Sustainable mobility in Europe: Potential market share for liquefied biomethane (bio-LNG) in the heavy-duty transport and maritime sectors in 2050

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Abstract: In Europe, hard-to-decarbonise sectors, such as the heavy-duty vehicle (HDV) and the maritime sectors, pollute almost half of the total greenhouse gas (GHG) emissions of European transport. These emissions need to be reduced quickly and the biofuel liquefied biomethane (bio-LNG) has potential to do this. However, no data is available on what this fuel could contribute to the future energy system. Literature research, company questionaries, and EU related policies have been used to study which environmental, technical, economic and policy factors influence bio-LNG uptake. An energy-based calculation model has been developed in Excel which calculates the bio-LNG market share and associated GHG emissions reduction for several scenarios. The model was validated based on several sensitivity analyses and well-to-wheel (WTW) calculations. Results show that the market share of bio-LNG in transport energy consumption could be between 1.7 and 21.7% in 2050. This corresponds with 46-405 TWh of bio-LNG. The GHG emissions reductions of the decentralized and centralized pathways and sustainable combinations variate between 97-174 % with relatively small differences between the pathways. Bio-LNG future uptake especially depends on set policies, permitting processes, fuel and sector competition and feedstock availability.

Keywords: Bio-LNG, WTW analysis, GHG emissions, market share, Europe, transport

1. INTRODUCTION

The latest publication of the Intergovernmental Panel on Climate Change (IPCC) states that large-scale and rapid GHG reductions are necessary to limit global warming to 1.5 °C. This temperature increase has negative consequences such as rising sea levels, catastrophic storms, and other potentially devastating effects for the life on earth [1]. That is also why in the Paris Agreement of 2015 the need to reach carbon neutrality in 2050 is stated. However, several sectors around the world are still not decarbonised, such as the transportation sector, which was responsible for 31.3% of the European Union (EU) 27 GHG emissions in 2019, being the HDV and maritime sector responsible for 41.1% of those emissions [2]. Thus, a substantial GHG emission reduction potential is needed.

1.1 Background and scope

As part of the solution, transport fuels originated from biomass, also called biofuels, can serve as sustainable replacements for fossil fuels. This year, the European Commission (EC) has set a target to include at least 14% of renewable energy in the transport sector by 2030, from which at least 3.5% has to be powered by advanced biofuels [3]. One of these advanced biofuels is bio-LNG. Bio-LNG is a currently available and sustainable fuel that is equivalent to fossil liquefied natural gas (LNG) and can therefore make use of the existing and mature infrastructure [4]. Bio-LNG is an excellent alternative for the decarbonization of the HDV and maritime sectors, as these sectors are still facing several difficulties in their electrification due to the complex combination of powerful engines and carrying a heavy payload. To give an example, a 40-ton truck with a 1,000 km range needs a very efficient battery of about 6.4 tons, while 280 kg of LNG could be sufficient for an LNG-powered truck [5]. Biomethane could originate from the following pathways: anaerobic digestion (AD), gasification, or power to methane (P2M), but only the AD pathway is chosen in this study due to the maturity and larger application of this technology compared to the others. The bio-LNG production is summarized in Figure 1. During the AD process, the feedstock is digested in a digester and converted to biogas, which consists of roughly 50-80% methane (CH_4) and 20-50% carbon dioxide (CO_2) [6]. Apart from biogas, the by-product digestate is also obtained.

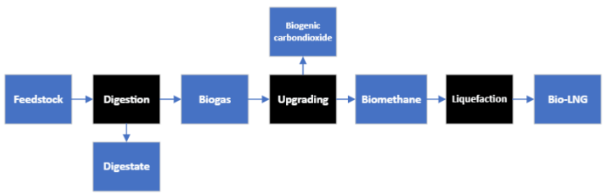

Figure 1. Schematic bio-LNG production process based on anaerobic digestion. The blue blocks relate to mass flows and the black blocks relate to process instrumentation

Then, biogas is upgraded to biomethane by removing the CO_2. This bio-CO_2 is another by-product of the process. Thereafter, biomethane is liquefied at -163 °C (at atmospheric pressure) to obtain bio-LNG [7].

1.2 Gap in knowledge

Relevant studies on bio-LNG, related to the HDV and/or maritime sectors from 2018 onwards were consulted to get an insight into the potential of the fuel in the mentioned

sectors and to perform a general literature review. Most studies agree on the advantages of bio-LNG as a fuel, such as GHG emissions reduction potential, existing infrastructure and scalability. However, criticisms regarding CH_4 slip, relatively high energy consumption during production, uncertain future bio-LNG uptake, negative business cases, local emissions, and tank-to-wheel (TTW) emissions are mentioned downsides of the fuel [8], [9]. Besides the pros and cons, it should be mentioned that the European bio-LNG production in 2050 is unknown. Consequential, this means that the potential market saturation and associated GHG emissions mitigation of bio-LNG in the HDV and maritime sectors are unknown. This is not beneficial for the discussion and uncertainty about the sustainable fuels/energy carriers to apply in hard-to-decarbonize sectors in the future. Further research is needed to quantify the role of bio-LNG in production and GHG emissions mitigation potential to potentially achieve the European environmental targets. The goal of this thesis is, therefore, to identify the technical, economic, policy, and environmental factors influencing market supply, market demand, infrastructure developments, and GHG emissions reduction potential of bio-LNG and to quantify the level of contribution of this renewable fuel to the future energy system of Europe. This led to the following research question: "What could be the market share of bio-LNG in the European HDV and maritime sectors in 2050 based on technical, economic, policy and environmental aspects and what could be the associated GHG emissions reductions?".
In chapter two the methodology is described and in chapter three the results are presented. In chapter four the discussion is shown which is followed by the conclusion in chapter five.

2. METHODOLOGY

First, the current gas/(bio-)LNG markets were described including production, demand, infrastructure, and market operation on a European scale, based on literature research. This was followed by performing a policy analysis of EU and European countries' policies which could be related to the future bio-LNG energy system and relevant information to this study was noted and summarized. The next step was to make an inventory of potential economic, technical, environmental and policy factors based on literature research, company questionaries and policies influencing bio-LNG uptake. This was followed by the development of (schematic) conceptual technical and environmental models. Once validated, a final calculation model was developed in Excel. Input data was fully assumed in the first place but adapted and validated due to literature research after finalizing the calculation model. Different scenarios, based on the influencing factors, were conducted, including extreme condition tests (ECTs), and ran besides performing several sensitivity analyses as validation to obtain the final results.

2.1 Current gas market

The current gas market was studied to gain knowledge about this energy system. Literature was used to obtain information about natural gas (NG), LNG, the current production of biomethane and bio-LNG, biomethane grid injection and upgrading and liquefaction technologies. The results of this section are stated in Appendix I.

2.2 2050 renewable gas market

The methodology to sketch the renewable gas market for biomethane and bio-LNG in 2050 was done in several steps. First, the expected AD-based biomethane supply for bio-LNG to transport was determined. Then the bio-LNG demand was studied and finally, the infrastructure was investigated. Literature research was mainly used to complete this task, but companies were also interviewed for additional information.
The potential biogas and biomethane production in Europe and the required and corresponding sustainable feedstock supply were estimated and calculated by various studies in recent years [10], [11]. Three studies were used to convert the biogas and biomethane potential to AD-based biomethane available for transport. The first share was defined for the separation of biogas and biomethane (10 %) [12]. The second share was applied to separate AD and gasification-based biomethane from P2M-based biomethane (86%) [10]. The third share was applied to separate AD-based biomethane from gasification-based biomethane (59%) [11]. Eventually, a share of 51% was allocated for AD-based biomethane which would be used by the HDV and maritime sectors [10].
Clarifying the bio-LNG demand in 2050 is a complex task due to many uncertainties, but several studies did model and estimate the European energy demand in 2050, which were analysed and information was gathered [13]. Based on this data, market demand ranges for the market share calculations were made.
For the gas infrastructure, several studies were used to understand what the future gas infrastructure could look like by 2050 [7]. Noteworthy information about these studies was summarized as results.

2.3 Policies

Literature research about renewable energy policies was performed to obtain potentially useful information for this study. Besides the EU policies, it was also important to obtain the policy view of European countries. Based on the European Biogas Association (EBA) statistical report of 2021 and the available information of the RegaTrace project information was gathered and summarized. In section 2.6.3 it is visible how the policies influence the model and in Appendix II the total policy results are stated.

2.4 Company questionaries

Besides literature studies and European policies, it was also important to obtain knowledge from companies which work with conventional and/or renewable gasses. Members of EBA and other possibly related companies were consulted to obtain knowledge about bio-LNG related subjects. The 21 companies consulted represented gas and/or fuel producers and demanders, research institutes and other types of market-related companies.

2.5 Influencing factors

By this time, it was possible to summarize which factors potentially could influence the European bio-LNG production potential in 2050. This was done by gathering information from the policies and company questionaries, but also several literature studies. In Appendix III all gathered influencing factors are stated.

2.6.2 Calculation model

The schematic overview of the calculation model is shown in Figure 2 and the complete model explanation is shown in Appendix V. Energy-based calculations were executed, where process efficiencies and energy consumptions of tanker trucks and bunker vessels were taken into account. Gas losses were assumed for each process step, where larger amounts of gas losses were assumed at the LNG-power engines due to CH_4 slip. The 100-year global warming potential of CH_4 was applied as this is the standard in European policies [14].

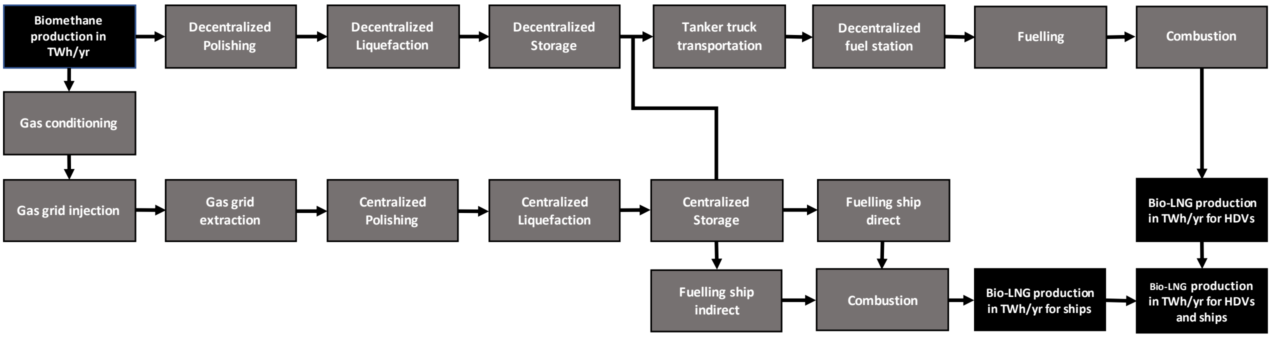

Figure 2. Schematic overview of the bio-LNG calculation model

2.6 Model

To simulate the bio-LNG production potential, a model was needed and developed. Before this final model was built, two (schematic) conceptual technical and environmental models were made in Visio. By building these schematic overviews, the needed inputs, calculations steps and outputs were visualised and confirmed by checking the outputs with the problem statement and the research question. Then, the final model, which is a calculation in Excel based on energy balances and the conceptual models, was built. Until this point in time, all input data was assumed, and then validated by literature, when possible. This was followed by scenario development, based on the influencing factors, including ECTs, which were also run in the model. Eventually, a sensitivity analysis was performed on several parameters to challenge the model to better understand the limits and flexibility.

2.6.1 Conceptual models

For this study, a technical conceptual model was created, which was the modelling foundation (see Appendix IV). The outputs obtained were the total AD-based bio-LNG production for transport (TWh), associated market shares and WTW energy consumptions. Also, an environmental conceptual model was made (see Appendix IV), which is based on the technical model. The outputs obtained were GHG emissions reductions and WTW GHG emissions for five sustainable combinations. GHG reduction measures, such as fossil-based CO_2 replacement by bio-CO_2, were used to create sustainable combinations. Once both models were finalized and validated, then the final model was built. The conceptual models were also checked by three companies before it was acknowledged to be finalized. The complete descriptions of the conceptual models, including the sustainable combinations descriptions, are shown in Appendix IV.

The model began with the biogas and biomethane production potential. Based on section 2.2, AD-based biomethane for transport was calculated. Energy consumption and GHG emissions were allocated to this biomethane to eventually calculate the WTW energy consumption and GHG emissions. Two pathways were created, where the centralized pathway injects biomethane into the grid and extracts it from the grid at centralized locations near harbours. The distinguishing between the transmission and distribution (different pressures) grid was made and the separation shares were assumed. Biomethane is then polished and liquefied on a relatively large scale and directly tanked by the end users or indirectly tanked by bunker vessels which transport the fuel from the harbour to the end users. A share was applied and assumed to realize that some centralized bio-LNG was transported to HDV fuelling stations. In addition, a share was used for bunker vessels, as it was assumed that not all centralized liquefaction would be located in harbours, so larger bunkering distances were assumed and taken into account. Decentralized bio-LNG is polished, liquefied and stored at farms. Subsequently, the fuel is transported to HDV fuelling stations by tanker trucks, as is done for the centralized bio-LNG allocated to HDVs. After the fuel is delivered, it is tanked and finally combusted by the end users.

The bio-LNG that is eventually used by the HDVs and maritime ships (cruise ship was assumed) was summed to obtain the total bio-LNG amount. WTW data was calculated by the summation of the energy consumption of the biomethane and bio-LNG production/processing steps. The bio-LNG market shares were calculated for several cases, such as the bio-LNG market share in the European transport energy demand in 2050. The GHG emissions reductions were determined based on the calculation methodology and fossil fuel comparator (94 g CO_2-eq/MJfuel) given in Appendix V of the policy renewable energy directive (RED) II [14]. The calculations were initially done with fully assumed input data. Subsequently, input data was validated based on literature or assumed when no references were found.

2.6.3 Scenarios

Several scenarios were conducted due to the uncertainty of how the energy system would operate in 2050. In total, seven scenarios were made and run. All the scenarios served to obtain results regarding the market share and corresponding GHG emissions reduction of bio-LNG besides WTW data. All scenarios were based on the gas for climate (GfC) scenario as data from GfC papers was applied and expected to be the most representative. Three scenarios, "GfC", "medium" and "low", were made based on GfC papers, and only differ in the share of biomethane to transport (51, 30 and 10%, respectively). In these two last scenarios, competition with other fuels was assumed to be more severe and policies were assumed to be less stimulating towards bio-LNG. Additionally, the bio-LNG market was assumed to be less developed. Also, "maritime" and "HDV" scenarios were built, where bio-LNG would only be used by one of those sectors. This was done to see what the maximum contribution of bio-LNG per sector could be. Lastly, extreme condition tests were applied to find the limits of the model based on efficient and inefficient input data. These scenarios are, likewise as the HDV and maritime scenarios, not likely to take place, but serve as validation for the model. When different values (i.e., efficiency) were found in literature, ranges were noted and averages were used for the five just described scenarios. For the ECT efficient and inefficient scenarios, the lower and upper values of the found input data were used. For the ECT efficient scenario the most optimist GHG emissions values and efficiencies were selected. For the ECT inefficient the opposite was done.

2.6.4 Sensitivity analysis

Several sensitivity analyses were made to check the modelling sensitivities and limits, to study the modelling operation and to check if the model results were valid.

It was assumed that the GfC scenario was sufficient to obtain the goals of the sensitivity which were mentioned earlier. Thus, for the sensitivity analyses, mainly the GfC scenario was applied. In Appendix VI is it shown which sensitivity analyses were made.

3. RESULTS

3.1 AD-based bio-LNG for transport

Although there are differences in methodology and assumptions between the studies, all show at least a biogas and biomethane production potential of 95 bcm by 2050. This is equal to 24% of the total NG consumption of the EU in 2020. Assuming that the total gas consumption reduces over the years, it is estimated that biomethane will be able to cover around 30-40% of the gas demand by 2050 [7]. Based on the EU NG consumption in 2021 (397 bcm) [15] the NG consumption would be between 238-317 bcm in 2050. Due the differences found in literature, a biomethane potential range was defined, using the lowest (95 bcm) and the highest value (165 bcm). If 165 bcm of biomethane is produced by 2050, a higher percentage of the future gas demand could be covered, representing around 52-69% of it. Also, the AD-based biomethane available for transport is determined by the applied shares and the biogas and biomethane production potential range, which resulted in a range of 236-411 TWh.

Based on the energy demand analysis, market share ranges were made for the market share calculations, which are presented in Table 1.

Table 1. European market share ranges in 2050

Parameter	Low [TWh]	High [TWh]
Total energy demand	8,510	9,831
Transport energy demand	2,163	3,188
Maritime energy demand	640	1,360
HDV energy demand	156	404

In addition, future gas infrastructure was studied. In conclusion, according to the studies, the future energy system will still have similarities to the current gas grid but will cooperate more with the electricity grid on a larger European scale. Biomethane will still be able to be injected into the gas grid and NG will potentially also still be used, but technical aspects such as gas composition and flow direction need to be safely secured [7].

3.2 Policy results

If policies are set towards zero TTW emissions, which is currently not the case for biomethane combustion in engines, future uptake could be complicated. However, if a WTW approach would be implemented, there would then be opportunities for bio-LNG in transport. In FuelEU Maritime policy a 75% cut of GHG emissions is proposed in 2050 [16]. Moreover, the RED III proposal was used for determining the 2050 climate goal, which is to be carbon natural.

3.3 Influencing factors

The most important influencing factors for bio-LNG future uptake are permitting processes, feedstock availability, by-products utilization, fuel/sector competition, gas losses and emissions, infrastructure availability, governmental support schemes, environmental policy approach, CAPEX, OPEX, and the chicken-egg-situation/dilemma.

3.4 Market share

In Figure 3 the market shares of bio-LNG in the European transport energy consumption are shown. Visible is that the GfC scenario has a market share between 7.3-18.7%. The medium scenario is between 4.3-11.0% and the low scenario has the lowest market share range of 1.4-3.7%. The ECT efficient has the highest potential market share (18.7%), which is identical to the GfC and maritime scenarios. The HDV and ECT inefficient results are slightly lower than other comparable scenarios (0.1 %).

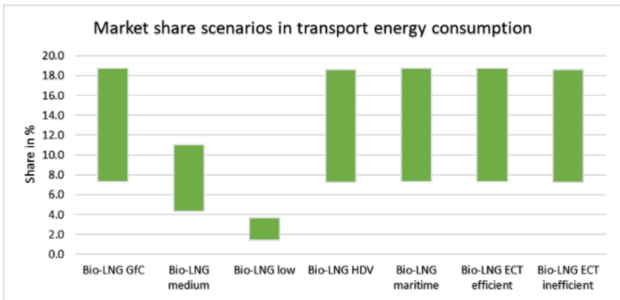

Figure 3. Market share of all scenarios in total European transport energy consumption in 2050

Additionally, it is useful to quantify these market shares with bio-LNG energy values. The 1.7% market share of the low scenario corresponds with 46 TWh, while the 18.7% market share of the ECT efficient corresponds with 405 TWh.

3.5 GHG emissions reduction

The GHG emissions reductions for all five sustainable combinations for the GfC, ECT efficient and ECT inefficient scenarios are shown in Figure 4. Visible is that the decentralized and centralized pathways show similar GHG emissions reductions for both pathways and sustainable combinations. The ECT inefficient GHG emissions reductions are constant for the decentralized and centralized pathways (95% and 96%, respectively). For the GfC scenario, both decentralized and centralized, the reductions are between 97%-107%. For the decentralized and centralized pathways of the ECT efficient scenario, these reductions are 124-123% and 174-173%, respectively. The GfC scenario is rather inefficient-orientated as the GHG emissions reductions are closer to the ECT inefficient than the ECT efficient. Also, it is visible that CO_2 replacement by bio-CO_2 results in higher GHG emissions reductions than the replacement of synthetic fertilizer by digestate reusage.

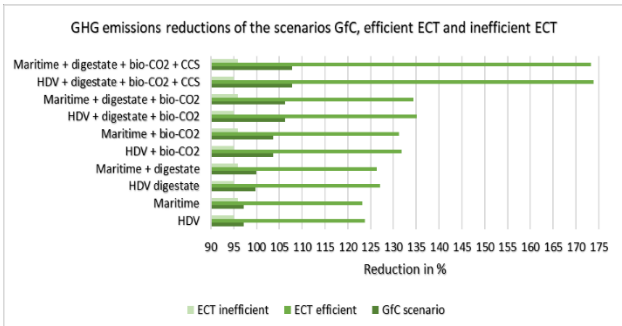

Figure 4. GHG emissions reductions for decentralized and centralized pathways for all GHG reduction possibilities for GfC, ECT efficient and ECT inefficient scenarios

3.6 WTW data

The HDV TTW energy consumption is 13.0 MJ/km, whereas the WTW energy consumption is between 18.4-21.6 MJ/km. Thus, the TTW energy consumption is higher than the WTT energy consumption. The differences between the environmental policy approaches, to compare fuels based on TTW or WTW basis, are visible. The TTW GHG emissions of HDVs are 1.1 g CO_2-eq/MJ, which is not compliant to be carbon neutral in 2050. However, when a WTW approach is applied, then a GHG emissions range of -7.3-2.6 g CO_2-eq/MJ is realized. For maritime, The TTW energy input/output ratio is 3.2, whereas the WTW energy input/output ratio range is between 4.4-5.2. The GHG emissions are represented by the TTW GHG emissions of 1.4 g CO_2-eq/MJ, while the WTW GHG emissions are between -7.4-2.6 g CO_2-eq/MJ.

3.7 Sensitivity analysis

A sensitivity analysis is performed for the TTW gas losses in the maritime sector in comparison with the output centralized GHG emissions reduction (see Figure 5). For the GfC scenario the TTW gas losses for maritime ships is assumed to be 0.25%, which would represent a GHG emissions reduction of about 97%. Visible is that there is a slight increasing downtrend which results in the fact that more TTW gas losses results in a lower GHG emissions reduction.

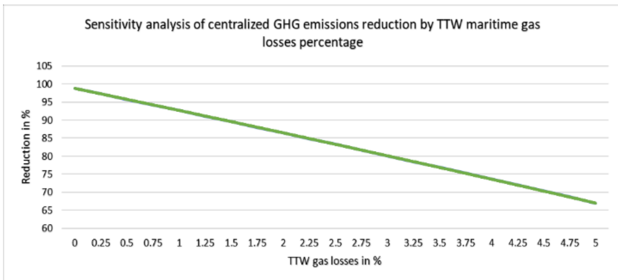

Figure 5. Sensitivity analysis of GfC centralized GHG emission reduction by TTW maritime gas losses percentage

4. DISCUSSION

Modelling results validation is performed by running several scenarios (including ECTs) and sensitivity analyses. Regarding the modelling results, generally, it can be stated that the results are logical. The ECTs show the lower and upper boundaries for results such as bio-LNG production, market shares and GHG emissions reductions and all the other scenarios are within these ranges. Furthermore, the sensitivity analysis results appear to be logical but are considered to be relatively sensitive, especially due to the number of assumptions.

Regarding GHG emissions reductions, some studies presented in the introduction mentioned HDVs' GHG reduction between 45-211% [9]. A somewhat similar reduction was also found in a study for bio-LNG in the maritime sector and amounted to 5-188%. The maximum GHG reduction found in literature is 395% [17]. The differences which were found in the model between the ECTs are 97-174%, which lies within the ranges mentioned. Depending on the chosen pathway and sustainable combination, bio-LNG could be compatible with the RED III proposal to be carbon natural in 2050, as GHG emissions reduction of more than 100% is possible. Based on the set goal in de FuelEU maritime, which mentions a GHG emission reduction of 75% [16], all pathways and sustainable combinations of bio-LNG production are compatible.

Bio-LNG market shares were calculated in this study, which will be discussed. The boundaries of the total energy consumption and the total energy consumption in transport are assumed to be valid, due to the number of consulted studies and the organisations that did the studies. However, the HDV and maritime sectors' energy consumptions in 2050 were more difficult to determine due to less available data. Based on literature studies, it can be concluded that the upper bounds of the HDV and maritime energy demands are too low, which results in too high market shares. For the HDVs, 156 TWh was selected in 2050, but it can be found that currently 425 TWh is used. For the maritime 640 TWh was selected, but other studies showed up to 2,114 TWh [16].

The WTW results appear to be in line with literature. WTW energy consumption of HDVs vary for different fuels between 10-32 MJ/km, while the GfC scenario results in 18.4-21.6 MJ/km [18]. Concerning the emissions, the GfC scenario can have negative emissions, depending on the sustainable combination selected (-7.4-2.6 g CO_2-eq/MJ). The WTW GHG emissions of maritime are also represented by this range. Furthermore, for maritime, the WTW energy input/output ratio range is between 4.4-5.2. It can be stated that fossil fuels consume less energy. However, hydrogen is comparable with the GfC scenario, while e-fuels have higher ratios [19].

During this study, there were some limitations, such as the processing of the influencing factors. A certain statistical methodology to determine, for example, which influencing factors were mentioned the most, could perhaps be an improvement. However, expected is that the results won't change significantly. Furthermore, it is noticed that European data about 2050 is challenging to obtain and this is the case for literature studies, policies and companies. European data turned out not to be always available. In those cases, EU data is often found and applied. A substantial amount of assumptions were needed to obtain a sufficient amount of data. Additionally, no standardized data about trucks/ships in 2050 is found, so information about these subjects was selected based on currently available data.

Due to a large number of assumptions and data about 2050, the conclusions that can be drawn are indicative. However, the results indicate positive and negative bio-LNG circumstances regarding what bio-LNG could contribute to the HDV and maritime sectors. Potential bio-LNG production potentials and associated GHG emission reductions are now available and could be used by the market as a guideline. Lastly, the model is easily adjustable, so if policy adjustments are made that influence bio-LNG, then the input data can be adjusted which would result in updated outputs and future predictions.

5. CONCLUSION

This study is performed to answer the following research question: "What could be the market share of bio-LNG in the European HDV and maritime sectors in 2050 based on technical, economic, policy and environmental aspects and what could be the associated GHG emissions reductions?"

The market share of bio-LNG in transport energy consumption could be between 1.7 and 21.7% in 2050, which is equivalent to 46-405 TWh of bio-LNG. The GHG emissions reductions of the decentralized and centralized pathways, in combination with the sustainable combinations, variate between 97 and 174% with relatively small differences between the pathways. Regardless of the applied pathway and sustainable combination, bio-LNG is compatible with the set 75% GHG emissions reduction mentioned in FuelEU maritime, but not all sustainable combinations are net zero by 2050. Bio-LNG future uptake especially depends on set policies, permitting processes, fuel and sector competition and feedstock availability.

Future model additions would be to implement input data from a standardized European database for WTW GHG emissions and energy consumption per feedstock, as this would be very beneficial for this study. Besides WTW data, it would also be valuable to implement economic aspects in the model.

6. ACKNOWEDGEMENTS

The author of this paper would like to express his gratitude and sincere appreciation to Marina Pasteris (EBA) and Folkert Faber (Hanze UAS), who supervised this thesis.

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8. APPENDICES

8.1 Appendix I: Current gas market

Combined European biogas and biomethane production in 2020 amounted to 191 TWh or 18.0 bcm of energy. From that total, 32 TWh or 3 bcm corresponded to biomethane production. In 2020, approximately 0.6 TWh of bio-LNG was produced, but based on the confirmed projects around 10.6 TWh will be produced per year by 2024 [7]. Around 295 LNG-powered ships are in operation worldwide, while 510 ships are on order. Currently, there are around 15,000 LNG trucks in Europe [5].

8.2 Appendix II: Policy results

For the HDV sector, the environmental policy approach in policies is crucial, as it determines whether biomethane can be used for transport or not. If a policy is set towards zero TTW emissions, which is currently not the case for biomethane combustion in engines, future uptake could be complicated. An example is the set CO_2 standards for cars and vans which applies a 100% GHG emission reduction target on a TTW/tailpipe approach as of 2035, meaning a practical (*de facto)* ban on the internal combustion engine. However, if a WTW approach would be implemented, there would then be opportunities for bio-LNG in transport. According to de AFID, it is expected that 2,904, 3,901 and 2,896 EU27 LNG road fuelling stations could operate in 2030, 2040 and 2050, respectively. The recommendation is for the Core TEN-T network to have one LNG refuelling station to serve HDVs every 400 km by 2025, with a 5,000 t capacity. An assessment in AFID showed that it is likely that 71 out of 90 TEN-T core ports will have LNG bunkering available by 2025, which ensures that the objective is met. In FuelEU Maritime a 75% cut of GHG emissions is proposed in 2050. This corresponds with a fuel mix of zero-emission and low-carbon fuels between 86% and 88% by 2050. Some technical and environmental data are also presented for several policy scenarios for 2030 and 2050, such as WTW GHG emissions for diverse biofuels and potential market shares of different fuel types in the total EU27 maritime fuel consumption. FuelEU Maritime stated a potential demand of bio-LNG in the maritime segment in 2050 (28 Mtoe, which his 326 TWh) and based on the corresponding 15.4% market share, it results in 181.82 Mtoe (2,114 TWh) of total fuel needed in the maritime sector. The WTW emissions of biomethane are determined to be 9.1 CO_2-eq/MJ [16]. Eventually, the RED III proposal was used for determining the 2050 climate goal, which is to be carbon natural.

In total there were 32 European countries used to obtain the results about the perspective of countries towards biomethane, bio-LNG and related infrastructure. The analysis resulted in a response rate between 14-36%. Generally, it can be stated that countries which have already implemented biomethane and/or bio-LNG, also state to use it in the longer term. The following countries (8) are most optimistic towards biomethane, bio-LNG and/or gas/LNG infrastructure: Italy (the only country with all + scores in both data sources), Germany, Finland, France, Sweden, Switzerland, Norway and the Netherlands. For 13 countries, bio-LNG is not applied yet, and for the remaining 11 countries, no information was found.

8.4 Appendix III: Influencing factors results

A concise summary of the most influencing factors is stated below, organized per technical, economic, environmental, policy, and general categories.

The technical factors inventory resulted in the largest number of factors. One of the most important factors mentioned is feedstock availability, as it is key for stable and predictable production. Boiloff and high energy consumption during the production of bio-LNG negatively influence the production, therefore, both factors are mentioned to be reduced. Bio-LNG related installations could be located all over Europe, where gas grid availability and gas/LNG properties play a role and could have consequences for the future energy system. The scalability and size of installations are also considered important. Bio-LNG infrastructure and TRL are generally mature, but LNG facilities of maritime ports are not located evenly throughout Europe. Lastly, differences in (liquid) gas properties, gas grid and LNG infrastructure that is currently present in Europe are important.

For the environmental category there are several important factors: by-products such as digestate and bio-CO_2 are important to be utilized as efficiently as possible to contribute to environmental circularity. Sustainable farming (for example improved land management) is mentioned as another important aspect. Energy crop usage is also a discussion point due to the food vs fuel debate and food security. CH_4 losses are also key, as it has a large impact on global GHG emissions, which influences the carbon intensity index, important for maritime. Other emissions such as NO_x, SO_x and PM also influence local environments, so it influences bio-LNG consumption.

For the economic category, it is mentioned that the business case should logically be positive. This will depend on both CAPEX and OPEX. The OPEX are variable over time (think of energy prices, feedstock costs, NG prices, and feed-in-tariffs) and affects the willingness to invest. Regarding the CAPEX, grid connection costs and liquefaction investments are particularly important for bio-LNG. The total cost of ownership is indicated as an important parameter as well. Underdeveloped markets, such as digestate and bio-CO_2 markets are underdeveloped, which affects the positive sustainable value of bio-LNG/biogas and biomethane.

Regarding the policy category, permitting processes are often mentioned as reducing the progression of bio-LNG projects. For the development of bio-LNG, a level playing field throughout Europe is important besides international and European collaboration. A European system concerning GOs would positively influence the market, as do potential support schemes. Regulations are also a method to speed up the transitions and another important factor would be the policy approach of comparing fuels bases on a TTW or WTW methodology. Another policy factor is governmental support schemes, which could influence diversely the bio-LNG sector if they are energy based (i.e., Dutch HBE system) or GHG reduction based (i.e., German TGH system). Political uncertainty, for example towards intended end-markets of biogas and biomethane, is also key.

Eventually, there are some general factors which affect more than one category. Fuel competition is important, as it shows if bio-LNG has a future. Bio-LNG is affected by feedstock production, so feedstock availability is key. The chicken-egg situation is a topic where are relatively new fuels, including bio-LNG, have to deal with. (bio-)LNG-powered fleet investments are reduced if there is insufficient bio-LNG production. On contrary, bio-LNG production investments could also be negatively affected by insufficient bio-LNG demand. Decisions to produce bio-LNG decentralized or centralized depend also on several technical and economic factors. Sector competition will also be critical, as more sectors could have demand for biogas and biomethane. Safety, energy security, reliability, certainty, flexibility and diversification are also aspects that have major consequences for bio-LNG consumption in 2050. Lastly, the life span of HDVs, and especially maritime ships, is affecting the whole bio-LNG potential consumption.

8.5 Appendix IV: Conceptual model

8.5.1 Technical

The technical conceptual model is visible in Figure 6 and works as follows: the starting point is the total European biogas/biogas production in 2050. Shares were allocated to obtain biomethane from AD that goes to transport, as presented in section 2.2. The properties and composition of biomethane were necessary to indicate at the start of the model for the subsequent calculations. Additionally, energy consumption for the production of this biomethane was assigned to eventually determine the WTW energy consumption of the fuel. Thus, the energy consumption of the bio-LNG production process (including combustion) was added to the initial energy consumption of biomethane production to obtain the total WTW energy consumption. Biomethane is produced centralized or decentralized. In the model, the centralized production situation was built considering that biomethane will be injected into the gas grid at decentralized production sites, and based on a European mass balance system, the gas would be extracted at a location where a relatively larger centralized liquefaction installation is located. For the decentralized pathway, it was assumed that biomethane would not be injected into the grid. For both processes, it was assumed that gas losses could occur at each process step. Starting with the decentralized pathway, the composition of biomethane was expected to not satisfy the liquefaction regulations. Biomethane would, therefore, be polished before the liquefaction, so energy efficiencies are required. After the liquefaction, the calculations are made with 100% CH_4 instead of LNG, which has a different composition throughout the European infrastructure. The produced bio-LNG should then be stored in a cryogenic storage before trucks load the fuel. Bio-LNG is then transported to (bio-)LNG fuelling stations and this is also the moment where the centralized and decentralized pathways connect. A share of the centralized bio-LNG will be transported by tanker trucks to HDV fuelling stations to fulfil HDV fuel demand. It was assumed that decentralized bio-LNG cannot satisfy maritime ships. The tanker trucks are bio-LNG powered, so the energy consumption of these trucks was needed. Specifications such as volume/mass constraints, and the distribution transport distance, were also needed and assumed. Finally, the HDV end users tank and combust the fuel, so an engine efficiency was needed to determine the fuel consumption. By this time, the total bio-LNG for the HDV sector was determined.

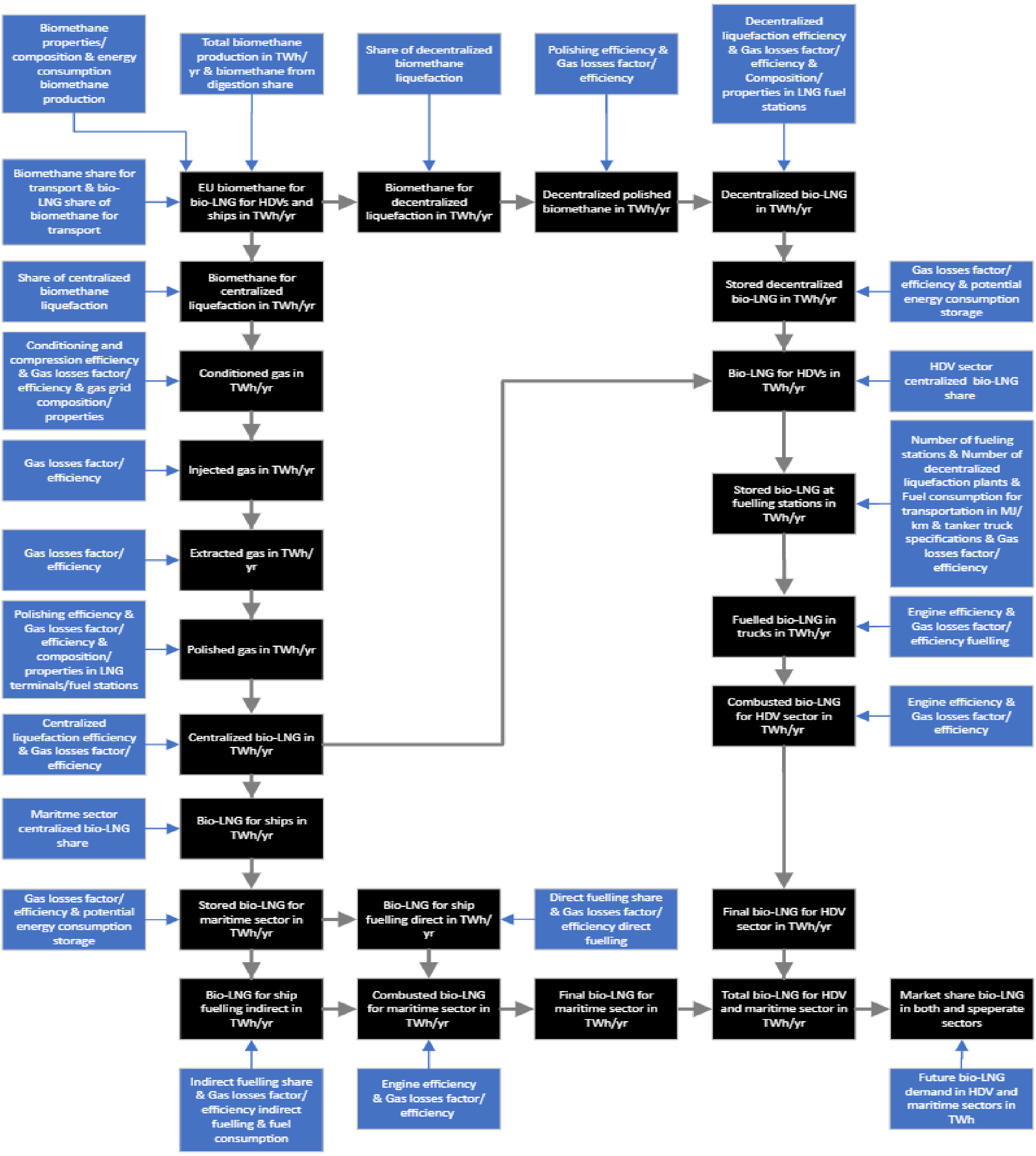

Figure 6. Technical conceptual model where the grey arrows indicate process flows, the blue arrows indicate information flows, the black blocks are materials or quantities and the blue blocks are inputs

For the centralized pathway, it was assumed that gas cleaning with allocated energy consumption was needed before the gas grid injection. Additionally, it was assumed that the injection takes place at the distribution grid or the transmission grid, so the gas will be compressed to different pressures and a share was assumed to divide the gas injection over the two grid types. Also, pressure losses due to the grid connection were taken into account. For the gas injection/extraction no energy consumption was considered. Likewise, with the decentralized pathway, the gas needs to be polished, liquefied and stored, so the same types of input parameters were used. After the separation of bio-LNG to HDVs, the remaining fuel will be used by the maritime sector and will be tanked by ships directly or indirectly. This fuel separation was also done by an assumed share. The centralized liquefaction was assumed to be located mostly in the harbours due to future biomethane gasification that potentially would be located in the harbours because of feedstock import (answer of a company). Fuel can be tanked directly by the end-users or it is fuelled indirectly by bunker vessels, where again two streams were made by the distinction of a share. This was done because it was assumed that not all liquefaction installations and storages are located in the harbour. When the fuel is transported by bunker vessels, the fuel consumption (bio-LNG) was taken into account based on assumed travel distances and engine efficiencies.

At that point, it was possible to determine the amount of bio-LNG that would be available for the maritime sector.

For both HDVs and maritime ships, annual travelling distances were allocated to determine the number of fully bio-LNG satisfied HDVs/maritime ships. Also, a separate drop-in ratio was assumed to determine the illustrative number of partly decarbonised transport modes. By this time, the total bio-LNG production was determined by the summation of the HDV and maritime bio-LNG production. Also, it was possible to determine the WTW energy consumption and the energy input/output ratios. These calculations were made to make comparisons with other fuels and to check to model results. Additionally, based on market research focused on future energy demands (see section 2.2) bio-LNG demands in 2050 were selected, and market shares for the combined and separate sectors were determined. At this time, the problem statement and research question (see section 1.2) were partly answered by the obtained outcomes, so the foundation for the actual model was finalized.

8.2.2 Environmental

The environmental conceptual model is shown in Figure 7 and will be described as follows: the environmental conceptual model is based on the technical conceptual model. The environmental analysis of the model starts with initial GHG emissions of yearly biomethane production out of the AD pathway, which was determined based on literature research and assumptions. These emissions were allocated as well-to-tank (WTT) GHG emissions and the WTT GHG emissions from the processing of biomethane to bio-LNG fuel stations were added to obtain the total WTT GHG emissions. For the bio-LNG production process, GHG emissions occur due to CH_4 losses, CH_4 slip, and electricity consumption, which was assumed not to be fully decarbonized in 2050. CH_4 slip in gas engines was assumed to still be present in 2050 and relatively high gas losses were allocated for this. Before the liquefaction, also CO_2 losses occur, but these were considered to be biogenic and will not contribute to negative climate change. Another assumption is that the CO_2 emissions due to bio-LNG combustion of transport trucks, bunker ships, final HDVs and maritime ships are also biogenic. Eventually, the TTW GHG emissions were calculated and added upon the WTT GHG emissions to obtain the total WTW GHG emissions. The RED II provides a GHG emissions calculation, which is used as guidance for this project [14]. The following GHG emissions-avoiding measures should be present in the model:

- Avoidance of emissions due to the replacement of fossil fuels.
- Avoidance of emissions due to the avoidance of CH_4 emissions from manure.
- Avoidance of the emissions associated with the production of mineral fertilisers.
- Avoidance of emissions due to the replacement of fossil CO_2 by bio-CO_2.
- Carbon capture and use or carbon capture and storage, using the separated biogenic CO_2 stream after biogas upgrading.

Besides the GHG calculation method of the RED II, a GHG reduction calculation methodology of RED II, based on a fossil fuel comparator was also used for this study [14]. Based on the just mentioned GHG emissions-avoiding measures five sustainable combinations were made to apply in the model. The first one is gross biomethane production and did only consider the avoided CH_4 emissions from manure. This scenario was applied as base for all sustainable combinations. The second combination did apply digestate as a replacement of synthetic fertilizer. The third combination replaces fossil CO_2 with bio-CO_2. The fourth combination did replace synthetic fertilizer with digestate-based fertilizer and did replace fossil CO_2 with bio-CO_2. The last combination is similar to combination four but did also apply CCS of bio-CO_2.

As with the technical conceptual model, this environmental model was validated and confirmed with the problem statement and research question.

8.6 Appendix V: Calculation model

Some calculations within the calculation blocks were standardized to simplify the model. The lower heating value (LHV) of biomethane was used to convert biomethane energy amounts to mass. This was done because conditioning, polishing and liquefaction efficiencies were expressed in kWh/kg, so the process' energy consumptions were able to calculate by this methodology. Furthermore, 15 °C and atmospheric pressure were chosen as input data for the temperature and pressure parameters, respectively. For CH_4, a global warming potential (GWP) of 28 was used to determine the GHG emissions due to gas losses, as this is the 100-year GWP which is the standard in European policies. Additionally, the gas losses were calculated in the most inefficient situations (i.e., gas losses of gas compression were assumed that gas losses take place after the compression instead of before). It is worth mentioning that

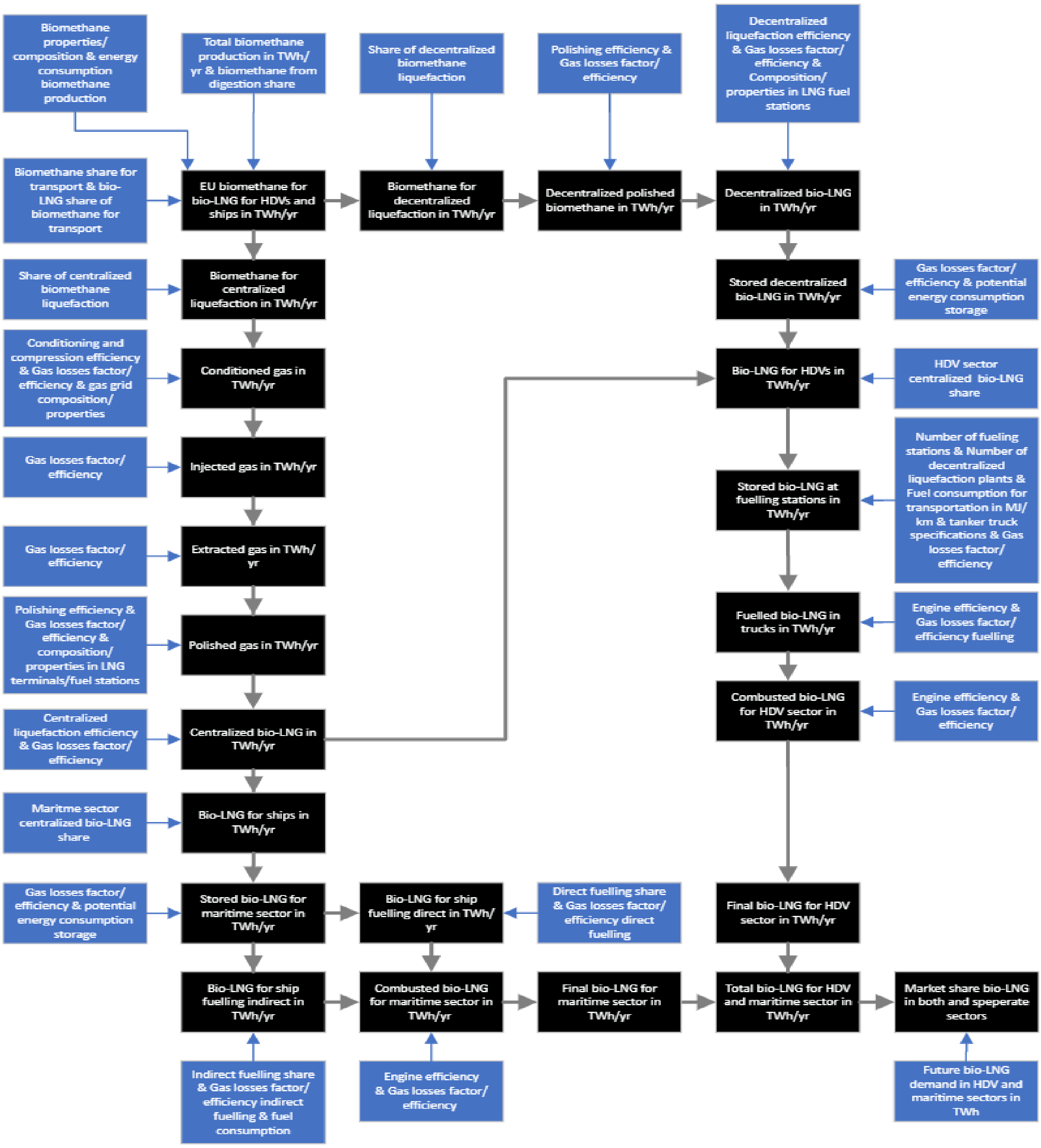

Figure 7. Environmental conceptual model where the grey arrows indicate process flows, the blue arrows indicate information flows, the black blocks are materials or quantities and the blue blocks are inputs

the engine calculations were performed for singular-fuel engines. Lastly, the calculation descriptions are based on energy content unless otherwise indicated, so if bio-LNG is mentioned, then the energy content of bio-LNG is meant.

Decentralized

The general calculations explained above were the only calculations used for the polishing and liquefaction processes, but different efficiencies were used. For the decentralized storage, only gas losses and associated GHG emissions were determined. The calculations concerning the transportation of bio-LNG to HDV fuelling stations were made as follows: first, the decentralized stored bio-LNG and the centralized bio-LNG to the HDV sector were summed to obtain the total bio-LNG for HDVs which needed to be transported by trucks to the fuelling stations. The LHV of CH_4 was used to determine the bio-LNG mass, which was needed for defining the number of tanker truck trips, which was calculated by mass-based capacity and volume-based capacity. The model automatically selects the highest amount of trips (based on mass or volume capacity) due to IF functions to increase the realism of the model. The fuel consumption/km and weight of the truck are inputs. Considering the LHV, the energy per ton kilometre [MJ/t.km] (empty truck) was determined and used for the calculation of total truck fuel consumption and is shown in Equation (1). The model is mass based, so the bio-LNG volume-based capacity was converted to mass by the density.

$$E_{final-trucks} = IF(x_m > x_v, x_m, x_v) * s_{trip} * \left((IF(x_m > x_v, m_m, m_v) + m_e) + m_e\right) + E_{truck} \quad (1)$$

Where $E_{final-trucks}$ is the final annual energy consumption of the tanker trucks [MJ], x_m is the mass-based trips amount [-], x_v is the volume-based trips amount [-], s_{trip} is the distance of a single voyage from storage to fuel station [km], m_m is the mass per load of mass-based capacity [ton], m_v is the mass per load of volume-based capacity [ton], m_e the mass of an empty truck [ton] and E_{truck} is the energy consumption of the truck [MJ/t.km].

This truck transport energy consumption was converted to the generalized unit [TWh] and subtracted from the initial bio-LNG energy content to obtain the amount of bio-LNG that reaches the fuelling stations. However, the bio-LNG reaching the fuelling stations was assumed to be further reduced due to transportation gas losses. Eventually, the HDVs tank the bio-LNG at the fuelling stations, where also losses could occur. The fuelling process block is identical to the fuel station calculation block. Lastly, the fuel is combusted in the HDVs. Before the final bio-LNG for HDVs was determined, a relatively larger share for gas losses/methane slip was allocated. The number of fully and partly decarbonized trucks was also determined by inputs such as HDV fuel efficiency, fuel density and LHV which lead to a fuel consumption per kilometre [MJ/km]. With the total energy amount and the HDV fuel consumption per kilometre, the total distance was calculated. In combination with an assumed drop-in fuel ratio the fully and partly decarbonised trucks were determined.

Centralized

This pathway starts with a relatively extensive calculation block which contains several equations. First, the density of biomethane is determined by inputs such as CH_4 and CO_2 volume percentages and densities. Based on the known volume and density, the biomethane mass was determined. Considering the mass and the known biomethane energy content, the LHV of biomethane was determined. It was assumed that there is some drying/cleaning energy consumption, but most of the drying/cleaning of the biomethane was expected to be already done at this stage in the process. The Wobbe index was then calculated and automatically checked with the inputs for the Wobbe index limit, to check if the biomethane was obliged to be injected into the gas grid (see Equation 2). The relative density was calculated by dividing the biomethane density by the air density at the same environmental conditions.

$$Wobbe = \frac{HHV_{gas}}{\sqrt{\rho_{rel}}} \quad (2)$$

Where Wobbe is the Wobbe index of the gas [MJ/m^3], HHV_{gas} is the higher heating value of the gas [MJ/m^3] and ρ_{rel} is the relative density of the gas related to air [-].

The biomethane was then compressed according to the gas grid conditions before gas grid injection. However, the pressure loss of the gas grid connection was initially determined, because the compressor should also overcome this pressure to inject gas into the grid. The model was built with an assumed separation share between the transmission grid and distribution grid, so different input values were needed. The equation used to determine the pressure losses of the transmission/distribution grid connections is shown in Equation 3. For simplicity in calculations, constant density was assumed in this formula, although this is usually not the case in practice.

$$\Delta p = \lambda * \frac{L}{D} * \frac{\rho}{2} * u^2 \quad (3)$$

Where Δp is the pressure loss [Pa], λ is the friction factor [-], L is the length [m], D is the diameter of the pipeline [m], ρ is the gas density [kg/m^3] and u is the gas flow speed [m/s].

The calculated pressure differences were added upon the gas grid pressures to determine the outlet pressures of the compressors. Next, the specific energy consumption was calculated per compressor (see Equation 4). Expected is that cooling (energy) would be needed in practice, but this energy consumption was neglected for this study.

$$w = \left(\frac{1+\eta_c}{\eta_e * \eta_i * \eta_m}\right) * z * Z * R * T_1 * \left(\frac{\gamma}{\gamma - 1}\right) * \left(\left(\frac{p_2}{p_1}\right)^{\frac{\gamma - 1}{z * \gamma}} - 1\right) \quad (4)$$

Where w is the specific work [J/kg], η_c is the cooling efficiency [-], η_e is the electrical efficiency [-], η_i is the isentropic efficiency [-], η_m is the mechanical efficiency [-], z is the number of compressor stages [-], Z is the compressibility factor [-], R is the specific gas constant [J/(kgK)], T_1 is the compressor inlet temperature [K], γ is the specific heat ratio [-], p_2 is the compressor outlet pressure [Pa] and p_1 is the compressor inlet pressure [Pa].

The specific work for the transmission grid was multiplied by the transmission grid allocated biomethane, as was done for the distribution grid. The drying/cleaning and compressors energy consumptions were summed to obtain the total energy consumption of the conditioning calculation block. The gas injection and gas extraction are identical calculations and only gas losses were taken into account during these process steps. The polishing and liquefaction steps are identical as only the energy consumption based on an input efficiency and the gas losses were determined. The produced bio-LNG is stored centralized and it was assumed that gas losses occur. The centralized bio-LNG was multiplied by the share of bio-LNG which would flow to the maritime sector and the other part will be transported by tanker trucks to HDV fuelling stations of the decentralized pathway. The centralized bio-LNG to the maritime sector was divided into direct fuelling and indirect fuelling. The indirect fuelling method has more gas losses than the direct fuelling method due to more process steps. Additionally, the energy consumption/km for bunkering ships was calculated based on ship specifications and assumed bunkering distances for inside and outside the harbours. The bunkering vessel volume was assumed and the number of trips was determined by the volumetric density, which was previously determined by with the density, LHV, and the energy contents of indirect bio-LNG in- and outside the harbours. The energy consumption per trip was multiplied by the number of trips to determine the bunkering energy consumption. Thus, the indirect pathway decreases the final bio-for maritime end users. However, this could be more efficient as end users sail less distance to harbours to tank, but this is out of the scope of this thesis.

Finally, bio-LNG is tanked by the maritime end user, what was assumed to be a cruise ship for the calculation method. The same calculation as with the bunkering ships was performed to determine the energy consumption/km, but different input values were selected. Gas losses (including CH_4 slip) were subtracted from the initial bio-LNG to obtain the total available bio-LNG for the maritime sector. Based on the energy consumption/km and the total available bio-LNG the annual maritime travel distance was determined. Additionally, based on an assumed annual cruiser ship travel distance, the number of fully decarbonised ships was determined. Similar to the HDVs, a drop-in ratio input was used to determine the amount of partly decarbonized ships. The cruiser's energy efficiency was also determined by applying the fuel consumption, engine power and LHV. The engine efficiency value was then used to calculate the useful energy, to eventually determine the WTW energy input/output ratio. This useful energy efficiency was also used for the calculation of the useful energy of the HDVs.

WTW GHG emissions and energy consumption

To confirm that the modelling results are valid, it is necessary to make comparisons with existing literature. WTW data is often presented in different units in literature, therefore, the model calculated the WTW data for several units for facilitating comparisons. The starting point for determining the GHG emissions and energy consumption of biomethane in 2050 was a GfC report (2022) [11]. In this report, shares were given for several categories of feedstock, which were used as inputs in the model for the energy consumption and GHG emissions. However, besides these feedstock shares, no data about GHG emissions and energy consumptions (of biomethane production) were given in this study. Thus, these had to be assumed or was taken from the literature. This made it possible to determine the WTW data for biomethane. The bio-LNG GHG emissions and energy consumptions were added to obtain the gross bio-LNG WTW GHG emissions and energy consumption. This gross GHG emissions consumption could be reduced by several GHG emissions reduction measures. Four more combinations of these measures were made (see Appendix V) and used in the model based on the same "share" methodology as emissions and energy consumption (for biomethane production) were applied for the feedstocks. For instance, a share is coupled to the amount of biomethane where digestate reusage/replacement takes place and contributing negative GHG emissions were allocated. However, energy is needed for this process, so it was assumed that energy consumption increases.

Additionally, the model needed to be able to allocate emissions and energy consumption from the centralized pathway towards the decentralized pathway if a certain amount of bio-LNG from the centralized pathway flows towards HDVs. If this would not be done, then the emissions and energy consumption of the centralized pathway would be too high and the decentralized pathway would receive additional bio-LNG where no GHG emissions and energy consumption would be accounted for, which does not represent the real case and reflects an incorrect process. These allocations were realized by the same share of centralized bio-LNG to the maritime sector. The emissions and energy consumption from the centralized bio-LNG production chain until the centralized storage were multiplied by this share and added upon the decentralized pathway.

WTW GHG emissions and energy consumption outcomes were converted to several types of units to make sure comparisons with literature were possible. GHG emissions [CO_2-eq] and energy consumption [MJ] were expressed per km, t.km and MJ. Eventually, the energy input/output ratio was determined by adding the energy consumption for the production of biomethane and bio-LNG upon the final bio-LNG energy content, which should then be divided by the already calculated useful energies of both HDVs and maritime ships.

Market shares

The market shares were calculated with ranges based on differences in energy demand for several studies for 2050.Thus, relatively low and high energy demands were found, which lead to higher and lower market shares, respectively. First, the total biomethane production was compared to the total energy consumption. Then, only cases for bio-LNG production were made, such as the total bio-LNG production compared to the total energy consumption. Furthermore, the market shares of bio-LNG for HDV, maritime and both sectors combined were compared to the total transport energy consumption. Lastly, the bio-LNG production of the HDV/maritime only scenarios were compared to the corresponding sectors' bio-LNG demands.

8.7 Appendix VI Sensitivity analysis

The first sensitivity analysis was how the total biomethane production would affect the bio-LNG production for all scenarios. The total biomethane production was also used in a sensitivity analysis for the low and high market shares. Thus, it was possible to compare the bio-LNG production with the low and high market shares. Furthermore, the

GHG emissions of electricity and manure were varied to see how the centralized and decentralized GHG emissions reductions would react. Also, the CH_4 v% in biomethane was varied and compared to the centralized and decentralized GHG emissions reductions, LHV and Wobbe index. TTW emissions of both pathways were compared to centralized and decentralized GHG emissions reductions, gas losses, bio-LNG production and market shares.
The sensitivity analyses described above were performed for one varying parameter, but also sensitivity analyses were run for two varying parameters, such as the AD-based biomethane share and the biomethane to transport share. These were varied and compared with the outputs bio-LNG production and low and high market shares. Lastly, the decentralized production ratio and the centralized bio-LNG to maritime ratio were varied with the outcomes of centralized and decentralized GHG emissions reductions, gas losses, bio-LNG production and low and high market shares.
Some sensitivity analysis results are presented in Figure 8, Figure 9, Figure 10, Table 2, and Table 3.

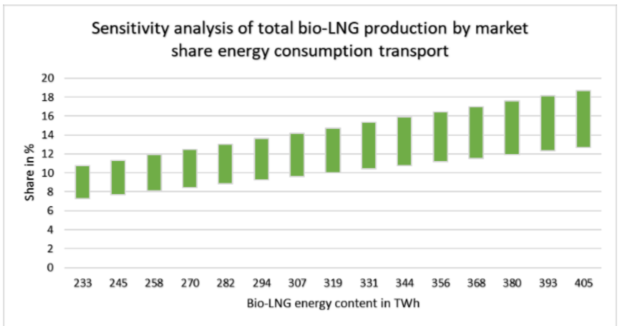

Figure 8. Sensitivity analysis of GfC bio-LNG production and market shares in transport for 95-165 biomethane production potential

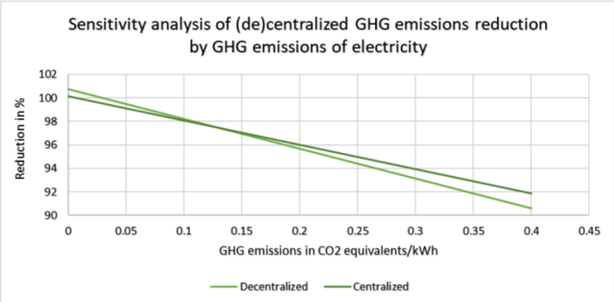

Figure 9. Sensitivity analysis of centralized and decentralized GHG emissions reduction by GHG emissions of electricity for the GfC scenario

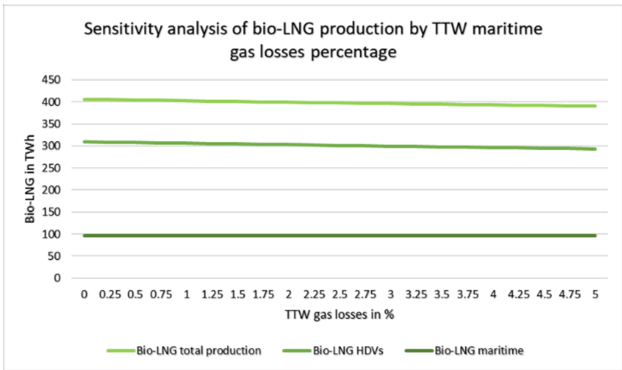

Figure 10. Sensitivity analysis of bio-LNG production by maritime TTW gas losses percentage for the GfC scenario

Table 2. Sensitivity analysis of bio-LNG production [TWh] GfC by AD biomethane ratio (horizontal data) and biomethane to transport ratio (vertical data)

Ratios	0.0	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.6	0.65	0.7	0.75	0.8	0.85	0.9	0.95	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.05	0	3	7	10	13	17	20	23	27	30	34	37	40	44	47	50	54	57	60	64	67
0.1	0	7	13	20	27	34	40	47	54	60	67	74	80	87	94	101	107	114	121	127	134
0.15	0	10	20	30	40	50	60	70	80	91	101	111	121	131	141	151	161	171	181	191	201
0.2	0	13	27	40	54	67	80	94	107	121	134	148	161	174	188	201	215	228	241	255	268
0.25	0	17	34	50	67	84	101	117	134	151	168	184	201	218	235	251	268	285	302	319	335
0.3	0	20	40	60	80	101	121	141	161	181	201	221	241	262	282	302	322	342	362	382	402
0.35	0	23	47	70	94	117	141	164	188	211	235	258	282	305	329	352	376	399	422	446	469
0.4	0	27	54	80	107	134	161	188	215	241	268	295	322	349	376	402	429	456	483	510	536
0.45	0	30	60	91	121	151	181	211	241	272	302	332	362	392	422	453	483	513	543	573	604
0.5	0	34	67	101	134	168	201	235	268	302	335	369	402	436	469	503	536	570	604	637	671
0.55	0	37	74	111	148	184	221	258	295	332	369	406	443	479	516	553	590	627	664	701	738
0.6	0	40	80	121	161	201	241	282	322	362	402	443	483	523	563	604	644	684	724	764	805
0.65	0	44	87	131	174	218	262	305	349	392	436	479	523	567	610	654	697	741	785	828	872
0.7	0	47	94	141	188	235	282	329	376	422	469	516	563	610	657	704	751	798	845	892	939
0.75	0	50	101	151	201	251	302	352	402	453	503	553	604	654	704	754	805	855	905	956	1006
0.8	0	54	107	161	215	268	322	376	429	483	536	590	644	697	751	805	858	912	966	1019	1073
0.85	0	57	114	171	228	285	342	399	456	513	570	627	684	741	798	855	912	969	1026	1083	1140
0.9	0	60	121	181	241	302	362	422	483	543	604	664	724	785	845	905	966	1026	1086	1147	1207
0.95	0	64	127	191	255	319	382	446	510	573	637	701	764	828	892	956	1019	1083	1147	1210	1274
1	0	67	134	201	268	335	402	469	536	604	671	738	805	872	939	1006	1073	1140	1207	1274	1341

Table 3: Sensitivity analysis of GfC bio-LNG production [TWh] by decentralized production ratio (horizontal) by centralized bio-LNG to maritime ratio (vertical)

Ratios	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
0	465.4	465.5	465.5	465.6	465.7	465.7	465.8	465.9	466.0	466.0	466.1	466.2	466.2	466.3	466.4	466.4	466.5	466.6	466.7	466.7	466.8
0.05	465.6	465.7	465.7	465.8	465.8	465.9	466.0	466.0	466.1	466.1	466.2	466.3	466.3	466.4	466.4	466.5	466.6	466.6	466.7	466.7	466.8
0.1	465.8	465.9	465.9	466.0	466.0	466.1	466.1	466.2	466.2	466.3	466.3	466.4	466.4	466.5	466.5	466.6	466.6	466.6	466.7	466.7	466.8
0.15	466.1	466.1	466.1	466.2	466.2	466.2	466.3	466.3	466.3	466.4	466.4	466.5	466.5	466.5	466.6	466.6	466.6	466.7	466.7	466.8	466.8
0.2	466.3	466.3	466.3	466.3	466.4	466.4	466.4	466.5	466.5	466.5	466.5	466.6	466.6	466.6	466.6	466.7	466.7	466.7	466.7	466.8	466.8
0.25	466.5	466.5	466.5	466.5	466.5	466.6	466.6	466.6	466.6	466.6	466.6	466.7	466.7	466.7	466.7	466.7	466.7	466.7	466.8	466.8	466.8
0.3	466.7	466.7	466.7	466.7	466.7	466.7	466.7	466.7	466.7	466.7	466.8	466.8	466.8	466.8	466.8	466.8	466.8	466.8	466.8	466.8	466.8
0.35	466.9	466.9	466.9	466.9	466.9	466.9	466.9	466.9	466.9	466.9	466.9	466.9	466.8	466.8	466.8	466.8	466.8	466.8	466.8	466.8	466.8
0.4	467.1	467.1	467.1	467.1	467.1	467.1	467.0	467.0	467.0	467.0	467.0	467.0	466.9	466.9	466.9	466.9	466.9	466.8	466.8	466.8	466.8
0.45	467.4	467.3	467.3	467.3	467.2	467.2	467.2	467.2	467.1	467.1	467.1	467.0	467.0	467.0	467.0	466.9	466.9	466.9	466.9	466.8	466.8
0.5	467.6	467.5	467.5	467.5	467.4	467.4	467.3	467.3	467.3	467.2	467.2	467.1	467.1	467.1	467.0	467.0	467.0	466.9	466.9	466.8	466.8
0.55	467.8	467.7	467.7	467.6	467.6	467.5	467.5	467.4	467.4	467.3	467.3	467.2	467.2	467.1	467.1	467.0	467.0	466.9	466.9	466.8	466.8
0.6	468.0	468.0	467.9	467.8	467.8	467.7	467.7	467.6	467.5	467.5	467.4	467.3	467.3	467.2	467.2	467.1	467.0	467.0	466.9	466.9	466.8
0.65	468.2	468.2	468.1	468.0	467.9	467.9	467.8	467.7	467.7	467.6	467.5	467.4	467.4	467.3	467.2	467.2	467.1	467.0	466.9	466.9	466.8
0.7	468.5	468.4	468.3	468.2	468.1	468.0	468.0	467.9	467.8	467.7	467.6	467.5	467.5	467.4	467.3	467.2	467.1	467.0	467.0	466.9	466.8
0.75	468.7	468.6	468.5	468.4	468.3	468.2	468.1	468.0	467.9	467.8	467.7	467.6	467.5	467.5	467.4	467.3	467.2	467.1	467.0	466.9	466.8
0.8	468.9	468.8	468.7	468.6	468.5	468.4	468.3	468.2	468.1	467.9	467.8	467.7	467.6	467.5	467.4	467.3	467.2	467.1	467.0	466.9	466.8
0.85	469.1	469.0	468.9	468.8	468.6	468.5	468.4	468.3	468.2	468.1	468.0	467.8	467.7	467.6	467.5	467.4	467.3	467.1	467.0	466.9	466.8
0.9	469.3	469.2	469.1	469.0	468.8	468.7	468.6	468.4	468.3	468.2	468.1	467.9	467.8	467.7	467.6	467.4	467.3	467.2	467.0	466.9	466.8
0.95	469.5	469.4	469.3	469.1	469.0	468.9	468.7	468.6	468.4	468.3	468.2	468.0	467.9	467.8	467.6	467.5	467.3	467.2	467.1	466.9	466.8
1	469.8	469.6	469.4	469.1	468.9	468.7	468.5	468.3	468.1	467.9	467.7	467.5	467.3	467.1	466.9	466.7	466.5	466.3	466.1	465.9	465.6