condensing modulating <100kW/Europe without Swi	Carbonfiber	11636	100006	0,00	MJ
acrylonitrile/market for acrylonitrile/GLO/kg	Carbonfiber	6329	100006	1,64	kg
methyl acrylate/market for methyl acrylate/GLO/kg	Carbonfiber	6514	100006	0,09	kg
flat glass, coated/flat glass production, coated/RER/kg	Windows	1356	100011	367,51	kg
metal working, average for aluminium product manufacturing/market for metal working, average for aluminium product manufacturing/GLO/k	Chairs terningen/Tyrhaug	8403	100012	0,30	kg
scrap aluminium/market for scrap aluminium/GLO/kg	Chairs terningen/Tyrhaug	12218	100012	0,30	kg
metal working, average for steel product manufacturing/metal working, average for steel product manufacturing/RER/kg	Chairs terningen/Tyrhaug	1939	100012	0,30	kg
polyethylene terephthalate, granulate, amorphous/polyethylene terephthalate production, granulate, amorphous/RER/kg	Chairs terningen/Tyrhaug	2653	100012	0,08	kg
synthetic rubber/synthetic rubber production/RER/kg	Chairs terningen/Tyrhaug	2676	100012	0,05	kg
sawnwood, hardwood, dried (u=10%), planed/market for sawnwood, hardwood, dried (u=10%), planed/RoW/m3	Chairs terningen/Tyrhaug	5320	100012	0,01	kg

Figure A.2: A$_{bf}$: Inventory for Aero42H2/Terningen/Tyrhaug



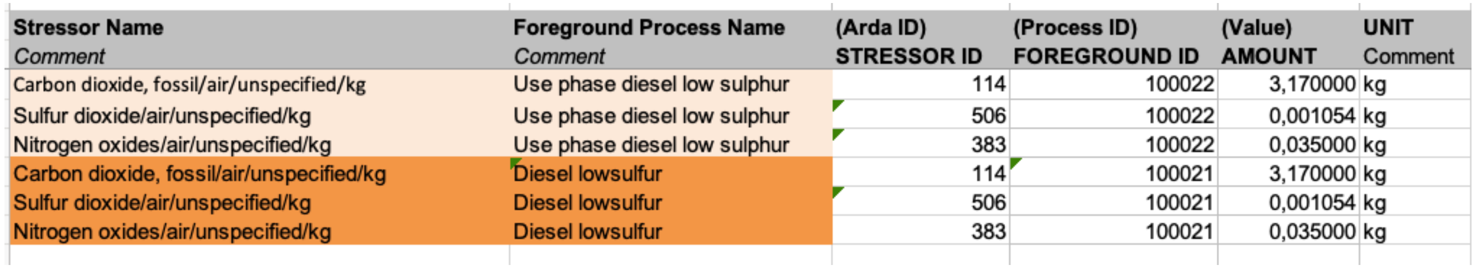
Background Name *Comment*	Foreground Process Name *Comment*	(Arda ID) BACKGROUND ID	(Process ID) FOREGROUND ID	AMOUNT	Unit *Comment*
alkyd paint, white, without solvent, in 60% solution state/alkyd paint production, white, solvent-based, product in 60% solution state/RER/kg	paint Terningen/Tyrhaug	2486	100014	1,00	kg
computer, desktop, without screen/market for computer, desktop, without screen/GLO/unit	Electronics_desktop	8573	100010	10,00	p
diesel/market for diesel/Europe without Switzerland/kg	Diesel	5832	100019	1428,00	kg
diesel, low-sulfur/market for diesel, low-sulfur/Europe without Switzerland/kg	Diesel lowsulfur	5834	100020	1428,00	kg
titanium, primary/titanium production, primary/GLO/kg	PEM-Electrolysis production	8077	100016	0,06	kg
aluminium, primary, ingot/aluminium production, primary, ingot/IAI Area, EU27 & EFTA/kg	PEM-Electrolysis production	7886	100016	0,00	kg
selective coat, stainless steel sheet, black chrome/market for selective coat, stainless steel sheet, black chrome/GLO/m2	PEM-Electrolysis production	8347	100016	0,01	kg
sheet rolling, copper/sheet rolling, copper/RER/kg	PEM-Electrolysis production	1955	100016	0,00	kg
polyethylene, high density, granulate/market for polyethylene, high density, granulate/GLO/kg	PEM-Electrolysis production	7036	100016	0,00	kg
spent activated carbon with mercury/market for spent activated carbon with mercury/GLO/kg	PEM-Electrolysis production	12226	100016	0,00	kg
platinum/market for platinum/GLO/kg	PEM-Electrolysis production	7992	100016	0,00	kg
transport, freight, lorry 16-32 metric ton, EURO5/transport, freight, lorry 16-32 metric ton, EURO5/RER/metric ton*km	PEM-Electrolysis production	2796	100016	1,00	tkm
electricity, high voltage/market group for electricity, high voltage/RER/kWh	PEM-Electrolysis production	10787	100016	0,60	kWh

Figure A.3: A_{bf}: Inventory for Aero42H2/Terningen/Tyrhaug



water, deionised, from tap water, at user/market for water, deionised, from tap water, at user/GLO/kg	PEM-Electrolysis hydrogen production	11805	100017	1000,00	kg
transport, freight, lorry 16-32 metric ton, EURO5/transport, freight, lorry 16-32 metric ton, EURO5/RER/metric ton*km	PEM-Electrolysis hydrogen production	2796	100017	2,36	tkm
electricity, high voltage/market for electricity, high voltage/NO/kWh	PEM-Electrolysis hydrogen electricity_BASECASE	1090	100018	5750,61	kWh
electricity, high voltage/market group for electricity, high voltage/RER/kWh	sensitivitet_el_RER_highvoltage	10787	100035	5750,61	kWh
electricity, high voltage/electricity production, natural gas, combined cycle power plant/NO/kWh	sensitivitet_el_natgas_highvoltage	9433	100023	5750,61	kWh
electricity, high voltage/electricity production, oil/NO/kWh	sensitivitet_el_oil_highvoltage	11078	100024	5750,61	kWh
electricity, high voltage/electricity production, wind, 1-3MW turbine, onshore/NO/kWh	sensitivitet_el_wind_highvoltage	9763	100025	5750,61	kWh
electricity, high voltage/market group for electricity, high voltage/UCTE/kWh	sensitivitet_el_UCTE_highvoltage	10792	100027	5750,61	kWh
electricity, high voltage/market group for electricity, high voltage/CN/kWh	sensitivitet_el_CN_highvoltage	10789	100029	5750,61	kWh
electricity, high voltage/electricity, high voltage, production mix/NORDEL/kWhelectricity, high voltage	sensitivitet_el_NORDEL_highvoltage	14141	100028	5750,61	kWh
internal combustion engine, for passenger car/internal combustion engine production, passenger car/GLO/kg	Engine production Terningen/Tyrhaug	8981	100007	2,00	p
electric motor, vehicle/electric motor production, vehicle/RER/kg	Engine production (electric motor)	2724	100008	2,00	p

Figure A.4: A_{bf}: Inventory for Aero42H2/Terningen/Tyrhaug



Stressor Name *Comment*	Foreground Process Name *Comment*	(Arda ID) STRESSOR ID	(Process ID) FOREGROUND ID	(Value) AMOUNT	UNIT Comment
Carbon dioxide, fossil/air/unspecified/kg	Use phase diesel low sulphur	114	100022	3,170000	kg
Sulfur dioxide/air/unspecified/kg	Use phase diesel low sulphur	506	100022	0,001054	kg
Nitrogen oxides/air/unspecified/kg	Use phase diesel low sulphur	383	100022	0,035000	kg
Carbon dioxide, fossil/air/unspecified/kg	Diesel lowsulfur	114	100021	3,170000	kg
Sulfur dioxide/air/unspecified/kg	Diesel lowsulfur	506	100021	0,001054	kg
Nitrogen oxides/air/unspecified/kg	Diesel lowsulfur	383	100021	0,035000	kg

Figure A.5: A_{Ff}: Inventory for Aero42H2/Terningen/Tyrhaug

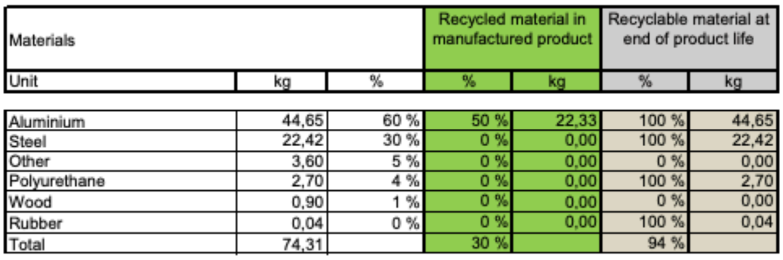
B Interiour and Exteriour calculations

To model for seating, there was used an environmental product declaration (EPD) of a ”Transit 24 three-seat sofa”(The Norwegian EPD Foundation 2017). The total weight of the system was adjusted according to the weight of the original seating system B.1.

There is assumed a total weight of 2104kg and 2200kg for the seating alone on Terningen/Tyrhaug and Aero42H2, respectively. This is calculated with the weight of one chair being 8kg. And a total seating of 263 and 275 for each vessel. The fraction of the materials for the chairs is assumed as in The Norwegian EPD Foundation 2017 and can be found in B.1. The Ecoinvent processes used are shown in table 12 in section 4.3.2.

Table B.1: Key data: Seating

Weight (1 seat)	8	kg
Total weight (row 4 seats)	32	kg
	Terningen/Tyrhaug	Aero42H2
Number of rows	65	68
Seats left	3	3
Total Weight all seats	2104	2200



Materials			Recycled material in manufactured product		Recyclable material at end of product life	
Unit	kg	%	%	kg	%	kg
Aluminium	44,65	60 %	50 %	22,33	100 %	44,65
Steel	22,42	30 %	0 %	0,00	100 %	22,42
Other	3,60	5 %	0 %	0,00	0 %	0,00
Polyurethane	2,70	4 %	0 %	0,00	100 %	2,70
Wood	0,90	1 %	0 %	0,00	0 %	0,00
Rubber	0,04	0 %	0 %	0,00	100 %	0,04
Total	74,31		30 %		94 %	

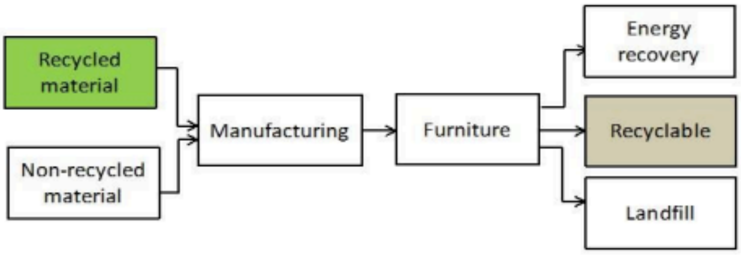
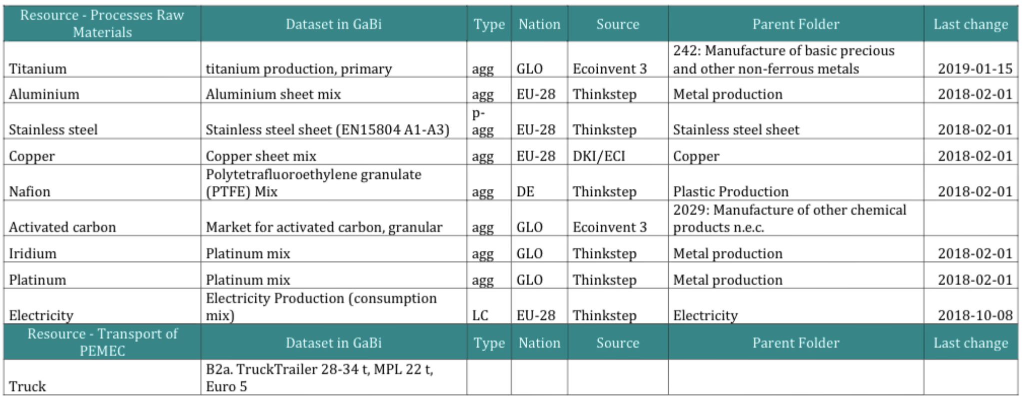


Figure B.1: Modeling of seating: Material fraction of total weight (The Norwegian EPD Foundation 2017)

There is done a simplified analysis of the windows. It was assumed a range of average window sizes. The weight of the total glass material used was estimated as seen in table 7, and the Ecoinvent process used for the glass material is shown in table 8 in section 4.3.2. The different window types are shown in figureB.2.

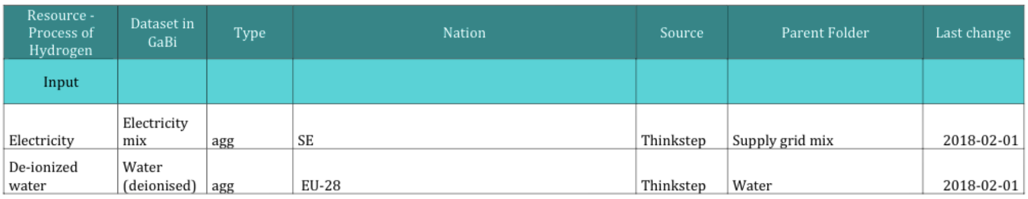
Figure B.2: Modeling of windows: Estimating the window types

C Original inventory: Electrolysis



Resource - Processes Raw Materials	Dataset in GaBi	Type	Nation	Source	Parent Folder	Last change
Titanium	titanium production, primary	agg	GLO	Ecoinvent 3	242: Manufacture of basic precious and other non-ferrous metals	2019-01-15
Aluminium	Aluminium sheet mix	agg	EU-28	Thinkstep	Metal production	2018-02-01
Stainless steel	Stainless steel sheet (EN15804 A1-A3)	p-agg	EU-28	Thinkstep	Stainless steel sheet	2018-02-01
Copper	Copper sheet mix	agg	EU-28	DKI/ECI	Copper	2018-02-01
Nafion	Polytetrafluoroethylene granulate (PTFE) Mix	agg	DE	Thinkstep	Plastic Production	2018-02-01
Activated carbon	Market for activated carbon, granular	agg	GLO	Ecoinvent 3	2029: Manufacture of other chemical products n.e.c.	
Iridium	Platinum mix	agg	GLO	Thinkstep	Metal production	2018-02-01
Platinum	Platinum mix	agg	GLO	Thinkstep	Metal production	2018-02-01
Electricity	Electricity Production (consumption mix)	LC	EU-28	Thinkstep	Electricity	2018-10-08
Resource - Transport of PEMEC	Dataset in GaBi	Type	Nation	Source	Parent Folder	Last change
Truck	B2a. TruckTrailer 28-34 t, MPL 22 t, Euro 5					

Figure C.1: Original Inventory for Electrolysis by Lundberg 2019



Resource - Process of Hydrogen	Dataset in GaBi	Type	Nation	Source	Parent Folder	Last change
Input						
Electricity	Electricity mix	agg	SE	Thinkstep	Supply grid mix	2018-02-01
De-ionized water	Water (deionised)	agg	EU-28	Thinkstep	Water	2018-02-01

Figure C.2: Original Inventory for Electrolysis by Lundberg 2019

D Sensitivity analysis: Hydrogen Production

The results from the change of electricity mixes are described in figure D.1, D.2, D.3,D.4.

The results are showing the total impact for the whole life cycle of the hydrogen production by electrolysis. The potential environmental impacts correlat ewith the amount of renewable and non-renewable energy sources in the electricity mixes, except for abiotic depletion where Norwegian wind power has high contribution, because of the wind power construction

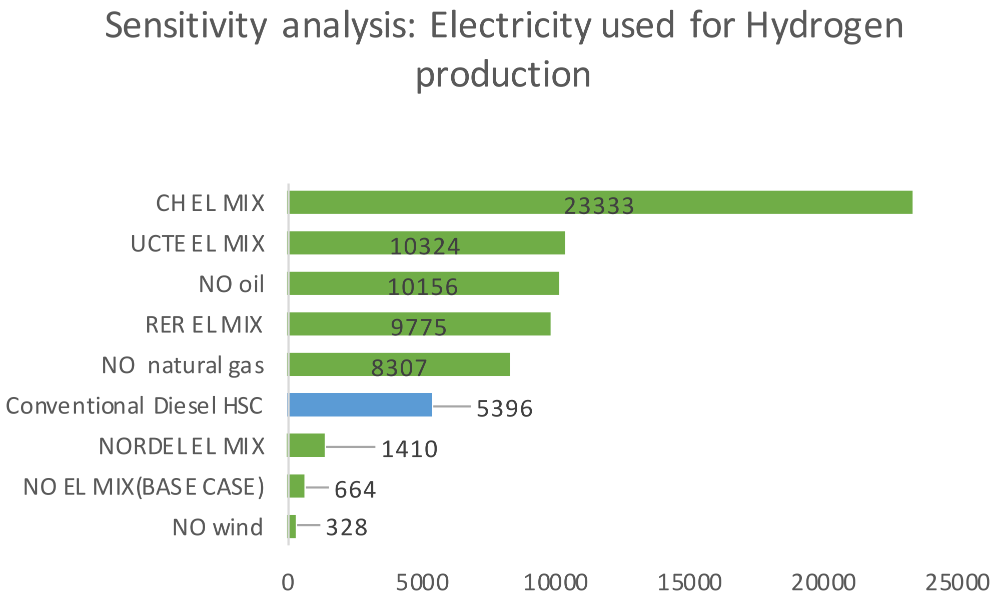


Figure D.1: Sensitivity analysis: Hydrogen Production, all impact categories

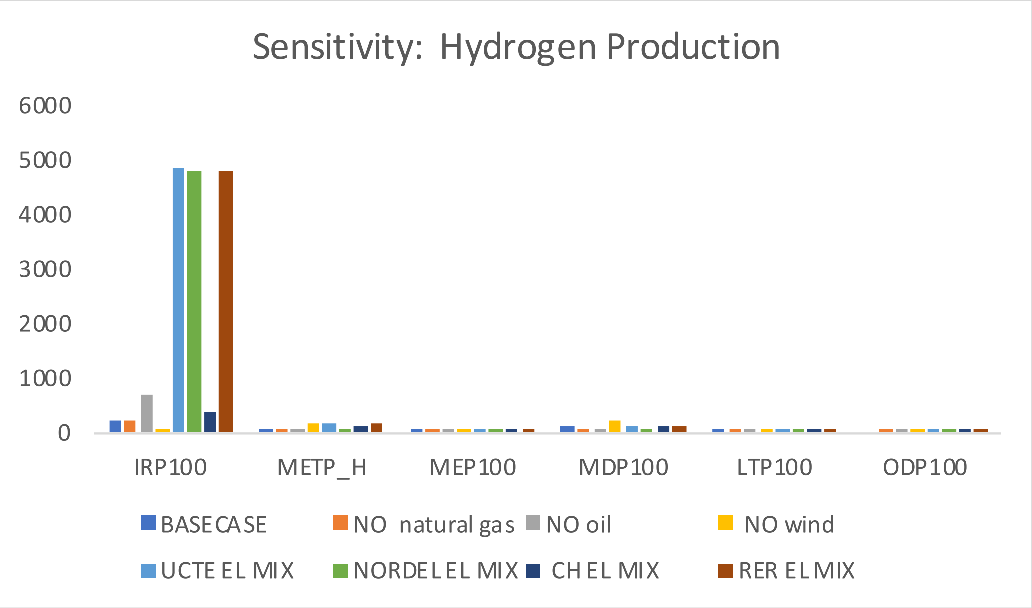


Figure D.2: Sensitivity analysis: Hydrogen Production, all impact categories

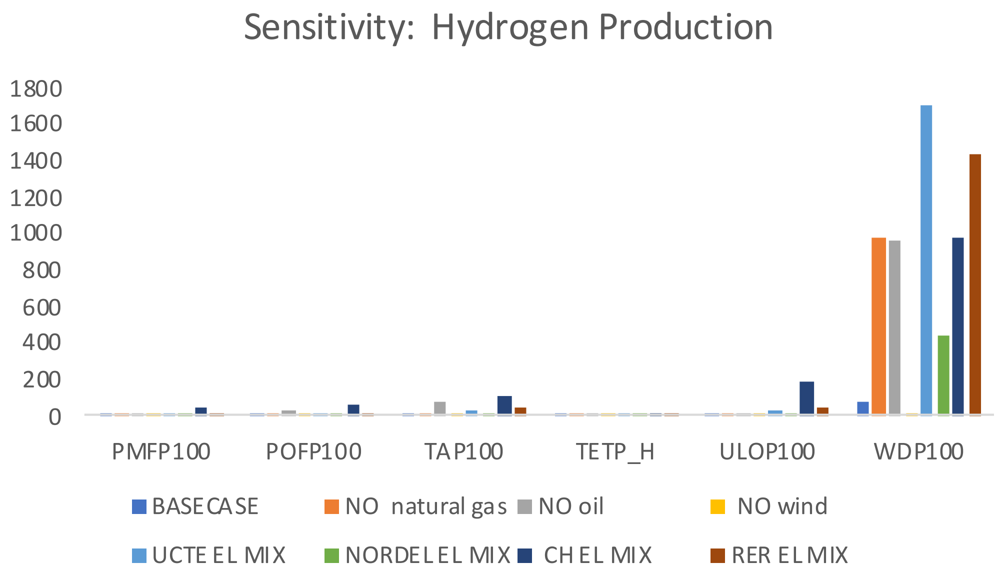


Figure D.3: Sensitivity analysis: Hydrogen Production, all impact categories

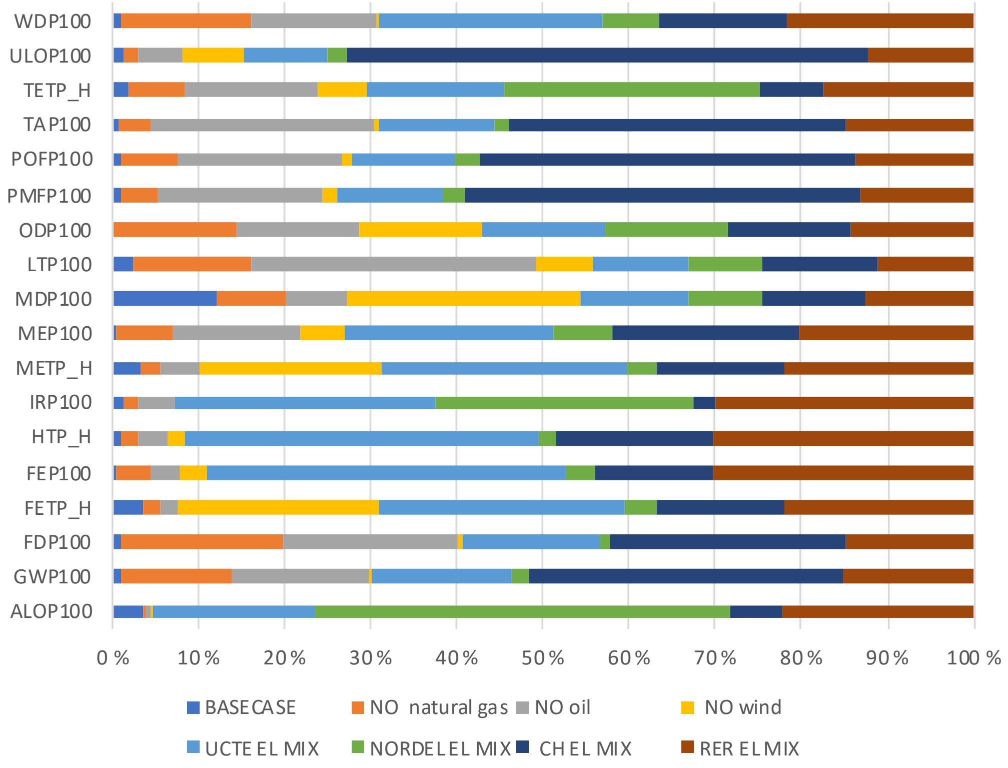


Figure D.4: Sensitivity analysis: 100% bar chart for Hydrogen Production, all impact categories

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