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An evaluation of the cost-competitiveness of maritime fuels – a comparison of heavy fuel oil and methanol (renewable and natural gas) in Iceland

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Abstract

Alternative fuels have been proposed to ensure compliance with the increasingly more stringent emission standards proposed by the International Maritime Organization. In addition, the Icelandic government aims to introduce 10% renewable energy into the maritime sector before 2030, as well as eventually phasing out the use of heavy fuel oil (HFO). This paper conducts an extended cost-competitiveness comparison concerning three fuels: conventional methanol (NG), renewable methanol (RN) and HFO in the context of the Icelandic maritime sector. NG, RN and HFO are compared and evaluated under three scenarios (low, medium and high) for fuel prices between 2018 and 2050, and three scenarios (low, medium and high) for the external costs of fuel consumption. The methodology for estimating external costs involved Impact Pathway Analysis for emissions of sulphur dioxide, nitrous oxide, particulate matter and non-methane volatile organic compounds, and increasing shadow prices for the costs of greenhouse gas emissions. The application of this methodology provides new information about the economic and environmental trade-offs between the three fuel types. In our findings, excluding external costs, HFO emerges as the most cost-competitive option. However, when the externalities of fuel consumption are monetised and added to the fuel price, NG is the most cost-competitive option when high values are assumed for external costs. RN is the most expensive option according to all trajectories for fuel prices and external costs, not becoming more cost-competitive than HFO under any scenario until the 2040s. Therefore, on cost criteria alone, it is improbable that the fuel will contribute to Iceland’s 10% renewable energy goal in the maritime sector before 2030 without subsidies or renewable marine fuel quotas.

Keywords: cost-competitiveness; maritime fuel; methanol; heavy fuel oil; externalities; Iceland

1. Introduction

1.1 Energy consumption and externalities of ship propulsion

In recent years, increased global attention has been given to ameliorating the negative externalities of the maritime sector, especially air and water pollution from fossil fuel combustion, which leads to largely unaccounted for external costs in relation to climate change and various human health impacts (Brynolf et al., 2014; MEPC, 2008; Merchan et al., 2019; Nunes et al. 2019). New emission regulations, set by the International Maritime Organization (IMO), address the quality of fuel, specifically the exhaust emissions produced by fuel combustion of ships (IMO, 2019). National targets, policies and regulations have also responded to the global agenda, both in terms of reducing harmful emissions and driving a transition to greater use of renewable energy. Several alternative maritime fuels have been proposed as substitutes for conventional fuels (OECD/IEA, 2016; Kesieme et al., 2019), including liquefied natural gas (LNG), liquefied biogas (LBG), methanol (Brynolf et al., 2014), dimethyl ether (DME) (Goeppert et al., 2009), liquid hydrogen (LH2), straight vegetable oil (SVE) and biodiesel (Gilbert et al., 2018). Internalisation of external costs is a critical issue in European transport research and policy development (Maibach et al., 2008). If emissions from maritime applications are not seen as costs within feasibility studies and their accounting omitted from regulatory frameworks, there is little incentive for maritime firms to mitigate environmental externalities by investing in alternative energy carriers or exhaust gas cleaning systems (EGCS).

In terms of maritime externalities, international shipping traffic constitutes a major impact on human health, and the economic value of the external costs has been shown to be considerable (Brandt et al., 2011; Tzannatos, 2011; Rozmiarak and Faasse, 2018). Maritime externalities were estimated to induce external costs in Europe of 58.4 billion €/year in 2000, and these are expected to increase to 64.1 billion €/year in 2020, constituting 7% and 12% of total health effects due to air pollutants in Europe (Brandt et al., 2011). A study by Tzannatos (2011) on the external costs of maritime fuel consumption in Greece, showed that in 2008, international and domestic shipping generated 7.4 million tonnes of CO_2, SO_2, NO_x, and PM. The aggregated external cost for those emissions was 2.95 billion € (2008 prices) (Tzannatos, 2011). International marine bunkers[1] emitted 682.35 million tonnes of carbon dioxide in 2016, equating to 2.1% of global anthropogenic carbon dioxide emissions (IEA, 2018a). The relative increase of emissions from international marine bunkers between 1990 and 2016, globally and in Iceland, is 83.6% and 85.6%, respectively (IEA, 2018a). In 2016, the Icelandic maritime fleet consumed approximately 229.9 kilotons (kt) of fossil fuel, of which 50.6% was marine gas oil (MGO), 26.8% marine diesel oil (MDO) and 22.6% heavy fuel oil (HFO) (Baldursson, 2017; Hellsing et al., 2018).

1.2 Icelandic policy background

The Icelandic maritime sector, which includes domestic navigation and the fishing fleet, are areas which policy makers need to consider in order to meet the nation's goal to reduce emissions, falling under the Effort Sharing Regulation of the European Union, by 29% in 2030 compared to 2005 levels (EC, 2016), and a carbon neutrality goal by 2040 (Ministry of Environment and Natural Resources, 2018). In a parliamentary resolution, accepted on 31st May, 2017, the Icelandic government set a sector-specific

[1] These exclude fuel consumption by ships engaged in domestic navigation, fishing vessels and military activities, but include all other fuel consumption linked to international navigation on the sea, inland lakes and waterways, and in coastal waters.

goal to transition from 0.1% to 10% utilisation of renewable energy in the maritime sector by 2030 (NEA, n.d.). This parliamentary resolution was then reflected in the contents of Iceland's Climate Action Plan 2018–2030, the first version of which was published on 10th September, 2018. The seventeenth point of the Action Plan directly addresses the future of Iceland's maritime sector by aiming to permanently phase out HFO usage in Iceland's territorial waters (Ministry of Environment and Natural Resources, 2018). This led to the publication of a new regulation by Iceland's Ministry of Environment and Natural Resources, lowering the permissible sulphur content of marine fuels used in the territorial sea and internal waters of Iceland from 3.5% down to 0.1% from 1st January, 2020 (Ministry of Environment and Natural Resources, 2019). This will directly affect the Icelandic maritime sector as 22.6% of its fuel consumption, i.e. the HFO, has 1.9% sulphur content on average (Baldursson, 2017). The 0.1% sulphur content standard effectively bans the use of HFO in Icelandic waters and exceeds the new regulatory standard for sulphur content set by the IMO. The revised MARPOL Annex VI of the IMO reduces the global sulphur content cap in maritime fuel from 3.5% to only 0.5%, effective from 1st January, 2020 (IMO, 2019). Therefore, direct action is required in Iceland, in terms of maritime energy utilisation and emissions, across four regulatory and policy aspects:

1. Before 2020, to meet the 0.5% global and 0.1% domestic sulphur cap;
2. Before, 2030, to meet the nation's 10% renewable energy objective for the maritime sector;
3. Before 2030, to meet the nation's carbon emission reduction target of 29% compared to 2005 levels and in accordance with the Effort Sharing Regulation of the European Union;
4. Before 2040, to meet the nation's overall carbon neutrality goal.

1.3 Aims, objectives and structure

In this paper, the cost implications of a maritime fuel switch in Iceland will be analysed and considered in the light of the nation's policy agenda to increase utilisation of renewable energy in its maritime sector and achieve carbon neutrality by 2040. The focus of this cost-competitiveness study will be on HFO, non-renewable methanol (NG) and renewable methanol (RN), a comparison that will include the external costs of consumption. A purely financial evaluation of the costs of utilising energy resources omits the economic value of externalities, leading to a potentially misleading estimate of its social welfare implications (Cook et al., 2016). The environmental impacts are extracted from a life-cycle assessment of the three fuel types (Brynolf et al., 2014), which are translated into monetary values via Impact Pathway Analysis and then aggregated to extend a conventional financial study of cost-competitiveness.

This paper thus has three main objectives using the case study of Iceland:

- To assess the economic value of environmental externalities for HFO, RN methanol and NG methanol;
- To compare, based on the value of environmental externalities and fuel prices, the cost-competitiveness of HFO, RN methanol and NG methanol over the period 2018-2050;
- To facilitate further discussion and inform the debate about the merits of different fuel types given the policy context demanding a transition from HFO to alternatives.

The reason for focusing on methanol, especially RN methanol, in this paper is that a methanol production plant is operational near the capital city of Reykjavík. Unlike many biofuels, such as those deriving from rapeseed, methanol fully complies with the EU's renewable criteria, which requires alternative fuels to reduce carbon dioxide emissions by at least 60% compared to fossil fuels (EC, 2015). RN methanol can thus contribute to Iceland's fulfilment of the 10% renewable energy policy objective for the maritime sector. Other alternative fuels in Iceland, such as hydrogen and bioethanol, currently have a very limited presence in Iceland, with no immediate prospect of large-scale production.

This paper is organised as follows. The remainder of the introduction provides background information concerning the production of methanol. Section 2 outlines the paper's methodology and its data sources. Section 3 sets out the results in relation to three fuel price trajectories and three external cost estimates. Section 4 contains a discussion on the main results and their practical and policy implications, before reflecting on some of the limitations of the study. Section 5 provides a brief conclusion and considers avenues for further research.

1.4 Background to methanol production

Methanol is a liquid fuel at ambient pressure and temperature, which is one of its main advantages in comparison to gaseous fuels. The burgeoning interest in methanol as a maritime fuel became apparent after the IMO created emission control areas (ECA), specifically for sulphur, i.e. Sulfur Emission Control Areas (SECA), which came into effect in 2015 in the Baltic Sea (Antturi et al., 2016). However, methanol can be utilised in several prime movers, i.e. two-stroke and four-stroke diesel engines, Otto engines and fuel cells, which makes the fuel flexible (Brynolf et al., 2014). The first application was the retrofitted RoPax ferry, Stena Germanica. Since 2015, at least one of its four engines have been fuelled by methanol. As of 2017, all four of Stena Germanica's engines were converted to dual-fuel methanol. Subsequently, seven Waterfront Shipping chemical tankers, built to run on methanol, entered service in 2016 (Ellis and Svanberg, 2018). These chemical tankers, as well as Stena Germanica, have methanol / diesel dual-fuel engines. Therefore, they can choose which fuel they operate on (Ellis and Svanberg, 2018).

Production of methanol can be derived from several feedstocks, including carbon dioxide from carbon capture and utilisation processes (CCU) but also fossil fuels and biomass (Edwards et al., 2013; Odejobi et al., 2015). CCU involves any process involving the capture of effluent carbon dioxide emissions and their recycling for further usage (Cuéllar-Franca & Azapagic, 2015). Methanol is most commonly produced through fossil fuel pathways, including coal. Natural gas is currently the most common feedstock, amounting to 90% of global methanol production via catalytic conversion of pressurised syngas (Bromberg & Cheng, 2010; Dalena et al., 2018). The fossil fuel production pathways have been commercial processes for around 80 years and are thus mature in comparison to newer production methods used in CCU processes (Fortes & Tzimas, 2016). Given the wide range of possible feedstocks, the potential production capacity of methanol is potentially high. However, the energy density, i.e. the lower-heating value (LHV) of methanol is 15.6 MJ/L, which is lower than conventional maritime fuels, such as HFO, which has a LHV of approximately 38.4 MJ/L (Kumar et al., 2011; Staffel, 2011). This means that, without efficiency improvements, commensurable engines require approximately twice the volumetric content of fuel when using methanol instead of HFO.

Since 2012, Icelandic-based methanol producer, Carbon Recycling International (CRI), has utilised effluent carbon dioxide emissions from a geothermal power plant to produce methanol. CRI uses electro-chemical conversion by water electrolysis to produce hydrogen, utilising electricity from the Icelandic energy grid, which is then combined with carbon dioxide emissions to produce RN methanol (CRI, n.d.). This is an example of a CCU process as the carbon dioxide as a waste stream is captured from the nearby Svartsengi Geothermal Power Plant. CRI then produces an economic product by utilising the captured carbon dioxide emissions as a raw material for fuel production (CRI, n.d.) effectively creating value out of waste. CRI utilises around 10% of Svartsengi's waste CO_2 stream, i.e. 5,500 tonnes per annum (in 2018) from which they produce approximately 5,000,000 L of methanol per annum (CRI, n.d.).

With regards to required electricity consumption, according to Mignard et al. (2003) and backed up by an email from a company representative at CRI[2], the conversion efficiency (the efficiency of the conversion process from one state to another) of the total production process (i.e. hydrogen production and methanol synthesis), when utilising effluent carbon dioxide emissions from a nearby power plant, is between 51-58%, and where waste heat is available this rises to 58-68%. The lower-heating value of methanol is 20.1 MJ/kg (SGS Inspire, 2020). As 1 MWh equates to 3600 MJ, it would theoretically take at minimum of 5.58 MWh of electricity to produce 1 tonne of methanol, or 20,100 MJ of methanol, assuming the conversion of electricity to methanol yielded zero losses of energy in the transition from one energy carrier, electricity, to another. Given the efficiency parameters of Mignard et al, (2003) and CRI, the electricity requirement is between 8.2–10.9 MWh per tonne of methanol for a total process efficiency spectrum of 68% and 51%, respectively.

The total amount of geothermal CO_2 flue-gas emitted in Iceland in 2017 was 146 kt (NEA, 2018a). CRI utilises around 10% of Svartsengi's CO_2 waste stream, or 5.5 kt tonnes per annum (CRI, n.d.). Therefore, 1.1 tonne of CO_2 can represent 1 m3 of methanol, or 15.6 GJ. Subsequently, if all effluent carbon dioxide from geothermal power plants in Iceland were to be captured and utilised for methanol production, this would equate to a production capacity of 133,158 m3 of methanol, i.e. 2077 TJ. To put this into context, the Icelandic maritime sector consumed 258 million L of oil in 2016, which is the equivalent of 9,914 TJ assuming average energy content for HFO, marine diesel oil (MDO) and marine gas oil (MGO) of 38.4 MJ/L. Subsequently, if all geothermal waste streams were to be utilised for methanol production, Iceland could meet 21% of the energy demand of its maritime industry.

2. Methods

The purpose of this paper is to carry out an extended cost comparison of maritime fuels, in which the negative externalities related to the combustion and production of HFO, RN methanol and NG methanol, are added to the cost side of a CBA in a fuel appraisal. The total cost ($TC_{€/tkm}$) of each fuel is the sum of fuel price ($FP_{€/tkm}$) and external cost ($EC_{€/tkm}$) at a given point in time.

$$TC_{€/tkm} = FP_{€/tkm} + EC_{€/tkm} \qquad (1)$$

[2] Personal email with Benedikt Stefánsson, Director of Business Development at CRI, 2018.

Where €/tkm is euros per tonne kilometre.

This study assesses the total cost of HFO, RN methanol and NG methanol for each year in the period 2018 to 2050. Furthermore, two different production pathways of methanol are assessed to evaluate how cost-effective a transition towards RN methanol, in comparison to NG methanol, could be for the maritime sector in Iceland. Consequently, the price of each fuel, given different timescales and production pathways, was estimated.

Except for the cost of carbon, the cost of externalities ($EC_{€/MJ}$) for different pollutants was assessed in terms of maritime externality literature based on Impact Pathway Analysis (IPA). IPA was developed by the ExternE project and involves the monetary estimation of environmental costs by following a pathway of source emissions to physical impacts to monetary valuation (Hainoun et al. 2010; Jorli et al., 2017). The IPA was undertaken using an LCA conducted by Brynolf et al. (2014), which compared HFO and methanol in a maritime engine. This step was done by multiplying the amount of each pollutant, relative to the functional unit (1 tkm), with the cost of the same amount of the respective pollutant. Finally, in accordance with equation (1), the total cost of the fuels was established.

The following sub-sections will outline the methodologies and datasets that were utilised for estimating the fuel and external costs of the three respective fuels.

2.1 External costs

Two approaches were adopting for estimating external costs. The external costs of all pollutants except CO_2 were estimated through an IPA. These cost estimates were derived using several air pollutant externality studies focused on the maritime context (Kotowska, 2017; Holland & Watkiss, 2004; Jiang et al., 2010; Maibach et al., 2008), all of which have been based on either the Clean Air for Europe Programme (CAFE) and/or Developing Harmonised European Approaches for Transport Costing and Project Assessment (HEATCO), see Table 1.

Table 1. Cost-factors: External cost of pollutants, from the at sea category, given in 2018 €/tonne.

Study	Country/Region	NOx	SO2	PM (ud)	NMVOC
Kotowska (2017)	EU	3,160		1,458	608
Holland et al. (2004)	Eastern Atlantic	6,542	6,133		
	Baltic Sea	2,862	2,181		
	English Channel	7,360	8,041		
	N. Mediterranean	8,450	6,406		
	North Sea	4,225	5,860		
Jiang et al. (2010)	North Sea	6,790	9,186		
Maibach et al. 2008)	Baltic Sea	3,544	5,043		555
	Mediterranean	681	2,726		333

	North-East Atlantic	2,181	2,998		444
	North Sea	6,951	9,404		2,108

The aforementioned studies provide cost estimates for NOx, SO_2, SO_x, $PM_{2,5}$, $PM_{undifferentiated}$ (PM_{ud}), NMVOC and VOC. However, the LCA (Brynolf et al., 2014) does not provide measurements for all of the above-mentioned pollutants. Therefore, only the pollutants that are both in the maritime externality literature (Kotowska, 2017; Holland & Watkiss, 2004; Jiang et al., 2010; Maibach et al., 2008) and the LCA (Brynolf et al., 2014) are shown in Table 3.1. The cost estimates derived from the literature are all converted into nominal 2018€ prices.[3] Given slight variations in the cost estimates between the underlying methodologies, i.e. CAFE and HEATCO, the average value of the nominal cost estimates is used as the basis of this part of the study. Furthermore, one standard deviation, σ, is added and subtracted from the mean, μ, to form a high and low case, while the mean is the medium case[4] (Table 2). Therefore, three plausible trajectories are provided to facilitate a 68% confidence interval of the external cost. This confidence interval is due to the dataset being relatively small, constituting 1 to 11 estimates for each pollutant.[5]

Table 2. External cost of pollutants, €/tonne, adopted from (Kotowska, 2017; Holland & Watkiss, 2004; Jiang et al., 2010; Maibach et al., 2008)

	NO_x	**SO_2**	**PM_{ud}**	**NMVOC**
Low	2272	3196	1458	76
Medium	4795	5798	1458	809
High	7318	8400	1458	1543

All external cost estimates in Table 2 are from the *at sea* category of air pollutant externality estimations from the maritime sector. Consequently, *near port* and *in port* externality estimation categories are omitted from this study as the maritime sector in Iceland is seldom in contact with areas that are anywhere near as densely populated as the locations upon which the emission externality studies are based, i.e. HEATCO and CAFE, as they determined their impacts using mainland European cities.

Data values for the external cost of greenhouse gas emissions are adopted from the European Investment Bank's (EIB) research and utilization of shadow prices for greenhouse gas emissions (EIB, 2015). Cost curves are in 2018 euros and based on three separate initial cost estimates of 15, 35 and 55 euros per tonne. The cost curves then follow assumptions of low, medium and high per annum increases between the periods 2018-2030, 2031-2040 and 2041-2050. These increases are in accordance with the EIB's estimates as shown in Table 3 and illustrated in Figure 1's trajectory. By 2050, the range in shadow prices is between 50 and 200 euros per tonne according to whether low or high starting costs and annual increases apply.

[3] Nominal values found via cumulative inflation of the €, i.e., 37,35%, 10,94% and 3,51% (Inflation Tool, n.d.) price increase from 2000, 2010 and 2014, respectively.
[4] Here we were faced with the fact that the data points for externality costs were too few to calculate the confidence interval without getting negative values at the lower end of the spectrum. Therefore, we had to put an assessment on the uncertainty without a conventional statistical analysis. The uncertainty spectrum is not verifiable beyond the extent that it represents a high and low case in an unbiased way between pollutants. With more data points we could have had a more rigorous analysis of distribution around the mean by utilizing confidence intervals.
[5] A higher confidence interval, such as two standard deviations from the mean would have resulted in a negative externality cost for certain pollutants.

Table 3. Incremental increases in shadow prices for greenhouse gas emissions from 2018-2050 (2018 euros).

		Time period		
		2018-2030	2031-2040	2041-2050
Low cost increase p.a.	Euros	0.5	1	2
Central cost increase p.a.	Euros	1	2	4
High cost increase p.a.	Euros	2	4	8

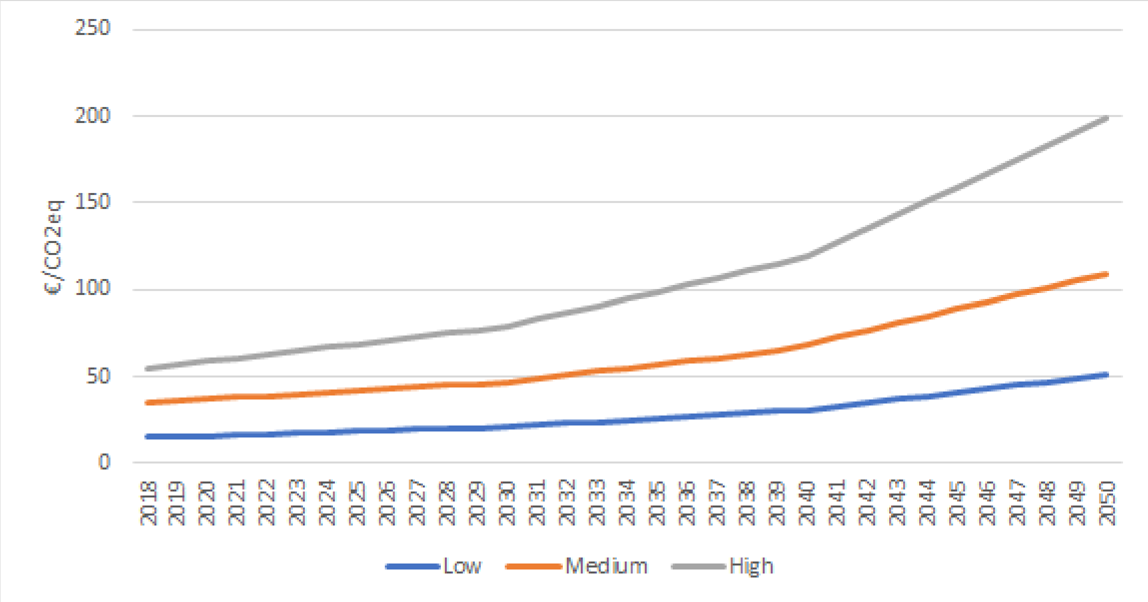

Fig. 1. Shadow price trajectories for greenhouse gas equivalents, 2018-2050 (2018 euros).

2.2 Life-cycle emissions

The amount of pollutant produced from each fuel's life-cycle includes emissions during the well-to-propeller (WTP) phase, differentiated into well-to-tank (WTT) and tank-to-propeller (TTP). WTT total emissions from RN methanol are 12.1 gCO_2eq/MJ[6]. WTT emissions from NG methanol are approximately 20 gCO_2eq/MJ (Brynolf et al., 2014). The WTT emissions of HFO are 6.7 gCO_2eq/MJ (Brynolf et al., 2014).

TTP emission factors are also derived from the study by Brynolf et al. (2014), which compared HFO and methanol in a commensurable engine and engine mode, i.e. engine size and operational mode. The results shown in Table 4 are derived from the combustion of HFO and methanol in a 14.68 MW medium-speed four-stroke diesel engine for the HFO, and a 14.68 MW dual-fuel engine, with 1% marine gas oil (MGO) as pilot fuel for the methanol. Engine efficiency was commensurable for both fuel tests, i.e. 41%. However, the cargo capacity of the vessel fuelled with methanol decreased by 4%, from 7,500 tonnes to 7,200 tonnes. This was due to larger storage requirements for methanol relative to HFO, due to the respective lower-heating values of the fuels and the size of the vessel. Subsequently, vessel efficiency is reduced to 0.0591 kWh work/t km for the methanol engine, compared to 0.0568 kWh work/t km for the HFO engine. Therefore, fuel consumption increases slightly in the case of methanol, i.e. 0.5189 MJ/t km compared to 0.4987 MJ/t km for HFO, due to the reduced cargo capacity of the

[6] Personal email with Benedikt Stefánsson, Director of Business Development at CRI, 2018.

methanol-fuelled vessel. Subsequently, pollution factors are adjusted according to increased fuel consumption, i.e. 4% increased energy consumption per t km. The functional unit in Brynolf et al. (2014) was 1 tonne cargo transported 1 km with a ro-ro vessel, i.e. 1 tkm. Although WTT emissions of CO2eq are higher than HFO in the cases of NG and RN methanol, all other pollutants are lower in concentration.

Table 4. WTT and TTP emissions (g/t-km) for HFO and Methanol (RN) and Methanol (NG), adjusted for vessel efficiency (Bengtsson et al., 2011; Brynolf et al., 2014).

Emissions to WTP (g/t-km)			
	HFO	**Methanol (NG)**	**Methanol (RN)**
Total WTP GHG (CO2eq)	43.2365	46.3818	42.0828
NOx	0.7979	0.1453	0.1453
SO2	0.3441	0.0000	0.0000
PM10	0.0464	0.0022	0.0022
NMVOC	0.0279	0.0000	0.0000

2.3 Total external cost of fuel life-cycles

For all external costs estimated using an IPA, these are the sum of costs generated by pollutants during a fuel's lifecycle, measured in g/tkm. The external costs ($EC_{€/tkm}$) of fuels, from production and shipping (WTT) and combustion (TTP), are established by multiplying the respective cost factor ($CF_{€/g}$) of each pollutant by the amount of the pollutant produced. The latter corresponds to the energy exerted in the main engine to propel the vessel and its cargo by 1tkm ($P_{g/tkm}$) (see equation 2).

$$EC_{€/tkm} = CF_{€/g} * P_{g/tkm} \qquad (2)$$

4.4 Price development of HFO

The initial HFO price corresponds to the price in June 2018, which is the average Rotterdam spot price of 57 €/bbl (IEA, 2018b). The following scenario assumptions for crude oil demand and production result in three potential price trajectories – low, medium and high – which are considered plausible for the period 2018-2050 (Shafiei et al., 2019). In the medium and high trajectories, price development is expected to increase linearly based on a constant growth rate. The three price trajectories for HFO are summarised as follows:

- **Low case:** constant HFO price of 57€/bbl;
- **Medium case**: Linear HFO price increase from 57€/bbl in 2018 to 101€/bbl in 2050, an average annual growth rate of 1.8%;
- **High case**: Linear HFO price increase from 57€/bbl in 2018 to 141€/bbl in 2050, an average annual growth rate of 2.9%.

2.5 Price development of methanol

This study looks at methanol cost from the perspective of two different production pathways, i.e. conventional (NG) and renewable (RN). Moreover, the renewable pathway in this study is explicitly methanol from a CCU production process, whilst NG methanol is from a natural gas to methanol pathway. Due to lack of data, the price for CRI's RN methanol fuel has been estimated utilising studies relating to the price difference between conventional and renewable pathways in methanol production (Goeppert et al., 2009; Clifre & Badr, 2007; Mignard et al., 2003), and the base prices of NG methanol from Methanex, the largest global producer and supplier of methanol.

Matzen et al. (2015) estimated that the proportion of electricity cost in a methanol plant, producing via a CCU pathway, was 23-65% of the total cost. Therefore, if we assume an electricity price according to EIA's (2019) LCOE estimation of hydroelectric power[7] of 39.1 2018$/MWh, i.e. 34.8 2018€/MWh[8], we can estimate that the electricity cost in an Icelandic methanol plant, with an efficiency of between 51% and 68%, is in the range 285 to 380 €/tonne. According to the estimate of Matzen et al. (2015), electricity cost amounts to between 23% and 65% of the total production cost. Under the higher proportion of 65%, the price of RN methanol is estimated to be between 439 and 586 €/tonne, whereby process efficiency is 68% and 51% (as per Mignard et al., 2003), respectively. Under the lower proportion of 23%, the cost is estimated to be between 1,242 and 1,655 €/tonne, whereby process efficiency is 68% and 51%, respectively.

The initial methanol price, for NG methanol, is retrieved from Methanex. In June 2018, their posted contract price was 380 €/tonne (Methanex, 2019). This date was chosen to correspond to the initial price chosen for the HFO price trajectories. With regards to the price development towards 2050 for NG methanol and RN methanol, this is assumed to follow the price development of natural gas (EIA, 2019) for NG methanol, and electricity prices (EIA, 2019) and learning curve estimations (Kersten et al., 2011; Schmidt et al., 2017) for RN methanol. Since learning curves for the CCU production processes applied by CRI are not available, a proxy is applied. In the case of solar photovoltaics, a cost reduction of 14% was derived per doubling of cumulative installed capacity (Kersten et al., 2011). Schmidt et al. (2017) revealed an expert opinion study that showed research & development (R&D) funding would decrease the capital costs of solid oxide electrolysis cells by 0-24%, and that the production costs would decrease by between 17-30% per doubling of cumulative installed capacity until 2030. Furthermore, the learning rates for alkaline and PEM electrolysers are expected to be 9-13%, respectively, from 2020-2030 (Hydrogen Council, 2020).

Given the relative immaturity of RN methanol production and the abovementioned learning rates of related and similar technologies, a linear price reduction was assumed for RN methanol of 20% and 30% in 2050, relative to 2018 prices. This reflects assumed cost reductions pertaining to technological advancements in CCU processes. Given the high variation of price estimations of CCU and electrolysis methanol, the initial price will be taken as the average of seven estimates[9], which equate to 921 €/tonne. A price increase is estimated for NG methanol in the period 2018-2050 in accordance with the NG methanol forecast of the IEA (2019), who assumed a 20-25% price uplift. In the medium and high

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[7] Approximately 73% of Icelandic electricity production currently derives from hydropower (NEA, 2019).

[8] This value is comparable to a LCOE estimate for a new Icelandic hydropower project, Hvammsvirkjun (93 MW), of 38.8 $/MWh (Askja Energy, 2016).

[9] These are 630 and 756 €/tonne provided via email correspondence with CRI, 1140 €/tonne from Mignard et al., 2003; and 439, 586, 1,242 and 1,655 €/tonne from (Mignard, et al., 2003; Matzen et al., 2015.

trajectories, the price development is expected to increase/decrease linearly. This is set out as follows and illustrated in Fig. 2.

NG methanol:

- **Low case**: constant NG methanol price of 380€/tonne;
- **Medium case**: NG methanol price increase from 380€/tonne in 2018 to 456€/tonne in 2050, an average annual growth rate of 0.6%;
- **High case**: NG methanol price increase from 380€/tonne in 2018 to 475€/tonne in 2050, an average annual growth rate of 0.7%.

RN methanol:

- **Low case**: CCU/electrolysis methanol price decrease from 921€/tonne in 2018 to 644€/tonne in 2050, an average annual decrease rate of -1.1%;
- **Medium case**: CCU/electrolysis methanol price decrease from 910€/tonne in 2018 to 736€/tonne in 2050, an average annual decrease rate of -0.7%;
- **High case**: constant CUU/electrolysis methanol price of 921 €/tonne.

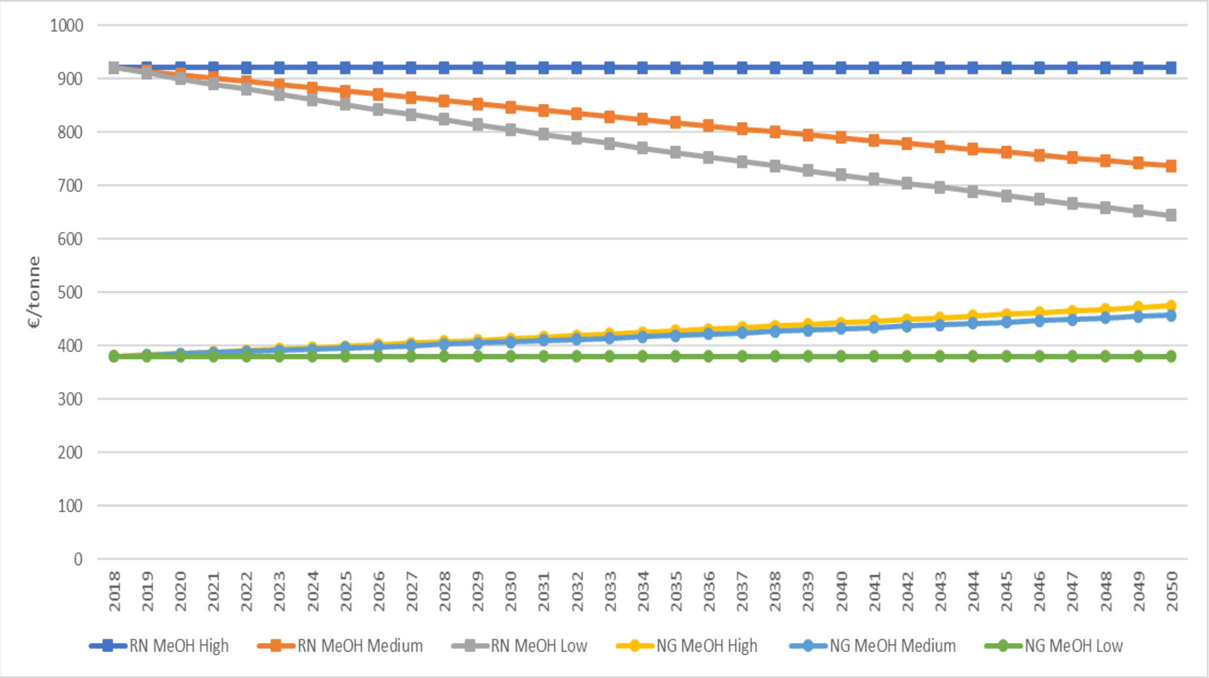

Fig. 2. Three price trajectories of RN and NG methanol, from 2018 to 2050 – low, medium and high scenarios.

3. Results

This section will outline the main results of the extended cost-competitiveness study. Fuel prices and external costs are outlined separately at first, before the total cost data is presented.

3.1 Fuel prices

The fuel prices for each of the three fuel types is assessed in accordance with the three potential price trajectories (low, medium and high) outlined in detail in this paper's methodology. Fig. 3 shows that all three price trajectories lead to lower costs for HFO compared to NG and RN methanol. When comparing the low fuel price scenarios in 2018, the cost of RN methanol, NG methanol and HFO was 0.022, 0.009 and 0.005 €/tkm, respectively. However, in 2050, in the low fuel price scenario, the cost of the same fuels is 0.016, 0.009 and 0.005 €/tkm, respectively. Therefore, the gap between the fuel prices of NG methanol and RN methanol is significantly reduced in the low fuel price scenario in 2050. When comparing the medium fuel price scenarios in 2050, the cost of RN methanol, NG methanol and HFO is 0.018, 0.011 and 0.008 €/tkm, respectively. Additionally, when comparing the high fuel price scenarios of 2050, the cost of RN methanol, NG methanol and HFO is 0.022, 0.012 and 0.012 €/tkm, respectively. The cost of HFO ranges from 0.005 to 0.012 €/tkm, NG methanol ranges from 0.009 to 0.012 €/tkm, and RN methanol ranges from 0.016 to 0.022 €/tkm.

With regards to HFO, the price of oil used in this study relied on a range of possible futures, including a high, low and a medium case. The different future price paths were derived from data from the U.S. Energy Information Administration as well as from the International Energy Agency's Global Energy Outlook. This range has been used in other studies in Iceland, for example in the GHG mitigation assessment plan for Iceland as well as in other academic studies (see Shafiei et al. 2018; 2019).

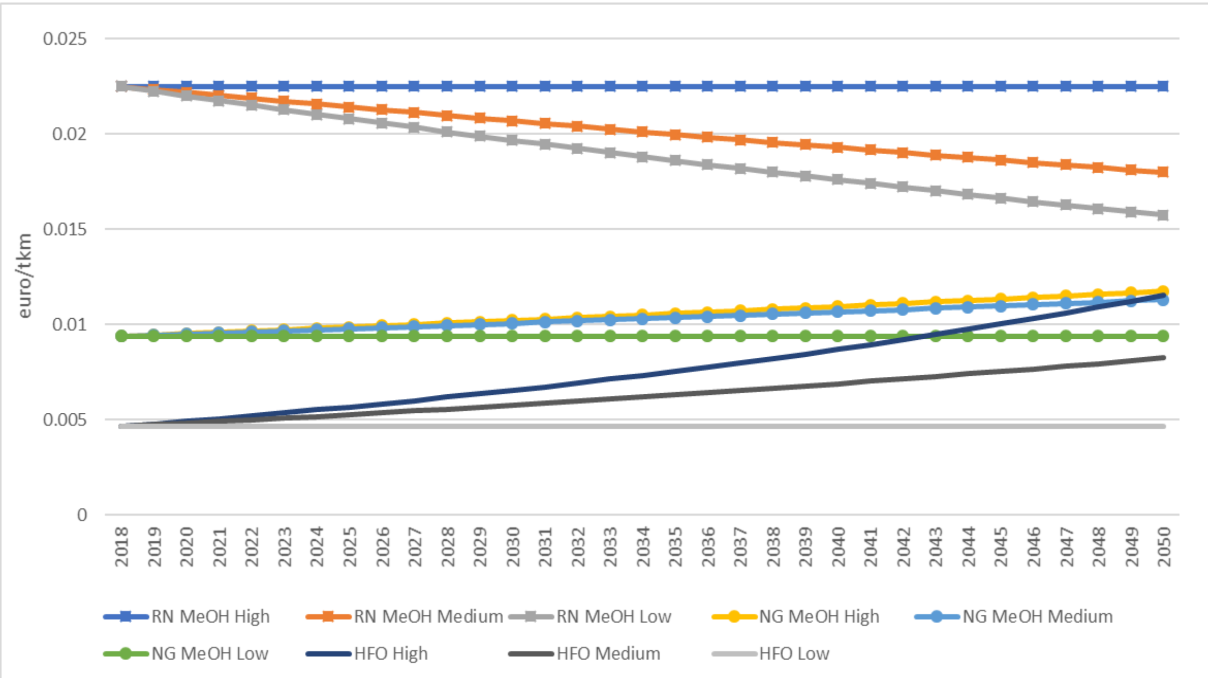

Fig. 3. Fuel price in €/tkm relating to low, medium and high estimates of fuel price for HFO, NG methanol and RN methanol.

3.2 External costs

External costs of all pollutants except greenhouse gases are assumed to be constant over the time horizon, but broken into the three estimates set out in the methodology: low, medium and high, where medium represented the mean cost estimate from the studies analysed, and low and high represented the mean value ±1 standard deviation. Fig. 4 depicts the results.

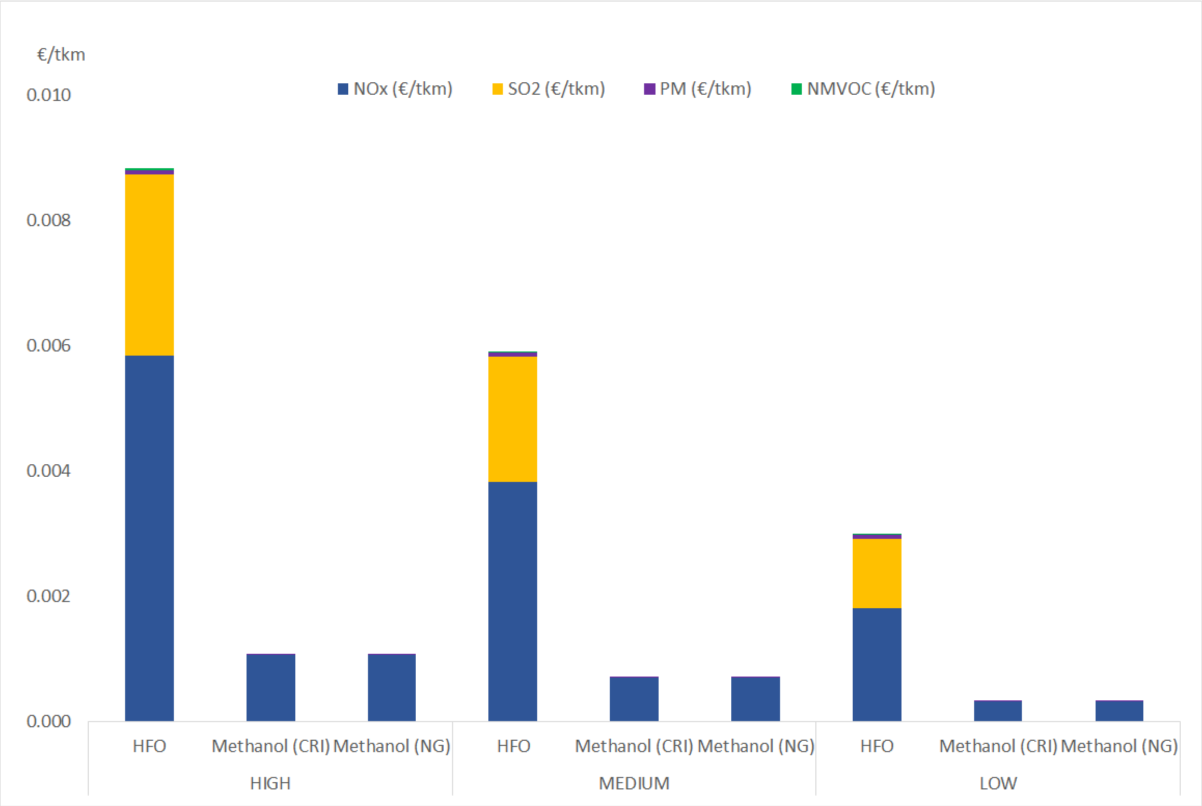

Fig. 4. Static external costs of pollutants relating to low, medium and high scenarios for HFO, NG methanol and RN (CRI) methanol.

The largest external cost associated with HFO, RN and NG methanol is NO_x. The second largest external cost is SO_2, but only for the HFO pathway as methanol use does not result in SO_2 emissions. When they are combined, NO_x and SO_2, are combined they contribute in the range of 97 to 99% of the total external costs relating to HFO utilisation. The PM and NMVOC external costs are low for all three fuels. The PM external cost constitutes between 0.7 and 1.9% of the total external cost for HFO. For RN methanol, PM constitutes between 0.2 and 0.3% of the fuel's total external cost, and between 0.1 and 0.3% of the total external cost for NG methanol. NMVOC constitutes between 0.1 to 0.3% of the total external cost for HFO. In addition, no NMVOC emissions relate to methanol combustion and therefore constitute 0% of the fuel's external cost.

3.3 Total cost

The total cost of the three fuels are represented in three separate scenarios, in Figs. 5 (high), 6 (medium) and 7 (low). These outcomes incorporate the low, medium and high estimates for both static and dynamic externalities, as well as the low, medium and high estimates for the fuel price and their assumed linear increases.

In Fig. 5, the high external cost scenario proportionally influences the total cost the most. NG methanol is the most competitive production pathway according to all three fuel price assumptions, and across the whole timespan of 2018-2050. HFO is more cost-competitive than RN methanol between 2018 and 2042. However, HFO is projected to become more expensive than RN methanol after 2042 under a low fuel price scenario and after 2047 under a medium fuel price scenario. Even under the high fuel price scenario, RN methanol is projected to be less cost-competitive than HFO in 2050. Under high external cost assumptions, NG methanol (low fuel prices) is the most cost-competitive scenario overall.

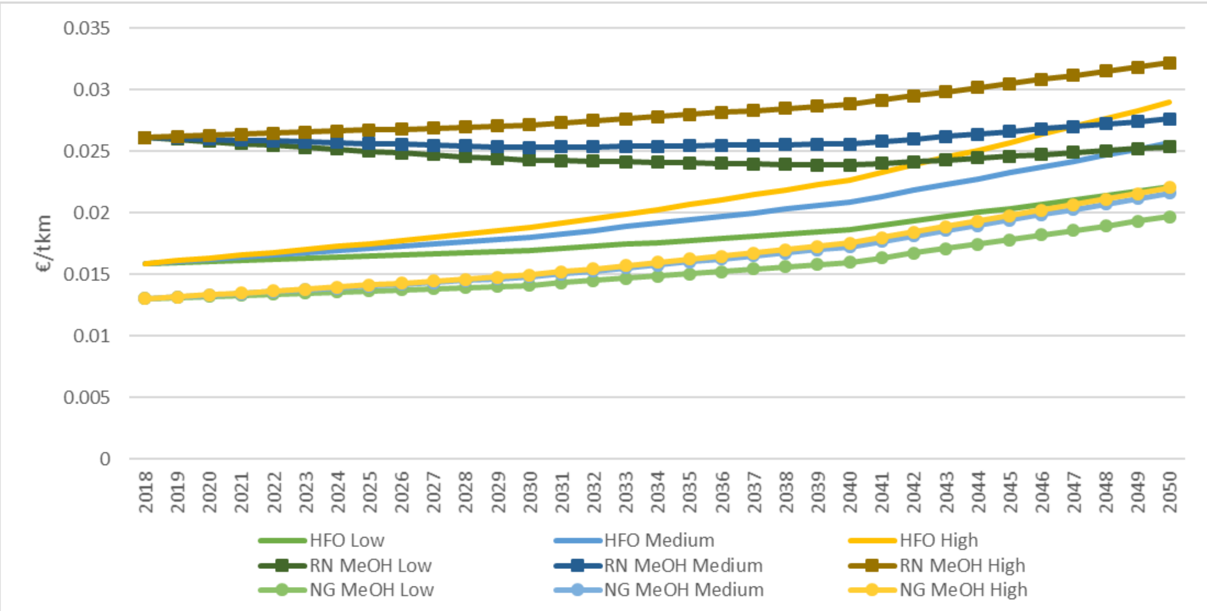

Fig. 5. High external cost scenario: Total cost in €/tkm of low, medium and high fuel price estimates.

In Fig. 6, the medium external cost scenario impacts the total cost of the respective fuels less than in the high externality scenario. Under these projections, NG methanol (high fuel price) is more cost-competitive than HFO (high fuel price) throughout the period 2018-2050, and increasingly so. This is also the case when comparing the low and medium fuel price trajectories, albeit the difference in cost-competitiveness between the production pathways is much less throughout the duration of the simulation, and the divergence in curves thus correspondingly smaller.

Only when a high fuel price is assumed for HFO in conjunction with a low fuel price for methanol does the latter become more cost-competitive than the former, and not before the year 2049. Under medium external cost assumptions, NG methanol (low fuel prices) is the most cost-competitive scenario overall.

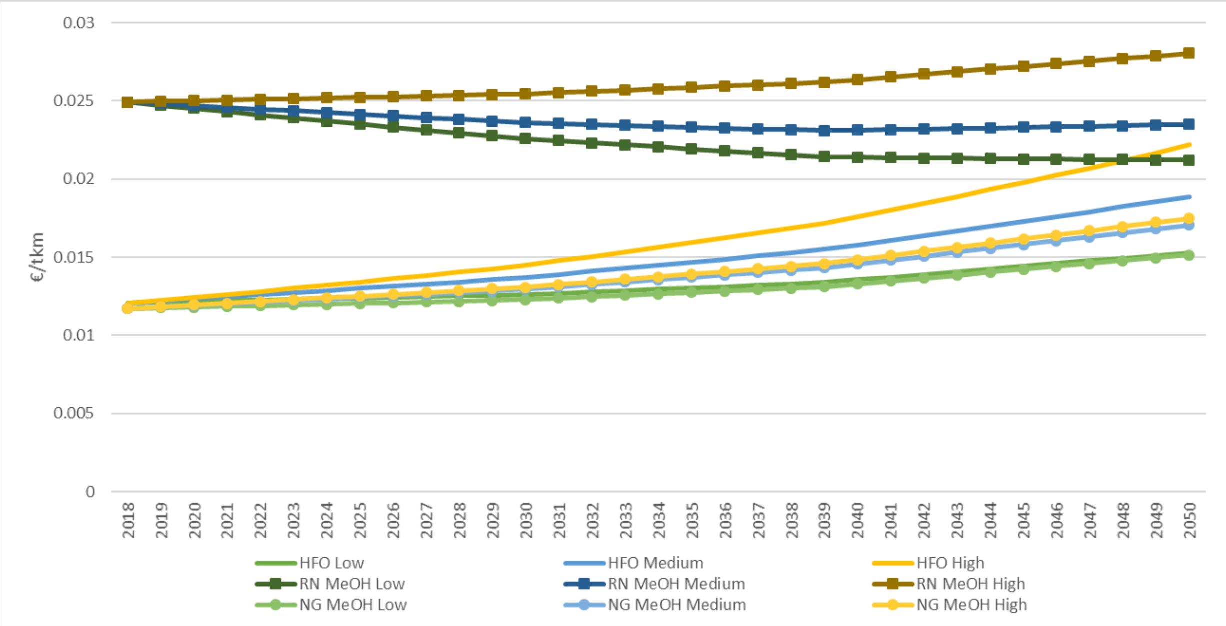

Fig. 6. Medium external cost scenario: Total cost in €/tkm, of low, medium and high case fuel price estimates.

In Fig. 7, the low external cost scenario has the least proportional impact on the total cost. Under these assumptions, RN methanol is the least cost-competitive of the three production pathways, remaining more expensive than NG methanol and HFO throughout the period 2018-2050 and irrespective of whether low, medium or high fuel price assumptions apply. Assuming high fuel costs for both production pathways, HFO becomes less cost-competitive than NG methanol after the year 2037. Under medium fuel prices, HFO is more cost-competitive than NG methanol through the period 2018-2050, although the margin is negligible by 2050. Under low fuel prices, NG methanol is less cost-competitive than HFO throughout the period 2018-2050, remaining 32% less expensive in 2050. Under low external cost assumptions, HFO (low fuel prices) is the most cost-competitive scenario overall.

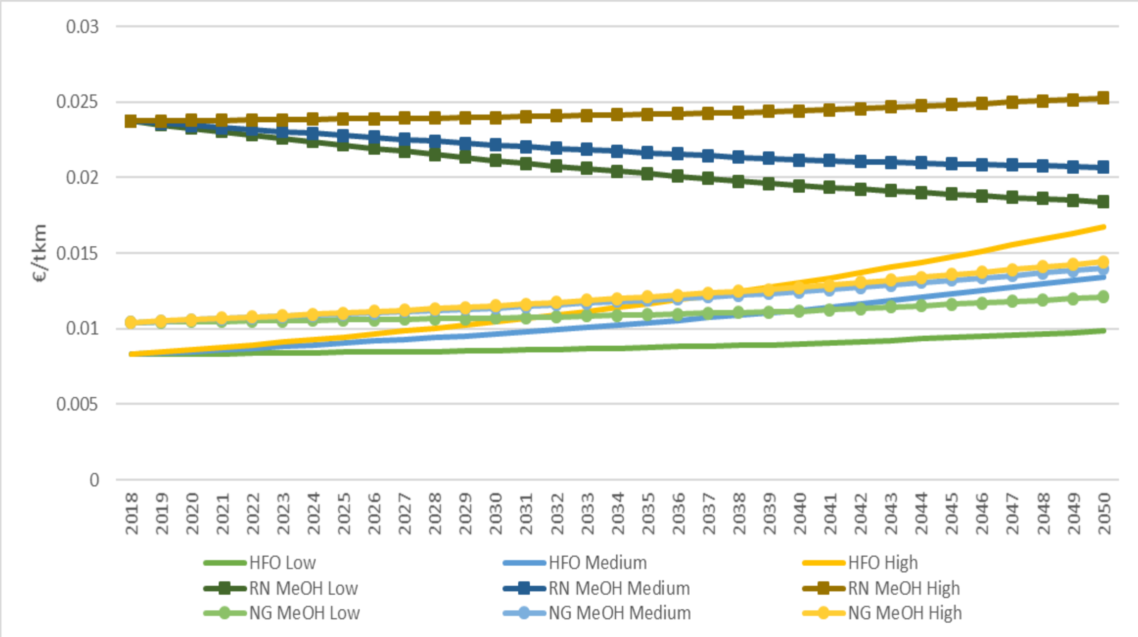

Fig. 7. Low external cost scenario: Total cost in €/tkm, of low, medium and high case fuel price estimates.

4. Discussion

4.1 Main cost competitiveness outcomes

The objective of this paper was to assess the cost-competitiveness of three fuels (HFO, NG methanol and RN methanol) in Iceland in the period from 2018 to 2050, having accounted for the economic value of environmental externalities. The results reveal that RN methanol is not cost competitive, irrespective of whether the externalities of its combustion are added to its fuel price. However, NG methanol becomes cost competitive, under high and medium fuel price trajectories in 2021 and 2028, respectively, assuming a high external cost assumption. Furthermore, NG methanol becomes cost competitive in Iceland in 2043, under a high fuel price trajectory, and assuming medium external costs.

The relatively high total cost of RN methanol is mainly because the fuel is currently produced at a pilot plant. The cost mark-up when comparing RN methanol to HFO in 2020 is 112%. By definition, production costs tend to be higher in such plants as "learning" has not yet taken place. However, from the perspective of reduced capital costs via learning rates, i.e. in the best-case economic scenario for RN methanol and where high external costs are assumed, RN methanol remains 9% more costly than HFO in 2050. Thus, RN methanol does not become cost competitive over the analysed time-period under any of the evaluated scenarios. This has practical and domestic and international policy implications.

4.2 Practical and policy implications

The results presented in this paper represent an addition to the ongoing debate and literature on the cost-competitiveness of renewable and non-renewable fuels (Bengtsson, 2011; MEPC 70, 2016), and the merits of transitioning to new energy carriers within the maritime sector (Dominkovic et al., 2018).

Utilising methanol for use in maritime engines is technologically feasible. The infrastructure for the storage and distribution of methanol can be adapted relatively easily to gaseous alternatives due to the liquid state of methanol under ambient conditions. A transition towards renewable methanol from HFO could be facilitated with NG methanol as a complement. However, despite Iceland's 10% renewable energy policy imperative in the maritime sector, this study shows that there are likely to be considerable economic barriers preventing this objective being met via RN methanol production without government subsidies or non-economic policy measures such as renewable marine fuel quotas (Hansson et al., 2019). They also reinforce the need for greater understanding of the economic feasibility and cost-competitiveness of not only RN methanol but other renewable fuel types in Iceland. It is advisable for the Icelandic government to conduct an extended cost-comparison study of all fuel options as part of a wide-ranging feasibility study on the optimal means of complying with their four main policy objectives on reducing emissions in the marine sector and overall. Moreover, in a regional context, the outcomes begin to add economic information to recent research focused on the feasibility of options for the decarbonisation of Nordic energy systems, which would facilitate superior emissions performance standards than required by the Paris Agreement and the Effort Sharing Regulation (EC, 2016; OECD/IEA, 2016). Given that the cost of electricity is likely to be higher in different national contexts to Iceland and this represents 23-65% of the total production cost, methanol production is potentially even less economically feasible elsewhere.

Iceland's Climate Action Plan 2018–2030, which paved the way for the new domestic regulation on the permissible sulphur content of marine fuels, asserted intent to eventually phase out HFO (Ministry of Environment and Natural Resources, 2018). A transition towards methanol would pave the way towards fulfilling that goal. However, Iceland also aims to achieve a target of 10% renewable energy in the maritime sector before 2030. In order to make a transition to RN methanol more economically feasible for maritime operators, the provision of financial support instruments would be required. This has been done before in Iceland in the case of electric-vehicles (EV), where value-added-tax was omitted from the cost of new EVs in order to facilitate a faster transition towards their take-up (ICCT, 2018). As a means of improving the cost-competitiveness of a renewably fuelled form of transportation in comparison to fossil-fuel alternatives, as well as reducing the negative externalities of fuel consumption, there is a comparable justification for the provision of subsidies by the Icelandic government to reduce the costs of RN methanol. Additionally, despite the outcomes in this study, it should be reiterated that a transition to methanol use in the maritime sector would facilitate compliance with the IMO's Annex VI requirements in 2020, both in terms of global sulphur emissions and ECAs, and the newly imposed Icelandic regulations imposing a maximum 0.1% sulphur content (Ministry of Environment and Natural Resources, 2019). Furthermore, the criterion to be sulphur free will become increasingly relevant as more areas around the world are declared ECAs. Methanol is sulphur free, which means that vessels utilising methanol will be able to comply with both the global sulphur emissions regulations, the terms of ECAs and Icelandic domestic regulations from 1 January 2020. It is likely despite economic feasibility issues and mainly due to IMO policy-compliance requirements that a recent global study by GlobalData (2019) projected that global methanol production would almost double from 142.91 to 284.72 million tonnes per annum between 2018 and 2030, with much of the growth focused on oil-reliant economies such as the US, Russia and Middle East. This would, however, remain less than 1% of global fuel demand in the maritime sector.

There are, however, potentially new policy initiatives emerging in Europe that would impact the cost-competitiveness of fossil versus alternative fuels in the maritime sector. The European Commission's new President, Ursula von der Leyen, announced that climate action for the maritime industry would be a part of her political agenda, including the prospect of accounting for the cost of carbon in the EU Emissions Trading Scheme (von der Leyen, 2019). Although this measure alone would only align the cost-competitiveness of HFO, NG methanol and RN methanol more closely with the results of this study rather than market prices, further initiatives within the EU ETS have been mooted that could incentivise a transition to greater use of alternative fuels. These include the potential establishment of a 'Maritime Transport Decarbonization Fund', which would hypothecate EU ETS revenues from the shipping sector into decarbonisation technologies, and a binding target for shipping companies to reduce the carbon intensity of their transportation activities by at least 40% by 2030 compared to a 2018 baseline (Carbon Market Watch, 2020).

The alternatives to HFO that have most commonly been considered by the maritime industry, in the short term, are low sulphur petroleum fuels and/or EGCS (CE Delft, 2016). These fuels and technologies can hardly be viable as a long-term solution given the challenges of climate change linked to greenhouse gas emissions, diminishing fossil fuel reserves, and the regulatory requirements that have been set by nations on utilising renewable energy. According to the Marine Environment Protection Committee (MEPC) 70 report, it is estimated that consumption of alternative marine fuels, such as LNG, methanol, biofuels, liquid propane gas (LPG) and dimethyl ether, will remain negligible by the end of 2020 (MEPC 70, 2016). Any shift towards greater methanol use, whether NG or renewable, in the maritime sector is thus a long-term technical solution to the challenges described above, and it should be considered in that context.

Currently, the production capacity of RN methanol at CRI's methanol plant in Svartsengi is 78 TJ, which amounts to 0.8% of the Icelandic maritime sector's total energy demand. The methanol plant at Svartsengi would have insufficient effluent carbon to produce 10% of the energy content required by Iceland's maritime sector, so additional capacity methanol plants would be required. However, the high availability of effluent carbon, water and renewable electricity in Iceland is likely to make such a project technically feasible, even though economic factors currently make such a venture unattractive. The amount of geothermal effluent carbon needed to produce 991 TJ of methanol (the 10% target) could potentially[10] be generated by two geothermal power plants of the scale of Svartsengi, which has a nameplate capacity of 74.4 MW. Moreover, the electricity required to produce 991 TJ of methanol would necessitate the use of approximately 3% of the total production capacity of electricity in Iceland. However, more research into the development of electrolysis for hydrogen production is needed, as the economic efficiency of this process still favours conventional methods, i.e. from fossil fuels (Nikolaidis and Poullikkas, 2017). Furthermore, CCU technologies are still in their early stages of development. The undertaking of more research and learning could, potentially, make CRI's pathway of methanol production cost-competitive, but this paper's results suggest that this eventuality is still likely to be several decades away. Further study of alternative renewable energy fuels and their cost-competitiveness is needed in Iceland, especially in relation to other biofuels.

4.3 Study limitations

Some limitations in the methodology chapter of this paper were identified. Firstly, there is a considerable degree of limitation associated with the lack of transferability of European emission cost estimates to the Icelandic context and very few international cost evaluations of methanol to date. With regards to externalities, the study's approach may have led to low-end estimates, such as in the case of the use of average annual carbon trading prices derived from the EU ETS and the omission of the in-port category of emissions due to the low population of Iceland compared to mainland European cities. In addition,

[10] Assuming effluent carbon emissions at the site of the second geothermal power plant of the same scale as at Svartsengi.

this paper assumed learning rates of between 20 and 30% with respect to RN methanol, and it will only be possible to verify the accuracy of this estimate in the future once the technological processes mature.

The first step in this paper's cost-competitiveness study was to analyse the quantity of emissions, based on the respective fuel types and combustion methods. Secondly, the external costs were calculated by multiplying pollutants by their corresponding marginal external cost. In both steps, there were a number of possible issues that could impact upon the validity and reliability of the data. In the first part, Brynolf et al.'s (2014), and Elliss & Svanberg's (2018) results on methanol's combustion characteristics are commensurable, even though they were comparing different engine types – 14 MW versus 1.3 MW. However, very few studies have outlined the combustion characteristics of methanol in a dual fuel compression ignition engine, and the only measurements are from bench trials by engine manufactures (Brynolf et al., 2014). This is due to the fact that methanol has only been utilised and assessed as a maritime fuel for a few years (Ellis & Svanberg, 2018). There are more recent studies involving LCA of methanol. However, there are none that compare HFO to methanol in this engine type or a commensurable maritime engine type.

With regards to externalities, references to N_2O and CH_4, are not yet found in the maritime external cost literature. However, they are greenhouse gases and could be monetised relative to CO_2, based on the global warming potential (GWP) of these emissions according to the IPCC's Fifth Assessment Report (AR5), i.e. 28-36 and 265-298, respectively. However, if these emissions were to be incorporated in the external costs of fuels, via the multiplication of CO_2 cost by its respective GWP factor, this would play a relatively insignificant role, i.e. <5% of the total external cost of HFO. The only emission factors that were included in the external cost analysis were limited to the ones that are currently reported in the literature on maritime externalities and the life-cycle assessment of fuels.

The second data step in the cost-competitiveness study, involving assessment of the economic implications of the pollutants, arguably incorporated a greater margin of uncertainty. Firstly, establishing the causal linkages between pollutants and public-health and/or environmental degradation impacts, is not always straight-forward and inevitably involves varying degrees of uncertainty (Lenzen, 2006). Secondly, little research has emerged on the topic of the health implications of pollution in Iceland, other than the effects of volcanic eruptions (Hlodversdottir et al., 2012), and those of hydrogen sulphide (H_2S) (Finnbjornsdottir et al., 2016). Therefore, future research is needed in Iceland on the topic of environmental externalities and especially within a maritime context, both close to the shore and in ports. In addition, this study's use of linear damage functions ignores the possibility of tipping points, which can involve exponential impacts to human health at certain concentrations. However, this study followed the IPA approach of the HEATCO and CAFE projects, which are considered to be best practice (Jiang et al., 2010).

The relatively limited number of maritime externality studies on which thus study is based has ensured that the outcomes amount to initial cost estimates. For example, estimates for PM_{ud} were only found in one study (Kotowska, 2017), and they were therefore not differentiated between the various trajectories, resulting in a constant PM external cost estimate of 1,458 €/tonne. Another concern is that the existing European maritime externality studies provide cost estimates in relation to the proximity of vessels to densely populated areas, differentiated into three categories: *in port*, *near port* and *at sea*. Near port and in port estimates are omitted from this paper which relied only on *at sea* estimates due to the small size of the Icelandic population in comparison to much higher-population European cities assessed within *in* *port* and *near port* assessments. IPA estimates for less populated cities, i.e. 50.000-100.000 persons (approximately the size of Reykjavik), and data on the amount of time spent by vessels in free sailing, manoeuvring and berthing, would be required to reliably factor the near and in port external cost estimates into the study. In addition to the assumptions outlined in the methodology concerning the cost of carbon, externality estimates in this paper may be lower end, and further research on the environmental damages and social costs of maritime pollutants is needed in an Icelandic context.

Finally, it is important to acknowledge that monetary valuation of the environmental impacts of fuel use represents only part of the decision-making process concerning the fuels that should be deployed to meet Icelandic and international policy requirements. Valuing impacts of externalities in this manner is important so that all the costs and benefits of investment projects can be evaluated using a comparable basis i.e. via the unit of money. However, as Cook et al. (2016) noted in relation to the externalities of Icelandic power projects, a weakness of this approach is that certain environmental and/or socio-cultural impacts may be of such severity that they are deemed unacceptable by various stakeholders, irrespective of their monetary value. As such, economic information concerning externalities and extended cost-competitiveness analysis should form part of the information used and criteria applied by decision-makers to arrive at stakeholder-led determinations based on the pursuit of sustainability. The use of appropriate decision-support tools, such as Multi-Criteria Decision Analysis, can play an important role in this regard, and their deployment has recently been called for in Iceland with respect to geothermal power projects (Cook et al., 2017; Cook et al., 2020).

5. Conclusions

This cost-competitiveness study evaluated the economic feasibility of introducing an alternative fuel into the maritime sector in Iceland, i.e. RN methanol. The economic cost of production, including the estimated value of environmental externalities, was compared between HFO, NG methanol and RN methanol over the period 2018-2050 according to low, medium and high trajectories for fuel prices and externalities. The results suggest that RN methanol is unlikely to be cost-competitive with HFO before the 2040s, assuming no government financial support or renewable energy quotas are imposed. NG methanol is more cost-competitive, having the lowest total cost of the three production pathways under the scenario of high external cost throughout the period 2018-2050. NG methanol also has lower total cost than HFO between 2018 and 2050 under the scenario of medium external cost and assuming a high fuel price. The results therefore indicate that NG methanol is already cost competitive with HFO for the owners of cargo ships, fishing vessels and cruise ships, but only if externalities are accounted for in the purchase cost of the fuel. Reducing maritime emissions and providing incentives to do so remains an urgent priority for policy-makers. Assessing and regulating pollutants in terms of their spatial distribution and effects on ecosystems and public health can provide an evidence base, which would greatly assist in justifying mitigation strategies that can be utilised to facilitate pathways towards greater marine sustainability.

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References

Antturi, J., Hänninen, O., Jalkanen, J. P., Johansson, L., Prank, M., Sofiev, M., & Ollikainen, M. (2016). Costs and benefits of low-sulphur fuel standard for Baltic Sea shipping. *Journal of environmental management*, *184*, 431-440.

Askja Energy. (2016). The wish-list of the Icelandic energy industry. Retrieved 6 January, 2020, from https://askjaenergy.com/2016/08/15/the-wish-list-of-the-icelandic-energy-industry/

Baldursson, E. T. (2017). Sulphur content of marine fuels in Iceland 2016. Retrieved 12 February, 2019, from https://www.ust.is/library/Skrar/Atvinnulif/Efni/Eldsneyti/Sulphur%20content%20of%20marine%20fuels%20in%20Iceland%202016.pdf

Beder, S. (2011). Environmental economics and ecological economics: the contribution of interdisciplinarity to understanding, influence and effectiveness. *Environmental Conservation 38 (2),* 140-150. Doi:10.1017/S037689291100021X

Bengtsson, S. (2011). Life Cycle Assessment of Present and Future Marine Fuels. Retrieved 13 May, 2019, from https://core.ac.uk/download/pdf/70591427.pdf

Brandt, J., Silver, J. D., Christensen, J. H., Andersen, M. S., Bonlokke, J. H., Sigsgaard, T., Geels, C., Gross, A., Hansen, A. B., Hansen, K. M., Hadegaard, G. B., Kaas, E., & Frohn, L. M. (2011). Assessment of Health-Cost Externalities of Air Pollution at the National Level using the EVA Model System. Retrieved 27, March, 2019, from http://ceeh.dk/CEEH_Reports/Report_3/CEEH_Scientific_Report3.pdf

Bromber, L., & Cheng, W. K. (2010). Methanol as an alternative transportation fuel in the US: Options for sustainable and/or energy-secure transportation. Retrieved 17 April, 2019, from https://afdc.energy.gov/files/pdfs/mit_methanol_white_paper.pdf

Brynolf, S., Fridell, E., & Andersson, K. (2014). Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol. *Journal of Cleaner Production*, 74, 86-95. Doi: 10.1016/j.jclepro.2014.03.052.

Carbon Market Watch. (2020). High time the maritime sector sailed into the EU carbon market. Retrieved from: https://carbonmarketwatch.org/2020/02/27/high-time-the-maritime-sector-sailed-into-the-eu-carbon-market/ (accessed 19 May 2020).

Cook, D., Davíðsdóttir, B., & Kristófersson, D. M. (2016). Energy projects in Iceland – Advancing the case for the use of economic valuation techniques to evaluate environmental impacts. *Energy Policy*, *94*, 104-113.

Cook, D., Davíðsdóttir, B., & Kristófersson, D. M. (2017). An ecosystem services perspective for classifying and valuing the environmental impacts of geothermal power projects. *Energy for Sustainable Development*, 40, 126-138.

Cook, D., Davíðsdóttir, B. & Malinauskaite, L. (2020). A cascade model and initial exploration of co-production processes underpinning the ecosystem services of geothermal areas. *Renewable Energy*.

CRI (Carbon Recycling International). (n.d.). World's Largest CO2 Methanol plant. Retrieved 18 April, 2019, from http://carbonrecycling.is/george-olah/

Cuéllar-Franca, R. M., & Azapagic, A. (2015). Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts. *Journal of CO2 utilization*, *9*, 82-102.

Dalena, F., Senatore, A., Basile, M., Knani, S., Basile, A., & Lulianelli, A. (2018). Advances in Methanol Production and Utilization, with Particular Emphasis toward Hydrogen Generation via Membrane Reactor Technology. Retrieved 20 April, 2019, from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6316867/

Dominkovic, D. F., Bacekovic, I, Pederson, A. S. & Krajacic. (2018). The future of transportation in sustainable energy systems: opportunities and barriers in a clean energy transition. *Renewable and Sustainable Energy Reviews, 82*, 1823-1838.

EC (European Commission) (2015). Directive 98/70/EC of the European Parliament and of the Council relating to the quality of petrol and diesel fuels and amending Council Directive 93/12/EEC. Retrieved from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:01998L0070-20151005 (accessed 19 May 2020).

EC (European Commission) (2016). Proposal for a regulation of the European Parliament and of the Council on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 for a resilient Energy Union and to meet commitments under the Paris Agreement and amending Regulation No 525/2013 of the European Parliament and the Council on a mechanism for monitoring and reporting greenhouse gas emissions and other information relevant to climate change. Retrieved from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52016PC0482 (accessed 4 February 2020)

ECSA (European Community Shipowners' Associations). (2010). Analysis of the Consequences of Low Sulphur Fuel Requirements. Retrieved 13 April, 2019, from https://www.schonescheepvaart.nl/downloads/rapporten/doc_1361790123.pdf

Edwards, R., Larivé, J. F., Rickeard, D., & Weindorf, W. (2013). Well-To-Tank Report Version 4.0: JEC Well-To-Wheels Analysis. Retrieved from https://iet.jrc.ec.europa.eu/about-jec/sites/about-jec/files/documents/report_2013/wtt_report_v4_july_2013_final.pdf

EIA. (2019). Levelized Cost and Levelized Avoided Cost of New Generation Resources in the *Annual Energy Outlook 2019.* Retrieved from https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf (7 May 2019)

EIB. (2015). EIB Climate Strategy – Mobilising finance for the transition to a low-carbon and climate-resilient economy. Retrieved 30 May, 2020, from https://www.eib.org/attachments/strategies/eib_climate_strategy_en.pdf

Ellis, J., & Svanberg, M. (2018). SUMMETH – Sustainable Marine Methanol. Retrieved 17 April, 2019, from http://www.methanol.org/wp-content/uploads/2018/05/SUMMETH-6-Benefits-Strategies-Implementation.pdf

Finnbjornsdottir, R. G., Carlsen, H. K., Thorsteinsson, T., Oudin, A., Lund, S. H., Gislason, T., & Rafnsson, V. (2016). Association between Daily Hydrogen Sulfide Exposure and Incidence of Emergency Hospital Visits: A Population-Based Study. Retrieved 11 May, 2019, from https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0154946

Fortes, M. P., & Tzimas, E. (2016). Techno-economic and environmental evaluation of CO2 utilisation for fuel production: synthesis of methanol and formic acid. Retrieved 17 April, 2019, from https://setis.ec.europa.eu/sites/default/files/reports/techno-economic_and_environmental_evaluation_0.pdf

Gilbert, P., Walsh, C., Traut, M., Kesieme, U., Pazouki, K., & Murphy, A. (2018). Assessment of full life-cycle air emissions of alternative shipping fuels. *Journal of Cleaner Production*, 172, 855-866. Doi: 10.1016/j.jclepro.2017.10.165

Global Data. (2019). Global Methanol Capacity and Capital Expenditure Outlook, 2019 – The Middle East and North America Lead Global Capacity Additions. Retrieved 20 November 2019, from: https://store.globaldata.com/report/gdch0056mar--global-methanol-capacity-and-capital-expenditure-outlook-2019-the-middle-east-and-north-america-lead-global-capacity-additions/?utm_source=mediacentre&utm_medium=pr&utm_campaign=190724a_gd_og_global_methanol_capacity_2019&utm_nooveride=1

Goeppert, A., Olah, G. A. & Prakash, G. K. S. (2009). Beyond Oil and Gas: The Methanol Economy. Germany: Wiley-VCH.

Hainoun, A., Almoustafa, A., & Aldin, M. S. (2010). Estimating the health damage costs of Syrian electricity generation system using impact pathway approach. *Energy*, *35*(2), 628-638.

Hansson, J., Månsson, S., Brynolf, S., & Grahn, M. (2019). Alternative marine fuels: Prospects based on multi-criteria decision analysis involving Swedish stakeholders. *Biomass and Bioenergy*, *126*, 159-173.

Hellsing, V. Ú. L., Ragnarsdóttir, A. S., Jónsson, K., Keller, N., Helgadóttir, Á, K., Jóhannsson, Þ., Guðmundsson, J., Snorrason, A., & Þórsson, J. (2018). *National Inventory Report: Emissions of Greenhouse Gases in Iceland from 1990 to 2016*. Retrieved 16 February, 2019, from https://www.ust.is/library/Skrar/Atvinnulif/Loftslagsbreytingar/NIR%202018%2015%20April%20submission.pdf

Hlodversdottir, H., Petursdottir, G., Carlsen, H. K., Gislason, T., & Hauksdottir, A. (2016). Long-term health effects of the Eyjafjallajökull volcanic eruption: a prospective cohort study in 2010 and 2030. Retrieved 11 May, 2019, from https://www.ncbi.nlm.nih.gov/pubmed/27609845

Holland, M., & Watkiss, P. (2004). Benefits Table databate: Estimates of the marginal external cost of air pollution in Europe. Retrieved 28 March, 2019, from http://ec.europa.eu/environment/enveco/air/pdf/betaec02aforprinting.pdf

Hydrogen Council. (2020). Path to hydrogen competitiveness. A cost perspective. Retrieved 31 May, 2020, from https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf

ICCT (International Council on Clean Transportation). (2018). Iceland is one of the world's most interesting electric vehicle markets. Retrieved 29 May 2019, from: http://theicct.org/blog/stff/iceland-ev-market-201807

IEA (International Energy Agency). (2018a). CO2 emissions from fuel combustion highlight. Retrieved 17 February, 2019, from https://webstore.iea.org/download/direct/2373?fileName=CO2_Emissions_from_Fuel_Combustion_2018_Highlights.pdf

IEA (International Energy Agency). (2018b). Average Rotterdam oil product spot prices, USD/barrel. Retrieved 13 April, 2019, from https://www.iea.org/statistics/kwes/prices/

IMO (International Maritime Organization). (2019). *Prevention of Air Pollution from Ships*. Retrieved 12 February, 2019, from http://www.imo.org/en/ourwork/environment/pollutionprevention/airpollution/pages/air-pollution.aspx

IMO (International Maritime Organization). (2015). Methanol as marine fuel: Environmental benefits, technology readiness, and economic feasibility. Retrieved 18 April, 2019, from http://www.imo.org/fr/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Report%20Methanol%2021.01.2016.pdf

Inflation Tool. (n.d.). Inflation calculator – Euro. Retrieved 11 May, 2019, from https://www.inflationtool.com/euro?amount=1&year1=2014&year2=2018

Jiang, L., Kronbak, J., & Christensen, L. P. (2010). External costs of maritime shipping: A voyage-based methodology. Maritime Research, Department of Environmental and Business Economics, University of Southern Denmark. Retrieved 14 March, 2019, from https://www.sdu.dk/-/media/files/om_sdu/institutter/iful/ime/externalcosts.pdf

Jorli, M., Van Passel, S., Sadeghi, H., Nasseri, A., & Agheli, L. (2017). Estimating human health impacts and costs due to Iranian fossil fuel power plant emissions through the impact pathway approach. *Energies*, *10*(12), 2136.

Kersten, F., Doll, R., Kux, A., & Huljic, D. M. (2011). PV-Learning Curves: Past and Future Drivers of Cost Reduction. Retrieved 21 April, 2019, from https://www.researchgate.net/publication/261173017_PV-Learning_Curves_Past_and_Future_Drivers_of_Cost_Reduction

Kesieme, U., Pazouki, K., Murphy, A., & Chrysanthou, A. (2019). Biofuel as an alternative shipping fuel: technological, environmental and economic assessment. *Sustainable Energy & Fuels*, *3*(4), 899-909.

Kotowska, I. (2017). External costs in feeder shipping as an element of a socio-economic analysis. Retrieved 31 March, 2019, from http://yadda.icm.edu.pl/yadda/element/bwmeta1.element.baztech-5808cc24-96f8-4dbf-a3d1-93934bc50eb8/c/kotowska_external_2_2017.pdf

Kumar, S., Kwon, H.T., Choi, K.H., Lim, W., Cho, J. H., Tak, K., & Moon, I. (2011). LNG: An eco-friendly cryogenic fuel for sustainable development. Retrieved 17 April, 2019, from https://www.sciencedirect.com/science/article/pii/S0306261911004247

Lenzen, M. (2006). Uncertainty in impact and externality assessments-implications for decision-making (13 pp). *The International journal of life cycle assessment*, *11*(3), 189-199.

Maibach, M., Schreyer, C., Sutter, D., Essen, H.P., Boon, B. H., Smokers, R., Schroten, A., Doll, C., Pawlowska, B., & Bak, M. (2008). Handbook on estimation of external costs in the transport sector. Retrieved 30 March, 2019, from https://ec.europa.eu/transport/sites/transport/files/themes/sustainable/doc/2008_costs_handbook.pdf

Matzen, M. J., Alhajji, M. H., & Demirel, Y. (2015). Technoeconomics and Sustainability of Renewable Methanol and Ammonia Productions Using Wind Power-based Hydrogen. Retrieved 20 April, 2019, from https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1021&context=cbmedemirel

MEPC (Marine Environment Protection Committee). (2008). Report of the Marine Environment Protection Committee on its Fifty-Eighth Session. Retrieved 17 February, 2019, from https://www.epa.gov/sites/production/files/2016-09/documents/mepc58-23-annexes13-14.pdf

Merchan, A. L., Léonard, A., Limbourg, S., & Mostert, M. (2019). Life cycle externalities versus external costs: the case of inland freight transport in Belgium. *Transportation Research Part D: Transport and Environment*, *67*, 576-595.

Methanex. (2019). Historical Methanex Posted Price. Retrieved 20 April, 2019, from https://www.methanex.com/our-business/pricing

Mignard, D., Sahibzada, M., Duthie, J. M., & Whittington, H. W. (2003). Methanol synthesis from flue-gas CO2 and renewable electricity: A feasibility study. Retrieved 20 April, 2019, from https://www.sciencedirect.com/science/article/pii/S0360319902000824?via%3Dihub

Ministry of Environment and Natural Resources. (2019). Regulation banning the use of heavy fuel oil in the territorial sea of Iceland. Retrieved 20 December 2019 from: https://www.government.is/diplomatic-missions/embassy-article/2019/12/06/Regulation-banning-the-use-of-heavy-fuel-oil-in-the-territorial-sea-of-Iceland/

Ministry of Environment and Natural Resources. (2018). *Aðgerðaráætlun í Loftslagsmálum 2018 – 2030*. Retrieved 12, February, 2019, from https://www.stjornarradid.is/lisalib/getfile.aspx?itemid=b1bda08c-b4f6-11e8-942c-005056bc4d74

NEA (National Energy Authority). (n.d.). Orkuskipti í samgöngum á landi og í haftengdri starfsemi. Retrieved 24 March, 2019 from https://orkustofnun.is/eldsneyti/orkuskipti/nr/1891

NEA (National Energy Authority). (2018a). Gas Emissions of Geothermal Power Plants and Utilities 1969-2017. Retrieved 22 April, 2019, from https://orkustofnun.is/gogn/Talnaefni/OS-2018-T003-01.pdf

NEA (National Energy Authority). (2018b). Sviðsmyndir um raforkunotkun 2018 – 2050. Retrieved 11 May, 2019, from https://orkustofnun.is/gogn/Skyrslur/OS-2018/OS-2018-07.pdf

NEA (National Energy Authority). (2019). Energy Statistics 2018. Retrieved from: https://orkustofnun.is/gogn/os-onnur-rit/orkutolur-2018-enska.pdf

Nikolaidis, P., & Poullikkas, A. (2017). A comparative overview of hydrogen production processes. *Renewable and sustainable energy reviews*, *67*, 597-611.

Nunes, R. A. O., Alvim-Ferraz, M. C. M., Martins, F. G., & Sousa, S. I. V. (2019). Environmental and social valuation of shipping emissions on four ports of Portugal. *Journal of environmental management*, *235*, 62-69.

Odejobi, O. J., Jisieike, C. F., & Anozie, A. N. (2015). Simulation and exergy analysis of processes for CO2 capture and utilisation for methanol production. *International Journal of Exergy*, *17*(4), 456-474.

OECD/IEA (Organisation for Economic Co-operation and Development / International Energy Agency (2016). Nordic Energy Perspectives 2016. Retrieved 21 April 2019 from: https://www.nordicenergy.org/wp-content/uploads/2015/12/Nordic-Energy-Technology-Perspectives-2016.pdf

Rozmiarek, M., & Faasse, A. (2018). External effects in the maritime sector leading to new economic perspectives. In *SHS Web of Conferences* (Vol. 58, p. 01027). EDP Sciences.

SGS Inspire. (2020). Methanol: Properties and uses. Retrieved 3 June, 2020, from https://www.methanol.org/wp-content/uploads/2020/03/SGS-INSPIRE-Methanol-Properties-and-Uses.pdf

Shafiei, E., Stefansson, H., Asgeirsson, E. I., Fazeli, R., Davidsdottir, B., Gestsson, M. H., & Leaver, J. (2019). Simulation-based appraisal of tax-induced electro-mobility promotion in Iceland and prospects for energy-economic development, submitted to Energy Policy.

Shafiei, E., Davidsdottir, B., Fazeli, R., Leaver, J., Stefansson, H., & Asgeirsson, E. I. (2018). Macroeconomic effects of fiscal incentives to promote electric vehicles in Iceland: Implications for government and consumer costs. *Energy policy*, *114*, 431-443.

Staffel, I. (2011). The Energy and Fuel Data Sheet. Retrieved 17 April, 2019, from http://www.claverton-energy.com/wordpress/wp-content/uploads/2012/08/the_energy_and_fuel_data_sheet1.pdf

Stena Line Freight. (n.d.). Sterna Germanica's Methanol Conversion. Retrieved 11 May, 2019, from https://www.stenalinefreight.com/news/Methanol-project

Tzannatos, E. (2011). Ship generated exhaust emissions and their externalities for Greece. Retrieved 28 March, 2019, from https://journals.sagepub.com/doi/pdf/10.1260/1759-3131.2.1.65

Von der Leyen, U. (2019). A union that strives for more – my agenda for Europe. Political guidelines for the next European Commission 2019-2024. Retrieved from: https://safety4sea.com/wp-content/uploads/2019/07/Ursula-von-der-Leyen-A-Union-that-strives-for-more-My-agenda-for-Europe-2019_07.pdf (accessed 19 May 2020).