MAGPIE

SMART GREEN PORTS

Gaps and developments Bio-LNG supply chain for future demand

D3.8 - GAPS AND DEVELOPMENTS BIO-LNG SUPPLY CHAIN FOR FUTURE DEMAND

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Abbreviations

AD, Anaerobic digestion

bcm, billion cubic meter

CAPEX, Capital expenditure

CEPCI, Chemical Engineering Plant Cost Index

CHP, Combined heat and power

CHS, Chemical Scrubbing

EEDI, Energy Efficiency Design Index

EU27, 27 countries of the European Union

FSRU, Floating storage and/or regasification units

GHG, Greenhouse gas(es)

HPWS, High-pressure Water Scrubbing

IRENA, International Renewable Energy Agency

LNG, Liquefied natural gas

M, Million

MAGPIE, sMArt Green Portsas Integrated Efficient multimodal hubs

MDT, Million dry tonnes

MP, Membrane permeation

MSW, municipal solid waste

Mtoe, Million tonnes of oil equivalent

EU, European Union

MW, Megawatt

MWth, Megawatt thermal

NA, Not available

OPEX, operational expenditure

O&M, Operation and Maintenance

PSA, Pressure Swing adsorption

PJ, Petajoule

REDII, Renewable Energy Directive (II)

VFAs, Volatile Fatty Acid(s)

y, year(s)

Country Abbreviations

AT, Austria

BE, Belgium

BG, Bulgaria

CY, Cyprus

CZ, Czech Republic

DE, Germany

DK, Denmark

EE, Estonia

ES, Spain

FI, Finland

FR, France

GR, Greece

HR, Croatia

HU, Hungary

IE, Ireland

IT, Italy

LT, Lithuania

LU, Luxemburg

LV, Latvia

MT, Malta

NL, Netherlands

PL, Poland

PT, Portugal

RO, Romania

SE, Sweden

SI, Slovenia

SK, Slovakia

UK, United Kingdom

Executive Summary

Introduction and Aim

Achieving net zero GHG emissions by 2050, as set by the European Commission, requires a shift to low-carbon technologies across sectors like transport and industry. Ports are essential in this transition due to their role in global trade. Decarbonizing ports involves integrating renewable energy, improving energy efficiency, electrification of uses and adopting cleaner fuels for maritime and land transport.

The MAGPIE project, with ten work packages, focuses on this transition. Work Package 3 explores how ports can accelerate the adoption of green energy carriers such as electricity, hydrogen, ammonia, and bio-LNG.

This deliverable aims to assess the challenges and opportunities of using bio-LNG as a transport fuel in ports by 2030 and 2050. To achieve this objective, the research questions presented in Table 1 were formulated and addressed in this report.

Table 1. Research Questions for Assessing the Bio-LNG supply chains in the Port of Rotterdam

Sector	Questions
Bio-LNG Demand	What is the projected demand for bio-LNG in 2030 and 2050?
Bio-LNG Infrastructure	What infrastructure and adaptations are required to supply bio-LNG to Ports?
Biomass and Bio-LNG supply potentials	How much biomass is needed to meet the projected demand for bio-LNG in Ports for 2030 and 2050?
Impacts of Bio-LNG supply	What are the efficiencies and costs associated with supplying bio-LNG to Ports in 2030 and 2050? What are the main hotspots, bottlenecks, and trade-offs in the bio-LNG supply to the Ports?

To address these research questions, an analysis was conducted using the Port of Rotterdam as a case study. The Port of Rotterdam serves as a representative example due to its strategic role in European logistics and its advanced LNG infrastructure. However, the model and methodologies developed in this study are designed to be applicable to other ports globally, providing valuable insights for similar port environments. The findings can therefore be adapted to support decision-making in other port regions aiming to adopt bio-LNG solutions.

Demand and bunkering of Bio-LNG

The global demand for LNG as a marine fuel is expected to grow steadily in the coming decades, driven by stricter environmental regulations and decarbonisation goals. As of 2024, LNG bunkering services are available at approximately 190 ports worldwide, with an additional 80 locations planning to adopt such infrastructure. Bio-LNG, considered a key component in the transition to cleaner fuels, is gaining traction, with around 70 ports currently offering bunkering services, primarily in Europe, North America, and Asia (Bio-LNG is a drop-in fuel that uses the same infrastructure as fossil LNG without modifications). However, challenges remain in scaling up production and ensuring sufficient infrastructure to meet future demand.

Currently, the port of Rotterdam accounts for approximately 23% of European and 3.3% of global bunkering fuel demand (for all fuels). It is expected that the demand for bio-LNG will increase during the transition to low carbon systems. This report assesses the demand for bio-LNG in the port of Rotterdam by conducting a literature review, aligning the scopes of various studies, and providing demand estimates for LNG in the Port of Rotterdam for the years 2030, 2040, and 2050. Figure 1 presents the projected LNG demand from various studies focused on the Port of Rotterdam. Some studies predict that the demand for LNG will peak by 2040 as it serves as a transition fuel, while others highlight its importance, especially for the maritime sector in 2050.

The studies evaluated in this report reveal a wide range of possible LNG demands in Rotterdam for 2030, 2040, and 2050, indicating significant uncertainties in the role of (bio)LNG as a transport fuel in the Port of Rotterdam. This LNG demand information was used as input for assessing the LNG value chains, estimating the biomass and technology deployment required to meet both low and high-end demand scenarios for 2030 and 2050. This wide range reflects differences between studies in assumptions about future fleet composition, fuel switching behaviour, policy trajectories and the expected role of LNG as a transition fuel, and these drivers are analysed in detail in the main body of the report.

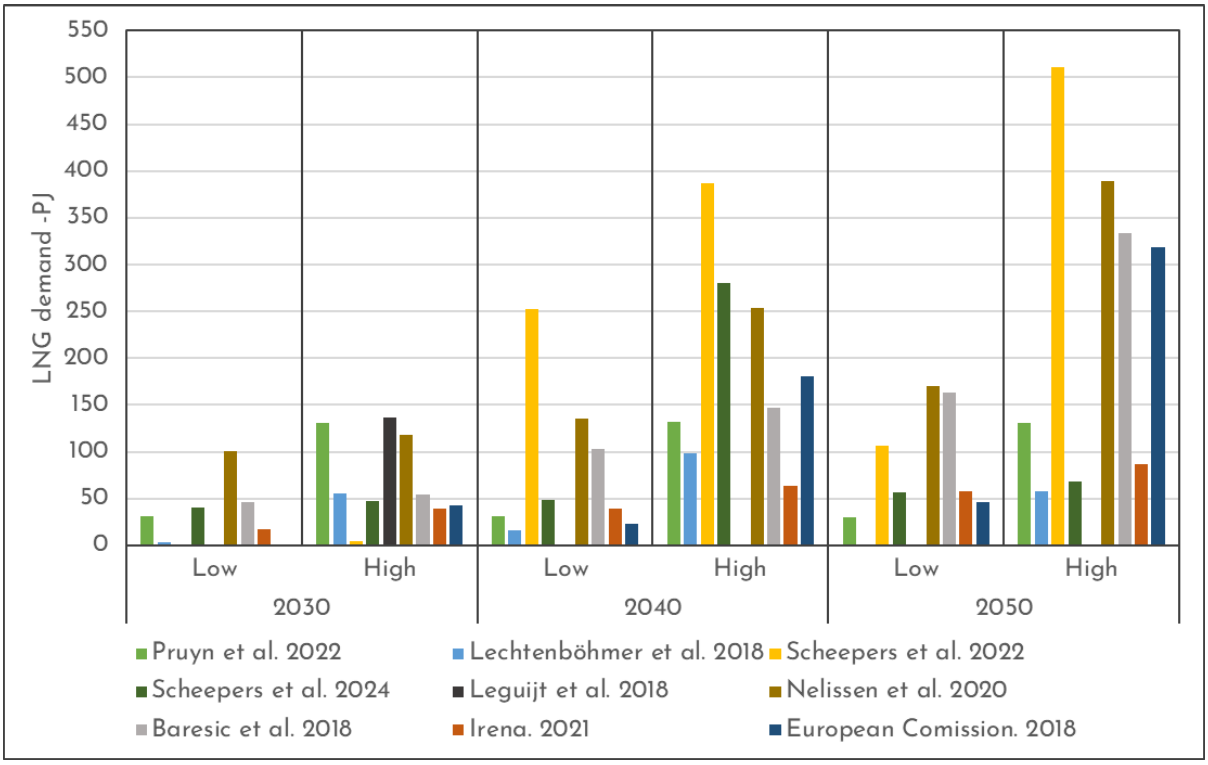

Figure 1. Projected Bio-LNG demand for 2030, 2040 and 2050 in different studies

LNG infrastructure and adaptation needs

LNG is crucial for the EU's gas supply, accounting for a significant portion of Europe's energy consumption. The EU imports over 120 billion cubic meters of LNG annually, with major importers being France, Spain, the Netherlands, Belgium, Germany and Italy. Domestic production covers only 10% of the EU's gas needs, making it heavily reliant on imports. The infrastructure includes numerous operational and planned LNG terminals across Europe, featuring storage and regasification units.

To integrate bio-LNG into the existing infrastructure, several adaptations are necessary. Expansion of biomethane production facilities is required to meet future demand (which is expected to grow significantly as shown in Figure 1). Moreover, current LNG terminals need modifications to support liquefaction for export, as well as additional cryogenic storage tanks to handle increased LNG volumes. Finally, improvements in LNG transport vehicles and intermediate biomethane storage facilities are essential. The primary challenge lies in scaling up bio-LNG production, which is currently less developed and presents higher uncertainties in terms of technological readiness and feedstock availability.

Biomass potential for Bio-LNG and biomethane production technologies

A comprehensive literature review was conducted to gather data on sustainable biomass potential in EU27 countries and the UK. This review provided inputs on biomass potentials for 2030 and 2050, which were used in the modelling of bio-LNG value chains. France, Germany, Spain, Poland, Sweden, and the UK have the highest biomass potential, with similar trends projected for 2030 and 2050. Data breakdowns show significant differences in potential by country and biomass type.

Technologies for producing biomethane include anaerobic digestion and gasification. Anaerobic digestion technology is well-established and widely deployed across Europe, with approximately 18,774 installations operating in 2020. In contrast, gasification for biomethane production remains at a lower maturity level, with fewer installations and greater technological and economic uncertainties. The scale-up of gasification technology will require significant investments and advancements to match the deployment levels of anaerobic digestion.

Anaerobic digestion is suitable for feedstocks with high water content, such as manure, biowaste, and lignocellulosic crops. Biomethane production via anaerobic digestion involves pre-treatment, anaerobic digestion, and biogas upgrading. Gasification is most suited for woody biomass, converting dry biomass into syngas, which goes in a methanation process to produce biomethane. The classification of suitable feedstocks identified agricultural residues, manure, biowaste, and lignocellulosic crops for anaerobic digestion. For gasification, appropriate feedstocks included wood, forestry residues, secondary forestry residues, prunings, and municipal solid waste (MSW). This distinction is important because it defines how available biomass streams are allocated to each technology pathway and therefore shapes the bio LNG supply potential assessed in the report.

Modelling the bio-LNG supply chain

To evaluate the potential of bio-LNG as a bunkering fuel in the Port of Rotterdam, a supply chain model was developed. The supply chain stages assessed in the model are shown in Figure 2. The model identifies bottlenecks and hotspots related to cost and efficiency at different stages. It allows for a detailed analysis of the impacts of potential improvements in the bio-LNG supply chain.

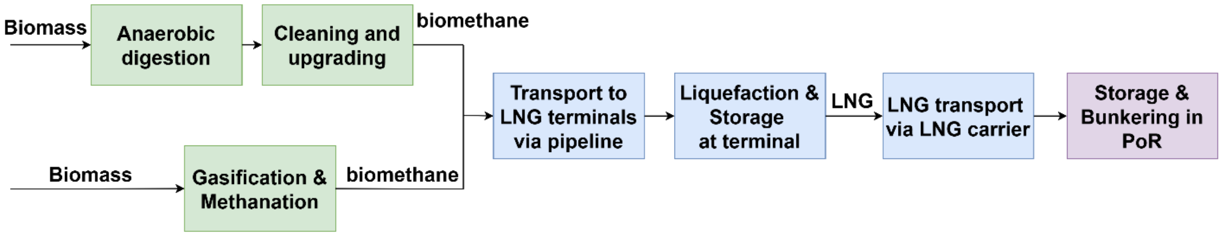

Figure 2. bio-LNG supply chain stages used in the supply chain model

Figure 3 depicts the structure of the bio-LNG supply chain model, divided into distinct steps that outline the stages of the bio-LNG supply chain shown in Figure 2. At each step, calculations of energy efficiency and cost are performed. Relevant data inputs describing the stages of the value chain are gathered at each stage of the model. A feedback loop is incorporated to refine data, as accurate estimation of energy efficiencies and costs is often required. One of the final steps involves aggregating the results of energy efficiency calculations and costs into the supply volume of LNG in the port of Rotterdam, the system cost, and the overall efficiency of the supply chain.

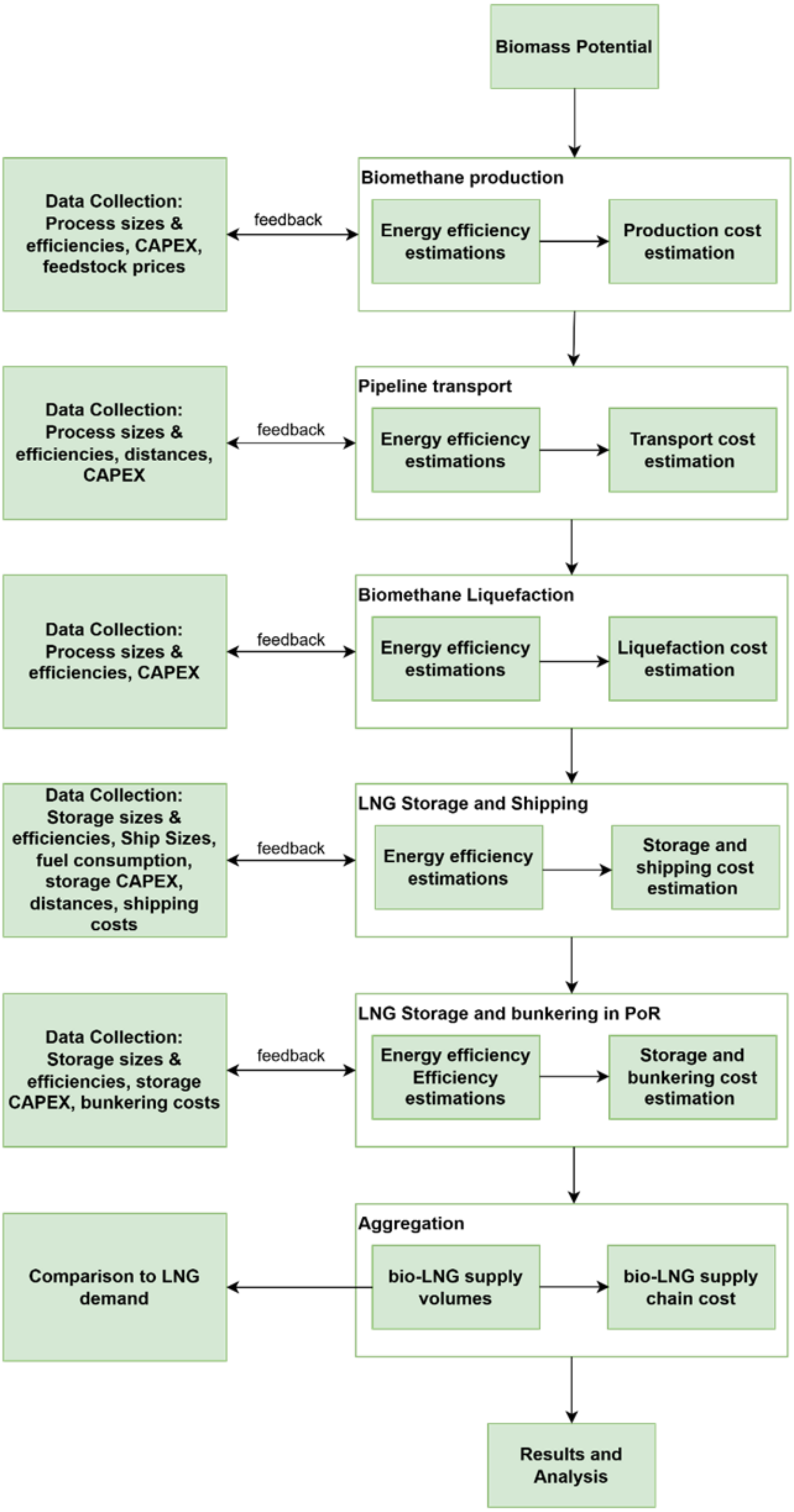

Figure 3. Structure of the bio-LNG supply chain model.

The model was tested by applying it to estimate potential bio LNG supply, technology deployment and associated costs for 2030 and 2050. Cyprus, Malta, and Luxembourg were excluded from the analysis due to high costs resulting from low biomass potentials.

Results for 2030

For 2030, the bio-LNG supply costs to the Port of Rotterdam were analysed for EU27 countries and the UK through anaerobic digestion, gasification, and a combined anaerobic digestion and gasification process. These cost figures are the aggregated outputs of the bio LNG supply model and are derived from the techno economic assessment described in Sections 5 and 6 of the report. The costs of bio-LNG via anaerobic digestion in EU27+UK ranged from 24 to 46 €/GJ depending on the country, with the production of biomethane dominating the costs, primarily due to feedstock expenses. Bio-LNG costs in EU27+UK via gasification were higher, ranging from 31 to 55 €/GJ, also largely influenced by biomethane production due to high CAPEX requirements and feedstock costs. The combined pathway showed costs between 31 and 48 €/GJ in EU27+UK depending on the country. Storage and transportation costs to Port of Rotterdam varied by country due to different storage times required to meet the minimum volume for using LNG carriers.

In 2030, under low demand scenarios of bioLNG for Port of Rotterdam, all pathways were sufficient. High demand scenarios of bioLNG for Port of Rotterdam required adjustments of the potential of biomass available for bioLNG (25 % of total biomass potential) in Port of Rotterdam (40 % of export rate of bioLNG to PoR), with anaerobic digestion covering 92%, gasification covering 100%, and the combined pathway covering 100%. Increasing biomass utilization or export rates could address the shortfall but would raise issues due to local demand.

These results come from the bio LNG supply model developed in this study, which combines feedstock availability, conversion yields, plant sizing and full techno economic calculations of the entire value chain. To meet 100% demand of PoR in high demand scenario with the anaerobic digestion pathway, 11% of Europe's biomass potential suitable for anaerobic digestion was needed. Gasification required 7% of biomass suitable for gasification, and the combined pathways needed 4% of the total biomass potential. Average system costs for 2030 for covering the demand of bioLNG in PoR (production in the Netherlands and imports from EU27+UK) ranged from 28 to 30 €/GJ for the anaerobic digestion pathway, 34 to 36 €/GJ for the gasification pathway, and 31 to 33 €/GJ for the combined pathway, all of which were higher than fossil LNG costs (4 to 13 €/GJ). The average system cost distribution to cover low and high demand figures for 2030 is presented in Figure 4.

Energy efficiency varied, with the anaerobic digestion pathway at 27%, the combined pathway at 38%, and the gasification pathway at 47%. Sensitivity analysis highlighted feedstock prices and CAPEX as significant cost influencers. Lower utilization and export rates increased costs due to smaller, less efficient systems.

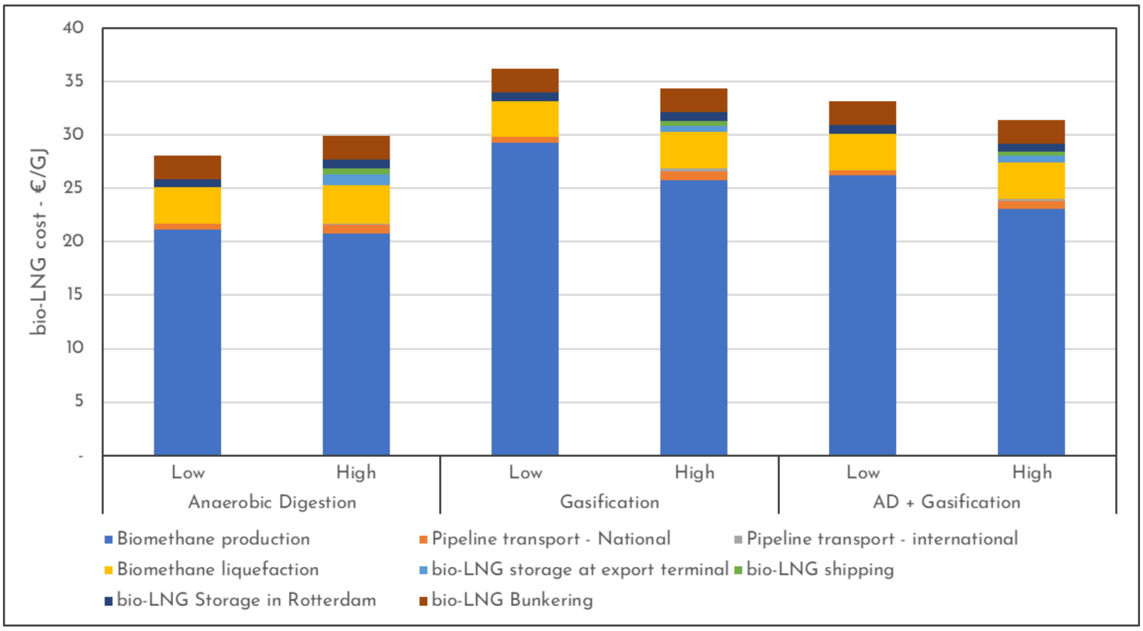

Figure 4. Average bio-LNG supply cost to the Port of Rotterdam in 2030

Results for 2050

These 2050 results are derived from the same bio LNG supply model used for 2030, using the 2050 biomass potentials, technology allocation, conversion yields and full techno economic calculations described in Sections 5 and 6 of the report. Costs remain similar to those for 2030, with the anaerobic digestion pathway for EU27 countries and the UK ranging from 25-43 €/GJ depending on the European country, the gasification pathway from 34-58 €/GJ, and the combined pathway from 30-55 €/GJ. Projections assume no significant CAPEX reductions by 2050, which is a limitation of the model. This limitation can be addressed by providing inputs with projected CAPEX reductions for 2050.

The bio-LNG supply potential via gasification is 47% higher than that via anaerobic digestion thanks to larger units and better efficiency in average of the process. Low demand scenarios for bioLNG in PoR can be met with 2.2% biomass for anaerobic digestion, 1.5% for gasification, and 0.8% for combined pathway.
High demand coverage for bioLNG in PoR is not fully covered by any of the pathways, considering a rate of use of 25% of biomass potential and an export rate of bioLNG to Port of Rotterdam of 40%, with 26% of demand covered for anaerobic digestion, 39% for gasification, and 65% for combined pathways. Meeting 100% of high demand scenarios would require significant biomass allocation: 37% of the EU27 and UK biomass suitable for anaerobic digestion, 25% of the EU27 and UK biomass suitable for gasification, and 15% of the total EU27 and UK biomass potential for the combined pathway. This challenges biomass availability regarding other potential biomass uses and also bioLNG uses in other ports and countries.

Average system costs for available bioLNG in PoR are presented in Figure 5. Costs for 2050 are 27-30 €/GJ for the anaerobic digestion pathway, 32-37 €/GJ for the gasification pathway, and 32-34 €/GJ for the combined pathway. Efficiency trends are similar to those in 2030, with biomethane production incurring major losses. Sensitivity analysis indicates that feedstock prices and CAPEX are major cost drivers, with trends mirroring 2030 results.

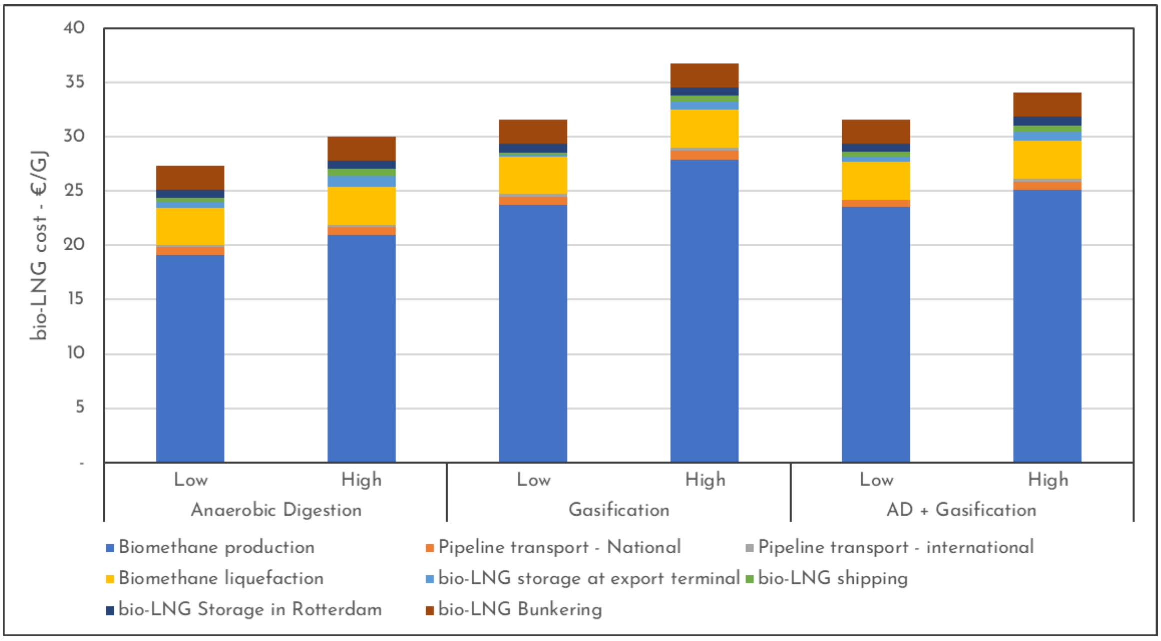

Figure 5. Average bio-LNG supply cost to the Port of Rotterdam in 2050

Conclusions and next steps

Conclusions

Bio-LNG Demand in Rotterdam

The demand for Bio-LNG in Rotterdam shows significant variation, with estimates for 2030 ranging from 0 to 136 PJ, for 2040 from 16 to 387 PJ, and for 2050 from 0 to 511 PJ. This highlights considerable uncertainty in the role of bio-LNG as a transport fuel in ports, particularly in the maritime sector.

LNG Infrastructure and adaptation needs

To accommodate bio-LNG in the current infrastructure for LNG, enhancements are necessary, including additional biomethane installations, expanded liquefaction plants, and increased storage capacity. The existing infrastructure can accommodate bio-LNG with these modifications, which primarily involve scaling up.

Biomass potentials and matching of feedstocks and technologies for bio-LNG production

Effective production of biomethane and bio-LNG depends on matching feedstocks with appropriate conversion technologies. Important factors include the biomass's volatile matter, recalcitrance, and water content. Suitable feedstocks for anaerobic digestion are agricultural residues, manure, biowaste, and lignocellulosic crops, while gasification is best for wood, forestry residues, secondary forestry residues, prunings, and municipal solid waste (MSW).

Evaluating biomass potential for bio-LNG supply chains in the EU27 and UK revealed significant opportunities for bioenergy production by 2030 and 2050, particularly in France, Germany, Spain, Poland, Sweden, and the UK. This assessment, detailed by feedstock type and country, supports the conversion of feedstocks into biomethane for bio-LNG supply at the port of Rotterdam.

Modelling the bio-LNG supply chain

A supply chain model was developed to evaluate the feasibility of supplying bio-LNG to the Port of Rotterdam from the EU27 countries and the UK up to 2050. The model examines biomass potential, biomethane production, transport, liquefaction, storage, and shipping. The model applies the technical parameters and cost inputs for each stage of the supply chain and calculates the resulting biomass needs, supply potential, energy efficiency and system costs, as described in detail in Sections 5 and 6.

The model has several limitations, including assumptions about biomass availability and capital expenditure for key stages of the supply chain. It excludes technological advancements (e.g., reduction of CAPEX through learning) projected for 2030 and 2050, and it lacks assessments of GHG emissions and competing biomass uses.

Results indicate that bio-LNG costs for 2030 and 2050 are significantly higher than fossil LNG (27-38 €/GJ vs. 4-13 €/GJ), driven by capital investment and feedstock costs. Energy losses are highest during biomethane production, followed by liquefaction and transport.

For 2030, meeting 100% of the high-end demand (136 PJ of bio-LNG) requires 494 PJ of biomass for anaerobic digestion, 290 PJ for gasification, or 362 PJ of the total biomass potential for the combined pathway. For 2050, meeting 100% of the high-end demand (511 PJ) requires 1800 PJ of biomass for anaerobic digestion, 1060 PJ for gasification, and 1377 PJ of the total biomass potential for the combined pathway.

Next steps

In assessing bio-LNG supply for ports, the next steps involve modelling various scenarios and configurations, where possible expanding to other ports. This will highlight biomass competition and biomethane or bio-LNG exports from different countries. The model will be tested in MAGPIE project scenarios and data inputs will be refined. Additionally, greenhouse gas emission accounting will be incorporated.

1. Introduction

Achieving net zero greenhouse gas (GHG) emissions by 2050 is a crucial goal set by the European Commission. This objective necessitates a transition to low-carbon technologies and systems. However, this transition is a complex challenge, involving multiple sectors (e.g., transport, industry) that currently heavily rely on fossil fuels, as well as the implementation of various options, such as the use of low-carbon energy carriers.

Sea ports play a key role in this transition. As major hubs for global trade and transport, ports are critical points in supply chains and are ideally positioned to facilitate the adoption of low carbon energy and goods. Ports need to be decarbonized to meet climate goals, which involves integrating renewable energy sources, electrification of uses and process, enhancing energy efficiency, and adopting cleaner fuels for maritime and land transport.

The MAGPIE project brings together an international team to showcase energy supply and digital solutions through practical demonstrations. This effort aims to advance green, intelligent, and integrated multimodal transport systems and ensure their adoption via the European Green Port of the Future Master Plan, supported by extensive dissemination and exploitation activities. The project is divided into ten main work packages. Work Package 3 is dedicated to examining how ports can enhance and speed up the adoption of green energy carriers in the transport sector. This work package delves into several energy carriers: electricity (T3.2), hydrogen (T3.3), ammonia (T3.4), and bio-LNG (T3.5) (Methanol is considered but a dedicated supply chain assessment is not carried out due to existing projects already exploring this area).

The aim of Deliverable 3.8 (D3.8) is to provide insights into the challenges and opportunities of supplying bio-LNG as transport fuel in ports in 2030 and 2050, using the Port of Rotterdam as a case study. D3.8 examines the projected demand for bio-LNG in the Port of Rotterdam, the necessary infrastructure, and the adaptations required for supplying bio-LNG. This deliverable also covers the types of biomass used for bio-LNG production, their compatibility with production technologies, and the amount of biomass needed to meet demand projections. Finally, the deliverable investigates bio-LNG supply costs in the Port of Rotterdam in 2030 and 2050. The report is structured as follows:

Chapter 2 describes the bio-LNG supply chain and defines the scope of the supply chain considered in this study.

Chapter 3 examines the current trend on bio-LNG bunkering and projected demand for bio-LNG. This chapter zooms into the Port of Rotterdam for the years 2030 and 2050, comparing different studies found in the literature.

Chapter 4 provides an overview of the LNG infrastructure in Europe and the adaptations required to accommodate bio-LNG.

Chapter 5 reviews the biomass potential for bioenergy in EU27 countries and the UK, matching feedstock types with technologies to produce bio-LNG.

Chapter 6 focuses on the modelling of the bio-LNG supply chain, describing the model used to evaluate the supply and costs of bio-LNG to the Port of Rotterdam. It also presents the results on bio-LNG supply costs for 2030 and 2050.

Chapter 7 concludes the deliverable with key findings from the study and outlines the next steps in assessing bio-LNG value chains in the context of smart green ports.

2. The bio-LNG supply chain

Bio-liquefied natural gas (bio-LNG) is a form of liquefied biomethane produced from biomass. Biomethane can be produced via anaerobic digestion and gasification from biomass. Biomethane is cooled to approximately -162°C to form bio-LNG. This process significantly reduces the volume of the gas, making it more efficient to store and transport over long distances. Bio-LNG can seamlessly replace conventional LNG in applications such as fuel for heavy-duty vehicles, marine transport, and industrial processes, providing a potential reduction in greenhouse gas emissions due to its renewable nature.

The escalating demand for sustainable energy sources has spurred significant interest in the bio-LNG supply chain, encompassing production, liquefaction, and distribution. Hence, a comprehensive understanding of this supply chain is vital to ensure that bio-LNG can adequately meet the rising energy demands in the forthcoming decades in ports. A detailed analysis of the different segments of the value chain is needed to understand the challenges and opportunities of bio-LNG as an energy carrier in ports. This chapter focuses on the most relevant aspects of the bio-LNG value chain.

2.1 Scope of the bio-LNG supply chain

The bio-LNG value chain consists of several steps (see Figure 6). The first step involves the production, collection, storage, and pretreatment of feedstocks to produce biomethane. The second step is the conversion of these feedstocks into biomethane using different technologies. The third step involves the production of bio-LNG, its storage, and transport to the end user(s). The fourth step focuses on the storage of bio-LNG at the end-user site and its use in ports (maritime shipping as the dominant application).

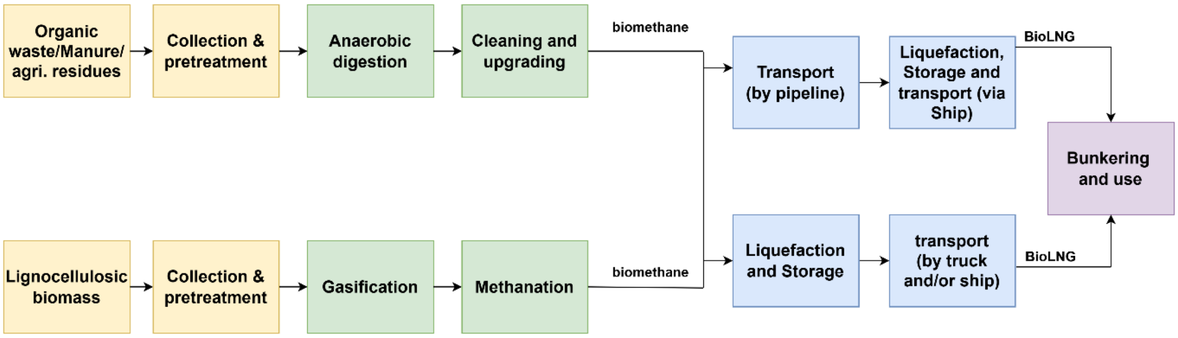

Figure 6. Description of the bio-LNG supply chain. Yellow boxes refer to feedstock collection and pre-processing, green boxes refer to biomass conversion, blue boxes refer to LNG transport and purple box refer to bunkering.

Feedstocks for producing bio-LNG can be classified into three types [1]. The first type includes feedstocks with high water content suitable for anaerobic digestion. The second type includes lignocellulosic feedstocks used for gasification. The third type consists of landfills, which produce methane in situ. However, this third option is excluded from this study due to limited information on their potential. Therefore, this work focuses on feedstocks suitable for anaerobic digestion and gasification.

Feedstocks suitable for anaerobic digestion are first used to produce biogas, which is then cleaned and upgraded into biomethane. Lignocellulosic feedstocks (with low water content) are gasified into syngas, which is then converted into methane through a methanation process, also delivering biomethane. Both options are considered in this study, and the matching of feedstocks with these technologies is elaborated in more detail in Chapter 5.

In both pathways, the methane produced is identical in characteristics, allowing it to be treated equally regardless of its source (drop-in biomethane). This implies that downstream technologies are equally valid for the different upstream production pathways. Various possibilities for transporting and liquefying biomethane are initially considered, for instance transporting biomethane via pipeline into liquefaction terminals, or liquefying next to biomethane production facilities (see Figure 6). Details on the most preferable pathway are later in the report.

The Port of Rotterdam is used as a case study to evaluate these value chains from a techno-economic perspective. The analysis focuses on the demand for LNG in the Port of Rotterdam, the supply of biomass and conversion into bio-LNG from European countries and the UK (EU27 + UK), the installations required to supply that LNG and the costs related to that supply. The analysis is carried out for bio-LNG in Rotterdam in the years 2030 and 2050. Details are presented in the upcoming chapters.

3. Demand and Bunkering of Bio-LNG

This chapter provides an overview of global trends in LNG and bio-LNG demand, serving as a foundation for a detailed analysis of the Port of Rotterdam as a case study. Bio-LNG is increasingly considered a key alternative fuel to support decarbonization in the maritime and transport sectors, driven by international climate goals and regulatory requirements. The chapter presents global trends and demand projections for bio-LNG up to 2050 and examines how these trends relate to the Port of Rotterdam.

The Port of Rotterdam has been selected as a case study to apply the developed methodology for assessing bio-LNG demand at the port level. The findings in this chapter are based on a review of existing literature, including deliverables from the MAGPIE project [2] and other authoritative sources that forecast LNG demand for maritime and industrial applications.

3.1 3.1 Global Trends and Projections for LNG and Bio-LNG Demand

The global energy sector is experiencing significant changes, with liquefied natural gas (LNG) playing an important role in the shift towards cleaner fuels. As countries work to meet climate targets and reduce greenhouse gas emissions, the demand for LNG and its renewable alternative, bio-LNG, is expected to increase significantly in the coming decades.

3.1.1 LNG Demand Projections

LNG plays a significant role in the global energy mix, particularly in regions aiming to diversify energy sources and reduce dependence on coal and oil. According to McKinsey & Company's "Global Gas Outlook to 2050," LNG demand is expected to increase by approximately 2 percent annually until it reaches a peak around 2046 (approx. 33 EJ). After this period, demand is projected to stabilise, with new capacity requirements primarily compensating for declines from aging projects [3].

The Gas Exporting Countries Forum (GECF) forecasts substantial growth in global natural gas trade, with LNG trade expected to more than double by 2050, reaching approximately 1,110 billion cubic meters (approx. 39 EJ). This expansion is anticipated to improve market integration, flexibility, and efficiency [4].

In contrast, the International Energy Agency (IEA) provides a more conservative projection, indicating that under certain scenarios, no additional LNG supply may be required until 2040. Existing and under-construction capacity (approx. 25 EJ) is considered sufficient to meet future global LNG demand [5].

3.1.2 Bio-LNG demand projections

Bio-LNG, produced from renewable biomass sources, is increasingly recognised as a sustainable alternative to conventional LNG. Its adoption is driven by the need to reduce emissions in sectors that are difficult to electrify, such as maritime shipping and heavy-duty transport.

According to SEA-LNG, bio-LNG could meet up to 3 percent of the total energy demand for shipping fuels by 2030 and up to 13 percent by 2050. When used as a drop-in fuel blended with fossil LNG at a 20 percent ratio, blended bio-LNG could supply up to 16 percent of the total energy demand for fossil fuel in 2030 and up to 63% in 2050 [1]. These values represent one set of global estimates and other studies report different outcomes depending on the assumptions made about fleet development, fuel switching and policy evolution.

The global bio-LNG market is expected to grow significantly, with estimates indicating it could reach a market size of USD 19.78 billion by 2030, with a projected compound annual growth rate of 41.1 percent from 2023 to 2030, according to Grand View Research[6].

3.2 Current Status of LNG and Bio-LNG Bunkering

The adoption of liquefied natural gas (LNG) as a marine fuel has increased significantly in recent years, driven by its environmental advantages over traditional fossil fuels such as heavy fuel oil and marine diesel. As the maritime sector faces growing pressure to decarbonise and comply with stricter environmental regulations, LNG has emerged as a viable transition fuel. It offers lower emissions of sulphur oxides, nitrogen oxides, and particulates.

3.2.1 LNG Bunkering: Present Status and Trends

LNG bunkering infrastructure has expanded considerably, with approximately 190 ports worldwide currently offering LNG bunkering services for marine applications. An additional 80 locations are in the process of planning or considering its implementation [7]. This widespread availability reflects the increasing confidence in LNG as a transition fuel to support decarbonisation efforts.

Singapore, the world's largest bunkering hub (Approx. 2.3 EJ), has experienced a substantial increase in LNG adoption as a marine fuel. In 2024, the port reported record-high marine fuel sales, reaching 54.92 million metric tonnes. Notably, sales of alternative bunker fuels, including LNG, exceeded one million tonnes. LNG bunkering volumes increased fourfold to over 460,000 tonnes compared to previous years [8]. This growth highlights the growing acceptance of LNG as a scalable marine fuel option.

In Europe, major ports such as Rotterdam, Antwerp, and Zeebrugge have become key LNG bunkering hubs by leveraging existing infrastructure to facilitate the transition to cleaner fuels. Globally, the number of LNG-fuelled vessels (excluding LNG carriers) is currently estimated at around 355, further driving demand for LNG bunkering services in Europe and elsewhere [9].

3.2.2 Bio-LNG: Emerging Opportunities

Bio-LNG is currently available at nearly 70 ports across Europe, North America, and Asia [9]. Key locations such as Singapore and Rotterdam are leading the transition to sustainable bunkering solutions. These ports are well positioned to integrate bio-LNG into their existing LNG infrastructure, enabling a seamless transition without requiring significant additional investment in storage and handling facilities.

A major advantage of bio-LNG is its compatibility with existing LNG-fuelled vessels. The current fleet of approximately 355 LNG-powered ships can use bio-LNG without modifications, making it an attractive drop-in fuel that can contribute to accelerating the maritime sector's decarbonisation efforts [9].

Despite its potential, accurate data for bio-LNG bunkering remains limited due to its relatively early stage of market adoption. However, early trends indicate strong growth. In Singapore, for instance, sales of biofuel blends—potentially including bio-LNG—increased by 69% in 2024, reaching 880,000 tonnes [8]. This increase reflects the growing interest in bio-LNG as a practical and sustainable solution for reducing shipping emissions.

3.2.3 Future Outlook

LNG bunkering infrastructure is expected to continue expanding globally, with increasing investments in storage and distribution facilities to meet rising demand. Although bio-LNG is still in its early stages, it is expected to play an important role in the maritime sector's long-term decarbonisation strategy. With existing LNG infrastructure being readily adaptable to bio-LNG, the maritime industry is well positioned to scale up its adoption in the coming years.

In summary, LNG bunkering has already established a strong presence in the global maritime sector, with major ports enhancing their capacity to accommodate growing demand. Bio-LNG, supported by existing infrastructure and regulatory incentives, is emerging as an essential component in the transition to cleaner shipping fuels.

3.3 Review of LNG demand in the MAGPIE project in the Port of Rotterdam

The starting point for analysing the demand for bio-LNG in the port of Rotterdam is derivable from task 3.1 of the MAGPIE project [2], which discusses energy requirements for various energy carriers and various transport modes, including maritime shipping, inland shipping, truck and rail. The project also aimed to predict future energy requirements for these transport modes, with a shift towards renewable energy sources by 2030, 2040, and 2050. The overarching goal was to estimate the scale of energy demand in the transport sector, both current and future.

For (bio)LNG, the relevant transport sectors are maritime shipping, inland shipping, and trucking according to the MAGPIE project [2]. Rail transport was excluded from this analysis as in the project it exclusively utilizes electricity as its energy medium, thus LNG was not considered. The energy requirements for transport in the port of Rotterdam, specifically for inland shipping, maritime shipping, and trucking, were estimated in D3.1 using bottom-up approaches to determine the low and high ends of bio-LNG demand in the Port of Rotterdam for these three transport modes (maritime shipping, inland shipping, and trucking).

For maritime shipping in 2030, the demand for bio-LNG in Rotterdam showed a range of 30 to 130 PJ (see Figure 7). The demand projections for 2040 and 2050 remain constant, reflecting the high uncertainties regarding the types of vessels that bio-LNG can serve. It is, however, unusual to find that the projected demand bandwidth remains equal for 2030, 2040, and 2050 without significant variations. The latest is mostly related to the fact that the assessment carried in Pruyn et al., [2], limits the scope of bio-LNG use in large vessels only.

In the case of inland shipping, the demand behaviour differs from maritime shipping. It is expected that demand will grow from 307 TJ in 2030 to 1,014 TJ in 2050 at the high end [2]. For trucks, the demand is expected to double by 2040 compared to 2030, reaching 1,100 TJ, but it is projected to decline to 0 by 2050. This is because inland vessels have limited decarbonisation alternatives, making bio-LNG a more persistent option. In contrast, trucks are expected to shift to zero-emission technologies such as battery electric and hydrogen drivetrains by 2050, reducing the long-term role of bio-LNG in road transport.

Combining the demand projections for the three transport modes in 2030, 2040, and 2050 shows that maritime shipping's contribution is significantly larger compared to the other modes, which are almost negligible, as presented in Figure 7. This also indicates that the port of Rotterdam will have a high demand for bio-LNG, primarily for the international shipping sector.

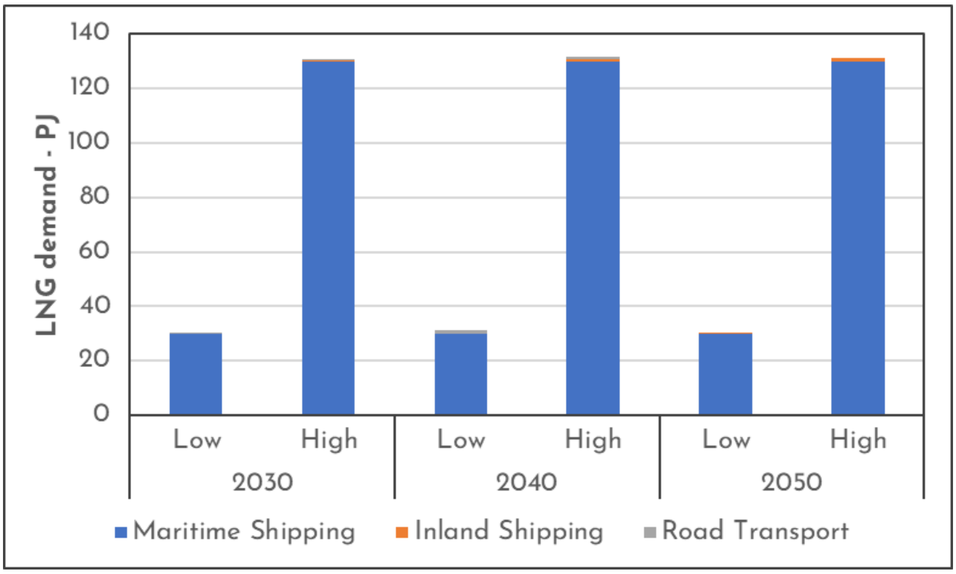

Figure 7. Bio-LNG demand in the port of Rotterdam estimated in the MAGPIE project [2].

3.4 Review of LNG demand in Rotterdam in other studies

This section reviews and compiles various studies projecting (bio)LNG demand. Table 2 presents the reviewed studies on LNG demand in the maritime shipping sector. Although those studies estimate the future demand for LNG as fuel for shipping, they have different scopes. To make these studies comparable, their scopes need to be aligned.

Only one study focuses specifically on the port of Rotterdam [10], while the others cover the Netherlands, Europe, or globally. For studies focused on the Netherlands, it is assumed that they also represent the Port of Rotterdam. While there are multiple ports in the Netherlands, the Port of Rotterdam is the largest and most significant for maritime shipping due to its substantial contribution to global and European bunkering [11].

For studies with a European scope, the demand figures were adjusted by a fraction representing the port of Rotterdam's contribution to European bunkering fuel demand. The port of Rotterdam is the largest European bunkering port and one of the top three worldwide, supplying approximately 10 million tonnes of bunker fuel annually [11, 12]. According to the Fuels Europe, the total marine fuel consumption in the EU27 is about 49 million tonnes [13]. Therefore, the port of Rotterdam accounts for approximately 23% of European bunker fuel demand. Assuming an average lower heating value of 41 MJ/kg, this equals approximately 410 PJ per year. This percentage was used to adjust the total demand to the Port of Rotterdam in the studies with scope in Europe.

The same percentage was assumed to remain constant for 2030, 2040, and 2050, indicating that the port of Rotterdam's share of bunkering capacity will remain unchanged. For studies with a global scope, a similar approach was applied. The port of Rotterdam's bunkering capacity of approximately 10 million tonnes was compared to the global shipping industry's fuel consumption of about 300 million tonnes [14], resulting in a 3.3% share of the total global bunkering capacity. This data was used to adjust the demand of the studies with a global scope to be aligned with the scope of the Port of Rotterdam. This approach assumes that the Port of Rotterdam follows similar fuel transition patterns as the global average, which allows for proportional downscaling of demand figures in the absence of detailed regional projections. This assumption was made to allow comparison across studies, since consistent projections of how Rotterdam's share of global or European bunkering will evolve are not available in the reviewed sources.

Table 2. Studies reviewed to estimate the demand of LNG.

Study	Scope
Pruyn et al., [2]	Port of Rotterdam
Lechtenböhmer et al., [10]	Port of Rotterdam
Scheepers et al., [15]	The Netherlands
Scheepers et al., [16]	The Netherlands
Leguijt et al., [17]	The Netherlands
Nelissen et al.,[18]	Global
Baseric et al., [19]	Global
Irena., [20]	Global
European Commission., [21]	Europe

Figure 8 presents the projected LNG demand from various studies for the Port of Rotterdam (Absolute values of LNG demand presented in Figure 8 are presented in Annex A). In these projections for LNG demand, fossil LNG, biofuels, synfuels, and bio-LNG were included. Bio-LNG can directly replace fossil LNG. Therefore, if a study projects the use of fossil LNG for 2030, 2040, or 2050, bio-LNG can be used instead. Some studies differentiate between the contributions of synfuels, biofuels and bio-LNG. While these distinctions may refer to other biofuels, bio-LNG is also a biofuel. Thus, bio-LNG can be included as part of the biofuel's contribution. Additionally, LNG can also contribute to synfuels, thus bio-LNG being an alternative counterpart. This inclusion may result in higher projected demands in some studies, as they combine fossil LNG, bio-LNG, other biofuels and synfuels. A detailed explanation of the studies considered in this study is provided below.

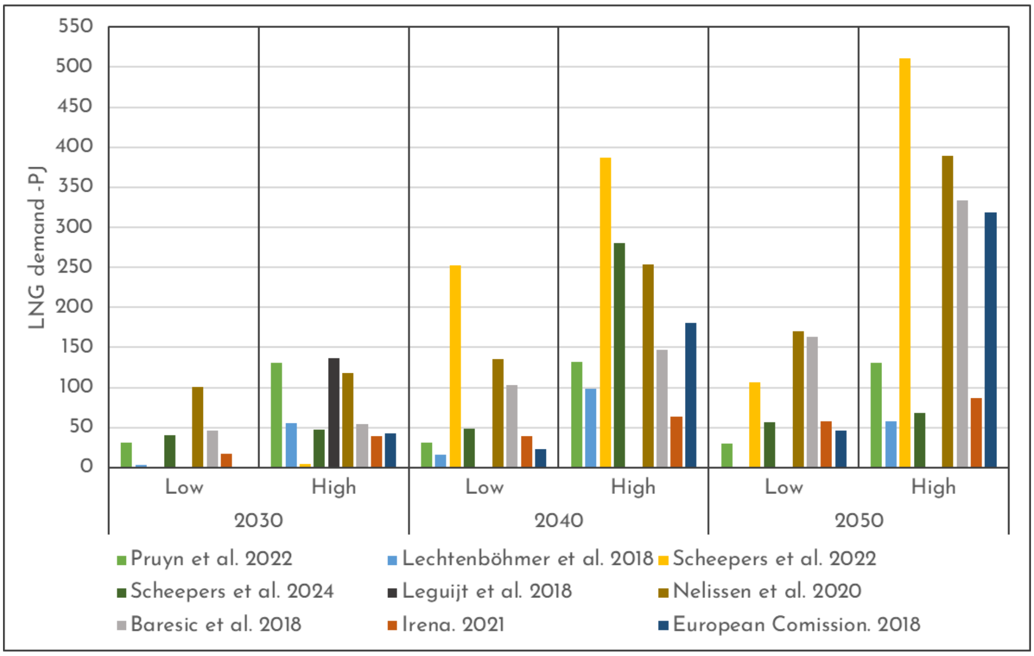

Figure 8. Projected Bio-LNG demand for 2030, 2040 and 2050 in different studies for the Port of Rotterdam.

The projections of Pruyn et al., [2] remain constant for both low and high-end demand for bio-LNG in 2030, 2040 and 2050. In this study, the demand was estimated using a bottom-up approach considering fleet characteristics such as vessel sizes, fuel consumption and average trip's duration [2]. This method differs significantly from other studies, which primarily focus on energy systems modelling under different scenarios. These scenarios provide the demands and projections for bio-LNG, fossil LNG, biofuels, and synfuels.

The study by Lechtenböhmer et al., [10] examined two pathways toward non-fossil maritime shipping: power-to-liquids, and power-to-liquids combined with power-to-gas. The projections mainly reflect the electrification of the maritime sector and the inclusion of biomass as biofuels. In the liquids pathway, fossil LNG does not play a role. However, there is a projected growth in synfuels from 2030 to 2050. Biofuels show a larger contribution in 2040, acting as a transition fuel, with decline over 2050, still maintaining a small contribution in both pathways. Both biofuels and fossil LNG increase in 2040 compared to 2030 but decrease to almost zero by 2050, in the liquids and gas pathway. In contrast, synfuels continue to grow from 2030 to 2050. Compared to the results by Pruyn et al., [2] , the results by Lechtenböhmer et al., [10] are significantly lower mostly due to an anticipated reduction in consumption of maritime fuels in the Port of Rotterdam.

The studies conducted by Scheepers et al. [15, 16] examine the projections of LNG. By modelling the "Transform" and "Adapt" scenarios, they aim to explore the reduction of greenhouse gas emissions in the Netherlands. This energy modelling includes various sectors, including the maritime sector. The study, published in 2022 [15], veals that in the Adapt scenario the modelled contribution of LNG in 2030 is negligible, which reflects the assumptions of that scenario rather than current market developments where LNG-fuelled vessels are increasingly ordered. However, this changes dramatically by 2040 and 2050, where LNG becomes a major contributor to the maritime fuels sector. Although the major contribution in this study is from fossil LNG, it is considered that this could also be covered by bio-LNG. The Adapt scenario also projects an increase in energy demand for the maritime sector from 2040 to 2050.

According Transform scenario [15], LNG's contribution becomes very dominant in 2040 and 2050, comprising synthetic LNG, bio-LNG, and fossil LNG. This explains the high projected demand for LNG, as it is considered the main fuel in the maritime sector. However, this picture changes dramatically in the 2024 study [16] due to updated targets for the maritime sector and the inclusion of ammonia as a fuel, which impacts the LNG projections. As a result, LNG's contribution is much smaller in the 2024 study compared to the 2022 study.

Similar to Lechtenböhmer et al. [10], the 2022 study by Scheepers et al. [15] identifies LNG as a transition fuel for the maritime sector. Comparing this study with MAGPIE projections shows that LNG demand in 2030 is almost negligible in both the low and high scenarios. However, demand increases sharply by 2040—reaching values eight (low scenario) to three (high scenario) times higher than MAGPIE projections [2]. Between 2040 and 2050, the low scenario shows a significant decline—dropping by a factor of 2.5—while the high scenario continues to rise, resulting in LNG demand nearly four times higher than in MAGPIE by 2050.

The 2024 update by Scheepers et al. [16]also supports the transitional role of LNG. Compared to MAGPIE, the low-end LNG demand in 2030 is about 30% higher, while the high-end is lower. In 2040, the projected demand is roughly double that of MAGPIE [2]. By 2050, the range varies widely—from half to twice the MAGPIE projection—depending on the scenario.

The study conducted by Leguijt et al., [17], focuses on estimating the growth of the LNG market based on four different scenarios. These scenarios reflect varying levels of effort to achieve the Paris goals and degrees of international cooperation. The first scenario examines a national level approach with minimal international cooperation and low effort toward the Paris goals. The second scenario considers a high commitment to the Paris goals but with low international cooperation. The third and fourth scenarios involve international cooperation, with the third scenario showing slow progress towards the goals and the fourth scenario demonstrating higher cooperation and effort towards the Paris agreements. The projections in this study were made for the year 2030 and compared to the results of the Magpie study for the same year. At the low end, the MAGPIE projections are significantly larger. Leguijt et al., [10] are almost negligible if no measures are taken and no international cooperation takes place, indicating a very small contribution of LNG. However, at the high end, the projections are similar in both studies.

Nelissen et al.,[18] estimated the global LNG demand for the maritime sector. The projections indicate that the LNG market tends to grow in the upcoming decades. Compared to the MAGPIE results for 2030, the global projections for LNG, when scoped down to Rotterdam, are higher by almost four times at the low end. However, for the high end, the 2030 projections are slightly lower than those of the MAGPIE study. For 2040, the global projections scoped down to Rotterdam show LNG consumption to be two to four times larger than the MAGPIE projections. For 2050, they are three to six times higher. The latter suggest that globally, LNG it is not expected to be a transition fuel as pointed out by other studies above.

The study by Baseric et al., [19] considers four scenarios: business as usual, high gas with major LNG involvement, transition with a lower role for LNG, and a limited gas scenario favouring biofuels. The projections show higher growth in 2050 compared to 2030 and 2040. For 2030, the high-end projections of the Magpie project are much larger, while Baseric et al., projections are 60% lower. For the low end, Baseric et al., projections are 50% larger than those of the Magpie project. Baseric et al., projections for 2040 are one to three times higher than Magpie's, and for 2050, they are three to six times higher. This aligns with the projections by Nelissen et al.,[18], which foresees LNG as a key bunker fuel in 2050.

The projections conducted by Irena., [20] indicate that energy demand in the maritime sector, particularly in the 1.5 scenario pathway, is expected to decrease. This aligns with studies by Scheepers et al. [15, 16], especially in the transform scenario. Irena's projections highlight the significant role of e-based molecules, such as ammonia, methanol, and hydrogen, in the maritime sector, with less emphasis on biofuels and LNG. However, LNG still plays a role, though not as prominently as in other studies. These projections differ from the Magpie project, which generally shows higher energy demand. Irena's projections also display a narrower range, likely due to the role of e-based molecules compared to biomolecules.

The European Commission [21] projects that the European maritime sectors will primarily use marine diesel and heavy fuel oil by 2030, with a minor contribution from LNG [21]. This trend is expected to continue in a baseline scenario through 2050. However, in alternative scenarios for 2050, a decrease in maritime fuel demand is projected, with LNG and biofuels making major contributions. This explains why the European Commission's projections show higher demand compared to Irena's, where e-based molecules are more prominent. Compared to Magpie's projections [2], the European Commission's projections [15] are approximately 1.5 to 2.4 times higher for 2030, 2040, and 2050.

The studies evaluated in this report reveal a wide range of possible LNG demands in Rotterdam for 2030, 2040, and 2050. This information on LNG demand is used as input for assessing the LNG value chains, which will estimate the biomass and technology deployment required to meet both low and high-end demand scenarios for 2030 and 2050.

Lastly, it is crucial to assess the realism of these ranges based on biomass availability in the EU-27 plus the UK, compared to the demand projected for the Port of Rotterdam. The ranges might impact the overall assessment, and in some cases, the available biomass might not be sufficient to meet the requirements. Additionally, this analysis only covers the demand for Rotterdam, but countries with potential biomass for LNG would consider their internal demand and the possibility of exporting surplus energy to the Netherlands, specifically to the Port of Rotterdam’s LNG terminal.

4. LNG infrastructure and adaptation needs

This chapter focuses on providing an overview of the current infrastructure of LNG in Europe, and the needs for adaptation to accommodate bio-LNG in the current infrastructure.

4.1 Overview of the LNG infrastructure in Europe

In Europe, LNG plays a crucial role in the EU's gas supply security. The demand for gas in the EU is approximately 350 billion cubic meters per year (12.5 EJ/year). Natural gas accounts for around one-quarter of Europe's overall energy consumption. A key objective of the European Energy Union strategy is to ensure that all EU countries have access to liquefied natural gas, as it can help diversify gas supplies and improve EU energy security in the short term while more sustainable solutions towards full decarbonization by 2050 are established [22].

The EU is the world's largest LNG importer, having imported over 120 billion cubic meters (bcm) in 2023. The primary importers within the EU are France, Spain, the Netherlands, Belgium, and Italy [23]. Only 10% of the EU's gas needs are met by domestic production, with the remaining 90% depending on imports. This highlights the EU's significant reliance on imported gas to meet its energy demand [22]. In 2021, many of these imports came from Russia, accounting for 41%, followed by other suppliers via pipeline at 39%, and imports of liquefied natural gas at 20%. However, this situation changed dramatically following Russia's invasion of Ukraine in February 2022. By 2023, imports of gas from Russia decreased to 8%, while imports from other suppliers via pipeline increased to 50%, and the share of LNG imports rose to 37%[22].

This shift has driven the rapid development of LNG infrastructure to accommodate the increased LNG imports. The EU has steadily expanded its energy import capacities, developed new LNG regasification and import terminals[22]. Nevertheless, there are still bottlenecks and infrastructure limitations. Across Europe, there are numerous LNG terminals, both planned and operational, which include (floating) storage and/or regasification units (FSRU). Table 3 provides an overview of these terminals, detailing their LNG storage capacity and status.

Table 3. Operational and planned LNG terminals in EU27 + UK [22].

Country	Terminal	Annual Capacity (bcm)	Storage Capacity (m^3)	Start-up Year	Status
Finland	Hamina-Kotka	0.13	30,000	2022	Operational
Finland	Inkoo FSRU	5	150,000	2023	Operational
Estonia	Tallinn LNG (Muuga)	4	160,000	NA	Planned
Estonia	Paldiski LNG Terminal	2.5	160,000	2024	Under construction
Latvia	Skulte LNG terminal	1.5	NA	NA	Planned
Latvia	Riga LNG	NA	40,000	NA	Planned
Lithuania	Klaipėda FSRU	4	170,000	2014	Operational

Table 3. Continued

Country	Terminal	Annual Capacity (bcm)	Storage Capacity (m³)	Start-up Year	Status
Poland	Gdańsk LNG	6.1	170,000	2025	Planned
Poland	Swinoujscie LNG Terminal	6.2	320,000	2016	Operational and expansion planned
Germany	Lubmin FSRU	5.2	170,000	2023	Operational and expansion planned
Germany	Stade LNG terminal	6	174,000	2024	Under construction
Germany	Brunsbüttel LNG terminal	7.5	170,000	2023	Operational and expansion planned
Germany	Wilhelmshaven	5.2	170,000	2022	Operational
The Netherlands	Eemsenergyterminal	8	180,000	2022	Operational
The Netherlands	Gate terminal Rotterdam	12	540,000	2011	Operational and expansion planned
Belgium	Zeebrugge LNG Terminal	14.8	566,000	1987	Operational and expansion planned
France	Dunkerque LNG Terminal	13	600,000	2016	Operational
France	Le Havre	5	142,500	2023	Operational
France	Montoir-de-Bretagne LNG Terminal	10	360,000	1980	Operational
France	Fos Cavaou LNG Terminal	8.5	330,000	2010	Operational and expansion planned
France	Fos-Tonkin LNG Terminal	1.5	80,000	1972	Operational
Spain	Bilbao LNG terminal	7	450,000	2003	Operational
Spain	Mugardos LNG Terminal	3.6	300,000	2007	Operational
Spain	Huelva LNG Terminal	11.8	619,500	1988	Operational
Spain	Cartagena LNG Terminal	11.8	587,000	1989	Operational
Spain	Sagunto LNG terminal	8.8	600,000	2006	Operational
Spain	Barcelona LNG Terminal	17.1	760,000	1969	Operational
Portugal	Sines LNG Terminal	7.6	390,000	2004	Operational
Malta	Malta Delimara LNG terminal	0.7	125,000	2017	Operational

Table 3. Continued

Country	Terminal	Annual Capacity (bcm)	Storage Capacity (m^3)	Start-up Year	Status
Italy	Porto Empedocle LNG terminal	8	320,000	NA	Planned
Italy	Portovesme FSRU	5	NA	NA	Planned
Italy	Piombino FSRU	5	170,000	2023	Operational
Italy	OLT Offshore LNG Toscana FSRU	5	137,100	2013	Operational
Italy	Panigaglia LNG terminal	3.4	100,000	1971	Operational
Italy	Porto Levante LNG terminal	9	250,000	2009	Operational and expansion planned
Italy	Ravenna	1	20,000	2021	Operational and expansion planned
Croatia	Krk LNG Terminal	2.9	140,000	2021	Operational and expansion planned
Greece	Dioriga Gas FSRU	2.5	210,000	2023	Planned
Greece	Revithoussa LNG Terminal	7	225,000	1999	Operational
Greece	Argo FSRU	5.2	170,000	2024	Planned
Greece	Thrace LNG	5.5	170,000	NA	Planned
Greece	Alexandroupolis LNG terminal	5.5	153,500	2024	Under construction
Cyprus	Vasiliko LNG terminal	2.44	137,000	2024	Planned
Ireland	Mag Mell	2.6	NA	NA	Planned
Ireland	Shannol LNG FSRU	7.8	NA	NA	Planned
UK	Isle of Grain	19.5	1,000,000	NA	NA
UK	Milford Haven South Hook	21	775,000	NA	NA

The European gas infrastructure (EU27+UK) consists of a coordinated network of import terminals, storage facilities, regasification plants, and an extensive distribution system that ensures the flow of natural gas across the continent [24]. The existing infrastructure is well-developed and capable of accommodating (bio)LNG and biomethane. Imported LNG is typically managed in LNG import terminals, where it is gasified before being injected into the European gas pipeline grid, which is used to transport it to demand points. The pipeline network is well-established and extensively used, composed of large pipelines, 36'' and above, for long-distance transportation, connecting major gas sources with distribution networks or industrial centres. It also includes pipelines of 24'' to 36'' and systems below 24''. The network features cross-border interconnection points within EU countries and with non-EU countries [24].

The European gas infrastructure includes numerous gas storage facilities in aquifers, salt cavities, caverns, and depleted fields both onshore and offshore. The total EU gas storage capacity is approximately 100 bcm, covering around one-third of the EU's annual gas consumption. This corresponds to roughly 3.6 exajoules (EJ) of stored energy, based on a lower heating value of 35.8 PJ per bcm of natural gas.

Details of the complexity of the gas infrastructure in Europe can be found in the system capacity map of the European network of transmission system operators for gas [24].

4.2 Infrastructure adaptation needs for bio-LNG

The previous section describes the maturity and complexity of the current gas infrastructure in Europe. However, to accommodate bio-LNG within this infrastructure, several adaptations are required.

Firstly, the number of biomethane installations across Europe must be increased. Although several biogas production and upgrading facilities currently exist (approx. 1,300 [25, 26]), these installations need to be expanded into larger facilities and greater numbers [1]. This expansion includes the challenge of feedstock collection, necessitating infrastructure for proper management of agricultural residues and organic wastes. Additionally, the gasification process needs to be scaled up to include biomethane production. The main issue is that gasification plants are not currently deployed and scaled-up as the case of anaerobic digestion units [27]. This therefore implies that gasification units require faster development into large-scale systems.

Another important aspect of infrastructure development to accommodate bio-LNG is the additional installation of liquefaction plants. While Europe receives large amounts of LNG, most terminals are storage and regasification units [22]. If biomethane is to be locally produced and exported as LNG, the current LNG terminals need to be adapted for export. Therefore, liquefaction plants must be installed to meet the demand for liquefied gas. Additionally, if LNG volumes increase in Europe, extra storage capacity in the form of cryogenic storage tanks will be necessary to maintain LNG in its liquefied state. Expansion of cryogenic processing equipment will also be required for handling LNG during loading and unloading of ships. These adaptations mostly denote scale up effects [28].

As described above, the current infrastructure for transporting natural gas can be used to accommodate biomethane. However, it is crucial to evaluate whether biomethane produced within the European Union impacts the system's capacity [28]. For example, if LNG is to be transported by road, LNG transport vehicles and related loading and unloading equipment will also need to scale up [28]. Another possible adaptation would be to accommodate intermediate storage or distribution terminals for LNG. Currently, Europe has a vast amount of gas storage systems, but relatively small capacity intermediate storage for LNG [24]. Unlike gaseous natural gas, LNG is stored in liquid form at cryogenic temperatures, requiring dedicated insulated tanks. As a result, existing underground gas storage facilities cannot be used for bio-LNG, and intermediate storage capacity specific to liquid fuels remains limited in Europe

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[1] The model developed in this study provides a comprehensive assessment of the required expansion of biomethane installations. It evaluates the necessary capacity increases to meet projected demand scenarios for 2030 and 2050, considering different levels of bio-LNG adoption. Furthermore, the model estimates the corresponding feedstock requirements and identifies potential supply bottlenecks within the EU27 and the UK. A detailed analysis of these aspects, including the potential infrastructure adaptations and supply chain implications, is presented in Chapter 6

In summary, the production of LNG requires scaling up, but the existing infrastructure for transporting natural gas can handle bio-methane and bio-LNG with only minor adaptations to account for scale effects. In consequence, for the purpose of assessing the bio-LNG value chain, it makes sense to use the current pipeline network in Europe which implies discarding the option of liquefying in biomethane production plants, which would require specialized truck transport of large quantities of LNG. It is therefore preferable to liquify biomethane for exporting in current LNG terminals and export it via LNG carrier to the Port of Rotterdam.

5. Biomass potential for Bio-LNG and biomethane production technologies

This chapter examines the biomass potential for fuel and chemical production in the EU 27 countries and the United Kingdom in 2030 and 2050. Understanding biomass potential is essential for assessing bio-LNG production in these regions and its potential supply to the Port of Rotterdam in 2030 and 2050.

5.1 Overview of biomass potential for bioenergy in EU27 countries and UK in 2030 and 2050

This section presents a literature review to gather information about the sustainable biomass potential in EU27 countries and the UK. Imports from outside the EU27 and the UK are not considered in this assessment. By examining recent publications on biomass potential, it aims to establish ranges representing the available biomass for potential bio-LNG production in 2030 and 2050. The publications assessed in this study employ various methods to estimate and evaluate the sustainable potential of different biomass sources. The objective is to understand and compare these publications and use the data as input for modelling the bio-LNG supply chain to supply LNG to the Port of Rotterdam.

According to Hoefnagels & Germer [29], a resurgence in lignocellulosic biomass for advanced biofuels is expected after 2030. This resurgence is linked to the role of bioenergy in achieving climate reduction targets through sustainable biomass supply. The study reviews several biomass supply estimates published from 2006 to 2017, highlighting the challenges in meeting bioenergy demand. It suggests that by 2030, domestic supply may not meet consumption levels. However, the supply could increase to 206 million tons of oil equivalent (Mtoe) by 2030 and 195 Mtoe by 2050. The decrease in supply potential in the central scenario is linked to increasing land-use restrictions, sustainability safeguards, and competing demands for land, rather than a reduction in biomass availability from agriculture or forestry. For comparison, primary energy consumption in the EU is approximately 1200 Mtoe, and final energy consumption is about 894 Mtoe (Eurostat, 2023), highlighting that even in high-supply scenarios, biomass would represent a share of the total energy mix rather than a complete replacement. In high supply scenarios, which include additional forest sources and energy crop cultivation, projections indicate a potential of 525 Mtoe by 2030, increasing to 597 Mtoe by 2050.

Forests are estimated to contribute 25%-36% of the potential biomass, though a portion is already utilized in the electricity and heat sectors. Solid biomass imports, primarily wood pellets, and liquid biofuels are expected to contribute between 4-40 Mtoe and 9-26 Mtoe respectively by 2050. Energy crops, particularly perennial ones, could account for 33%-56% of the EU biomass potential. Achieving this will require substantial efforts in scaling up commercial production, developing infrastructure, enhancing farmer experience, and ensuring regulatory compliance [29].

A study conducted by Concawe [30], provides a detailed analysis of the bioenergy sector's growth in Europe. The study predicts a significant expansion, with bioenergy increasing from 175 Mtoe in 2020 to an estimated range of 210-320 Mtoe by 2030, and further rising to 350-535 Mtoe/y by 2050 (Also quantified in million dry tonnes (MDT), projecting approximately 437.5 MDT in 2020, 525-550 MDT by 2030, and an anticipated range of 875-1338 MDT by 2050. This estimation is supported by Borzęcka et al. [31]. Their projection indicates that the biomass required to meet the growing bioenergy demand will reach 360

Mtoe/year (equivalent to 900 million dry tons), with an additional 15 Mtoe/year likely to be imported (only 4 % of imports).

Panoutsou & Maniatis [32] published a report estimating the potential of sustainable biomass in the European Union and the UK for 2030 and 2050. The focus was on evaluating possibilities for advanced biofuel production. The analysis considered domestic feedstocks from agriculture, forestry, and waste, following the guidelines of RED II Annex IX (Part A and B). Three scenarios were evaluated: low biomass mobilization, enhanced mobilization in selected countries, and increased availability through research and innovation.

In the first scenario, titled Low Biomass Mobilization, farming and forest practices remain unchanged from 2020 levels. Only 25% of unused land is utilized for lignocellulosic crops. The primary focus is on using agricultural residues, forestry by-products, and wastes for energy production and other biobased sectors, while also incorporating measures for biodiversity conservation.

The second scenario, Enhanced Mobilization in Selected Countries, involves improved cropping and forest management practices in countries with high biomass potential or low supply costs. Countries with strong innovation profiles include Germany, France, Sweden, Finland, Italy, the United Kingdom, Austria, and Spain. Countries with low biomass supply costs are Poland, Romania, the Czech Republic, Hungary, and Bulgaria. Techniques such as crop rotation and agroforestry are employed, with 50% of unused land allocated for biomass crops. This scenario continues to focus on using residues and wastes, along with efforts in biodiversity conservation.

The third scenario, Enhanced Availability Through Research and Innovation & Improved Mobilization, sees all EU27 Member States and the UK adopting advanced farming and improved management practices across all feedstocks. The highest portion of unused land (75%) is dedicated to lignocellulosic crops. As in the previous scenarios, there is a strong emphasis on the use of residues and wastes, complemented by biodiversity conservation measures.

In the work of Panoutsou & Maniatis [32], the total net biomass available for bioenergy production, including imports and excluding non-transport uses, is projected to be between 126 and 262 Mtoe in 2030 and between 101 and 252 Mtoe in 2050. This corresponds to the production of advanced and waste-based biofuels amounting to 46 to 97 Mtoe in 2030 and 71 to 176 Mtoe in 2050. The study adopts conservative assumptions, suggesting that the actual biomass potential might exceed these estimates and anticipates higher biomass potentials than currently estimated. Table 4 presents the aggregated biomass potentials of the reviewed sources.

Table 4. Summary of low and high estimates of biomass available for bioenergy and biofuels in million dry tonnes (MDT). MDT estimated by using the heating value of 2.5 MDT per Mtoe based on [32]

Source	2030 (Million dry tonnes)		2050 (Million dry tonnes)		Comments
	Low estimate	High estimate	Low estimate	High estimate	
Panoutsou & Maniatis [32]	520	860	539	915	Only for bio energy and sustainable forestry.
Hoefnagels & Germer [29]	515	1312	488	1492	Focuses only on lignocellulosic biomass. High supply scenarios, integrating additional forest sources and energy crop cultivation.
Concawe [30]	525	550	525	800	The high estimate in 2050 includes the use of algae, which is said to be uncertain due to high costs.

5.2 Matching Feedstocks with Technologies to Produce bio-methane

The production of bio-methane (and later bio-LNG) requires the appropriate matching of feedstocks with suitable technologies. The choice of feedstock significantly influences the efficiency and sustainability of the bio-methane production process. Each feedstock type has distinct characteristics (e.g., moisture content, composition) that affect the selection of the conversion technology.

The studies reviewed above ([29, 30, 32]), categorize biomass types, including cereal straw, maize stover, agricultural prunings, oil crop residues, manure, secondary agricultural residues, lignocellulosic crops, stem wood, primary forest residues, secondary forest residues (including post-consumer wood), biowastes, and municipal solid waste (MSW). For clarity, these biomass types are grouped into the following categories: agricultural residues, manure, biowaste, lignocellulosic crops, wood, forestry residues, secondary forestry residues, prunings, and municipal solid waste (MSW). The following sections explain the reasoning behind the selection of feedstocks for the two chosen technologies in this study for producing biomethane: anaerobic digestion and gasification.

5.2.1 Feedstocks suitable for anaerobic digestion

The first step in matching feedstocks with technologies is to properly understand them. This section begins with a description of the anaerobic digestion process, followed by the characteristics of the feedstocks shown in Table 5.

Historically, anaerobic digestion was used mainly to treat animal manure, sewage sludge, and waste with high water content [33].In the 1970s, increased environmental awareness and the search for renewable energy led to its application in treating industrial, agricultural, and municipal wastes [33]. Figure 9 illustrates the process of biomethane production via anaerobic digestion. Initially, wet biomass undergoes pre-treatment to remove large particles. The pre-treated biomass is then subjected to anaerobic digestion, where microorganisms decompose it in the absence of oxygen, producing biogas and digestate. The biogas, consisting mainly of methane and carbon dioxide, is cleaned to remove impurities such as hydrogen sulphide and water vapor. Subsequently, the biogas is upgraded to separate methane from carbon dioxide, yielding high-purity biomethane. Concurrently, the digestate is dewatered to extract water and solid material. The solid fraction undergoes composting, generating nutrient-rich compost and flue gas [34]. This process is carried out under wet conditions and biomass with large water contents will benefit from it [34].

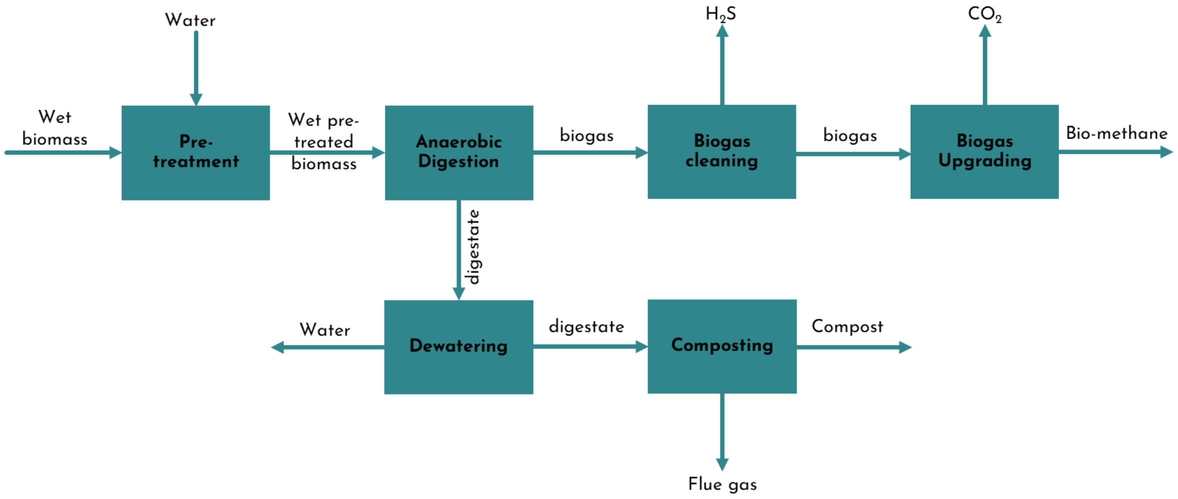

Figure 9. Simplified block diagram of biomethane production via Anaerobic Digestion. There is an additional CHP unit that is used to cover the process own heat and electricity demand.

When selecting materials for anaerobic digestion, it is crucial to evaluate factors such as total solids content, the proportion of volatile solids, the carbon-to-nitrogen ratio, biodegradability, and water content. Different biomass feedstocks have varying capacities to produce methane, depending on their inherent degradability and carbon-oxidation state [35]. Only the organic biodegradable fraction contributes to biogas production. Additionally, the distribution of organic macromolecules like proteins, fats, and carbohydrates in the feedstock significantly affects suitability, as their degradation produces volatile fatty acids (VFAs), which are essential substrates for bacteria in anaerobic digestion [36]. High fat content increases VFA production, while high protein content leads to elevated ammonia levels.

As an example, manure from intensive farming, excrement is typically collected as slurry, with dry matter contents ranging from 3% to 30%. Agricultural wastes and by-products can have dry matter contents ranging from less than 1% to over 20%. The biodegradable organic matter content generally ranges from 70% to over 95% of the dry matter content. Substrates with less than 60% organic matter are rarely considered suitable for anaerobic digestion.

The water content of slurries can fluctuate seasonally, affecting operational conditions. High water content increases digester volume and heat input requirements, while high total solids content can disrupt fluid dynamics and lead to process failure, requiring dilution with water. These issues can be mitigated by altering operational conditions, mixing feedstocks, and implementing appropriate pretreatment methods [33].

Water content in biomass plays a crucial role in determining the most appropriate conversion methods due to its impact on product and by-product yields. From a logistical perspective, biomass with higher water content increases weight and reduces the energy content available for storage and transportation [37]. Additionally, high water content can degrade biomass quality over time during logistics operations. Among the various types of biomass, such as agricultural residues, manure, and biowastes, which are widespread and pose logistical challenges for collection and conversion, anaerobic digestion emerges as a more suitable option for feedstocks with high water content compared to gasification processes, which necessitate dry biomass (further details provided in the upcoming section) [34].

In the case of lignocellulosic crops, water content typically ranges from 70% to 80%. This implies that significant water removal is necessary to utilize lignocellulosic crops for gasification, incurring a considerable energy penalty and costs (see section 5.2.2). Consequently, it was determined that lignocellulosic crops would also be utilized for biomethane production through Anaerobic Digestion (see Table 5).

Anaerobic digestion provides a practical solution for feedstocks with logistical challenges. In 2020, there were approximately 18,774 installations across Europe [38], making it a decentralised method for converting biomass into biomethane. Anaerobic digestion units typically have capacities between 350 Nm^3/h and 2000 Nm^3/h (see data in Chapter 6), which corresponds to approximately 2.0 MWth to 11.1 MWth of biomethane production after upgrading. These plants are relatively small and distributed across various regions, allowing local feedstock utilisation and reducing transportation costs. In contrast, gasification units are fewer in number and operate at significantly larger scales, typically ranging from 42 MWth to 300 MWth (please refer to chapter 6). This requires a more centralised approach to biomass processing due to the need for concentrated feedstock supply. Although anaerobic digestion plants are widely deployed across Europe, gasification technology is still emerging and requires further development and investment to achieve the same level of deployment.

5.2.2 Feedstocks suitable for gasification

Similar to anaerobic digestion, feedstocks are matched with the gasification pathway to produce biomethane. Figure 10 illustrates a simplified flow diagram outlining the process of producing biomethane via gasification. The gasification step converts dry biomass into syngas, an intermediate primarily composed of carbon monoxide (CO) and hydrogen (H2), with smaller fractions of methane (CH4) and carbon dioxide (CO_2). This conversion occurs through high-temperature reactions in the presence of a controlled amount of oxygen or steam, facilitating partial oxidation of the biomass. This resulting gas can then be utilized as either a fuel, such as biomethane, or as raw material for chemical processes [39]. Subsequently, the syngas undergoes cleaning to remove impurities, ensuring compliance with necessary quality standards for downstream processing.

The clean syngas is then subjected to methanation, a process facilitated by nickel-based catalysts crucial for achieving high conversion efficiencies and producing high-purity biomethane [40]. Any off-gases, tar, char, or excess syngas are combusted (some fractions can be used in other applications such as biochar), aiding in by-product management and energy recovery. This combustion process generates flue gas primarily consisting of CO_2, water vapor, and trace amounts of other gases [34].

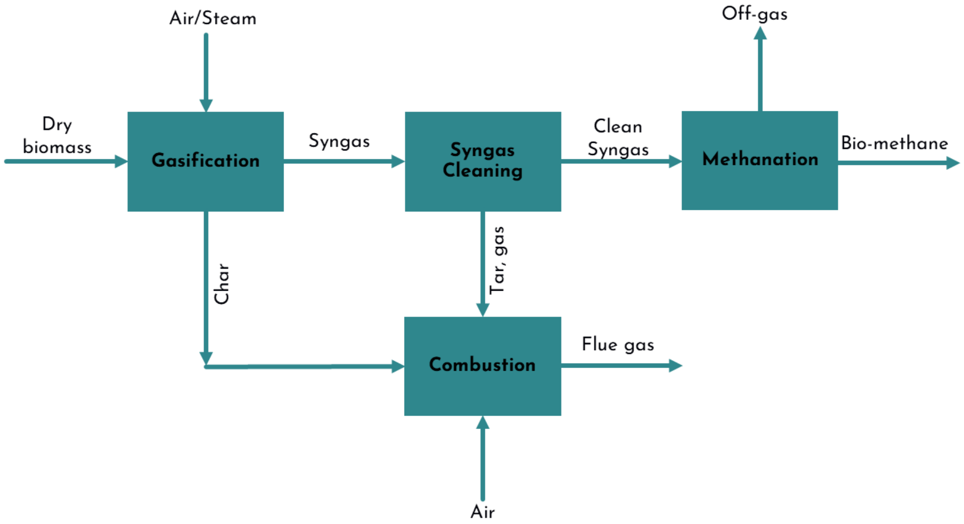

Figure 10. Simplified block diagram of biomethane production via Gasification. The off-gas are residual gases (including small traces of methane) after the gas cleaning step, including oxygen and nitrogen.

Table 5 displays a significant range of woody biomass considered in this study. Generally, woody biomass shows to be more suitable for gasification than for anaerobic digestion for biomethane production, owing to various key factors associated with the physical and chemical properties of the material and the involved processes. A crucial factor is the high lignin content inherent in woody biomass, rendering it highly resistant to biological degradation, thereby impeding effective breakdown in anaerobic digestion processes [41, 42]. The intricate and rigid structure of wood hampers accessibility to the enzymes and microbes utilized in anaerobic digestion, resulting in diminished biomethane yields [41]. Additionally, gasification processes exhibit less sensitivity to the type of biomass feedstock and can manage a broad spectrum of biomass materials, including those with high lignin content such as wood [41, 42]. Conversely, anaerobic digestion is more suited to less recalcitrant organic materials and generally performs better with agricultural residues or food waste rather than woody biomass [41].

The water content plays a crucial role in gasification processes. Water in biomass diminishes its energy output and, during gasification, exacerbates challenges by elevating tar production, resulting in the formation of wet wood gas [43]. In principle, feedstocks with a moisture content ranging from 5% to 30% are suitable for gasification. Typically, woody biomass carries a moisture content of approximately 50% when harvested, necessitating drying to achieve levels of around 10% to 15% [39]. Similar to feedstocks for anaerobic digestion, managing water content in woody biomass presents logistical challenges. However, it's noteworthy that the forestry industry in Europe, responsible for managing the majority of woody biomass, is well-established [40]. Hence, proper treatment and management of woody materials for the bioeconomy enable large-scale processing, offering a more centralized production compared to anaerobic digestion. Consequently, woody biomass types (refer to Table 5) were selected for use as raw materials in biomethane production via gasification.

Table 5. Biomass classification used in the assessment of bio-LNG supply chains.

Feedstock	Description	Technology Matching
Agricultural Residues	Residues from crop production processes include straw, stalks, and husks. These encompass cereal straw, maize stover, oil crop residues, and secondary agricultural residues.	Anaerobic digestion
Manure	Animal waste, typically from livestock farming.	
Biowaste	Organic waste from domestic or industrial sources includes food scraps and yard trimmings.	
Lignocellulosic Crops	Energy crops rich in cellulose and lignin, such as switchgrass and miscanthus.	
Wood	Woody biomass from trees, branches, and wood processing residues.	Gasification
Forestry Residues	Residues from forestry operations, including tops, branches, and bark.	
Secondary Forestry Residues	Additional residues generated from forestry activities, often consisting of small branches and twigs.	
Prunings	Trimmings from trees and shrubs in agriculture and horticulture.	
Municipal Solid Waste	Mixed waste from households and businesses, including organic, paper, plastic, and other materials.	

For municipal solid waste (MSW), both anaerobic digestion (AD) and gasification are viable conversion technologies. However, gasification was chosen for this feedstock for several reasons. While anaerobic digestion is efficient for organic waste, it is best suited for homogeneous, biodegradable waste streams. In contrast, gasification is more versatile for mixed MSW due to its robust processing capabilities and lower pretreatment requirements [42, 44]. MSW's heterogeneous composition includes a mix of organic, inorganic, and non-biodegradable materials. Gasification can handle this diverse feedstock by converting all carbon-based materials into syngas [44]. From a logistical perspective, MSW is often centrally located, making it easier to handle for large-scale gasification technologies compared to anaerobic digestion (See Chapter 6 for the differences in processing capacities between anaerobic digestion and gasification technologies for biomethane production). Table 5 presents the biomass classification used in this study to assess the bio-LNG supply to the Port of Rotterdam.

5.3 Biomass potential for the assessment of bio-LNG supply chains

One of the key objectives of the literature review on biomass potential in the EU and the UK for 2030 and 2050 was to derive proper input data for assessing the bio-LNG supply chain. A crucial aspect of this evaluation is the completeness and clarity of the data sources used [29, 30, 32]. The sources for estimation were clear, as were the assumptions behind the biomass potential assessments. The studies presented a wide range of biomass potential for bioenergy, as shown in Table 4.

Based on these ranges, the estimation at the midpoint was selected, avoiding the extremes. This study uses biomass availability data for 2030 and 2050 from the study of Panoutsou & Maniatis [32]. The data presented in this study allows for a breakdown into different categories of feedstock types, which enabled grouping these estimations into the categories shown previously in Table 5.

This approach ensures that the input data from Panoutsou & Maniatis [32] aligns with the categorization and conversion of biomass sources into biomethane used in this study. The figures below show the aggregation of biomass available in different countries for 2030 (see Figure 11) and 2050 (see Figure 12). This aggregation accounts for the biomass types shown in Table 5 and is broken down by country and type by volume.

This breakdown allows us to identify which countries have the highest potential for bio-LNG and the preferred technology or ratio of technologies for bio-LNG production. For instance, in 2030, the countries with the highest biomass potential are France, followed by Germany, Spain, Poland, Sweden, and the UK. The remaining countries have significant amounts of biomass but not to the same extent. Some countries, like Malta and Cyprus, have very low potential. The trends remain similar for 2050, with France as the dominant country, followed by Germany, Spain, Poland, Sweden, and the UK. Detailed data on the different feedstock types and their volumes can be found in Annex B.

It is important to note that linking the biomass potential mentioned earlier to bio-LNG production remains challenging due to the limited availability of detailed and publicly accessible data. Many countries do not report bio-LNG production separately from other bioenergy products such as biogas or biomethane. Furthermore, information on feedstock use is often scattered across different sectors, making it difficult to achieve a clear and comprehensive understanding.

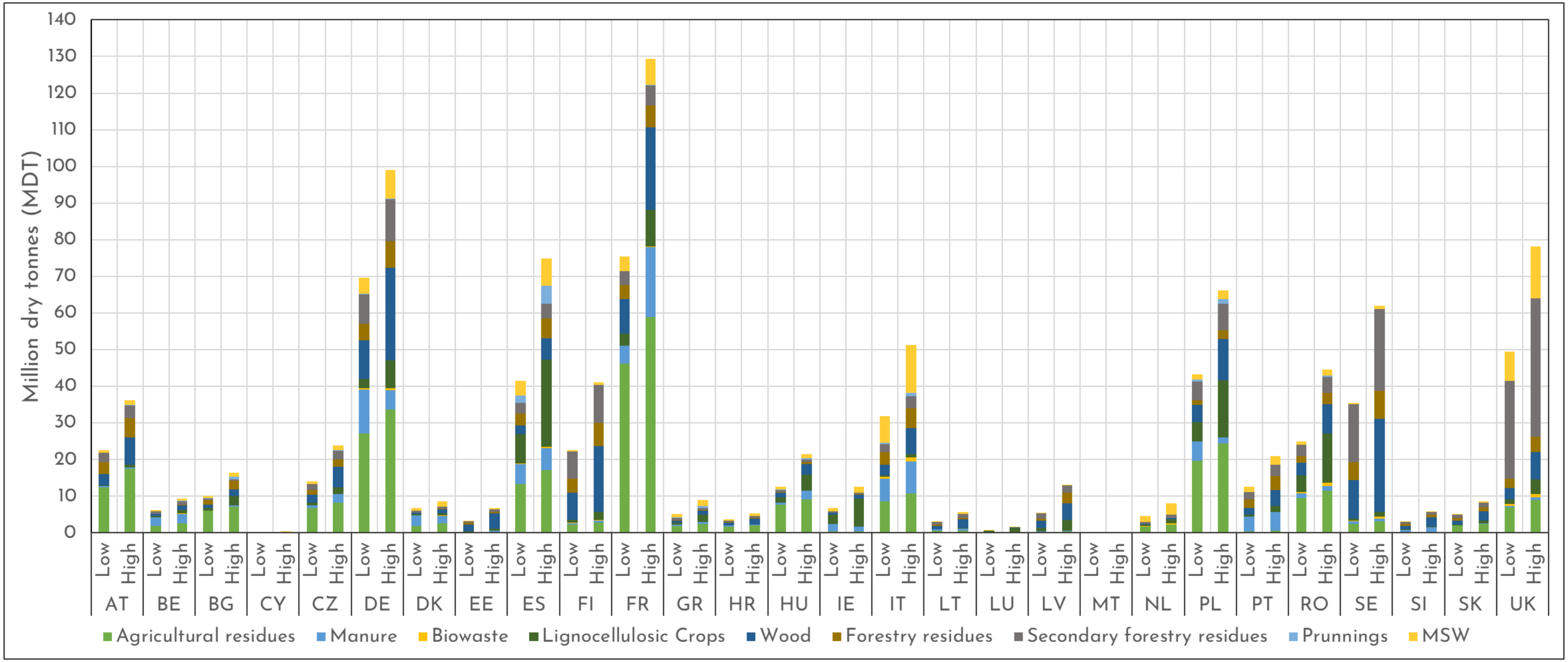

Figure 11. Projections of biomass potential for bioenergy in EU27 and the UK in 2030. Adapted from [32].

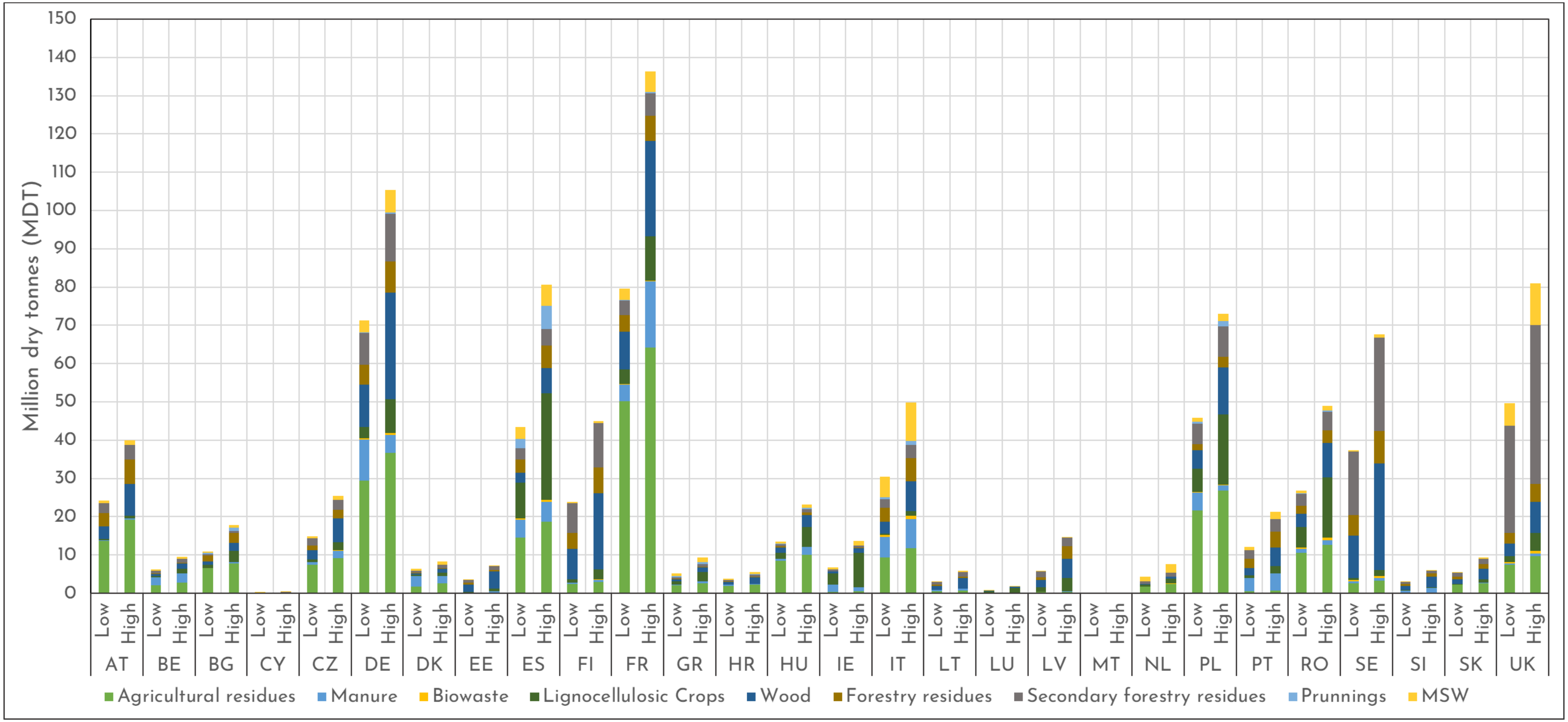

Figure 12. Projections of biomass potential for bioenergy in EU27 and the UK in 2050. Adapted from [32].

6. Modelling the bio-LNG supply chain

The report up to this point has provided an overview of the bio-LNG value chain. Chapter 2 describes potential pathways for producing biomethane/LNG and transporting it to the port of Rotterdam. Chapter 3 examines the potential demand for bio-LNG in the port of Rotterdam for the years 2030, 2040, and 2050. Chapter 4 focuses on the infrastructure and adaptation needs of the bio-LNG value chain to deliver biomethane to the port of Rotterdam. Chapter 5 discusses the potential biomass in EU27 countries plus the UK for the years 2030 and 2050. That chapter also matches technologies with feedstocks to produce bio-LNG, connecting to the pathways described in Chapter 2.

The report follows a systematic approach to the bio-LNG value chain, emphasizing the use of existing LNG infrastructure in Europe. It suggests that the most relevant configuration involves biomethane production facilities injecting biomethane into the European pipeline network and liquefying it at current LNG terminals (considering necessary adaptations). The transport from various LNG terminals to the port of Rotterdam is therefore done via LNG carriers. This study assumes biomethane is liquefied at existing LNG terminals in the country of origin, leveraging established liquefaction and loading infrastructure. Transport to Rotterdam is then conducted via LNG carriers. While pipeline transport to Rotterdam followed by local liquefaction would be possible, it would require new large-scale liquefaction capacity at the port, which is not currently in place. Figure 13 shows the selected value chain configuration to assess the bio-LNG potential for bunkering in the port of Rotterdam.

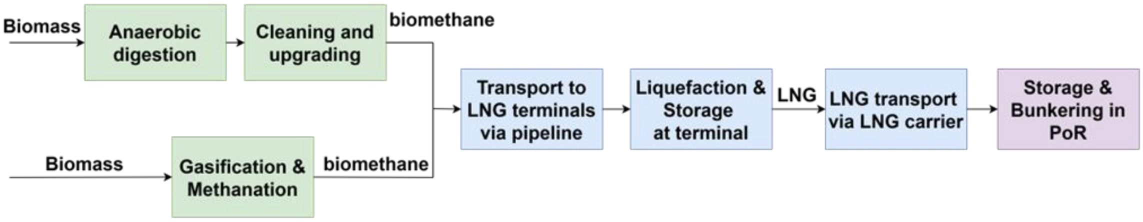

Figure 13. value chain configuration used to assess the bio-LNG potential for bunkering in the port of Rotterdam.

To evaluate the potential of bio-LNG as bunkering fuel , a supply chain model was developed. The objective of this model is to offer insights into the challenges and opportunities of bio-LNG supply to a port from biomethane/LNG produced in the EU27 and the UK. Furthermore, the model identifies bottlenecks and hotspots related to cost and efficiency in different supply chain stages. It enables a detailed analysis of the impacts of potential improvements in the bio-LNG supply chain.

It was decided to use the Port of Rotterdam as a case study to apply the model. The structure followed in this deliverable as well as the bio-LNG supply chain model help in addressing the following questions (see Table 6):

Table 6. Research questions for the assessment of the bio-LNG supply chain for smart ports adapted to the case of the Port of Rotterdam

Sector	**Questions**
Bio-LNG Demand	What is the projected demand for bio-LNG in the Port of Rotterdam in 2030 and 2050?
Bio-LNG Infrastructure	What infrastructure and adaptations are required to supply bio-LNG to the Port of Rotterdam from EU27 countries and the UK?
Biomass and Bio-LNG supply potentials	How much biomass is needed from EU27 countries and the UK to meet the projected demand for bio-LNG in the Port of Rotterdam for 2030 and 2050?
Impacts of Bio-LNG supply	What are the efficiencies and costs associated with supplying bio-LNG to the Port of Rotterdam in 2030 and 2050? What are the main hotspots, bottlenecks, and trade-offs in the bio-LNG supply to the Port of Rotterdam?

6.1 Model Description

The bio-LNG supply chain model is structured in different steps (seeFigure 14) that describe the stages considered in the value chain configuration (see Figure 13). At each step, calculations of energy efficiency and cost are performed. Each step of the model includes gathering relevant inputs describing the stages of the value chain. A feedback loop is incorporated, as refinement of data is often required to estimate energy efficiencies and costs accurately. One of the final steps of the model involves aggregating the results of energy efficiency calculations and costs into the supply volume of LNG in the port of Rotterdam, the system cost, and the overall efficiency of the supply chain. This information is used to derive results and analyse them to draw conclusions.

It is important that in terms of costs, the data represents the year 2022. Cost data for 2030 and 2050 is difficult to predict. Estimations for 2030 and 2050 are based on projections of biomass potentials and LNG demand. The outputs of the model describe, however, potential changes in costs for 2030 and 2050 compared to 2022 costs.

The following sub-sections presents a detailed description of the model, including assumptions and data used.

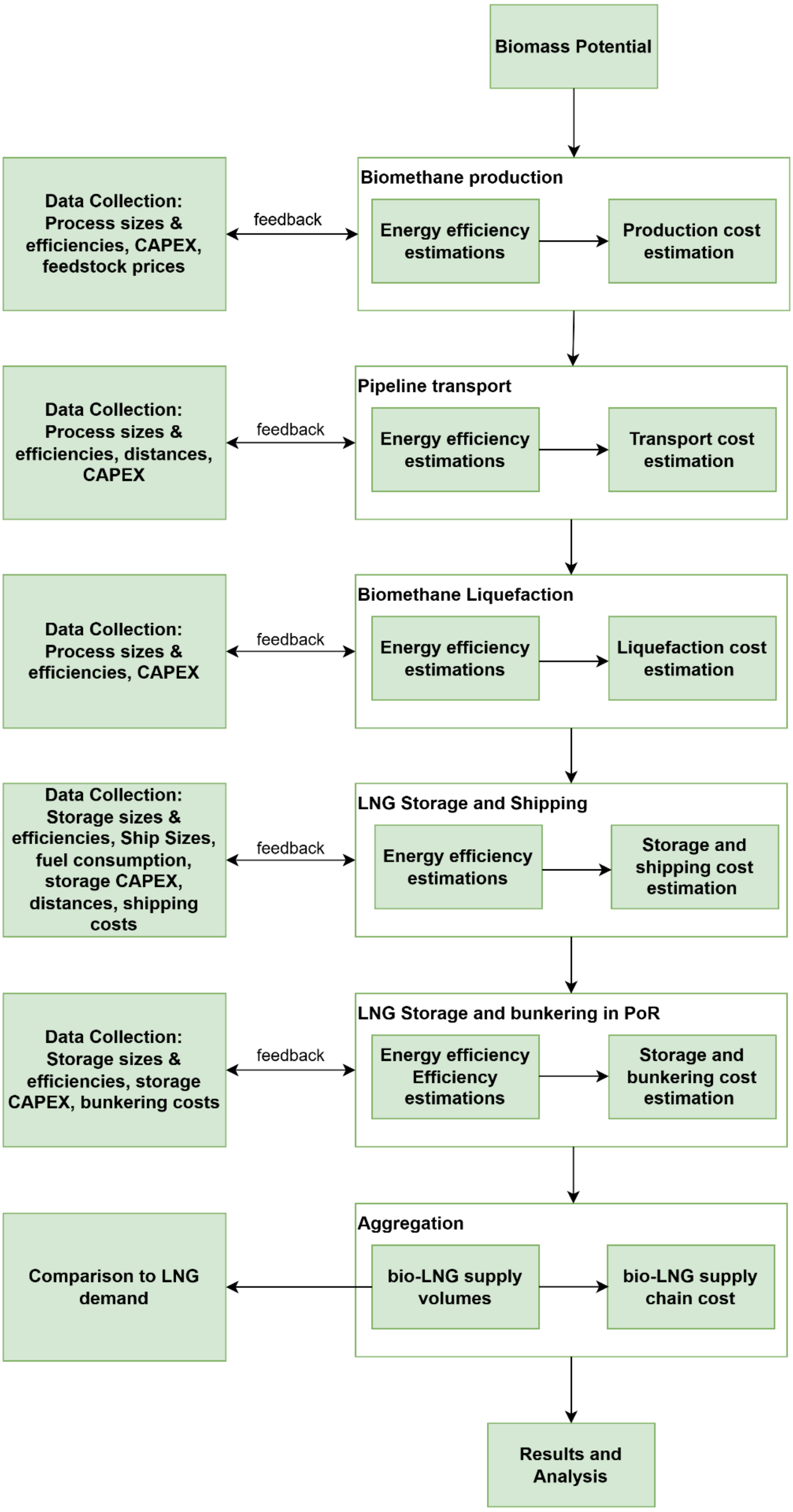

Figure 14. Structure of the bio-LNG supply chain model

6.1.1 Biomass Potential

The first step involves providing the biomass availability, divided by the types of feedstocks mentioned in Table 5, for the two technologies (anaerobic digestion and gasification) and for the years 2030 and 2050 (for details, see Chapter 5). This data includes all EU 27 countries plus the UK. This step is the starting point for determining the biomethane production potential in each country by feedstock type and technology type.

6.1.2 Biomethane production

Biomass utilization rate

In this model, a potential utilization rate of feedstocks for LNG production in different countries was assumed, considering competing uses for biomass (see Table 7). The rate indicated that a certain percentage (assumed 25%) of biomass would be used for LNG, with the remaining biomass allocated for other applications. This assumption is subjected to sensitivity analysis. This step also involved matching the feedstocks with the appropriate technology types, determining which feedstocks are suitable for anaerobic digestion and which for gasification, as mentioned in Chapter 5 (see Table 5). The feedstocks for anaerobic digestion include agricultural residues, manure, biowaste, and lignocellulosic crops. The feedstocks for gasification include wood, forestry residues, secondary forestry residues, prunings, and municipal solid waste. All biogas produced is assumed to be upgraded to biomethane before liquefaction, which means that no separate percentage is assigned to direct biogas use.

Table 7. Utilization rate per feedstock type for biomethane production. This rate is applied identical for all countries and for 2030 and 2050. Sensitivity analysis is carried out.

Anaerobic digestion				**Gasification**				
Agricultural residues	Manure	Biowaste	Lignocellulosic Crops	Wood	Forestry residues	Secondary forestry residues	Prunings	MSW
25%	25%	25%	25%	25%	25%	25%	25%	25%

Biomethane potential

The next step involved estimating the potential biomethane production per country. This required collecting data on the conversion of various feedstocks into biomethane using two types of technologies: anaerobic digestion and gasification. It is important to note that each feedstock type yields different amounts of biomethane. For instance, agricultural residues used in anaerobic digestion produce different yields compared to lignocellulosic crops. The yield of biogas, measured in cubic meters per ton of dry matter, depends on the characteristics of the feedstocks, including their volatile matter and carbon content (see Table 8).

Table 8. Biogas yields per feedstock type used in the model for anaerobic digestion. The yields are averages gathered from Lam et al., [1].

Biomass Type	**Biogas production yield - Nm³ biogas/tons dry biomass**
Manure	260
Biowaste	350
Lignocellulosic Crops	570
Agricultural residues	260

In anaerobic digestion, biogas contains CO_2, necessitating the use of upgrading technology to produce high-purity methane. Various upgrading technologies, such as high-pressure water scrubbing, chemical scrubbing, PSA, and membrane permeation, have different yields in biomethane production. Therefore, an average value of the upgrading technologies for each feedstock type was assumed to account for the CO_2 removal from the biogas stream. Table 9 shows the conversion yields of biomass into methane including both the anaerobic digestion and upgrading of biogas into biomethane. The weighted average values were used in the model.

Table 9. Biomethane production yields per feedstock type including anaerobic digestion and upgrading. Weighted average values used for the modelling and assumed identical in 2030 and 2050.

Upgrading Technology	Biomethane production yield – TJ/ktonne dry biomass			
	Agricultural residues	Manure	Biowaste	Lignocellulosic Crops
HPWS - Water Scrubbing	5.22	5.22	7.23	12.13
CHS - Chemical Scrubbing	4.79	4.79	6.65	11.2
PSA - Pressure Swing adsorption	5.27	5.27	7.3	12.25
MP - Membrane permeation	5.26	5.26	7.28	12.22
Weighted Average [a]	**5.11**	**5.11**	**7.08**	**11.89**

[a] The weighted average was estimated considering a distribution of upgrading plants as 39% for HPWS, 30% for CHS, 14% for PSA and 17% for MP. The distribution of upgrading plants was assumed identical for all countries in Europe. The distribution was estimated based on the data from [45].

For gasification, it is assumed that the energy efficiency of the system is equal for all feedstocks with a 63% energy efficiency (except from MSW assumed of 50%). This assumption is made after reviewing different gasification technologies and seeing relatively low uncertainties in the outputs of methane in comparison to the feedstocks types [46, 47]. Moreover, his assumption means that 0.63 terajoules of methane are produced per terajoule of biomass input into the gasification system (except for MSW assumed as 0.5 TJ biomethane/TJ dry biomass). There is about 16.8 TJ per ktonne of dry biomass.

Table 10. Biomethane conversion yields per feedstock types for gasification technologies. Yields assumed identical for 2030 and 2050.

Biomethane production yield	Feedstock type				
	Wood	Forestry residues	Secondary forestry residues	Prunings	MSW
TJ/TJ dry biomass	0.63	0.63	0.63	0.63	0.50
TJ/kt dry biomass	10.55	10.55	10.55	10.55	8.44

Using the information on the conversion yields for the two technologies and feedstocks, the potential biomethane production in different countries was estimated for 2030 and 2050. The estimates also consider the biomass utilization rate (see Table 7), accounting for potential competing uses of biomass. This utilization rate significantly impacts the amount of biomethane available for export to the Netherlands, and sensitivity analysis was conducted to address its impact on the overall model.

Biomethane production cost estimation

After estimating the biomethane potential, the next step was to determine the number of installations required per feedstock type and technology type to meet this potential production. A distribution of sizes was considered for both anaerobic digestion and gasification units. Specifically, for anaerobic digestion, units with capacities of 300, 500, 1000, and 2000 Nm^3 biogas/h, which roughly equals to 2.0, 2.9, 5.7 and 11.1 MWth biomethane after upgrading, were considered as typical anaerobic digestion unit sizes [48].

For all anaerobic digestion cases the composition of biogas was assumed as 64% CH_4 and 36% CO_2 by volume, which is the typical biogas composition [1]. For gasification, the distribution of units with capacities of 42, 84, 200, and 300 MWth, range of capacities from first of a kind to large scale [46, 47]. For both cases the distribution of sizes impacts economies of scale, for which it is assumed that an initial distribution of 20%, 20%, 30% and 30% was chosen initially. However, this can lead to situations in which there are large plants built but not sufficient biomass available to cover the plant needs, and thus large costs. To overcome this issue, a distribution of plant sizes was estimated in each country starting from the initial distribution shown above, but checking what is the capacity factor. In this case, the criteria of a capacity factor above 95% was used.

Anaerobic digestion (AD) units are smaller and more decentralized, handling dispersed biomass sources such as agricultural residues and manure, with typical capacities ranging from 350 to 2000 Nm^3/h (2.0 MWth to 11.1 MWth). In contrast, gasification units, with capacities of 42 MWth to 300 MWth, require higher biomass concentrations, making them more centralized and dependent on robust supply chains for feedstock such as woody residues and municipal solid waste. While gasification benefits from economies of scale, it faces challenges in securing sufficient feedstock, whereas AD offers flexibility in siting and feedstock procurement.

Using conversion yield data from Table 9 and Table 10, along with the biomethane potential for each country, the number of required installations per unit size and technology type for different countries was determined. In the case of bio-methane obtained via anaerobic digestion, a plant unit is composed of the following sections: anaerobic digestion, composting, upgrading, and combined heat and power (CHP). The CHP unit is included because it provides the heat and electricity required to cover the internal energy demand of the anaerobic digestion process. The cost data used to estimate the capital expenditure (CAPEX) of the required units for biomethane production via anaerobic digestion is presented in Table 11. The cost data for estimating the CAPEX of the required units for biomethane production via gasification is presented in Table 12.

Table 11. Cost data used to estimate capital investment of anaerobic digestion units (including upgrading). Data gathered from [27, 43, 48] and updated to 2022 using the chemical engineering plant cost index (CEPCI$_{2022}$=816).

System size		**CAPEX**					
		AD	**Composting**	**Upgrading**	**CHP**	**Total**	
Nm^3/h	MWth	k€/(Nm^3/h)	k€/(Nm^3/h)	k€/(Nm^3/h)	k€/(Nm^3/h)	k€/(Nm^3/h)	k€/MWth
350	2.0	2.71	0.27	4.52	2.19	9.69	1,744
500	2.8	2.44	0.24	3.73	2.04	8.44	1,519
1000	5.6	2.03	0.20	2.64	1.77	6.65	1,197
2000	11.1	1.62	0.16	1.87	1.54	5.20	936

Table 12. Cost data used to estimate capital investment of gasification units. Data gathered from [46, 47] and updated to 2022 using the chemical engineering plant cost index (CEPCI$_{2022}$=816).

System size	CAPEX
MWth	k€/MWth
42	3,414
84	2,805
200	1,983
300	1,642

After estimating the number of units per country and technology type, the CAPEX for each unit size and technology type was calculated. This information was used to estimate the installation cost per country and the unit distribution necessary to produce the estimated biomethane potential. The CAPEX data enabled the estimation of Operation and Maintenance (O&M) costs, assumed to be 5% of the CAPEX (typical for chemical processes). Additionally, the amount of biomass required for biogas production provided the basis for estimating feedstock cost contributions. Various data (see Table 13) on feedstock costs for producing biomethane in each country were used, assuming equal cost distribution across Europe, due to the lack of detailed country-specific data. While this is a rough estimation, actual feedstock costs may vary between countries. Feedstock costs are important contributors to costs of biomethane as well, therefore sensitivity analysis is carried out on the assumed feedstock prices.

Table 13. feedstock prices used in the model. The average values were the values used. Price data derived from [1, 46, 49-51]. Cost can vary depending on collection and logistics. The numbers used in this study are generic values found in literature.

Feedstock type	Low- €/tonne	High- €/tonne	Average- €/tonne
Agricultural residues	40	75	58
Manure	0	30	15
Biowaste [a]	0	30	15
Lignocellulosic crops	60	125	93
Wood	100	130	115
Forestry Residues	30	100	65
Secondary Forestry Residues [b]	30	100	65
Agricultural residues	40	75	58
Municipal solid waste	0	30	15

[a] Assumed to be similar to manure prices

[b] Assumed to be similar to primary forestry residues prices

Using the CAPEX, O&M costs, and feedstock costs (OPEX), the cost of biomethane production at the plant gate was estimated (defined as the sum of O&M cost, feedstock costs and annualized CAPEX). Energy costs were not included, as it was assumed that the systems would use the same gas to cover their energy requirements. A lifetime of 20 years and a discount rate of 10% were considered to annualized the CAPEX using Equation 1 (Equation applied for all estimations of annualized CAPEX across the supply chain) [52]. The result was an estimation of the required annual investment in million euros to produce the desired amount of biomethane per country, and the levelized costs of methane at the plant gate. Methane losses were also estimated to assess the energy efficiency of the systems, accounting for losses during conversion and internal energy use.

$$Annualized\ CAPEX\ \left(\frac{€}{year}\right) = CAPEX\ (€) \cdot \frac{i}{1 - \frac{1}{(1+i)^t}}$$

Equation 1. Annualized CAPEX, with plant lifetime (t) and discount rate (i)

6.1.3 Pipeline transport

After estimating the cost of biomethane production, the transport of biomethane was analysed. It is important to consider the current infrastructure of natural gas pipelines in Europe, which is a well-interconnected network transporting natural gas between different regions. Several export and import terminals, mostly LNG regasification terminals, can be converted into LNG export terminals, as discussed in section 4.2. Thus, it was assumed that current locations of natural gas terminals in Europe can also be used for the purpose of storing and exporting LNG.

The best option to transport biomethane from production facilities to end users or export terminals is via pipeline (giving the vast infrastructure in place). The amount of biomethane to be transported per country to LNG terminals was estimated in the previous step, while the approximate distance was roughly calculated using natural gas infrastructure maps [24]. For internal transport within each country, an average distance was considered as shown in Table 14. To estimate the costs and biomethane losses due to energy consumption in the transport process, it was assumed that gas would be transported 50% in 24-inch pipelines and 50% in 36-inch pipelines at a 70 bar pressure(based on descriptions from current natural gas network in Europe [24]), with a pressure drop of 5 bar per 100 kilometres [53]. In the model the pipeline network is assumed to be newly installed. Newly installed pipeline costs were used because consistent cost data for using the existing gas network are not available, so depreciation of new capacity provides a transparent and comparable cost basis across countries.

Table 14. National and cross border distance of biomethane transport via pipeline. The National transport distance is the average (assumed) distance per country to mobilize biomethane to the export terminal. Countries with cross border pipeline transport correspond to those where there are non-export terminals, except for Belgium, Germany, and the UK (a fraction of biomethane assumed to be transported via pipeline to Rotterdam).

Country	Country Abbreviation	National pipeline transport distance - km	Cross border pipeline transport distance - km
Austria	AT	400	100
Belgium	BE	200	200
Bulgaria	BG	300	50
Cyprus	CY	150	-
Czech Republic	CZ	250	500
Germany	DE	500	200
Denmark	DK	250	50
Estonia	EE	150	-
Spain	ES	500	-
Finland	FI	700	-
France	FR	500	-
Greece	GR	400	-
Croatia	HR	300	-
Hungary	HU	300	300
Ireland	IE	150	-
Italy	IT	500	-
Lithuania	LT	200	-
Luxemburg	LU	100	250
Latvia	LV	200	-
Malta	MT	40	-
Netherlands	NL	100	-
Poland	PL	300	-
Portugal	PT	250	-
Romania	RO	350	450
Sweden	SE	600	700
Slovenia	SI	200	-
Slovakia	SK	250	900
United Kingdom	UK	500	200

Transporting biomethane requires an initial compression stage to pressurize the gas (to 70 bar). The number of recompression stages needed (to account for the pressure drop) and the power required for initial and recompression stages were estimated using Equation 2. This information enabled the estimation of the energy efficiency of pipeline transport and the delivered amount of LNG to export terminals or country borders in cases of countries without export terminals (*e.g.,* Austria).

$$P_{comp} = m \cdot \dot{C_p} \cdot T_1 \cdot \left[\left(\frac{P_2}{P_1} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right] \cdot \frac{1}{\eta}$$

Where:

- Pcomp: Power of the compressor (MW).
- m˙: Mass flow rate of the gas (kg/s).
- Cp : Specific heat capacity at constant pressure (2.21 J/kg.K).
- T1: Initial temperature of the gas (15 °C).
- P1 and P2: Initial and final pressures, respectively (final pressure 70 bar, initial pressure for 1st compression stage 1 bar, initial pressure for recompression stages 65 bar).
- γ: Heat capacity ratio (Cp/Cv = 1.4 for methane).
- η: Efficiency of the compressor (0.75).

Equation 2. Estimation of Power Requirements in compression and recompression units. This equation is derived based on the first law of thermodynamics for a steady-flow process and the isentropic relations for a gas [53].

The investment needed for pipelines of 24 and 36 inches was calculated using the information shown in Table 15. The CAPEX of compression and recompression units was assumed as 2 M€/MW [53]. Similar to biomethane production, 5% of the capital investment was considered for operation and maintenance (O&M). The annualized CAPEX was estimated with a 40-year lifetime and a 10% discount rate using Equation 1. Cost of transport is then composed by the annualized CAPEX and O&M.

Table 15. CAPEX data of pipelines for biomethane transport [53].

Pipeline size	Cost	Unit
24 inch	120,000	€/km/bcm/y
36 inch	80,000	€/km/bcm/y

The amount of biomethane per country and per technology delivered to export terminals or to country border (in case there is no export terminal) was estimated. The next step was to consider the amount of biomethane to be exported by each country, assuming around 40% of the biomethane can be exported to the Netherlands from each producing country. This was done to account for potential own consumption in each country, and thus only the biomethane surplus is available for exports. A sensitivity analysis was conducted to understand the impact on the supply potential of biomethane to the Port of Rotterdam.

For countries without specific export terminals, extra pipeline transport was considered. For example, biomethane produced in Austria requires approximately 400 kilometres of national pipeline and an additional 100 kilometres of international pipeline to transport to the nearest export terminal in Italy. Similar assumptions were made for the other countries without export terminals like the Czech Republic (transport to Germany). The cross border required kilometres for pipeline transport can be found in Table 14.

Countries like Germany, Belgium, and the UK have direct pipeline connections to the Port of Rotterdam, allowing transport via pipeline or LNG shipping. It was assumed that 30% of the methane can be transported via pipeline, with the remainder transported by LNG carrier. With these additional pipeline kilometres, the required compression and recompression units and the associated costs for cross-border pipeline use were estimated.

This analysis included estimating the additional losses and costs for cross-border pipeline transport. The list of export terminals assumed in this study are shown in Table 3.

6.1.4 Biomethane Liquefaction

For this study, biomethane liquefaction was assumed to happen at the export terminals, due to the already existing pipeline infrastructure. This enabled the estimation of the amount of LNG produced in each terminal, the associated biomethane losses, and the related costs. The efficiency of methane liquefaction was 0.9 megajoules of energy output per megajoule of methane input (estimated based on the specific energy consumption described in [54]). This implies that 10% of the biomethane input to the liquefaction process is used for self-consumption.

Liquefaction costs were composed by annualized CAPEX and O&M, which were determined using the information provided in Table 16.

Table 16. Cost data and assumptions to estimate biomethane liquefaction costs [54].

Parameter	Value	Unit
CAPEX	20,000	€/TJ/y
Lifetime	20	years
Discount rate	10%	%
O&M	5% of CAPEX	%

6.1.5 LNG Storage and Shipping

Using information on LNG terminals' locations (see Table 3), the distances required to transport LNG to the port of Rotterdam via maritime shipping using LNG carriers were estimated using the Sea Routes app [55]. Each export terminal has different capacities for LNG production, necessitating an analysis of potential shipping sizes and the storage required at the export terminals.

To select the most suitable vessel size for transporting LNG to the Port of Rotterdam, criteria were developed. First, the travel time needed from the export terminal to the Port of Rotterdam was analysed. The travel time was estimated using the distance to be travelled, the speed of the vessel, and the time for loading and unloading. The vessel speed was assumed to be 20 knots (37 km/h), with a loading and unloading time of 24 hours each. With the travel time per round trip (assuming the vessel is loaded one way and empty on the return trip), the maximum number of round trips per year was estimated for a single ship covering the route. For all vessel sizes (see Table 17), a specific fuel consumption of 0.18 kg of fuel per kWh was used for loaded vessels, and 0.178 kg of fuel per kWh for empty vessels using (bio) LNG as fuel and constant power operation [56, 57]. To apply the specific fuel consumption data consistently across vessel sizes, it was assumed that the engines operate at constant power during the voyage.

The sizes of LNG carriers and their respective engine sizes are presented in Table 17. It shows that smaller LNG carriers have a higher specific power-to-size ratio compared to larger carriers. This is primarily due to the inefficiencies in hull resistance, propulsion systems, and boil-off gas management[58, 59]. The Energy Efficiency Design Index (EEDI) reinforces the trend that larger ships are generally more efficient on a per-unit basis [58, 60].

Table 17. Sizes of LNG carries, engine sizes and power to size ratio.

Carrier Size - m^3	Engine size - MW	Power to size ratio [a] - kW/m^3
2,500	3	1.20
5,000	5	0.92
10,000	7	0.71
20,000	11	0.54
40,000	16	0.41
125,000	32	0.26
150,000	37	0.24
175,000	40	0.23
210,000	45	0.21
250,000	51	0.20
266,000	53	0.20

[a] power to size ratio can be described as $\frac{kW}{m^3} = 25.133 \cdot (carrier\ size - m^3)^{-0.388}$. Equation derived from correlating data on engine sizes of LNG carriers at different vessel sizes and propulsion systems [53, 58, 59, 61-63]

Using different vessel sizes, ranging from 2,500 to 266,000 m³, and considering the amount of LNG to be transported to the Netherlands, the number of round trips required per vessel size was estimated. Given the large number of size options (see Table 17), two potential problems were identified: a vessel being too small to handle the required amounts (necessitating more vessels, which was discarded as an option) or a vessel being too large, requiring excessive time and storage at the export terminal to fulfil its capacity.

The following approach was used to select the most suitable vessel size. If the estimated number of round trips for a vessel size exceeded the maximum number of round trips per year (calculated using the vessel speed, distance, and loading and unloading time), that ship size was discarded. For ships with an estimated number of round trips equal to or lower than the maximum, the utilization rate per year was used as the selection criterion. The utilization rate is defined as the ratio of LNG to be transported over the number of round trips times the vessel size. This ensures that the selected vessel makes the best use of its capacity to transport LNG to the Port of Rotterdam on a yearly basis. In this study one vessel per route was assumed, and the vessel size was selected based on its ability to cover the yearly LNG volume within the maximum number of allowable round trips. In this study, the storage in an LNG terminal is equal to the size of the carrier, which represents the safety storage amount of energy required to guarantee transport to Rotterdam.

CAPEX for LNG storage was assumed to be 800 €/m³ for a 160,000 m³ tank capacity, based on data from Thunder Said Energy [55]. Economies of scale for LNG storage tanks were considered, using a scaling factor of 0.5 (Conservative assumption given the high scalability of LNG storage tanks [64, 65]). The cost of storage was then based on the annualized CAPEX and O&M (assumed as 5% of CAPEX). Transport costs were estimated using charter rates and port fees, which are typical charges (generally in €/day) for vessel transport. These rates depend on vessel sizes and were scaled using a 0.8 scaling factor, based on a typical charter rate for a 150,000 m³ carrier of 100,000 €/day and port fees of 90,000 €/day [53, 66]. It is important to note that these fees can vary by port and carrier, but the scaled approach was followed due to a lack of detailed information. Additionally, storage and transport losses of LNG were estimated (considering boil-off loses (0.1% per day [53]) and energy use for doing both operations).

6.1.6 LNG Storage and Bunkering in the Port of Rotterdam

Given that the model assumes the available LNG is to be exported into Port of Rotterdam, it is important to consider the costs of managing the LNG and the costs associated with its bunkering for fuel applications, especially in the maritime sector.

For these aspects, two primary considerations are necessary: the storage of LNG in the port and the bunkering process. First, the required storage capacity was estimated based on the flows from previous steps and an assumed storage autonomy of two months (autonomy time can vary across years and/or seasons). The CAPEX of LNG storage in the Port of Rotterdam was estimated using the same figures presented in the previous section. The cost for storage includes the annualized CAPEX and O&M costs (assumed 5% of the capital investment).

The final stage of the value chain at the Port of Rotterdam includes bunkering as a significant cost component. Bunkering involves various operations that incur additional expenses. The cost of bunkering depends on the method used. Due to the large uncertainties in bunkering prices, a conservative approach was taken, assuming a bunkering cost of 2.2 €/GJ of LNG supplied (equivalent to 7.9 €/MWh, 110 €/tonne, 49.5 €/m^3). This estimate is based on the cost ranges provided by [1, 18]. The cost structure of bunkering was assumed to be identical to that in the previous steps. This includes O&M costs at 5% of CAPEX and annualized CAPEX calculated over a 20-year lifetime with a 10% discount rate. The back-calculated specific CAPEX for bunkering was estimated at 278 €/m^3.

6.1.7 Aggregation

The aggregation of results accounts for LNG supply volume into the Port of Rotterdam and bio-LNG supply cost. The aggregation of energy efficiency estimates the energy losses across different stages of the value chain. The aggregated efficiency includes the following stages: biomethane production, national and international pipeline transport, methane liquefaction, LNG storage at the export terminal, LNG shipping, and finally LNG storage and bunkering in the Port of Rotterdam. The energy efficiency calculations derive the supplied LNG volume in the Port of Rotterdam. This supplied LNG is then compared to the LNG demand figures presented in Chapter 3.

The aggregated systems cost includes the following stages: biomethane production, national pipeline transport, cross-border international pipeline transport, methane liquefaction, LNG storage at the export terminal, LNG shipping, LNG storage in the Port of Rotterdam, and LNG bunkering.

The current model provides a high-level assessment of bio-LNG storage and the associated costs of transferring bio-LNG to vessels. However, it does not go into detailed analysis regarding the specific infrastructure requirements for dedicated bunkering facilities at the Port of Rotterdam, such as additional bunkering vessel needs, or onshore refueling infrastructure. These aspects could be explored in a later stage of the study, where a more detailed infrastructure evaluation can be incorporated to complement the existing cost and supply chain analysis.

6.2 Model Results

The results of the model focus on identifying the potential supply volumes of LNG to the port of Rotterdam from different EU-27 countries and the UK, as well as the LNG cost per country. The results are separated into pathways: anaerobic digestion, gasification, and combined gasification and anaerobic digestion. The cost analysis of the different countries allowed for ranking the countries that provide the lowest cost of bio-LNG under the specified conditions: 25% biomass utilization (see Table 7) and a 40% export rate from each country (see section 6.1.3).

It is important to note that the Netherlands will always be the first option to supply bio-LNG to the port of Rotterdam. Subsequently, the ranking follows which country provides the lowest cost of LNG to the Port of Rotterdam. The results for 2030 and 2050 are discussed and provided below.

6.2.1 Results for 2030

Figure 15 shows an indication of the cost of supplying bio-LNG to the Port of Rotterdam from different EU27 countries and the UK via anaerobic digestion. Cyprus, Malta, and Luxembourg were excluded due to extremely high costs, primarily caused by low biomass availability. Hence, these countries are not included in further analysis.

For the case of the Anaerobic digestion pathway, the results indicate that the cost of bio-LNG ranges between 24 and 46 €/GJ (This corresponds to approximately 86–166 €/MWh, 1,200–2,300 €/tonne of LNG, and 540–1,035 €/m^3 of LNG, based on typical LNG (bio-LNG) energy content and density), which are slightly higher than the ranges presented by [1], but in the same order of magnitude. The cost of bio-LNG via anaerobic digestion is largely dominated by the production of biomethane, which accounts for approximately 70% of the total cost in most countries. The contributions of methane liquefaction and bunkering are also significant and similar across all countries. The cost of storage at the export terminal varies by country. This variation is due to differences in the required storage times to meet the carrier capacity needed to deliver the liquefied methane to the port of Rotterdam.

When analysing the costs of biomethane production, the breakdown reveals that feedstock contributes between 40% and 60%, followed by annualized CAPEX and lastly, O&M costs. Translating this contribution into the final cost of bio-LNG, feedstock costs contribute about 30%-40% of the total costs. Therefore, reductions in feedstock prices would strongly impact the cost of bio-LNG in Rotterdam.

As shown in Figures 15 to 17, biomethane production is also the main source of cost differences between countries in the bio-LNG value chain. Although generic feedstock prices per tonne are assumed similar across Europe in Table 13, biomethane production costs differ between countries due to differences in feedstock mix, technology mix and plant size distribution. Countries rely on different combinations of manure, biowaste, agricultural residues, lignocellulosic crops and woody residues, which leads to different feedstock costs per unit of biomethane because yields and costs per tonne are not identical. In addition, the model allocates discrete anaerobic digestion and gasification plant sizes per country and applies a minimum capacity factor, which results in different shares of small and large units and therefore different specific capital costs. These aspects together explain why biomethane production costs vary between countries, even when the same generic feedstock price assumptions are used.

Figure 16 illustrates the indicative costs of bio-LNG supply to the Port of Rotterdam via gasification. The results indicate that the cost of bio-LNG ranges from 31-55 €/GJ, which is

20-30% higher than that of anaerobic digestion. Similar to anaerobic digestion, the cost of bio-LNG produced via gasification is primarily influenced by biomethane production, accounting for up to 80% of the total cost. When analysing the cost contribution of biomethane production, the largest portion is due to the annualized capital investment in the first step of the supply chain. Overall, bio-methane production plants using gasification are more expensive than those using anaerobic digestion. However, they are more energy efficient (system efficiency results presented in Figure 20). Although specific costs per gigajoule are higher than for anaerobic digestion, this higher efficiency and the use of additional feedstocks such as woody residues and municipal solid waste increase the overall supply potential in the combined pathway and reduce the biomass required per unit of LNG. Figure 17 shows the potential bio-LNG cost when both anaerobic digestion and gasification are used to be supplied into the Port of Rotterdam. The analysis is analogous for this combined pathway but cost laying between 31-48 €/GJ.

It is important to mention that the bio-LNG cost projected here are for the year 2022, using biomass feedstock availability potential for 2030. Projections on capital cost reductions are not included in this analysis. However, for 2030, it is unlikely that CAPEX changes dramatically compared to the 2022 baseline. The main reason to this is that in both pathways the learning process up to 2030 is relatively slow.

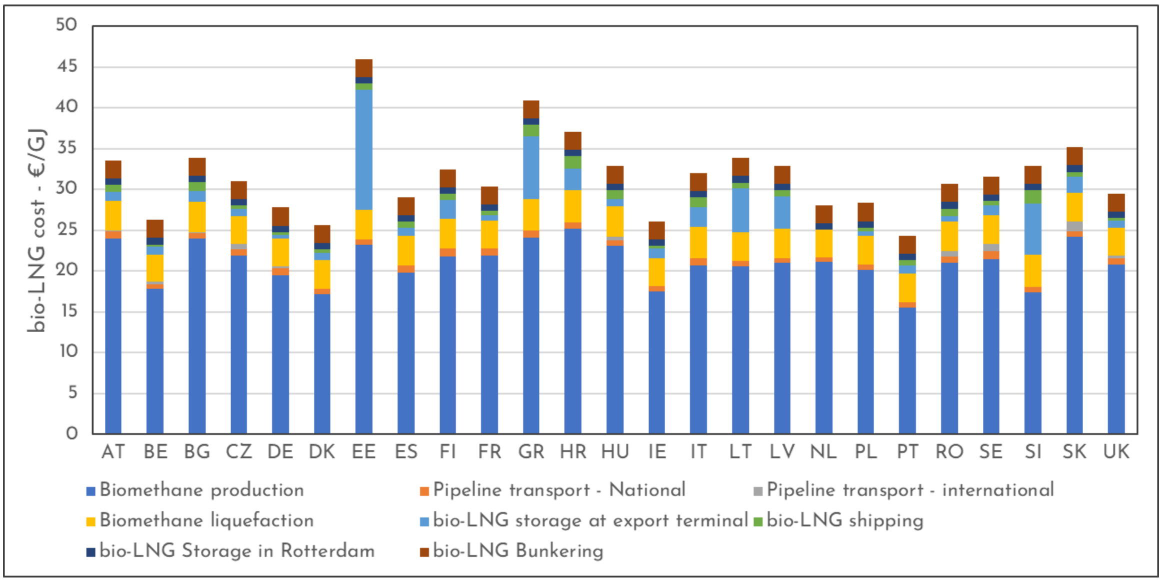

Figure 15. bio-LNG cost at the port of Rotterdam supplied by different EU 27 countries and the UK via anaerobic digestion in 2030.

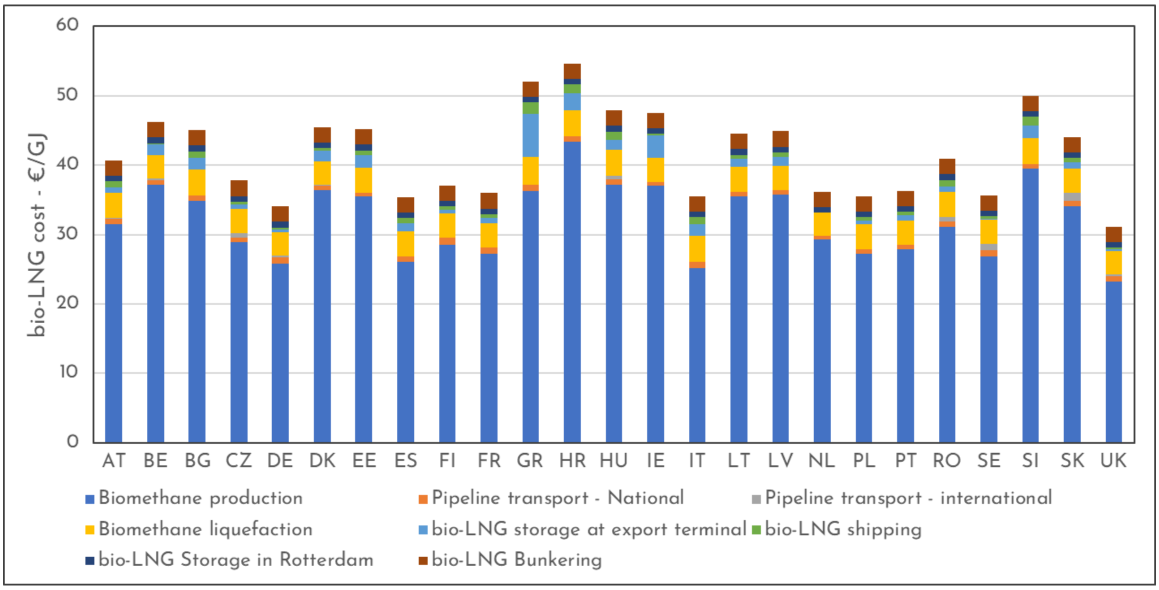

Figure 16. bio-LNG cost at the port of Rotterdam supplied by different EU 27 countries and the UK via gasification in 2030.

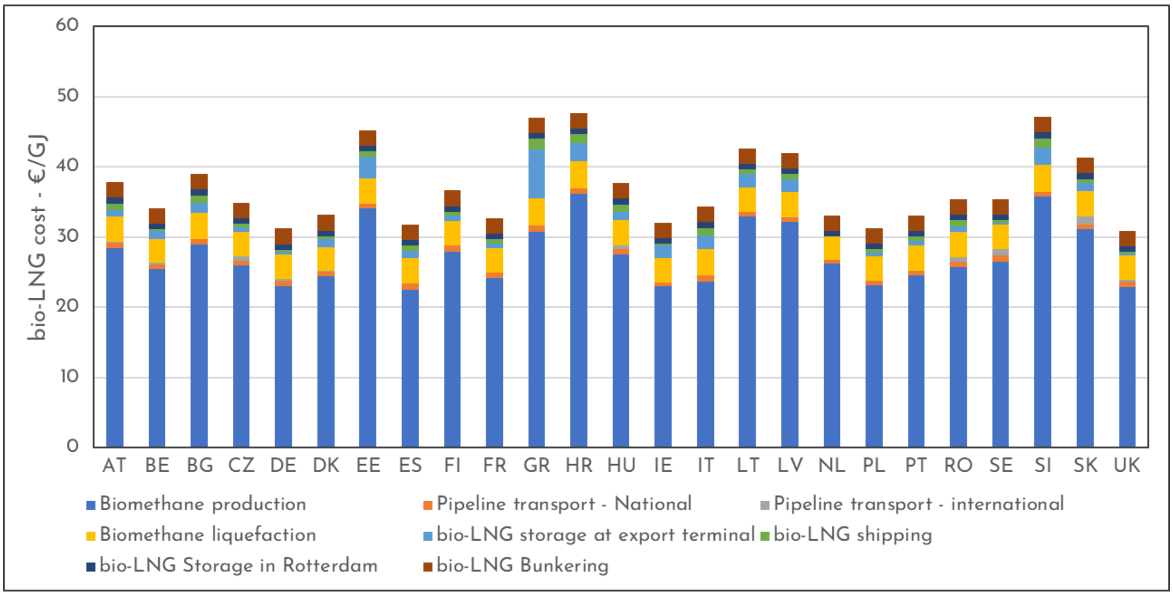

Figure 17. bio-LNG cost at the port of Rotterdam supplied by different EU 27 countries and the UK via anaerobic digestion + gasification in 2030.

Figure 18 illustrates the bio-LNG supply potential to the Port of Rotterdam from various EU 27 countries and the UK (with a 25% biomass utilization rate and 40% export rate to Rotterdam in each country). In general, the supply potential via gasification is higher than that via anaerobic digestion because gasification has higher conversion efficiency and can operate at larger plant scales, which increases the amount of biomethane produced per unit of biomass. Overall, gasification supply is 56% higher than that of anaerobic digestion. Among the countries, France, Germany, the UK, Spain, Sweden, and Poland have the highest supply potential.

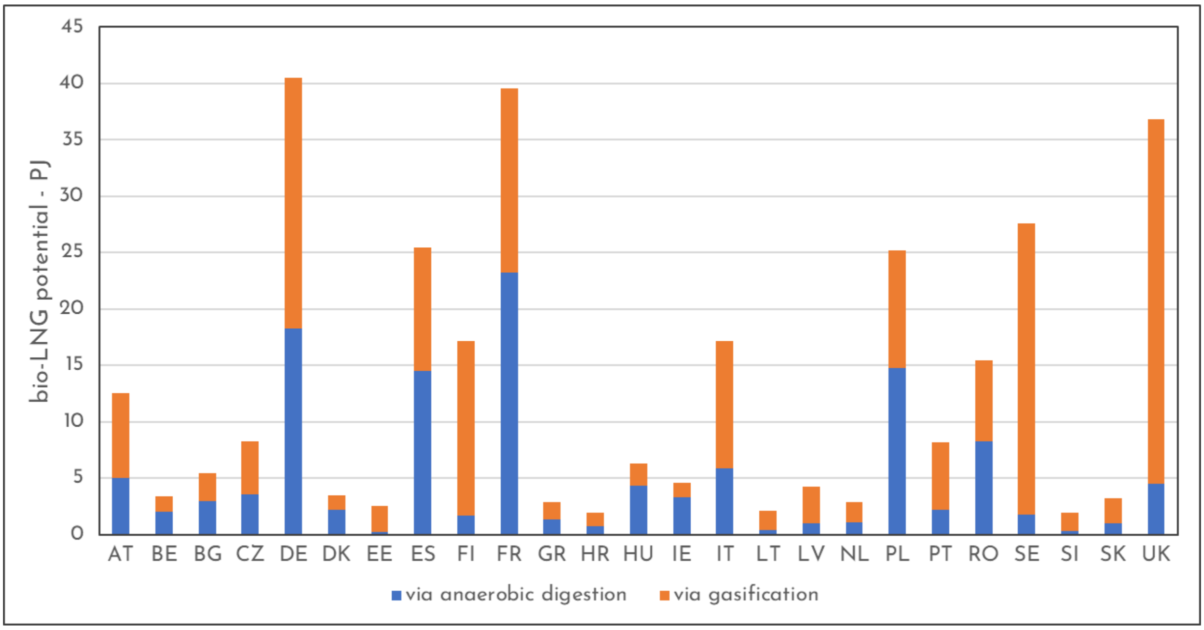

Figure 18. bio-LNG supply potential to the Port of Rotterdam in 2030 (with a 25% biomass utilization rate and 40% export rate to Rotterdam in each country)

The results shown in Figure 15, Figure 16 and Figure 17 were used to identify the countries with the lowest costs and rank them in ascending order (with the Netherlands always ranked highest, as it is assumed that local production should be prioritized before importing from other countries). The cost, supply potential of each country, and the supply pathway were used as criteria to evaluate which countries are preferable for meeting the demand projections. The output of this analysis includes the system costs and whether the biomass potential covers the demand projections (see Table 18).

Table 18. System results of bio-LNG supply to the port of Rotterdam in 2030 (25% biomass utilization rate and 40% export rate to Rotterdam in each country).

Systems		**LNG Demand - PJ** [a]	**LNG supply - PJ**			**Supply/ Demand**	**Biomass required -PJ**
			A. Digestion	Gasification	Total		
Anaerobic Digestion	2030 - Low	0.3	0.3	0.0	0.3	100%	1.0
	2030 - High	136.1	124.6	0.0	124.6	92%	453.7
Gasification	2030 - Low	0.3	0.0	0.3	0.3	100%	0.7
	2030 - High	136.1	0.0	136.1	136.1	100%	289.6
Anaerobic Digestion+ Gasification	2030 - Low	0.3	0.1	0.2	0.3	100%	0.8
	2030 - High	136.1	56.8	79.3	136.1	100%	361.7

[a] The 0,3 PJ and 136,1 PJ values were selected from the 2030 demand ranges analysed in Chapter 3 (excluding the 0 PJ case, which would trivially result in zero supply) and are used as illustrative low and high demand levels for the Port of Rotterdam.

The results presented in Table 18 show that the demand projection at the low end for 2030 can be supplied in all pathways. Utilizing a biomass rate of 25% and an export rate of 40% means that even if countries are not using the biomass exclusively for bio-LNG, with 60% of local production for their own consumption, the demand can be met. However, for the high-end demand, particularly in the anaerobic digestion pathway (while gasification and combined pathways cover 100% of the demand), only 92% of the demand can be covered at the given biomass utilization and export rates.

This implies that adjustments are needed to fully meet the demand. One option is to increase the biomass utilization rate while keeping the export rate fixed. Alternatively, increasing the export rate to the Port of Rotterdam could help, although this rate is already high at 40% of local production. This high export rate may be questioned due to the significant natural gas demand within the countries, raising the issue of why local bio-LNG should be sold to the Port of Rotterdam. This decision depends on national agendas, regarding decarbonization and defossilization strategies.

Increasing the biomass utilization rate would reduce the diversification of biobased products to other sectors. Addressing this issue in the current model is challenging, and a more detailed model is required to consider competition with other biomass uses, restrictions due to demand in different countries, and competition with other decarbonization/defossilization options such as electrification.

To cover 100% of the demand using anaerobic digestion, 494.4 PJ (as 453,7 PJ cover 92 %) of biomass is required (with an export rate of 40% from each country), which is approximately 11% of the biomass potential at the European level for anaerobic digestion technologies. Since the model uses a biomass utilization rate of 25 % per country, the available supply is not sufficient to cover the full demand in this pathway. For gasification, up to 7% of the biomass potential in Europe would need to be used to produce bio-LNG to cover the demand at the Port of Rotterdam. In contrast, the combined pathway would require about 4% of the total biomass potential in Europe to meet the high-end demand in 2030.

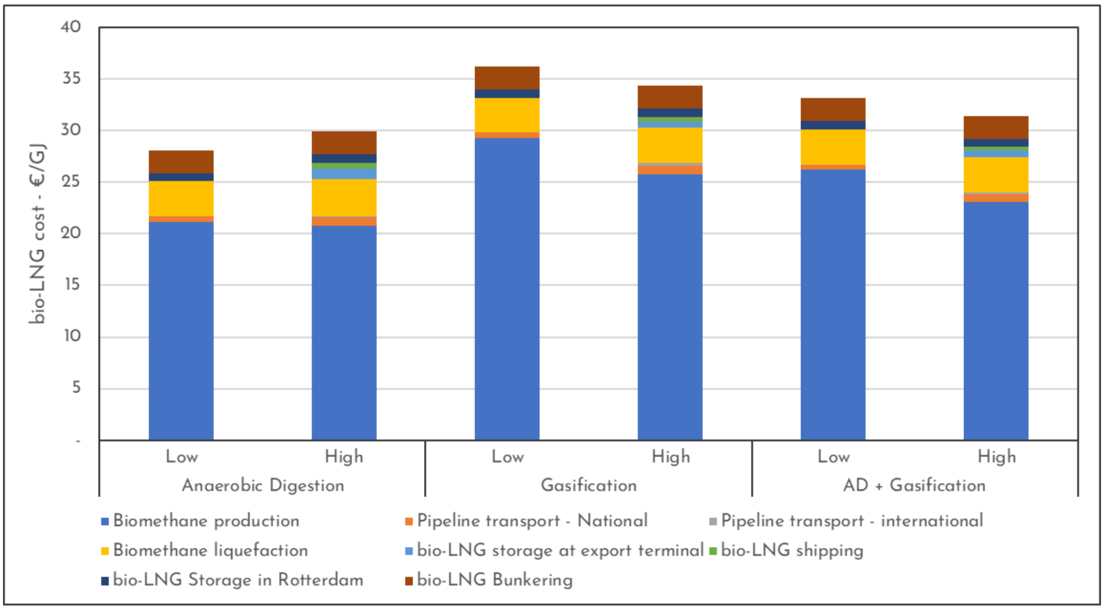

Figure 19. Average bio-LNG supply cost to the Port of Rotterdam in 2030 (25% biomass utilization rate and 40% export rate to Rotterdam in each country). The indicative price of fossil LNG in 2022 ranged from 4 to 13 € per GJ [1]

The results of the average costs of bio-LNG to the port of Rotterdam for 2030 are presented in Figure 19. For anaerobic digestion, the costs range between €28 and €30 per gigajoule for low and high demand, respectively. At the low demand level, there is no contribution from bio-LNG storage at export terminals or bio-LNG shipping, indicating that local production in the Netherlands can meet the demand at that cost. For high demand, all countries (except Malta, Cyprus, and Luxembourg) contribute, resulting in a higher cost. The small cost difference between low and high demand scenarios is mainly explained by the fact that biomethane production dominates the total cost, and this cost component does not change substantially between the two demand levels. Additional imports increase total volumes but do not drastically change the average system cost.

For the gasification pathway, costs are higher for low demand (€36/GJ) compared to high demand (€34/GJ). This is because the Netherlands has lower biomass potential than other countries, limiting the scale of biomethane production installations. Smaller capacities lead to higher costs per unit, unlike countries like Germany, France, or the UK, where the effect of economies of scale is more evident. The relative position of other countries in Figure 17 is not only driven by total biomass potential but also by feedstock mix, plant size distribution and logistics, so countries such as Ireland, Portugal, Denmark and Poland show slightly lower costs than Germany or France due to a more favourable combination of these factors.

The combined pathway, which involves both anaerobic digestion and gasification, has costs between €31 and €33 per gigajoule. Generally, gasification system costs are higher than those for anaerobic digestion due to the significant capital investment required. While anaerobic digestion costs are lower, at a biomass utilization rate of 25% and an export rate of 40%, it cannot fully meet the demand. Therefore, a combined supply chain using both gasification and anaerobic digestion pathways is preferred. When compared to the price of fossil LNG, which ranges from 4 to 13 € per GJ [1] (Indicative price band and is expressed here in 2022 euro values. It is used only as a reference for comparison with the modelled bio-LNG costs and reflects the volatility and uncertainty of fossil LNG prices), the costs of bio-LNG are 2 to 11 times higher.

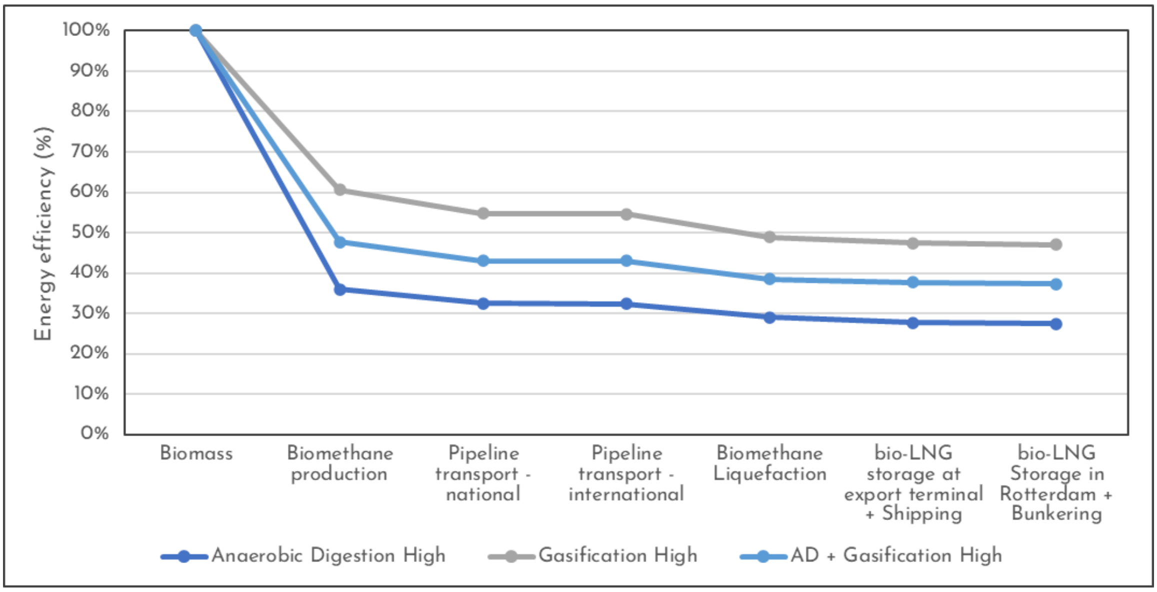

Figure 20. Systems energy efficiency for bio-LNG supply in 2030 (high end only)

Figure 20 illustrates the energy efficiency of the system, highlighting energy losses across different steps of the supply chain. In all three pathways, the biomethane production step exhibits the highest energy losses, as previously described. Additionally, significant energy loss occurs during the transportation of biomethane via pipelines, primarily due to the energy required to compress the methane to the pressure of the pipeline network. Liquefaction also contributes to substantial energy losses in the system. Storage and bunkering in the port of Rotterdam result in energy losses, but these are not as significant as those in the previously mentioned steps. The final efficiency for the anaerobic digestion pathway is 27%, followed by the combined pathway of anaerobic digestion and gasification with a 38% efficiency. The highest efficiency is 47% for the gasification pathway. These efficiencies reflect the proportion of energy contained in the biomass that is ultimately delivered at the end of the supply chain in the form of LNG.

Sensitivity Analysis

Figure 21 shows the results of the sensitivity analysis of the system cost of bio-LNG supply to the port of Rotterdam. For the case of anaerobic digestion, the parameters that influence the cost the most are feedstock prices and the CAPEX of biomethane production. As described previously, the cost of feedstock plays a crucial role in the system cost. However, a decrease in capital investment costs in the biomethane production step will significantly reduce the overall cost. Compared to fossil prices, the ranges remain high.

The export rate and biomass utilization rate also have a significant impact. When the utilization rate and export rate decrease, likely due to competition for biomass with other uses and reluctance of countries to export bio-LNG to the Port of Rotterdam, the cost of bio-LNG increases significantly. This occurs primarily because smaller systems must be used, leading to higher costs in the biomethane production stage, and the need for longer storage times of LNG in export terminals to accumulate the LNG required to load a carrier.

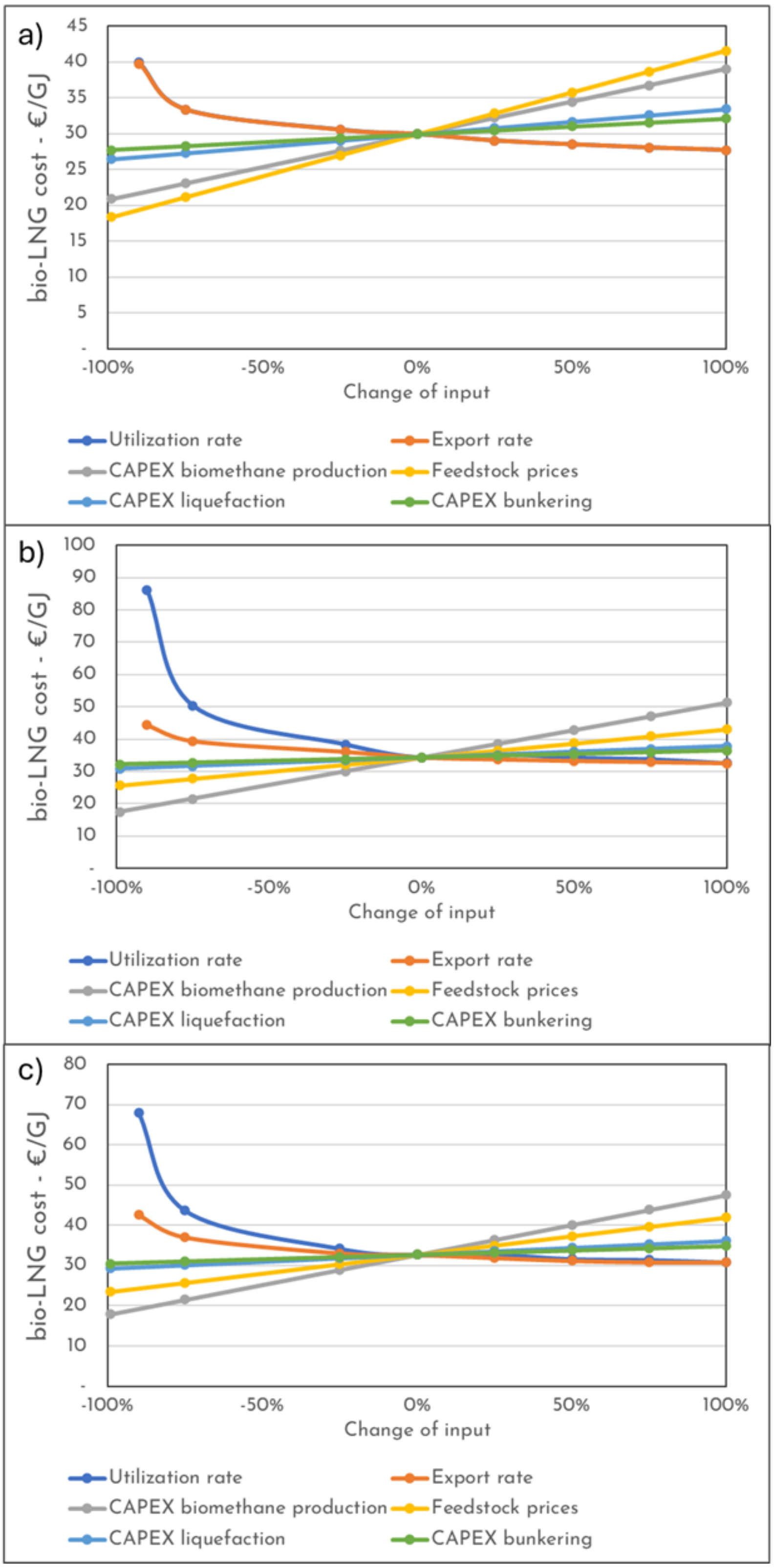

Figure 21. Results of sensitivity analysis on systems costs for 2030. a) Anaerobic digestion pathway, b) gasification pathway, c) Combined pathway (Anaerobic digestion + gasification)

In the gasification pathway, the impact of the CAPEX on biomethane production is more significant than that of feedstock prices. This indicates a need to reduce the CAPEX of gasification plants by 2050. While significant reductions are unlikely by 2030, there is potential for cost decreases by 2050. The results also show that the biomass utilization rate significantly affects the cost of the gasification pathway. This is because gasification technologies tend to move towards centralized operations, unlike anaerobic digestion. If the biomass utilization rate decreases, the system must use small-scale gasification systems, potentially leading to underused facilities or those operating at low-capacity factors. This situation increases the cost per unit and decreases production volume. The export rate also affects costs, but not as significantly as the biomass utilization rate. Both parameters are crucial for the availability and supply of bio-LNG to the Port of Rotterdam. In the combined case, both CAPEX and feedstock costs are important, reflecting aspects of the previous two pathways.

6.2.2 Results for 2050

Figure 22 shows the cost of supplying bio-LNG to the Port of Rotterdam in 2050 using the anaerobic digestion pathway. The cost trend is similar to that described for 2030, with only minor fluctuations. Biomethane production, mainly due to feedstock costs, dominates up to 70% of the total cost of bio-LNG, which ranges from 25 to 43 €/GJ.

Figure 23 illustrates the indicative costs of supplying bio-LNG to the Port of Rotterdam via gasification. The results indicate that the cost of bio-LNG ranges from 34 to 58 €/GJ, approximately 30% higher than that of anaerobic digestion. Similar to anaerobic digestion, the cost of bio-LNG produced via gasification is primarily influenced by biomethane production, accounting for up to 80% of the total cost. The cost trend is very similar to that presented for 2030.

Figure 24 shows the potential cost of bio-LNG when both anaerobic digestion and gasification are used for supply to the Port of Rotterdam. The cost ranges between 30 and 55 €/GJ. The overall cost level is similar to that of 2030 (31–48 €/GJ), with a slightly lower minimum value and a higher maximum value rather than a systematic cost decrease. The wider interval in 2050 is mainly due to changes in biomass potentials and feedstock composition between 2030 and 2050 across countries, combined with the higher demand level in 2050 and the way the model selects the cheapest supply options first and adds more expensive options when additional supply is needed. In some countries, higher biomass potentials in 2050 allow larger plants or a more favourable mix of anaerobic digestion and gasification, which reduces costs, while in others the available biomass remains limited or shifts towards more costly woody and waste feedstocks, so meeting the higher demand requires more expensive units and leads to higher levelised costs.

Projections on capital cost reductions are not included in this analysis. However, for 2050, it is likely that CAPEX will change significantly compared to the 2022 baseline. Although the current data used in the model do not reflect CAPEX reductions for 2050, if such data become available, it can be easily implemented in the model since CAPEX is an input parameter. Likewise, projections of feedstock prices for 2050 can be easily implemented in the model as input parameters.

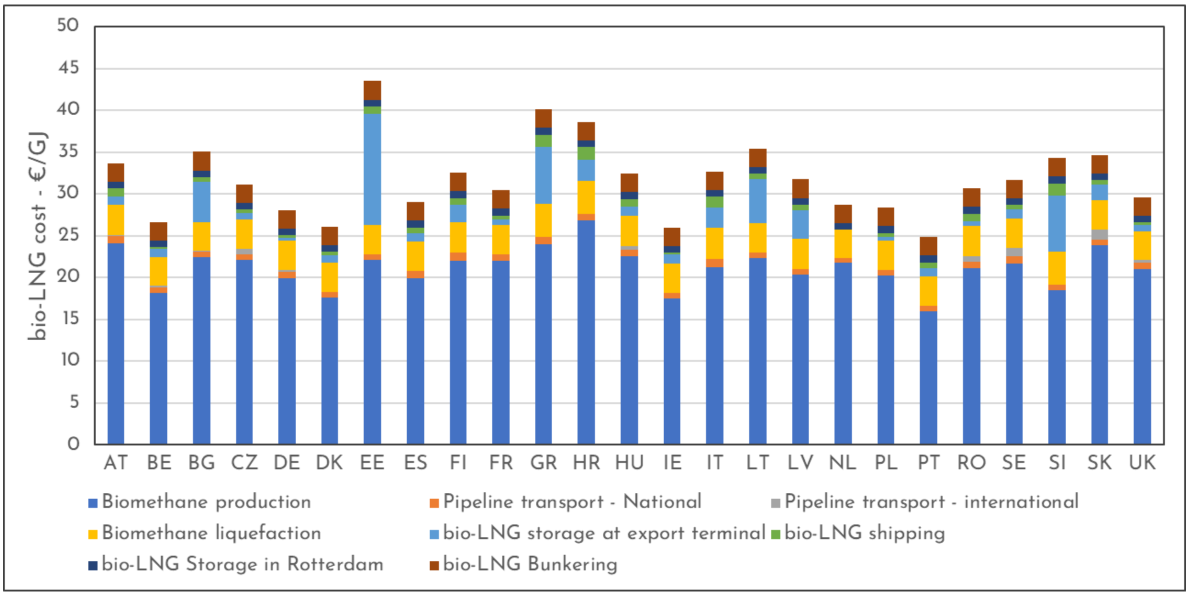

Figure 22. bio-LNG cost at the port of Rotterdam supplied by different EU 27 countries and the UK via anaerobic digestion in 2050.

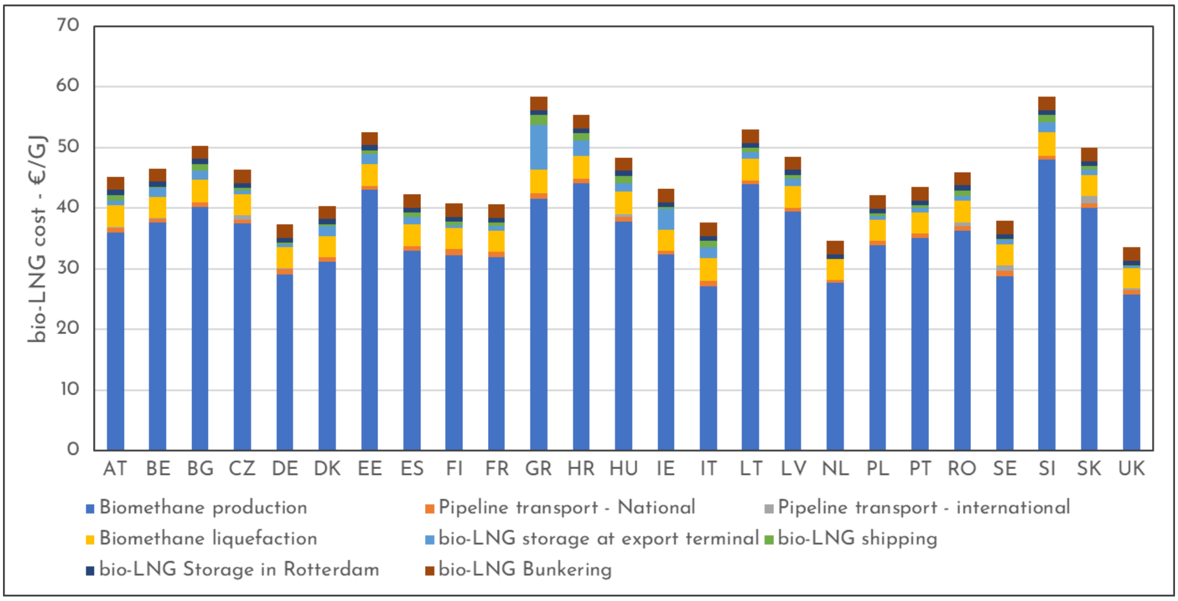

Figure 23. bio-LNG cost at the port of Rotterdam supplied by different EU 27 countries and the UK via gasification in 2050.

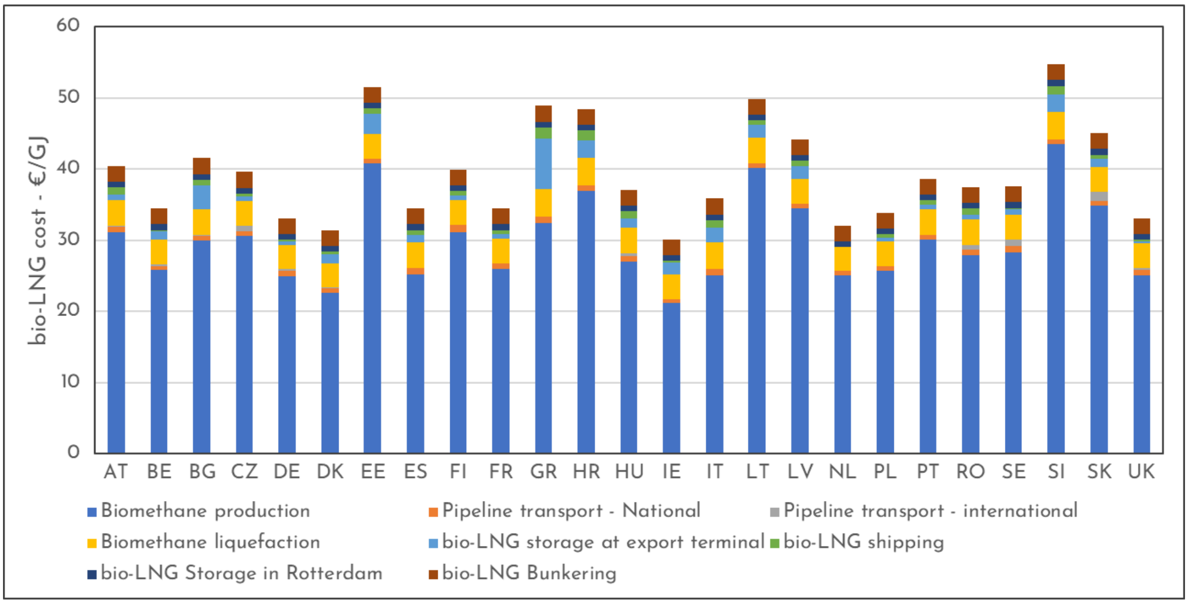

Figure 24. bio-LNG cost at the port of Rotterdam supplied by different EU 27 countries and the UK via anaerobic digestion + gasification in 2050.

Figure 25 shows the potential bio-LNG supply to the Port of Rotterdam from various EU 27 countries and the UK. The calculations assume a 25% biomass utilization rate and a 40% export rate to Rotterdam for each country. The supply potential through gasification is 47% higher than that through anaerobic digestion, which is consistent with the 2030 projections.

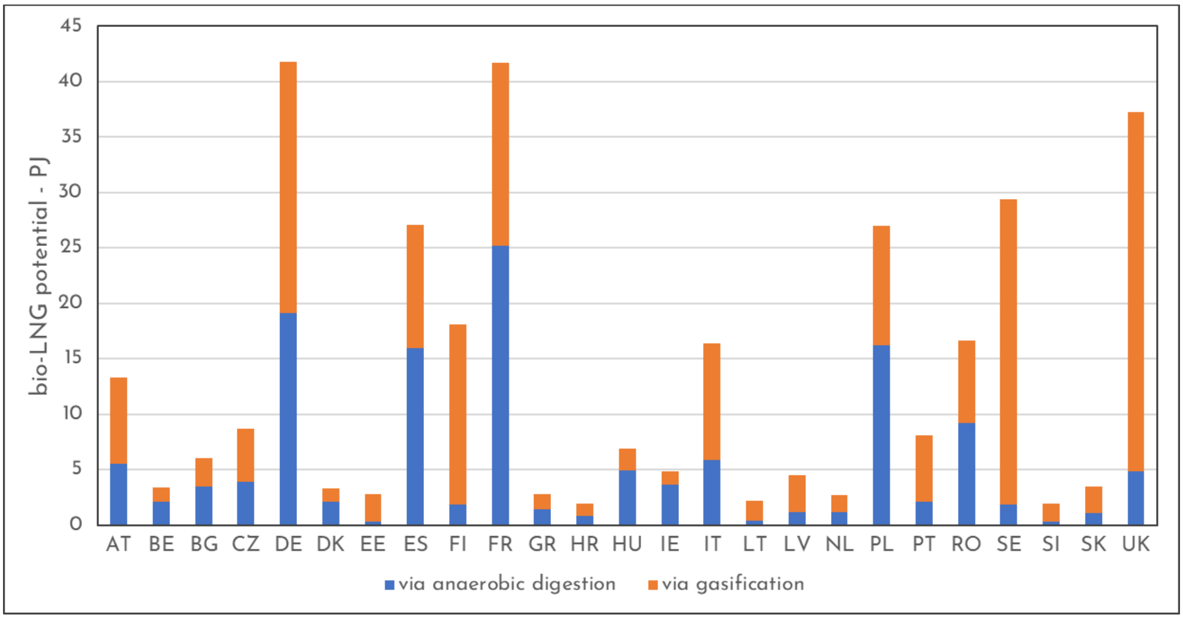

Figure 25. bio-LNG supply potential to the Port of Rotterdam in 2050 (with a 25% biomass utilization rate and 40% export rate to Rotterdam in each country)

Table 19 presents the results of the bio-LNG supply potential and its ability to meet demand projections. Under the assumptions of a 25% biomass utilisation rate and a 40% export rate to Rotterdam, all three pathways can fully meet the low-end demand projection of 30 PJ of LNG in the port of Rotterdam. For anaerobic digestion, the biomass required to meet this demand is about 2.2% of the biomass potential suitable for this process. For gasification, this share is around 1.5% of the biomass suitable for gasification. When the combined pathway is used, this share is approximately 0.8% of the total biomass potential in 2050 in the EU27 and the UK.

The picture differs significantly for the high-end demand case. Given the assumptions of a 25% biomass utilisation rate and a 40% export rate to Rotterdam, only 26% of the demand can be covered through anaerobic digestion. Gasification covers approximately 39%, and the combined pathway covers about 65%.

Table 19 shows that for the high-end cases, the amount of biomass required accounts for approximately 10% of the total suitable biomass for each pathway. To cover 100% of the high-end demand in the Port of Rotterdam, approximately 1800 PJ of biomass are required for anaerobic digestion, which is about 37% of the total suitable biomass. For gasification, 1060 PJ of biomass are needed, which is about 25% of the total suitable biomass. The combined case requires 1377 PJ of biomass, accounting for 15% of the total biomass potential in Europe to meet the bio-LNG demand of 511 PJ.

These figures are high, indicating that a substantial amount of biomass would need to be allocated solely for bio-LNG production for the Port of Rotterdam. To put this in context, if other uses of biomass become dominant, if the logistics of biomass collection and conversion become critical, potentially limiting the full exploitation of biomass potential, if there is a diversification of demand in other markets, such as the use of bio-LNG for other ports or household applications, and if the likelihood of EU27 and UK countries exporting bio-LNG to Rotterdam is low, then meeting this high demand becomes very challenging by only using biomass in EU27 and the UK.

Table 19. System results of bio-LNG supply to the port of Rotterdam in 2050 (25% biomass utilization rate and 40% export rate to Rotterdam in each country)

Systems		**LNG Demand - PJ** [a]	**LNG supply - PJ**			**Supply/ Demand**	**Biomass required -PJ**
			A. Digestion	Gasification	Total		
Anaerobic Digestion	2050 - Low	30.0	30.0	0.0	30.0	100%	108.0
	2050 - High	511.3	134.7	0.0	134.7	26%	482.0
Gasification	2050 - Low	30.0	0.0	30.0	30.0	100%	62.2
	2050 - High	511.3	0.0	198.1	198.1	39%	418.6
Anaerobic Digestion+ Gasification	2050 - Low	30.0	9.4	20.6	30.0	100%	72.1
	2050 - High	511.3	134.7	198.1	332.8	65%	900.5

[a] The 30 and 511,3 PJ values were selected from the 2050 demand ranges analysed in Chapter 3 and are used as illustrative low and high demand levels for the Port of Rotterdam.

Figure 26 illustrates the cost of bio-LNG supplied in the port of Rotterdam. As demand increases, the cost of bio-LNG also rises across all three pathways. For anaerobic digestion, the cost of bio-LNG ranges between 27 and 30 €/GJ. For gasification, the cost is between 32 and 37 €/GJ, and for the combined case, it is between 32 and 34 €/GJ. In the low-demand scenario for 2050, the results differ from those of 2030. The lower end demand cannot be met solely by the bio-LNG production in the Netherlands which has a relatively higher bio-LNG cost than other countries. In terms of bio-LNG efficiency (see Figure 27), the analysis is analogous to that of 2030, with the biomethane production stage incurring the major energy losses.

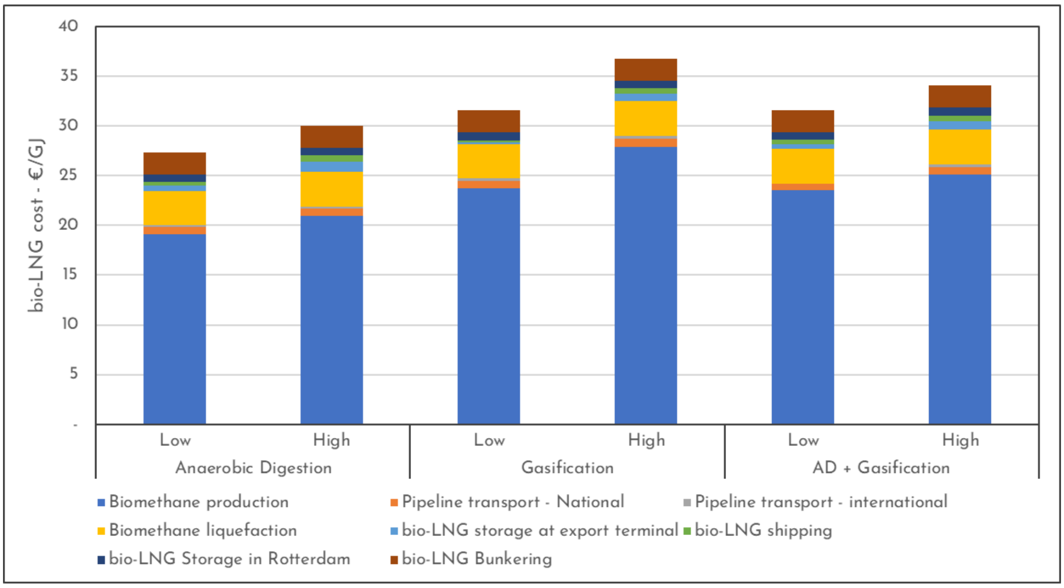

Figure 26. Average bio-LNG supply cost to the Port of Rotterdam in 2050 (25% biomass utilization rate and 40% export rate to Rotterdam in each country). Coverages shown in Table 19. The indicative price of fossil LNG in 2022 ranged from 4 to 13 € per GJ [1]

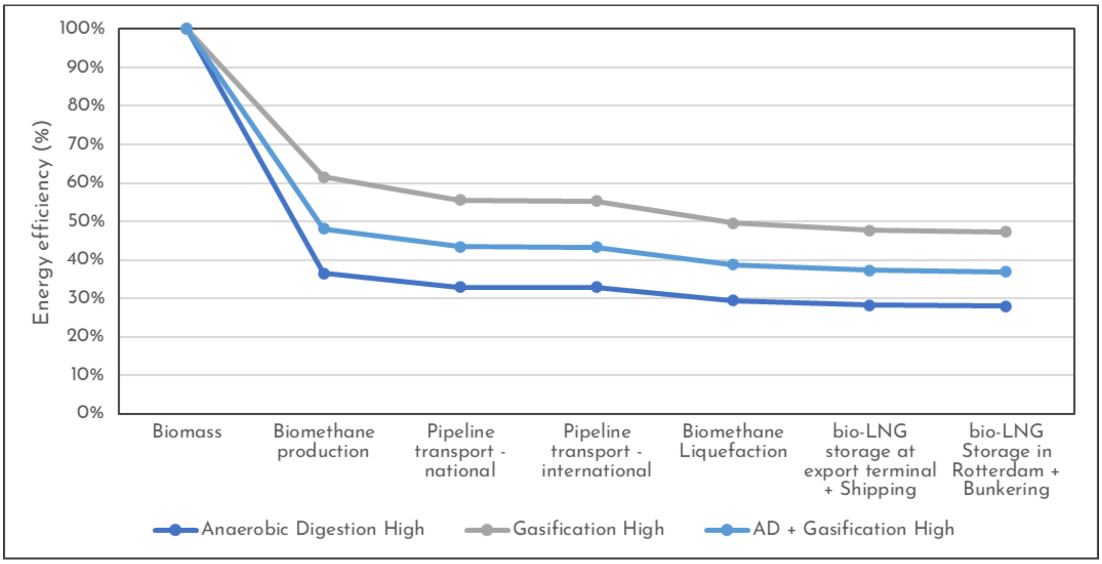

Figure 27. Systems energy efficiency for bio-LNG supply in 2050 (high end only)

Sensitivity Analysis

Figure 28 presents the sensitivity analysis results of the system cost for supplying bio-LNG to the port of Rotterdam. In the anaerobic digestion pathway, feedstock prices and the CAPEX of biomethane production are the primary cost influencers, which is very similar to the 2030 case. The export rate and biomass utilisation rate also notably impact the costs and the trends are identical to those reported for 2030.

In the gasification pathway, the influence of CAPEX on biomethane production costs is more pronounced than that of feedstock prices, indicating the big role of CAPEX reductions of gasification plants by 2050. In the combined pathway, both CAPEX and feedstock costs are crucial, reflecting the combined influences seen in the anaerobic digestion and gasification pathways.

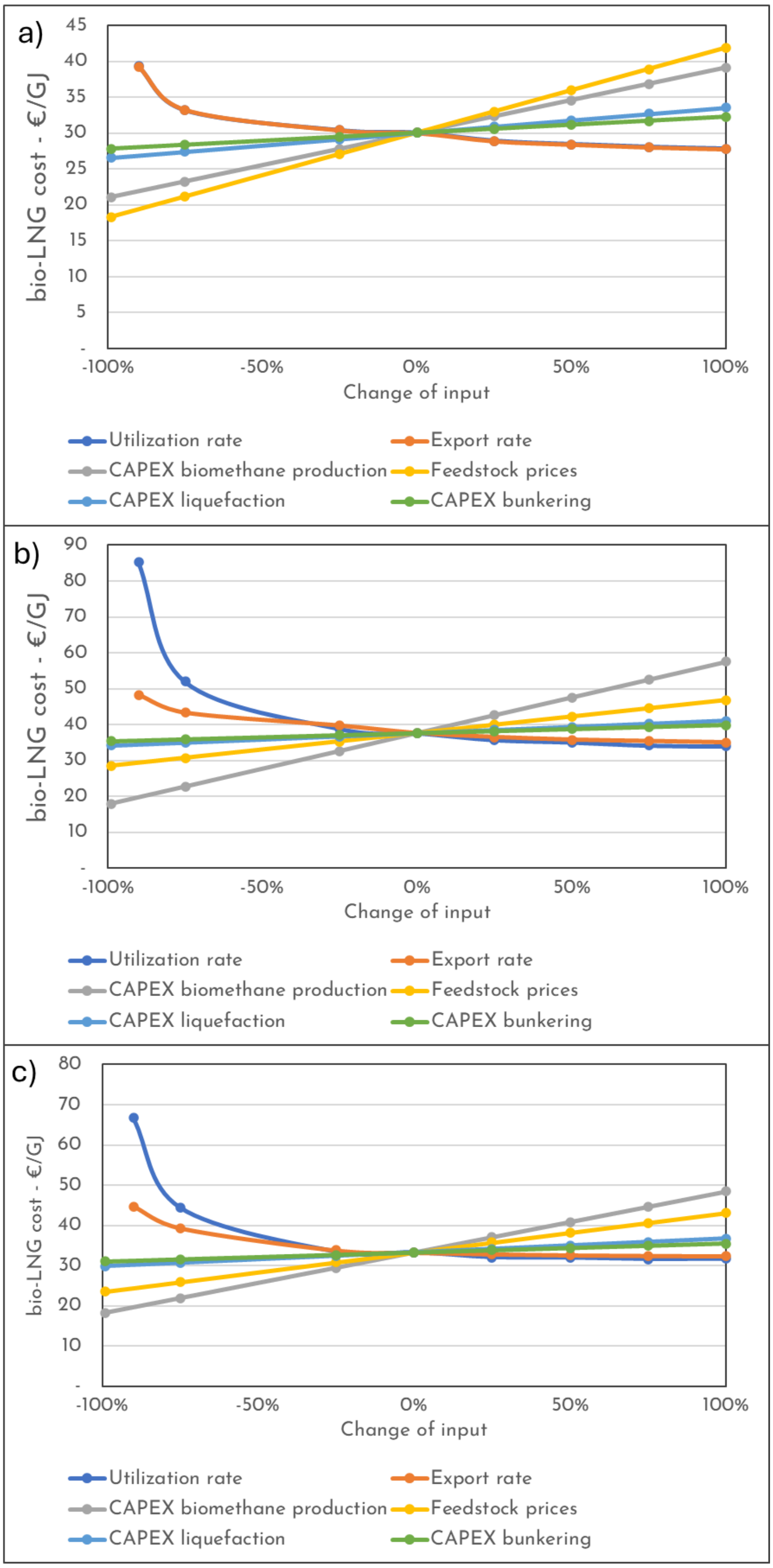

Figure 28. Results of sensitivity analysis on systems costs for 2050. a) Anaerobic digestion pathway, b) gasification pathway, c) Combined pathway (Anaerobic digestion + gasification)

7. Conclusions & Next steps

7.1 Conclusions

Demand for bio-LNG bunkering in the Port of Rotterdam

The demand for bio-LNG in the Port of Rotterdam varies widely due to different assumptions about future energy use. For 2030, estimates range from 0 to 136 PJ, with the highest for maritime shipping. By 2040, estimates are between 16 and 387 PJ. For 2050, projections range from 0 to 511 PJ, showing uncertainty about bio-LNG's long-term role. These variations highlight the need for flexible planning to meet future bio-LNG demands and support renewable energy transition.

LNG infrastructure and adaptation needs

The LNG infrastructure in Europe is crucial for securing the EU's gas supply, which heavily relies on imports, particularly LNG. The current European LNG infrastructure is well established and expanding. This infrastructure primarily consists of import terminals, storage facilities, regasification plants, and pipelines, which efficiently handle and manage natural gas. To accommodate bio-LNG in the existing infrastructure, enhancements are necessary, including additional biomethane installations, expanded liquefaction plants, and increased storage capacities. With these modifications, the existing infrastructure can accommodate bio-LNG, primarily through scaling up. The model developed in this study can also be used to provide the installation needs to cover certain demand of bio-LNG.

Biomass potentials and matching of feedstocks and technologies for bio-LNG production

Effective production of biomethane and bio-LNG relied on strategically matching feedstocks with suitable conversion technologies. Key criteria for this matching included volatile matter, recalcitrance, and water content of the biomass. Suitable feedstocks for anaerobic digestion were agricultural residues, manure, biowaste, and lignocellulosic crops. For gasification, appropriate feedstocks included wood, forestry residues, secondary forestry residues, prunings, and municipal solid waste (MSW).

Assessing biomass potential for bio-LNG supply chains in the EU27 and UK showed significant opportunities for bioenergy production by 2030 and 2050. France, Germany, Spain, Poland, Sweden, and the UK had the highest biomass potential. This potential, presented by feedstock type and country, allowed for a detailed assessment of feedstock conversion into biomethane in the supply chain model for bio-LNG supply at the port of Rotterdam.

Modelling the bio-LNG supply chain

A supply chain model was developed to evaluate the feasibility of supplying bio-LNG to the Port of Rotterdam from the EU27 countries and the UK, focusing on the period up to 2050. The model assesses biomass potential, biomethane production, transport, liquefaction, storage, and shipping.

The model has limitations due to assumptions about biomass availability and capital expenditure, without considering technological advancements projected for 2030 and 2050. It also does not include a detailed assessment of GHG emissions, potential emission savings, and competing biomass uses.

Results for 2030 and 2050 show that bio-LNG costs are significantly higher than fossil LNG (27-38 €/GJ for bio-LNG compared to 4-13 €/GJ for fossil LNG), driven by capital investment for biomethane production and feedstock cost. Energy losses are highest during biomethane production, followed by liquefaction and transport.

Two critical factors influencing bio-LNG costs are biomass utilization and the willingness of producing countries to export bio-LNG to the Port of Rotterdam. Lower biomass utilization rates due to competing uses and reluctance from producing countries to export bio-LNG can lead to increased costs.

The model allows for assessing the biomass requirements to meet 100% of the high-end demand (136 PJ of bio-LNG) for 2030. The anaerobic digestion pathway would require 11% (494 PJ) of the EU 27 and UK biomass potential suitable for anaerobic digestion. The gasification pathway would require 7% (290 PJ) of biomass suitable for gasification, while the combined pathways would need 4% (362 PJ) of the total biomass potential for 2030.

For 2050, to cover 100% of the high-end demand (511 PJ), the anaerobic digestion pathway would require 37% (1800 PJ) of the EU 27 and UK biomass potential suitable for anaerobic digestion. The gasification pathway would require 25% (1060 PJ) of biomass suitable for gasification, and the combined pathways would need 15% (1377 PJ) of the total biomass potential for 2050.

7.2 Next steps

The next steps in assessing the bio-LNG supply for ports involve using the model to include potential scenarios and configurations. This will provide detailed insights into the competing uses of biomass and the linkages of biomethane or bio-LNG exports from different countries. The model is also planned to be tested in task 3.6. Fine-tuning of data inputs is expected and will be addressed in future steps. Furthermore, the model will be expanded to incorporate aspects such as greenhouse gas emission accounting.

Annex A

This annex provides detailed information of LNG Demand in the Port of Rotterdam for the years 2030, 2040 and 2050. Table A1 shows the projected Bio-LNG demand for 2030, 2040 and 2050 in different studies.

Table A1. Projected Bio-LNG demand for 2030, 2040 and 2050 in different studies

Study	**Demand - PJ**					
	2030		2040		2050	
	Low	High	Low	High	Low	High
Pruyn et al., [2]	31	131	31	132	30	131
Lechtenböhmer et al., [10]	3	55	16	98	0	57
Scheepers et al., [15]	0	4	253	387	106	511
Scheepers et al., [16]	41	47	48	280	57	68
Leguijt et al., [17]	0	136	NA	NA	NA	NA
Nelissen et al.,[18]	101	118	135	254	170	389
Baseric et al., [19]	47	54	103	147	163	333
Irena., [20]	17	39	39	64	58	86
European Commission., [21]	0	43	23	181	46	319

Annex B

This annex provides absolute values of biomass potential by feedstock type for the EU27 countries and the UK for 2030 and 2050. Table B1 shows the low-end biomass potential for 2030. Table B2 shows the low-end biomass potential for 2030. Table B3 shows the low-end biomass potential for 2050. Table B4 shows the high-end biomass potential for 2030.

Table B1. 2030 Low End Biomass Potential in EU27 Countries and the UK. Values in million dry tonnes.

Country	Agricultural residues	Manure	Biowaste	Ligno. Crops	Wood	Forestry residues	Secondary forestry residues	Prunings	MSW
AT	12.43	0.24	0.05	0.22	3.14	3.24	2.43	0.04	0.78
BE	1.92	2.21	0.10	0.31	0.51	0.09	0.68	0.03	0.36
BG	5.95	0.00	0.02	0.80	0.81	1.32	0.36	0.27	0.56
CY	0.01	0.00	0.00	0.06	0.00	0.00	0.05	0.00	0.08
CZ	6.78	0.72	0.01	0.62	2.34	1.16	1.70	0.02	0.75
DE	27.11	12.00	0.34	2.50	10.54	4.64	7.99	0.12	4.32
DK	1.79	2.99	0.05	0.23	0.40	0.09	0.49	0.00	0.74
EE	0.07	0.12	0.01	0.21	1.71	0.56	0.39	0.00	0.21
ES	13.37	5.32	0.29	7.89	2.48	3.24	2.81	2.01	4.13
FI	2.17	0.42	0.09	0.77	7.47	3.84	7.38	0.00	0.41
FR	46.17	4.84	0.09	3.32	9.40	3.80	3.72	0.10	3.91
GR	1.85	0.30	0.01	0.68	0.48	0.20	0.60	0.17	0.91
HR	1.71	0.36	0.01	0.03	0.64	0.24	0.34	0.02	0.38
HU	7.73	0.48	0.01	1.43	1.20	0.31	0.56	0.11	0.65
IE	0.33	2.09	0.01	2.55	0.45	0.06	0.36	0.00	0.87
IT	8.62	6.09	0.63	0.32	2.95	3.40	2.23	0.36	7.23
LT	0.50	0.36	0.03	0.03	1.01	0.21	0.76	0.00	0.26
LU	0.12	0.00	0.01	0.37	0.09	0.02	0.03	0.00	0.05
LV	0.29	0.06	0.01	0.97	1.93	0.65	1.37	0.00	0.10
MT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NL	1.59	0.00	0.20	0.35	0.18	0.01	0.60	0.02	1.66
PL	19.70	5.21	0.04	5.18	4.69	1.44	5.07	0.47	1.37
PT	0.45	3.88	0.09	0.51	1.82	2.28	2.10	0.00	1.39
RO	9.52	1.19	0.49	4.47	3.36	1.84	3.08	0.12	0.93
SE	2.46	0.60	0.29	0.45	10.54	4.96	15.71	0.00	0.52
SI	0.05	0.78	0.00	0.04	1.06	0.54	0.44	0.00	0.11
SK	2.01	0.00	0.01	0.22	1.06	0.68	0.94	0.01	0.16
UK	6.93	0.30	0.56	1.34	3.07	2.60	26.64	0.01	7.89
Total	181.63	50.54	3.46	35.87	73.36	41.42	88.83	3.89	40.73

Table B2. 2030 High End Biomass Potential in EU27 Countries and the UK. Values in million dry tonnes.

Country	Agricultural residues	Manure	Biowaste	Ligno. Crops	Wood	Forestry residues	Secondary forestry residues	Prunings	MSW
AT	17.43	0.36	0.09	0.67	7.52	5.23	3.45	0.11	1.40
BE	2.51	2.63	0.18	0.94	1.23	0.16	0.96	0.07	0.64
BG	7.14	0.36	0.04	2.41	1.94	2.26	0.51	0.71	1.00
CY	0.01	0.00	0.01	0.18	0.01	0.00	0.07	0.00	0.14
CZ	8.28	2.27	0.02	1.86	5.62	2.01	2.40	0.06	1.34
DE	33.72	5.19	0.62	7.51	25.30	7.32	11.33	0.30	7.78
DK	2.50	2.09	0.09	0.68	0.97	0.17	0.70	0.00	1.33
EE	0.10	0.42	0.03	0.64	4.11	0.29	0.85	0.00	0.39
ES	17.11	5.91	0.52	23.66	5.96	5.33	3.99	4.91	7.44
FI	2.74	0.54	0.17	2.31	17.94	6.24	10.46	0.00	0.74
FR	58.93	19.11	0.17	9.95	22.55	6.02	5.27	0.26	7.04
GR	2.38	0.48	0.02	2.04	1.16	0.21	0.55	0.45	1.64
HR	2.01	0.18	0.01	0.10	1.53	0.21	0.48	0.04	0.68
HU	9.17	2.33	0.03	4.29	2.87	0.55	0.80	0.30	1.17
IE	0.48	1.19	0.02	7.64	1.08	0.10	0.51	0.00	1.57
IT	10.84	8.60	1.13	0.95	7.09	5.46	3.16	0.93	13.01
LT	0.66	0.48	0.05	0.08	2.43	0.38	1.08	0.00	0.47
LU	0.15	0.00	0.01	1.11	0.22	0.04	0.04	0.00	0.09
LV	0.38	0.12	0.01	2.91	4.63	2.97	1.94	0.00	0.17
MT	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
NL	2.21	0.00	0.37	1.06	0.44	0.02	0.85	0.05	2.99
PL	24.35	1.61	0.08	15.54	11.26	2.46	7.20	1.24	2.47
PT	0.64	4.96	0.16	1.53	4.37	3.84	2.98	0.00	2.51
RO	11.40	1.37	0.88	13.41	8.06	3.07	4.36	0.31	1.68
SE	3.09	0.78	0.52	1.35	25.31	7.68	22.29	0.00	0.94
SI	0.08	1.43	0.00	0.11	2.54	0.85	0.63	0.01	0.20
SK	2.42	0.12	0.01	0.67	2.55	1.11	1.33	0.03	0.28
UK	9.02	0.60	1.02	4.02	7.38	4.14	37.78	0.04	14.21
Total	229.77	63.11	6.23	107.61	176.06	68.10	125.98	9.82	73.32

Table B3. 2050 Low End Biomass Potential in EU27 Countries and the UK. Values in million dry tonnes.

Country	Agricultural residues	Manure	Biowaste	Ligno. Crops	Wood	Forestry residues	Secondary forestry residues	Prunings	MSW
AT	13.65	0.21	0.04	0.26	3.29	3.56	2.55	0.05	0.58
BE	2.11	1.99	0.07	0.37	0.54	0.09	0.71	0.03	0.27
BG	6.56	0.00	0.01	0.95	0.85	1.45	0.38	0.33	0.41
CY	0.01	0.00	0.00	0.07	0.00	0.00	0.05	0.00	0.06
CZ	7.47	0.64	0.01	0.73	2.46	1.22	1.78	0.03	0.56
DE	29.42	10.80	0.26	2.96	11.07	5.10	8.39	0.14	3.21
DK	1.82	2.69	0.04	0.27	0.42	0.10	0.52	0.00	0.55
EE	0.07	0.11	0.01	0.25	1.80	0.59	0.63	0.00	0.16
ES	14.50	4.79	0.21	9.32	2.61	3.56	2.95	2.41	3.07
FI	2.36	0.38	0.07	0.91	7.85	4.22	7.75	0.00	0.31
FR	50.20	4.35	0.07	3.92	9.87	4.18	3.90	0.12	2.91
GR	2.04	0.27	0.01	0.80	0.51	0.21	0.41	0.21	0.68
HR	1.88	0.32	0.00	0.04	0.67	0.25	0.36	0.02	0.28
HU	8.50	0.43	0.01	1.69	1.26	0.32	0.59	0.14	0.48
IE	0.37	1.88	0.01	3.01	0.47	0.06	0.38	0.00	0.65
IT	9.28	5.48	0.47	0.37	3.10	3.57	2.34	0.43	5.37
LT	0.55	0.32	0.02	0.03	1.06	0.22	0.80	0.00	0.20
LU	0.13	0.00	0.01	0.44	0.10	0.02	0.03	0.00	0.04
LV	0.31	0.05	0.00	1.14	2.03	0.68	1.44	0.00	0.07
MT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NL	1.67	0.00	0.15	0.42	0.19	0.01	0.63	0.02	1.24
PL	21.67	4.69	0.03	6.12	4.92	1.51	5.33	0.57	1.02
PT	0.50	3.49	0.06	0.60	1.91	2.39	2.20	0.00	1.04
RO	10.51	1.07	0.36	5.28	3.53	2.02	3.23	0.14	0.69
SE	2.66	0.54	0.22	0.53	11.07	5.46	16.50	0.00	0.39
SI	0.06	0.70	0.00	0.04	1.11	0.57	0.46	0.00	0.08
SK	2.21	0.00	0.00	0.27	1.12	0.72	0.98	0.01	0.12
UK	7.47	0.27	0.42	1.58	3.23	2.86	27.97	0.02	5.87
Total	198.01	45.48	2.57	42.39	77.03	44.96	93.27	4.66	30.30

Table B4. 2050 High End Biomass Potential in EU27 Countries and the UK. Values in million dry tonnes.

Country	Agricultural residues	Manure	Biowaste	Ligno. Crops	Wood	Forestry residues	Secondary forestry residues	Prunings	MSW
AT	19.15	0.32	0.07	0.79	8.28	6.28	3.80	0.13	1.07
BE	2.77	2.36	0.14	1.12	1.35	0.17	1.06	0.08	0.49
BG	7.87	0.32	0.03	2.84	2.14	2.48	0.56	0.85	0.77
CY	0.01	0.00	0.00	0.21	0.01	0.00	0.08	0.00	0.11
CZ	9.12	2.04	0.02	2.19	6.18	2.21	2.65	0.08	1.03
DE	36.69	4.68	0.47	8.88	27.83	8.05	12.46	0.36	5.94
DK	2.61	1.88	0.07	0.80	1.07	0.19	0.77	0.00	1.01
EE	0.11	0.38	0.02	0.76	4.52	0.32	0.94	0.00	0.30
ES	18.62	5.32	0.40	27.96	6.55	5.86	4.39	5.90	5.68
FI	2.99	0.48	0.13	2.73	19.73	6.86	11.51	0.01	0.57
FR	64.24	17.20	0.13	11.76	24.81	6.63	5.80	0.31	5.37
GR	2.62	0.43	0.01	2.41	1.27	0.23	0.60	0.54	1.26
HR	2.21	0.16	0.01	0.11	1.69	0.23	0.53	0.05	0.52
HU	10.09	2.10	0.02	5.07	3.16	0.61	0.88	0.36	0.89
IE	0.53	1.07	0.01	9.03	1.19	0.11	0.56	0.00	1.20
IT	11.73	7.74	0.86	1.12	7.79	6.01	3.48	1.12	9.94
LT	0.73	0.43	0.04	0.09	2.67	0.42	1.19	0.00	0.36
LU	0.16	0.00	0.01	1.31	0.25	0.04	0.04	0.00	0.06
LV	0.42	0.11	0.01	3.43	5.10	3.27	2.14	0.00	0.13
MT	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
NL	2.36	0.00	0.28	1.25	0.48	0.02	0.93	0.06	2.29
PL	26.79	1.45	0.06	18.37	12.38	2.71	7.92	1.49	1.89
PT	0.71	4.46	0.12	1.81	4.81	4.22	3.28	0.00	1.91
RO	12.58	1.24	0.67	15.84	8.87	3.38	4.80	0.38	1.28
SE	3.36	0.70	0.40	1.60	27.84	8.45	24.51	0.01	0.72
SI	0.09	1.29	0.00	0.13	2.79	0.94	0.69	0.01	0.15
SK	2.66	0.11	0.01	0.80	2.81	1.22	1.46	0.03	0.21
UK	9.77	0.54	0.78	4.75	8.11	4.55	41.55	0.05	10.85
Total	250.97	56.80	4.76	127.17	193.67	75.43	138.58	11.79	56.01

Annex C

Conversion table of energy units used in the report.

Table C1. Energy Unit Conversion Table

From	To	Value	Notes
1 PJ	TWh	0.278 TWh	1 TWh = 3.6 PJ
1 PJ	GWh	277.78 GWh	
1 PJ	bcm CH_4	~0.028 bcm	Based on LHV of CH_4: ~35.8 PJ/bcm
1 PJ	ktoe	23.88 ktoe	1 toe = 41.87 GJ
1 PJ	Mtoe	0.0239 Mtoe	
1 bcm CH_4	PJ	~35.8 PJ	Based on lower heating value (LHV)
1 bcm CH_4	TWh	~9.94 TWh	
1 TWh	PJ	3.6 PJ	
1 Mtoe	PJ	41.87 PJ	
1 tonne dry wood	GJ	~18-20 GJ	Depends on species and moisture content
1 MDT (10^6 tonnes)	PJ	~18,000-20,000 PJ	Used as average for woody biomass

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