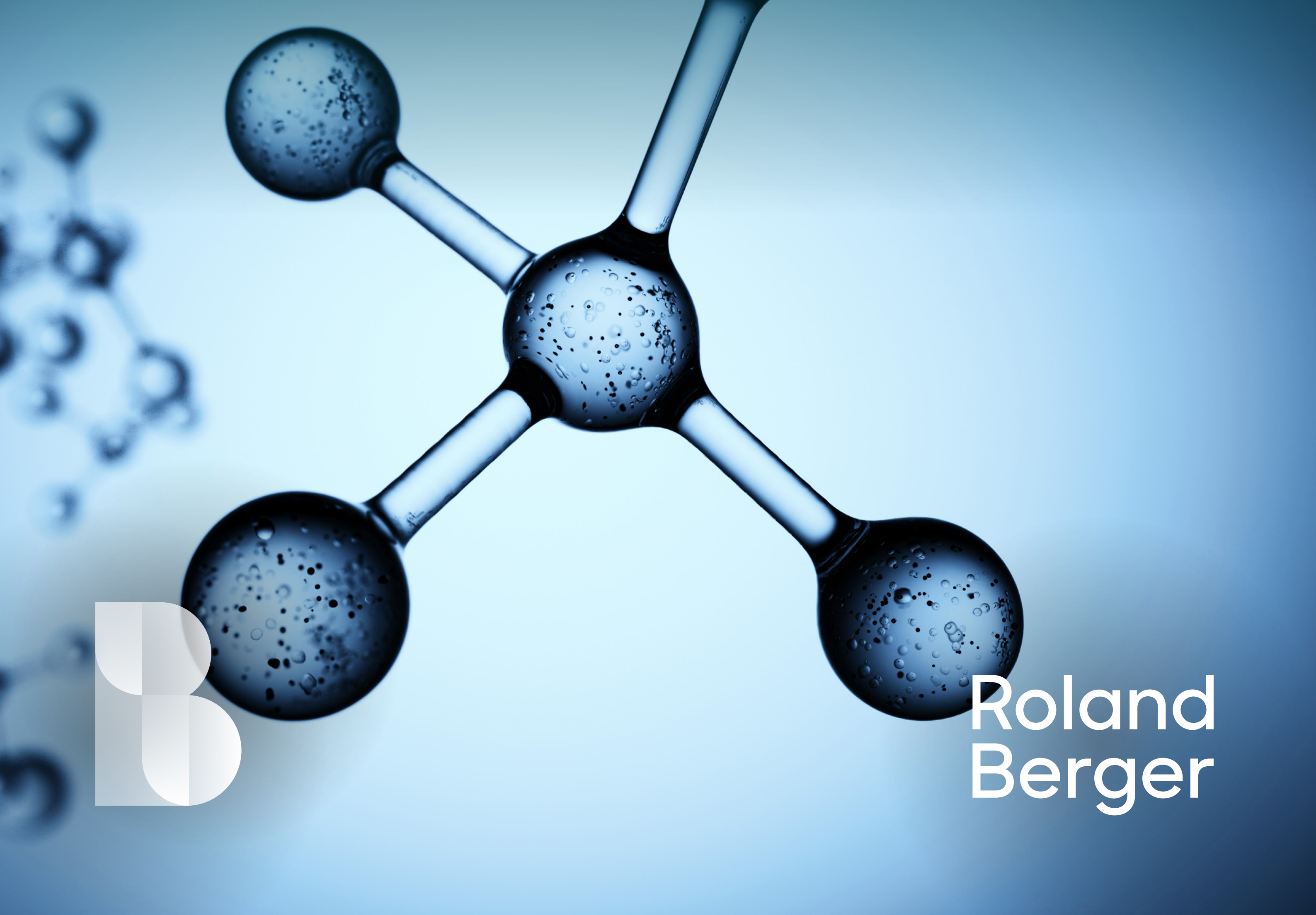
REPORT

Feasibility and potential of e-methane in the future energy mix

A comprehensive comparison of renewable energy vectors across the entire value chain in the Netherlands *van put tot pit*



Roland Berger

Foreword

The energy transition is both a necessity and an opportunity as the Netherlands strives to meet its ambitious climate goals. In this transition, exploring diverse renewable energy vectors is essential to ensuring a reliable, sustainable, and cost-effective energy system. E-methane, a renewable vector produced using renewable hydrogen and captured CO_2, is one such option that warrants careful consideration.

This report, *Feasibility and potential of e-methane in the future energy mix,* examines e-methane's potential role in the Netherlands' energy landscape, comparing it to other renewable vectors across the entire value chain *van put tot pit.* Commissioned by Gasunie and GasTerra, it has been independently prepared by Roland Berger BV ("Roland Berger") based on publicly available data, ensuring a transparent and objective assessment.

The insights in this report contribute to the ongoing dialogue on the future of energy in the Netherlands, providing relevant perspectives for policymakers, industry stakeholders, and market players. They are also applicable to other regions that share a similar reliance on natural gas and are likely to require substantial imports to meet their future renewable energy needs. A separate appendix details the assumptions and data sources used in this study.

Executive summary

Renewable energy vectors will play a critical role in the energy transition, especially in sectors that are difficult to electrify. Multiple renewable energy vectors exist, and a comprehensive comparison across the entire value chain, tailored to specific end-use cases, is essential to assess their potential and identify the most viable options for specific end-use cases. The goal of this study is to evaluate the feasibility and potential of e-methane, compared to the other renewable energy vectors biomethane, hydrogen, LOHC, ammonia and methanol, within the future energy mix of the Netherlands. The analysis includes the cost-competitiveness of these vectors across the entire value chain, from production to transportation, transmission, storage, distribution and end-use in the Netherlands. Additionally, non-financial factors such as technological maturity, environmental impact, safety characteristics and land-use efficiency are also considered.

E-methane is a renewable energy vector with a carbon neutral cycle synthesized by combining CO_2 captured from a point source or the air via DAC with renewable hydrogen. When combined with carbon capture and storage of the CO_2 released during the combustion, e-methane produced with biogenic CO_2 or DAC can even achieve negative emissions. While e-methane is expected to become more widely available and cost-competitive in long term, it will still be more expensive than CO_2 compensated natural gas and will require more cohesive regulation to scale up.

When comparing renewable energy vectors, e-methane produced from DAC has slightly higher production costs compared to ammonia and LOHC, as e-methane requires CO_2 in addition to renewable hydrogen. E-methane produced from biogenic CO_2 has lower production costs than CO_2 from DAC, but biogenic CO_2 availability is expected to be limited in the long term. In terms of transportation, pipelines are the most cost-competitive option for shorter distances, provided sufficient volumes are transported. For medium to longer distances, shipping becomes more cost-competitive. E-methane's landed cost at port is competitive with other renewable energy vectors when delivered in their end-use state. For hydrogen-specific applications, ammonia and liquid hydrogen offer the lowest landed cost.

Five key use cases where e-methane could play a role were selected for further analysis: iron and steel production, process heat for the five large industrial clusters in the Netherlands, process heat for the dispersed industrial cluster 6, central dispatchable electricity production and decentral heating. These use cases were selected based on their feasibility for e-methane and their projected demand in the Netherlands. Together, they are forecasted to represent more than 70% of the total Dutch e-methane demand. Among these, e-methane emerges as a cost-competitive vector in the long term – towards 2040 and beyond – for end-use cases with high downstream costs, specifically decentral heating, industrial process heat for cluster 6 and central dispatchable electricity production. These use cases demand extensive pipeline networks for distribution or significant seasonal storage. E-methane's cost advantage stems from its ability to serve as a "drop-in" replacement for natural gas, effectively leveraging existing natural gas infrastructure, such as transmission, seasonal storage, distribution and end-use conversion, unlike hydrogen, which requires costly modifications to the current system. E-methane's cost-competitiveness is further bolstered by its lower CAPEX intensity, the technological maturity of its downstream processes, its positive emissions impact, its safety advantages and its efficiency in land use and logistics.

Initially, e-methane could be produced using biogenic CO_2. However, due to feedstock limitations, large-scale adoption will depend on DAC for CO_2 sourcing. While DAC presents significant potential, uncertainties around its costs pose challenges for the long-term cost-competitiveness of e-methane.

Ultimately, e-methane is a promising renewable energy vector for specific use cases with high downstream costs in the Netherlands and similar regions, where established natural gas infrastructure can be leveraged for renewable energy distribution. Its efficiency in terms of capital and operational costs, emissions, safety, land use and transportation makes it a viable vector in the renewable energy mix. Given the capital-intensive nature of the energy transition, adopting e-methane conserves financial and human resources, minimizes delays and enhances societal value, enabling a more resource-efficient transition. However, to realize the full potential of e-methane, it will be essential to advance technological maturity through R&D and demonstration projects, reduce renewable hydrogen production costs and scale DAC solutions to ensure economic viability. Additionally prioritizing high-impact end-use cases and implementing supportive regulatory frameworks will be key to driving e-methane adoption and integration into the future energy mix.

Contents

The need for renewable energy vectors

Renewable energy vectors are critical to the energy transition, especially in sectors that are difficult to electrify. To identify the most viable renewable energy vectors for a net-zero future, a comprehensive comparison at the value chain level is essential. This study aims to evaluate e-methane in comparison to other renewable energy vectors across the entire value chain – from production to transportation, transmission, distribution, storage and end-use – considering both financial and non-financial factors

1

The need to address global warming and its impact has led to global initiatives to achieve net-zero greenhouse gas emissions (GHG) or climate neutrality. These plans are rooted in the recognition that human activity, particularly the burning of fossil fuels, has significantly increased the concentration of GHGs in the atmosphere and changed the Earth's climate. To mitigate their impact and limit global temperature rise, the European Union, like many other governing bodies, has set an ambitious goal to achieve climate neutrality by 2050, in line with the Paris Agreement's aim to limit the temperature increase to 1.5 °C above pre-industrial levels.

As part of the EU's net-zero strategy, the Netherlands has committed to substantial GHG emission reductions: 55% by 2030 compared to 1990 and net-zero by 2050[1]. These targets reflect a commitment to transitioning to a sustainable and resilient energy system.

In the energy transition, as much of the energy consumption as possible should be electrified while sustainable energy vectors will play a vital role in sectors where electrification is not feasible

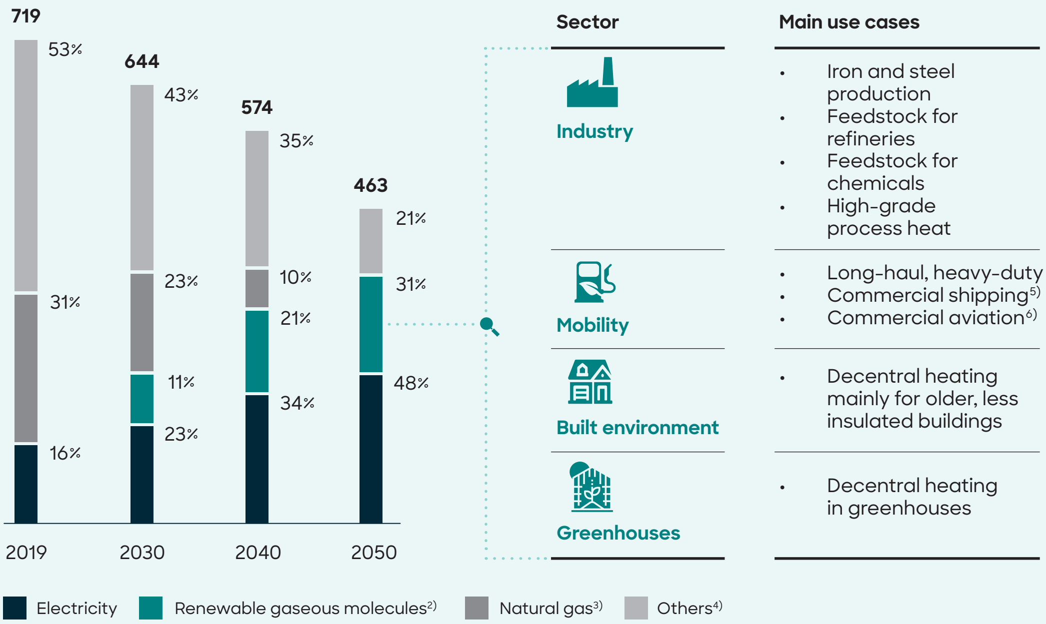
The energy transition relies on multiple levers, with electrifying as much energy consumption as possible being a key priority. Due to their higher efficiency, electric technologies reduce overall energy demand compared to fossil-based systems. For example, electric vehicles and heat pumps are more energy-efficient than conventional combustion technologies. Furthermore, GHG emissions can be minimized by powering electrification through low-emission sources such as solar, wind, geothermal, nuclear and hydropower.

In addition to electrification, energy efficiency measures - such as insulating buildings to reduce heating requirements - are crucial for further lowering energy use. While an increasing number of processes are becoming viable for electrification, it is still likely that no more than 50-60% of the Dutch final energy demand will be electrified by 2050. Sectors like heavy industry, aviation and shipping will not be fully electrified efficiently or economically before 2050. Industrial processes such as chemicals production or iron and steel manufacturing often require high-temperature process heat, which cannot be efficiently supplied by electricity. Certain fossil fuels, such as natural gas, are also used as feedstocks to produce key materials and substances, such as plastics, which require carbon atoms. Such industries and sectors need non-fossil, near-to-total net-zero alternatives if they are to decarbonize.

These so-called sustainable energy vectors such as renewable gaseous molecules (which include renewable hydrogen and its derivates and biomethane), synthetic fuels and biofuels are expected to play an increasingly vital role in replacing fossil fuels and supporting the transition to a net-zero future. The Integrated Infrastructure Outlook 2030-2050 (II3050), which forecasts future energy demand in the Netherlands for different sectors, was used as a starting point for projecting how the share of renewable energy vectors will develop in the Netherlands' future energy mix. ▶ A

1 The Dutch Climate Law

A Renewable gaseous molecules are expected to play an increasingly important role in decarbonizing non-electrifiable sectors [TWh][1)]



1) Only final energy demand is shown, meaning for example that electricity produced from renewable gaseous molecules (i.e. hydrogen and biomethane) will show as electricity demand. Demand forecasts are taken from the II3050 report, using the EU's International Ambition (IA) scenario for 2030 and the International Trading (INT) scenarios for 2040 and 2050, which are most comparable; 2) Hydrogen (derivatives) and biomethane; 3) Includes imported natural gas; 4) Includes other energy sources such as heat and oil which could also be (partially) delivered by sustainable energy vectors; 5) Excludes international shipping; 6) Excludes international aviation

Source: II3050

Sustainable energy vectors will likely form a significant part of the imports needed to meet the Dutch energy demand

The Netherlands has traditionally relied on domestic natural gas, largely from the Groningen gas field[2]. However, with the decline of natural gas production, imports have increased in recent years. To meet GHG reduction targets, the Netherlands aims to boost domestic renewable energy production, primarily from solar and wind. According to the II3050 report, the Netherlands will have around 120 GW in renewable electricity production capacity by 2040: 70 GW from solar PV, 35 GW from offshore wind and 15 GW from onshore wind. In addition, electrolysis capacity for hydrogen production is forecasted at 15 GW[3]. But even if these forecasts are realized, it will not meet total energy demand in 2040.

Energy imports will therefore be necessary. Most of these imports are expected to come in the form of sustainable energy vectors from regions that are expected to produce a surplus of energy such as the Middle East and North Africa (MENA), the US and southern and northern Europe.

2 2030-2050 Integrated Infrastructure Outlook, Netbeheer Nederland, 2023

3 Based on the International Trading (INT) scenario

Sustainable energy vectors can be classified into low-carbon and renewable vectors. This study focuses specifically on renewable energy vectors

Sustainable energy vectors can be categorized into low-carbon vectors, derived from fossil sources with carbon mitigating technologies such as carbon capture, and renewable vectors, derived from renewable energy[4] sources such as solar, wind or biomass. For example, blue hydrogen is a low-carbon vector, which can be produced through autothermal reforming of natural gas combined with carbon capture and storage (CCS). These sustainable energy vectors will not only supply energy for sectors that cannot be electrified but also serve as renewable feedstocks for certain industrial processes, such as refining and chemicals production.

Low-carbon vectors are likely to play a key role in the short to medium term due to their cost-competitiveness compared to renewable energy vectors. However, the focus of this study is on renewable energy vectors, as they are expected to be critical in reducing dependency on finite fossil resources and achieving net-zero emissions in the long term.

4 For the purposes of this study, within renewable energy, renewable electricity is defined as electricity generated from solar, wind, hydropower, geothermal or nuclear systems. Although nuclear energy is not classified as renewable in the EU, its carbon emissions are very low. Nuclear can thus be used for production of renewable energy vectors if the average emission intensity of the electricity grid is <18 g CO_2e/MJ

DEEP DIVE

Renewable energy vectors can be distinguished based on whether their origin was organic or synthetic. ▶ B

Organic renewable energy vectors are derived from organic matter, such as plants or animal waste, which mainly consists of carbon and hydrogen atoms. These carbon atoms come from atmospheric carbon dioxide (CO_2) absorbed by plants and converted into organic matter. From this matter, gaseous vectors like biomethane (CH_4) and liquid vectors like biomethanol (CH_3OH) can be produced.

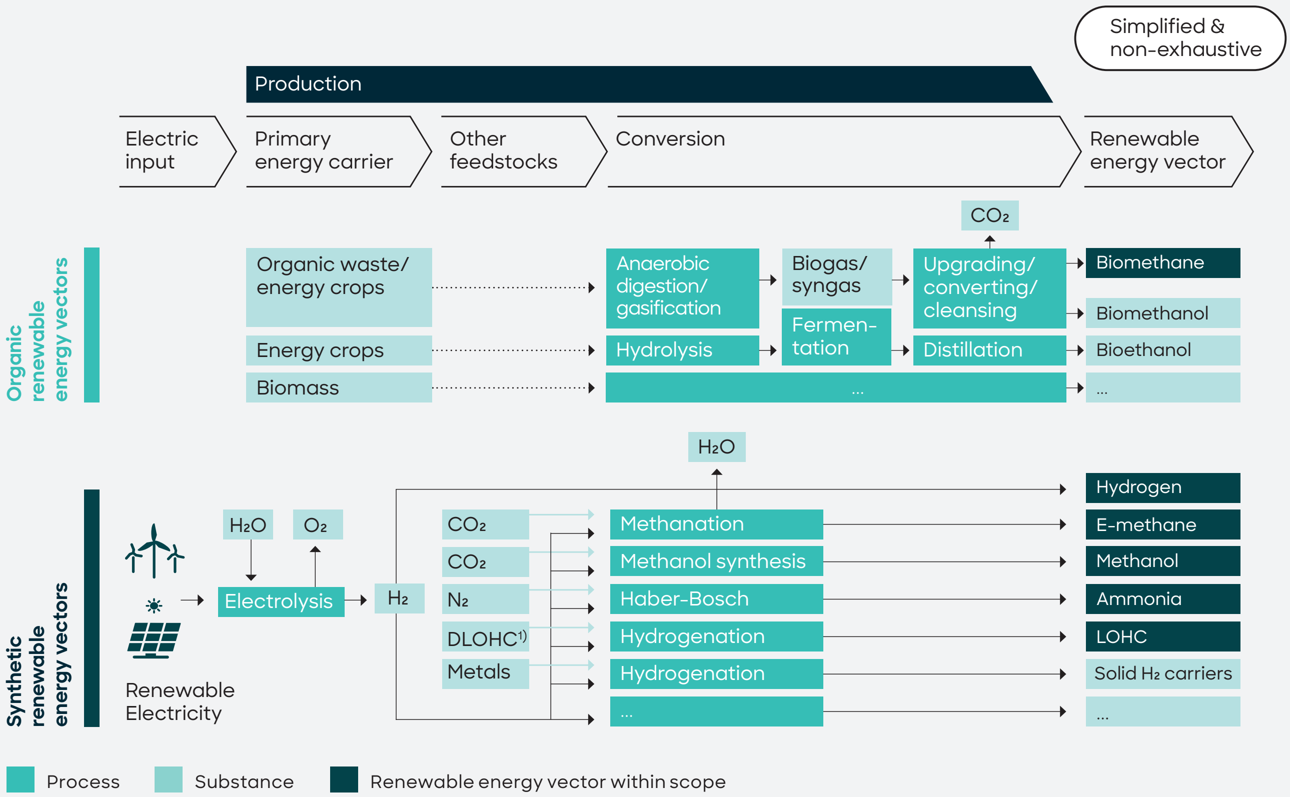
When organic renewable energy vectors are combusted, CO_2 is released back into the atmosphere. This CO_2 is considered part of the short carbon cycle, having been recently absorbed by organisms, and is thus considered net-zero emissions. In contrast, combusting fossil fuels releases CO_2 from the long carbon cycle: that CO_2 was absorbed from the atmosphere millions of years ago, and its release contributes to current atmospheric buildup of CO_2.

Synthetic energy vectors are chemically produced, starting with renewable electricity. This electricity can split water into hydrogen and oxygen via electrolysis to produce renewable hydrogen, which can either be used directly or converted into other synthetic renewable energy vectors to increase energy density and facilitate transportation or meet specific end-use requirements.

Examples of such hydrogen carriers include liquid organic hydrogen carriers (LOHC), ammonia (NH_3) and methanol (CH_3OH). LOHC can absorb and release hydrogen, making it transportable like oil. Ammonia, produced from hydrogen and nitrogen via the Haber-Bosch process, liquefies at -33 °C, making it easier to transport than in gaseous form. After transport, ammonia can be potentially reconverted into hydrogen by ammonia cracking or can be directly used as feed-stock for fertilizers or fuel for applications such as shipping and electricity. Methanol, produced either organically or synthetically, can also be transported as a liquid (under room temperatures) and later reconverted to hydrogen or used directly as chemical feedstock or fuel for applications such as shipping. Hydrogen can also be converted into solid hydrogen carriers such as sodium boron hydride, iron hydride and magnesium hydride. These solid hydrogen carriers are being further explored in initiatives such as the Iron Power alliance. However, this and other solid hydrogen carriers are considered out of scope for the purpose of this study due to the relatively lower technological maturity compared to other hydrogen carriers.

Like methanol, renewable methane (CH_4) can be produced either organically or synthetically. Methane from an organic source is called biomethane, while synthetic methane is also known as e-methane. E-methane is produced through methanation of hydrogen produced through electrolysis and CO_2. The notable aspect of renewable methane is that it is chemically close to natural gas, allowing the use of existing natural gas infrastructure and equipment for its transportation, storage and end-use. Additionally, renewable methane can be reconverted back to hydrogen if needed.

B Organic renewable energy vectors are produced from biomass, whereas synthetic renewable energy vectors are produced from renewable hydrogen



1) Dehydrogenated liquid organic hydrogen carrier

Source: European commission, Desk research

Within renewable energy vectors, this study takes a close look at e-methane and compares it to renewable hydrogen (derivatives) from beginning to end of the value chain considering both financial and non-financial factors

Over the years, numerous studies – e.g. from leading organizations International Energy Agency (IEA) and International Renewable Energy Agency (IRENA) – have compared renewable hydrogen and its derivatives, focusing primarily on the initial stages of the value chain: from production to long-distance transportation and reconversion. The costs and challenges in the latter stages of the value chain, including storage, distribution and end-use conversion, are rarely considered. Yet local investments in these downstream stages will be essential to ensure the scalability and viability of renewable energy vectors. They are not just operationally significant, they will drive the overall cost-effectiveness, reliability and integration of the vectors into the economy.

Moreover, most existing studies tend to focus on a single aspect of comparison, such as financial metrics, GHG emissions intensity, or technological maturity. While these analyses are valuable, they do not offer the integrated perspective necessary for informed decision-making. Thus, a comprehensive comparison of energy vectors across the entire value chain *(van put tot pit)* is required.

This study seeks to address these gaps by evaluating both the financial and non-financial feasibility of e-methane and comparing it to renewable hydrogen and its derivatives from beginning to end of the value chain. Despite its potential advantages in the latter value chain stages of transportation, storage and end-use conversion, e-methane has rarely been the subject of renewable energy vector studies. Only recently have Agora[5] and Frontier[6] compared e-methane with renewable hydrogen and its derivatives, but these studies focused only on the initial value chain steps. A recently published multi-criteria analysis (MCA)[7] of hydrogen carriers in the Netherlands does include e-methane for comparison throughout the value chain but provides only a high-level cost estimate that is largely based on the HyDelta report[8].

This comprehensive assessment of e-methane and other vectors thus incorporates financial factors, GHG emissions, technology readiness levels (TRL) and safety considerations, and does so across the entire value chain. By examining all these dimensions, this study offers a nuanced evaluation that will enable stakeholders to identify the most suitable renewable energy carrier for specific situations.

It is important to note that multiple renewable energy vectors likely will coexist in the future. However, each vector requires local infrastructure, ranging from import and storage facilities to transportation networks and end-use conversion equipment. Given the investment costs and spatial requirements, developing full infrastructure for each renewable energy vector

5 Hydrogen import options for Germany, 2023
6 Comparative analysis of import costs of synthetic methane to Germany, 2024
7 Comparison of hydrogen carriers – Multi-criteria analysis of supply chains in the Netherlands, 2024
8 Value Chain Analysis – Hydrogen value chain literature review, 2021; Risks, uncertainty and collaboration in the hydrogen-based value chain – Technical analysis of hydrogen supply chains, 2023

likely is uneconomical and given the required man-power likely is unfeasible. Consequently, choices must be made based on use cases of the vectors in all aspects of the value chain.

The goal of this study is to evaluate the feasibility and potential of e-methane within the future energy mix of the Netherlands

This study aims to investigate the potential of e-methane alongside other renewable energy vectors biomethane, hydrogen, LOHC, ammonia and methanol. Using 2040 as the reference year, this study therefore provides a long-term perspective, extending towards 2040 and beyond, on the future energy mix in the Netherlands in terms of:

- Demand for renewable energy vectors through the lens of various use cases in the Netherlands
- The cost-competitiveness[9] of renewable energy vectors across the entire value chain
- Additional factors such as technological maturity, environmental impact, safety characteristics and land-use efficiency

The study is structured as follows: Chapter 2 introduces the e-methane energy vector and the status of its development. Chapter 3 identifies the key use cases that are potentially attractive for e-methane. Chapter 4 outlines the boundary conditions and key input assumptions used in the study. Chapter 5 compares the cost of e-methane to other energy vectors for identified use cases. Chapter 6 evaluates the energy vectors on non-financial parameters such as emissions, safety and land use. Chapter 7 presents the conclusions and recommendations of the study.

9 Cost-competitiveness only includes actual costs and excludes government subsidies or other financial schemes

DEEP DIVE

A typical value chain for renewable energy vectors imported into the Netherlands begins with production. This involves producing the primary energy carrier, such as biomass or renewable hydrogen, and converting it into the renewable energy vector. ▶C

The next step is long-distance transportation, where the renewable energy vector is first prepared for transportation – either compressed for pipelines or liquefied for vessels – and then transported. Shipping also includes storage at both the production and import locations, followed by gasification at the import location if the vector was liquefied.

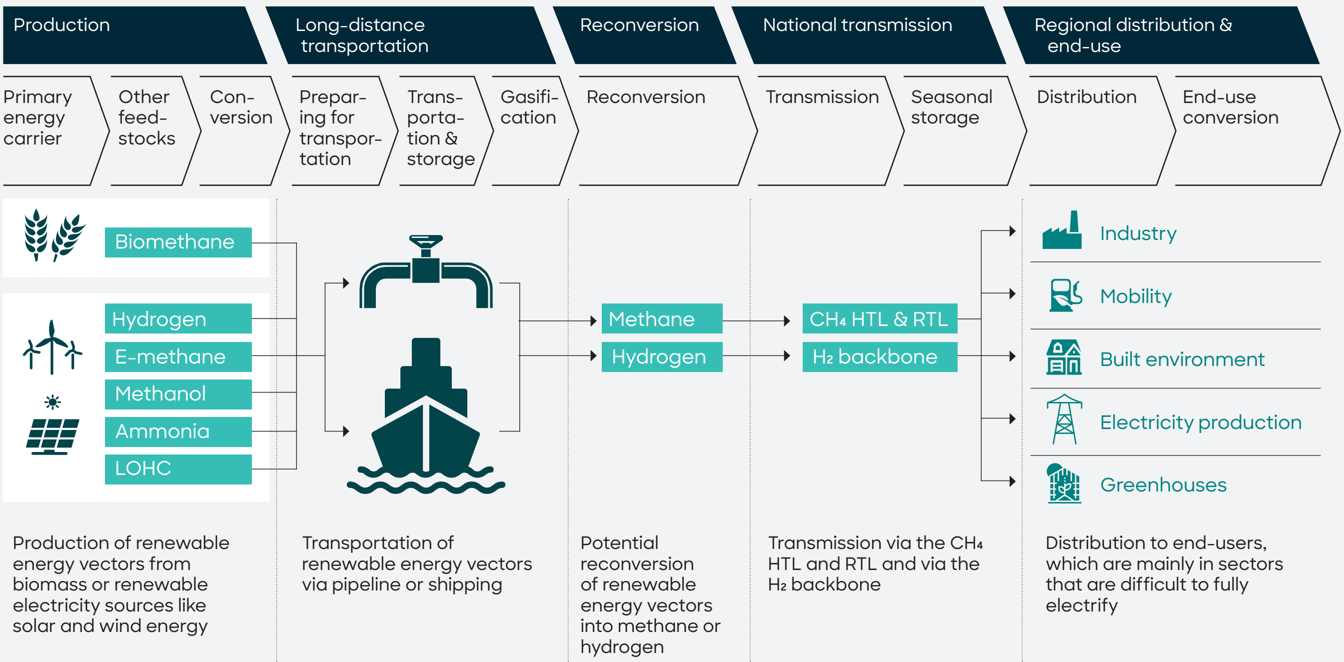
The third step involves the potential reconversion of the renewable energy vector into hydrogen, depending on the end-use. For instance, oil refining requires hydrogen, necessitating reconversion. Conversely, in fertilizer production, ammonia is needed, so reconversion is unnecessary if the renewable energy vector is ammonia.

After potential reconversion, the renewable energy vector enters the national transmission network, which may include seasonal storage. The Netherlands has an extensive transmission and storage network for methane, which includes main (HTL) and regional (RTL) transmission pipelines. There are also plans to develop a hydrogen backbone by 2030[10], including sufficient storage capacity to operate the system. This would require repurposing part of the existing HTL and RTL from methane to hydrogen, including the necessary adjustments. The transmission methods for other vectors like ammonia and methanol are still being determined.

10 Hynetwork roll-out plan (https://www.hynetwork.nl/en/about-hynetwork/the-roll-out-plan)

Finally, the renewable energy vectors are distributed to end-users. The final step varies greatly depending on the use case. While for e-methane, most existing end-use equipment for natural gas can likely be used as-is, additional investments are likely required to adapt the equipment to be suitable for other energy vectors like hydrogen.

C The value chain for renewable energy vectors includes production, transportation, reconversion, national transmission, regional distribution and end-use



E-methane, potentially attractive renewable energy vector

E-methane is a renewable energy vector which can serve as a "drop-in" vector, leveraging the existing natural gas infrastructure and thus minimizing transition costs. When produced using biogenic CO_2 or DAC and combined with CCS at end-use, it will enable negative emissions. While e-methane is expected to become more widely available and cost-competitive in the future, it will still be more expensive than CO_2 compensated natural gas and will require more cohesive regulation to scale up

2

The Netherlands' transition to net zero involves substantial changes in the energy mix. Natural gas, which comprises about one-third of the country's energy supply[11], primarily consists of methane (85-90%) alongside smaller quantities of hydrocarbons like ethane and propane, as well as traces of non-hydrocarbon gases such as CO_2 and nitrogen. The exact makeup of natural gas can vary depending on its source, including conventional reservoirs, shale formations or coal seams.

E-methane can serve as a "drop-in" vector, leveraging the existing natural gas infrastructure and thus minimizing transition costs

An option for decarbonizing the Dutch energy supply is e-methane, a renewable gas created by combining renewable hydrogen with GHG-neutral CO_2. E-methane can be synthesized to meet the specific compositions of L-gas and H-gas[12] utilized in the Netherlands, making it nearly identical to natural gas in terms of combustion properties, calorific value and behavior within pipeline systems. This alignment enables e-methane to serve as a "drop-in" replacement, effectively leveraging the existing natural gas infrastructure – such as LNG terminals, vessels, storage facilities, pipelines and end-use equipment. By doing so, it has the potential to minimize additional downstream investments needed during the energy transition. While e-methane's production costs will be higher than hydrogen due to the additional conversion step, its ability to minimize infrastructure changes may offset these costs. This allows for a less disruptive and therefore possibly less costly shift from fossil fuels to renewable energy vectors – while still meeting the aims of the Paris Agreement.

E-methane is a renewable energy vector with a carbon neutral cycle, as the CO_2 emitted during combustion equals the CO_2 captured during its production

E-methane is synthesized by combining CO_2 captured from biogenic point sources or from the air via direct air capture (DAC) with renewable hydrogen produced via electrolysis[13]. When combusted, e-methane releases the same amount of CO_2 which was previously captured during its production – thus effectively resulting in a carbon neutral cycle with no net increase in CO_2 emissions to the atmosphere. In combination with CCS of the CO_2 released during combustion, even negative emissions can be achieved. E-methane can also be created with CO_2 captured from the combustion of fossil fuels. In this case, the fossil source from which the CO_2 is captured is considered the CO_2 emitter.

The Sabatier method remains the only commercialized synthesis method for e-methane – for now

E-methane can be produced via several methods, including Sabatier methanation, hybrid methanation, direct methanation and biological methanation. Currently, the Sabatier pro-

11 IEA

12 L-gas refers to low-calorific gas (from the Groningen gas field) and H-gas refers to high-calorific gas (from most other places in the world)

13 The RED II Delegated Act restricts the eligibility of CO_2 captured from industrial activities until 2041 (or 2036 for CO_2 from electricity production) for RFNBO, meaning that only CO_2 captured through DAC or from biogenic sources can be used for e-methane production after 2040 if used as RFNBO

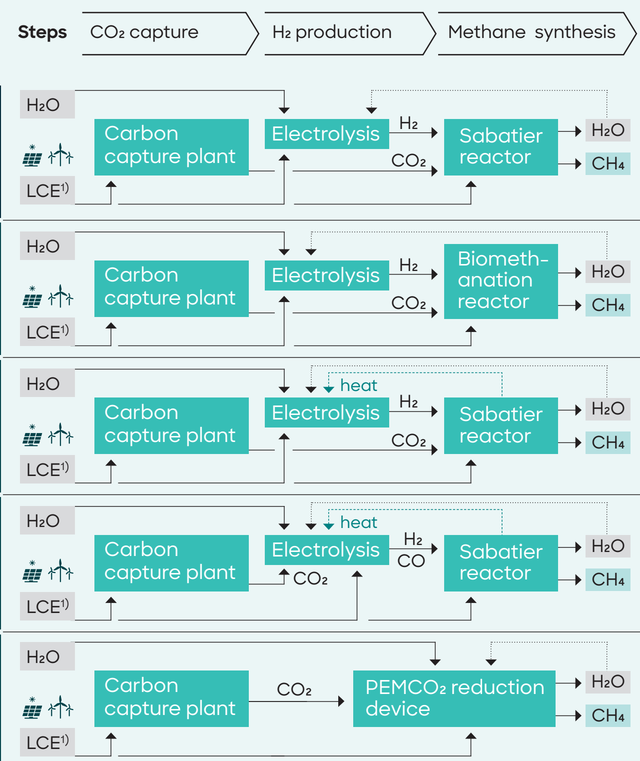
cess is the only commercially viable method. It involves a chemical reaction between hydrogen and CO_2 over a nickel catalyst at 200-500 °C, achieving an overall process efficiency of both electrolysis and methanation of about 65%. ▶ D

Emerging technologies such as biological methanation leverage microorganisms to catalyze the reaction between hydrogen and CO_2 at low temperatures, achieving efficiencies of up to 65%. Hybrid methods improve efficiency by utilizing heat from the exothermic reaction to support hydrogen production. Examples include conventional Sabatier methanation integrated with hydrogen electrolysis and solid oxide electrolyzer cell (SOEC) methanation. In SOEC methanation, water and CO_2 are co-electrolyzed to produce hydrogen and carbon monoxide (CO), which are subsequently converted to methane, potentially achieving efficiencies of up to 90%. Direct methanation combines water electrolysis and CO_2 reduction in a single step using proton-exchange membrane (PEM) electrolysis, achieving efficiencies of up to 80%. These emerging methods represent promising advancements in the efficiency and scalability of e-methane production in the future.

D There are five main methods to synthesize e-methane, but Sabatier is the only commercialized method

Simplified & non-exhaustive

Process flow



Technology		Reaction method	Methanation temp. [°C]	Overall process efficiency[2] [%]	Technological maturity
Commercial	Conventional Sabatier methanation	Chemical	200-500	60-65	High
Innovative	Biological methanation	Biochemical	35-65	60-65	Medium
Innovative – Hybrid methods	Sabatier methanation	Electro-chemical	220	70-80	Medium
Innovative – Hybrid methods	SOEC methanation	Electro-chemical	800	75-90	Low
Innovative	$PEMCO_2$ methanation	Electro-chemical	60-80	70-80	Low

1) Low carbon energy; 2) Figure comprises efficiency of electrolysis and methane synthesis

Source: Japan Gas Association, IEA, Store & Go, DENA

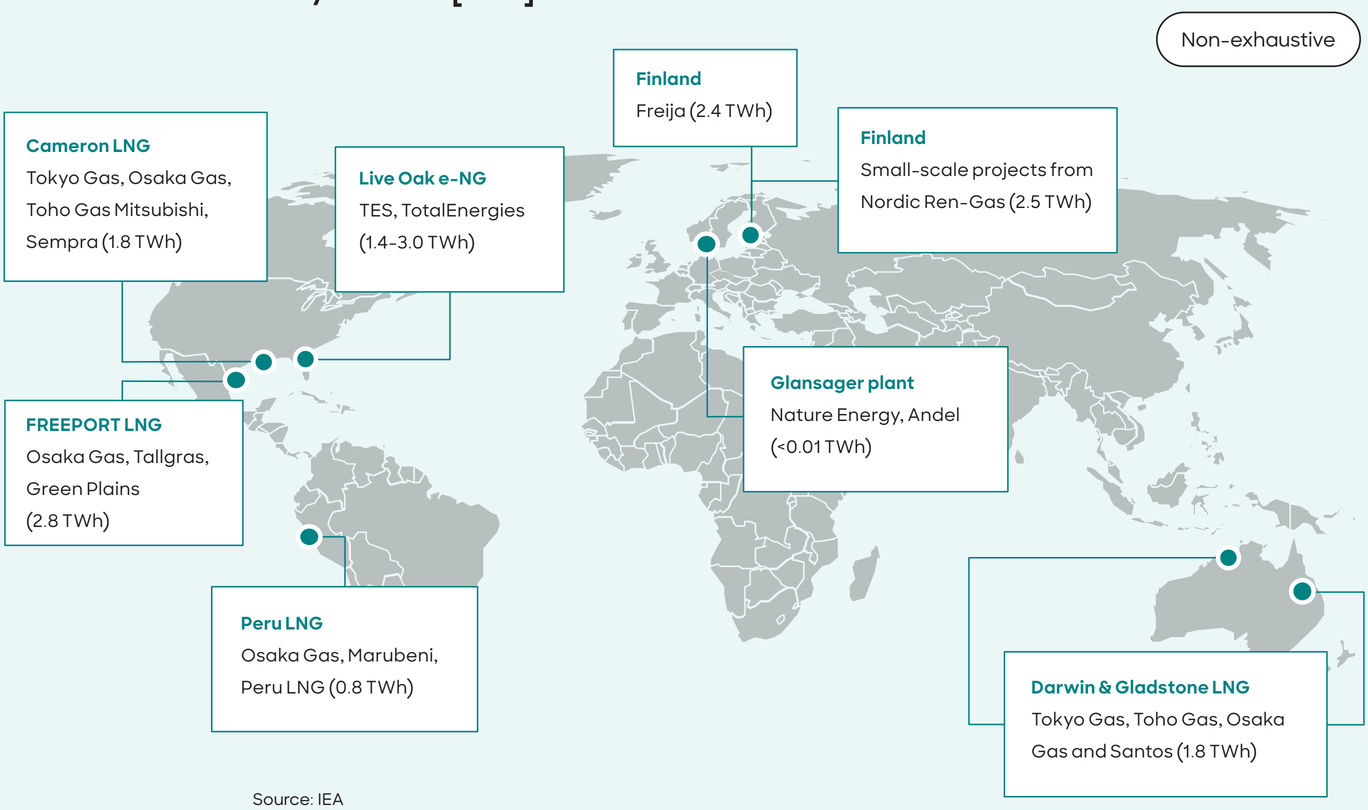
Despite the potential of these newer methods to improve efficiency, they are not yet commercially available, making Sabatier methanation the most viable production method for e-methane today. It is therefore the reference production method in this study.

E-methane is gaining momentum, with global production expected to exceed 10 TWh by 2030

The IEA projects global e-methane production could exceed 10 TWh by 2030[14], contingent on securing investments in ongoing projects. ▶ E These projects are in regions with abundant and low-priced renewable electricity, primarily the US, Australia and the Nordics, with over 50% of supply expected from the US. Japan positions itself as a leader in e-methane development, aiming to source 1% of city gas from e-methane by 2030 and 90% by 2050, with major investments in large-scale production abroad, including in Cameroon and the US. In Europe, TES is planning to build an e-methane import hub in Germany[15], while Ren-Gas leads small-scale projects in Finland targeting 2.5 TWh. The sector is also gaining momentum with the formation of the global e-NG[16] coalition, which includes several industry leaders[17].

14 E-methane - a new gas for a net-zero future, IEA
15 TES is planning to build an LNG import terminal in Germany with the aim to later import e-methane produced in US
16 E-natural gas is synonymous with e-methane
17 https://www.eng-coalition.org/

E Global e-methane production could potentially exceed 10 TWh by the year 2030 [TWh]

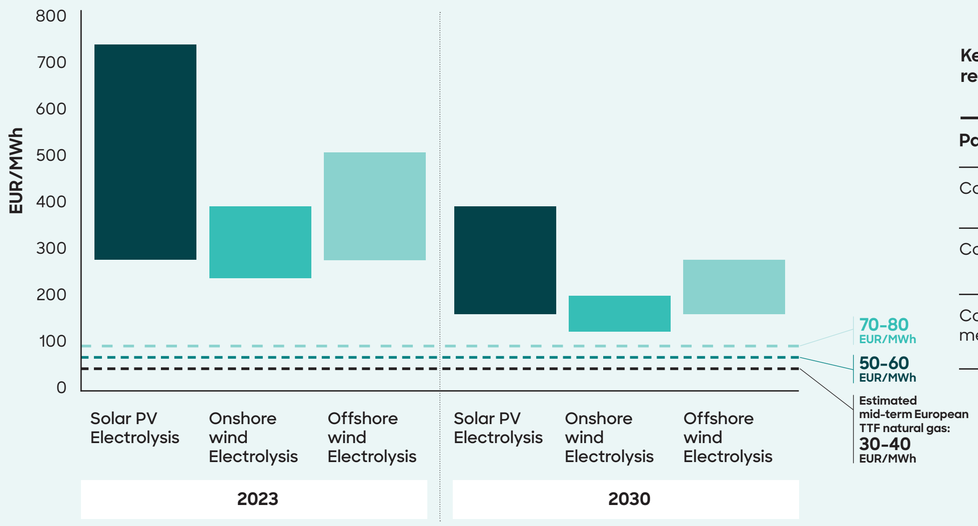


Source: IEA

E-methane production costs are expected to drop by 2030, though not below the cost of natural gas

Based on IEA calculations, current e-methane production costs are in the range of 250-700 EUR/MWh. This is largely driven by the cost of renewable hydrogen and the GHG-neutral CO_2. By 2030, e-methane production costs are expected to drop to 150-300 EUR/MWh due to reductions in the costs of renewable hydrogen and carbon capture, improved methanation efficiency and economies of scale. ▶ F However, even at these lower costs e-methane production costs remain several times that of natural gas, which is expected to be priced at EUR 50-80 EUR/MWh, including the ETS price.

F According to IEA, current e-methane costs are in the range of 250 - 700 EUR/MWh (3-12 x NG prices including ETS) - Costs projected to decrease by 2x by 2030 [EUR/MWh]



Key cost reduction drivers		Impact on production cost
Parameter	**Trend**	
Cost of H_2	↘	High
Cost of DAC	↓	Medium
Cost of methanation	↘	Low

- - - NG price assuming an ETS price of EUR 100 per ton CO_2 emitted
— — NG price assuming an ETS price of EUR 200 per ton CO_2 emitted
↑ Costs strongly increasing
↗ Costs increasing
↘ Costs decreasing
↓ Costs strongly decreasing

Source: IEA, Desk research

E-methane is expected to meet renewable fuel regulations globally, but a more cohesive regulatory framework is essential for its scale-up

E-methane is expected to meet the regulatory requirements for renewable fuel in key regions such as the US, EU and Japan. For example, e-methane can be classified as a renewable fuel of non-biological origin (RFNBO) under the EU's Renewable Energy Directive (RED) II.

However, the regulatory framework for e-methane is still in the early stages of development. While existing policies like the EU Green Deal indirectly support the transition to e-methane, they do not explicitly identify e-methane as a primary energy vector for decarbonization.

That being said, the source of CO_2 used in methane synthesis is increasingly scrutinized in global legislation. The International Organization for Standardization (ISO) has established international standards for calculating the carbon footprint of e-methane, allowing CO_2 from air, biogenic sources, or a company's own operations to be considered eligible. Japan's Clean Gas Certificate scheme allows the use of CO_2 for e-methane as long as it does not contribute to an increase in atmospheric CO_2 levels upon combustion, though it does not specify the exact eligible CO_2 sources. In the EU, the RED II Delegated Act restricts the eligibility of CO_2 captured from industrial activities until 2041 (or 2036 for CO_2 from electricity production), meaning that only CO_2 captured through DAC or from biogenic sources can be used for e-methane production after 2040. In line with these EU regulations, this study considers only CO_2 captured from biogenic sources or via DAC for e-methane production, as well as for methanol production which is produced via renewable hydrogen and captured carbon.

While e-methane is contributing to carbon reduction targets today, the regulatory environment remains fragmented and in development. For large-scale deployment, enhanced and more cohesive regulations will be essential to scale up e-methane production.

End-use cases key in determining viability of renewable energy vector

By 2040, the Netherlands' projected demand for renewable energy vectors will be 137 TWh. Five key use cases are particularly promising for e-methane adoption based on feasibility and projected demand of e-methane. For each use case, considerations in different parts of value chain have been defined for both e-methane and hydrogen

3

Evaluating the feasibility and potential of e-methane in comparison with other renewable energy vectors requires analyzing a number of end-use cases in which demand for renewable gaseous molecules is significant and e-methane is a feasible option to meet that demand.

Projected demand in 2040 for renewable gaseous molecules is 137 TWh

E-methane and other renewable energy vectors are expected to be crucial for decarbonizing sectors that are difficult to electrify fully, such as industry, dispatchable electricity production, the built environment and greenhouses. Key sectors like fertilizers and refineries will also rely on these renewable energy vectors as feedstock. The future demand for renewable molecules will depend on factors like industrialization trends, electrification progress and grid capacity. To estimate the projected demand in the Netherlands, the II3050 report has been used as a reference for this study.

This study uses the international trading (INT) scenario as the reference case for projecting energy demand in the Netherlands[18]. The INT scenario assumes an important role for international supply chains and global trading of renewable energy vectors. The choice for this scenario was driven by the belief that coordinated global efforts are essential for achieving climate neutrality, given the shared nature of the climate crisis. The choice of scenario influences the cost of transporting renewable energy vectors in the Netherlands, as the costs directly depend on the total transported volume. The higher the volume the lower the cost per transported MWh. The study will also determine the sensitivity of other scenarios to transportation costs.

The II3050 report does not explicitly mention or forecast future e-methane demand. As e-methane has similar use cases to both hydrogen and biomethane, this study considers the total hydrogen and biomethane demand as the total addressable market for e-methane (and other renewable energy vectors). For the purpose of this study, renewable hydrogen and renewable methane (i.e. biomethane and e-methane) are collectively referred to as renewable gaseous molecules.

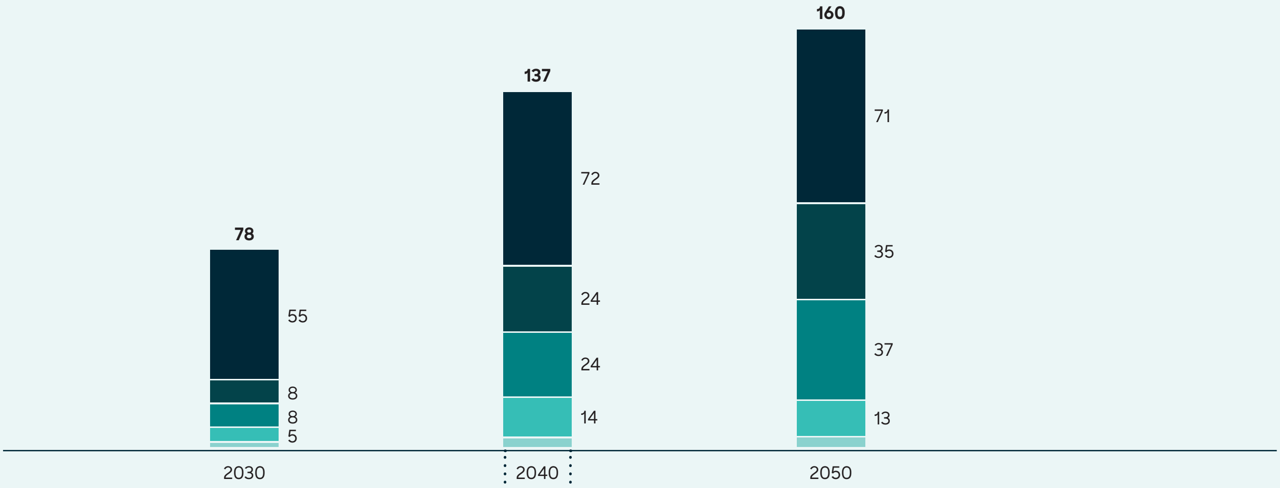
The total projected demand for renewable gaseous molecules in the Netherlands in 2040, according to the INT scenario, is 137 TWh[19,20]. The largest share of this demand (72 TWh) is expected from industry, followed by mobility, the built environment, electricity production and greenhouses. ▶ G

18 The II3050 report outlines four scenarios for the future energy transition, varying in the degree of government control versus market-driven developments. Moreover, the scenarios differ in the scale of the transition – whether national, regional or international – and consider the varying technology and energy carrier choices made by different sectors. The four scenarios are decentral initiatives (DEC), national leadership (NAT), European integration (EUR) and international trading (INT). For further details on the II3050 report, please refer to the appendix

19 In each use case, demand refers to domestic demand in the Netherlands and does not account for international demand. For example, the demand for renewable gaseous molecules in shipping is based solely on domestic requirements and does not include fuel bunkering for international shipping

20 Figure A shows the final energy demand for renewable gaseous molecules in 2040, which is 121 TWh. That number does not include renewable gaseous molecule demand for electricity production and district heating, which is included in the 137 TWh given here

G **Demand for renewable gaseous molecules is expected to be driven primarily by the industrial, mobility and built environment sectors [TWh]**

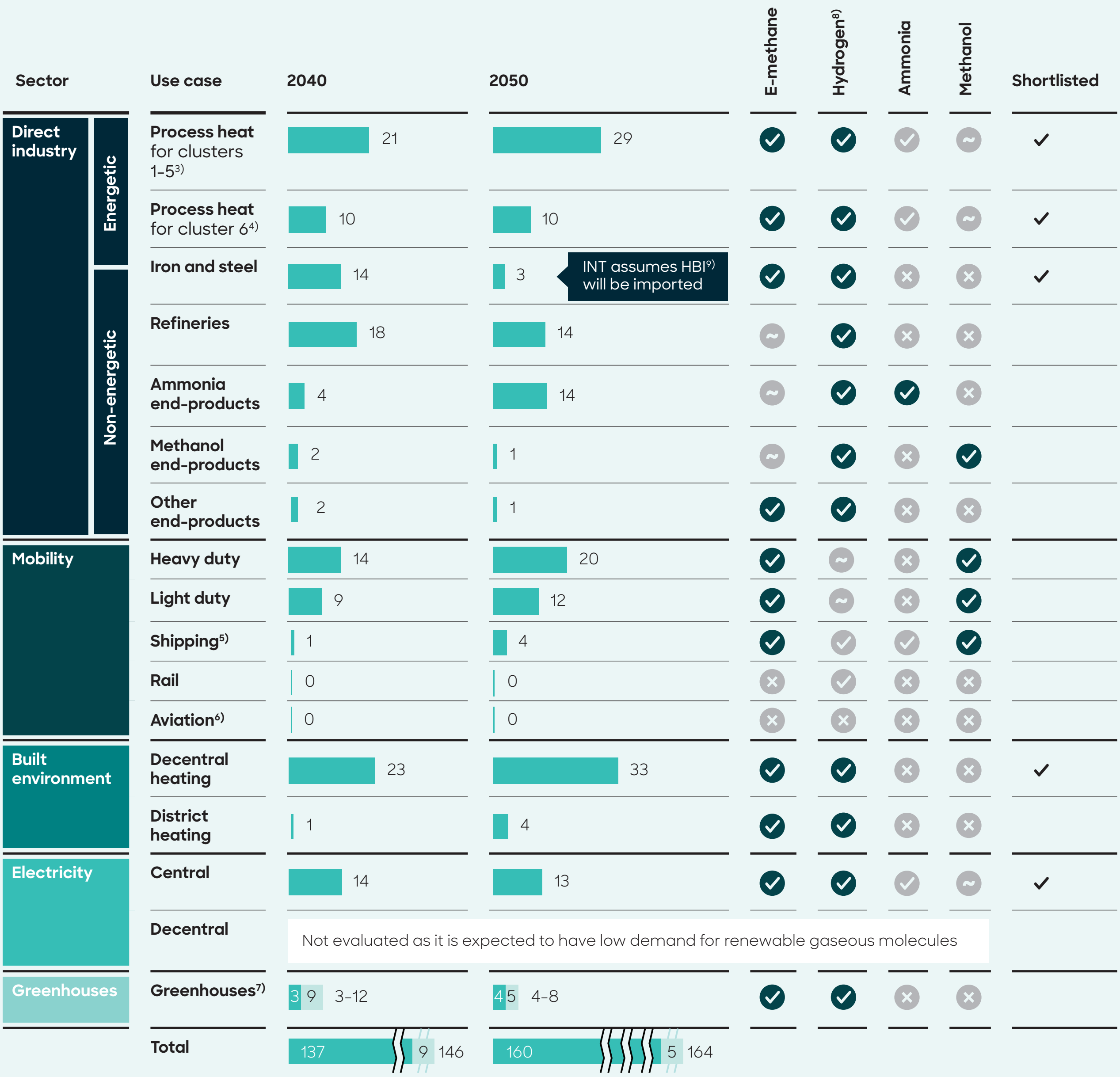


Sector		Use case	Demand [TWh]	Description
Direct industry	Energetic	**Process heat** for clusters 1-5[1)]	21	Renewable gaseous molecules used for moderate and high-temperature heat for industrial processes across different industries[3)]
		Process heat for cluster 6[2)]	10	
	Non-energetic	**Iron and steel**	14	Methane or hydrogen used for moderate and high-temperature heat and as feedstock for steel production
		Refineries	18	Hydrogen used as feedstock for hydrocracking and desulfurization to produce petroleum products
		Ammonia end-products	4	Hydrogen or ammonia used as feedstock to produce ammonia end-products in the chemicals industry
		Methanol end-products	2	Hydrogen or methanol used as feedstock to produce methanol end-products in the chemicals industry
		Other end-products	2	Methane and/or hydrogen used as feedstock to produce several other end-products in the chemicals industry
Mobility		**Heavy duty**	14	Renewable gaseous molecules used as fuel for trucks and buses
		Light duty	9	Renewable gaseous molecules used as fuel for cars and vans
		Shipping[4)]	1	Renewable gaseous molecules used as fuel for inland shipping
		Rail	0.1	Renewable gaseous molecules used as fuel for freight and passenger trains
		Aviation[5)]	0.04	Renewable gaseous molecules used as fuel for domestic (cargo) flights
Built environment		**Decentral heating**	23	Renewable gaseous molecules used for decentral heating and other energy use of residential and utility buildings
		District heating	1	Renewable gaseous molecules used for heating water, which is centrally distributed to residential and utility buildings
Electricity		**Central**	14	Renewable gaseous molecules used for centralized power plants for flexible electricity generation
		Decentral	0[6)]	Renewable gaseous molecules used for decentralized power plants for electricity generation for local use
Greenhouses		**Greenhouses**	3	Renewable gaseous molecules used for decentral heating of greenhouses for agriculture

1) Includes refineries and ammonia, methanol and other end-products; 2) Includes the food and beverage industry, paper industry and other industries; 3) Excludes demand for high-temperature heat for iron and steel production; 4) Excludes ~60 TWh forecasted demand for international bunkering of synthetic and biofuels in the Netherlands, based on IRENA report on decarbonizing the shipping sector, which estimates 3.5 EJ of 8.5 EJ total global shipping demand in 2040 to be for synthetic and biofuels and 6% of global bunkering to be in the Netherlands; 5) Excludes ~20 TWh forecasted demand for synthetic aviation fuel (SAF) for international aviation in the Netherlands in 2050, based on INT scenario in II3050 report; 6) Not evaluated as it is expected to have little demand for renewable gaseous molecules

Source: II3050

H Iron and steel, process heat, decentral heating and central dispatchable electricity production are shortlisted as main use cases for e-methane to further deepdive [TWh] 1), 2)



Sector		Use case	2040	2050	E-methane	Hydrogen[8]	Ammonia	Methanol	Shortlisted
Direct industry	Energetic	Process heat for clusters 1–5[3]	21	29	✓	✓	(✓)	~	✓
		Process heat for cluster 6[4]	10	10	✓	✓	(✓)	~	✓
	Non-energetic	Iron and steel	14	3 (INT assumes HBI[9] will be imported)	✓	✓	×	×	✓
		Refineries	18	14	~	✓	×	×	
		Ammonia end-products	4	14	~	✓	✓	×	
		Methanol end-products	2	1	~	✓	×	✓	
		Other end-products	2	1	✓	✓	×	×	
Mobility		Heavy duty	14	20	✓	~	×	✓	
		Light duty	9	12	✓	~	×	✓	
		Shipping[5]	1	4	✓	(✓)	(✓)	✓	
		Rail	0	0	×	(✓)	×	×	
		Aviation[6]	0	0	×	×	×	×	
Built environment		Decentral heating	23	33	✓	✓	×	×	✓
		District heating	1	4	✓	✓	×	×	
Electricity		Central	14	13	✓	✓	(✓)	~	✓
		Decentral	Not evaluated as it is expected to have low demand for renewable gaseous molecules						
Greenhouses		Greenhouses[7]	3 9 3–12	4 5 4–8	✓	✓	×	×	
		Total	137 9 146	160 5 164					

Considered as a feasible option: ✓ **Not considered:** (✓) Likely not a feasible option for NL; ~ Likely not economically viable; × Not technologically proven or low maturity, feasible only for niche applications

1) Figure details the applicability of the renewable energy vectors as a final energy form for the end use case. For example, hydrogen for process heat can be delivered as hydrogen or via ammonia or other liquid hydrogen carriers; 2) For further details on applicability of energy vectors per use case, please refer to the appendix document; 3) Includes refineries and ammonia, methanol and other end-products; 4) Includes the food and beverage industry, paper industry and other industries; 5) Excludes ~60 TWh forecasted demand for international bunkering of synthetic and biofuels in the Netherlands, based on IRENA report on decarbonizing the shipping sector, which estimates 3.5 EJ of 8.5 EJ total global shipping demand in 2040 to be for synthetic and biofuels and 6% of global bunkering to be in the Netherlands; 6) Excludes ~20 TWh forecasted demand for synthetic aviation fuel (SAF) for international aviation in the Netherlands in 2050, based on INT scenario in II3050 report; 7) Light green bar represents demand from district heating, potentially to be served by renewable gaseous molecules; 8) Hydrogen as a molecule for end-use, also includes other molecules as hydrogen carriers; 9) Hot briquetted iron

Source: II3050, Desk research

In industry, renewable gaseous molecules can provide moderate to high-temperature process heat, which is difficult to electrify. They are also needed as essential feedstock for chemical processes, enabling the production of key materials and reducing reliance on fossil inputs.

In mobility, demand is primarily driven by heavy-duty transportation, while in the built environment, it is driven by (hybrid) decentral heating for residential and utility buildings. In electricity production, renewable gaseous molecules will play a role in dispatchable power production to balance the intermittency of renewable energy sources like wind and solar, which are forecasted to provide most of the electricity produced.

Five key use cases were selected for deeper analysis based on their feasibility for e-methane and projected demand in 2040

The projected renewable gaseous molecule demand could be met by several renewable energy vectors. This study considers e-methane alongside hydrogen, ammonia and methanol. ▶H It is important to note that this is considering the form in which the molecule is consumed in the end-use conversion step. Therefore, any energy vector used as a hydrogen carrier (e.g. ammonia, LOHC or methanol) that is imported to the Netherlands and then reconverted into hydrogen before use will be represented in this overview as hydrogen, rather than the original energy vector.

E-methane could fulfill up to 80% of the renewable gaseous molecule demand in the Netherlands, but this study narrows its scope to five end-use cases[21]:

- Iron and steel
- Process heat for clusters 1-5
- Process heat for cluster 6
- Decentral heating in the built environment.
- Central dispatchable electricity production

These cases were selected based on two criteria: 1) they must be feasible for e-methane use and 2) they must have significant renewable gaseous molecule demand in 2040. For example, ammonia end-products are excluded as a feasible use case since the sector requires either hydrogen or ammonia directly as an energy vector. Although hydrogen can be produced from e-methane through steam methane reforming, using e-methane to produce hydrogen is energy and cost-inefficient, making it an uneconomic and illogical option. Together, these five use cases are forecasted to represent more than 70% of the total Dutch e-methane demand.

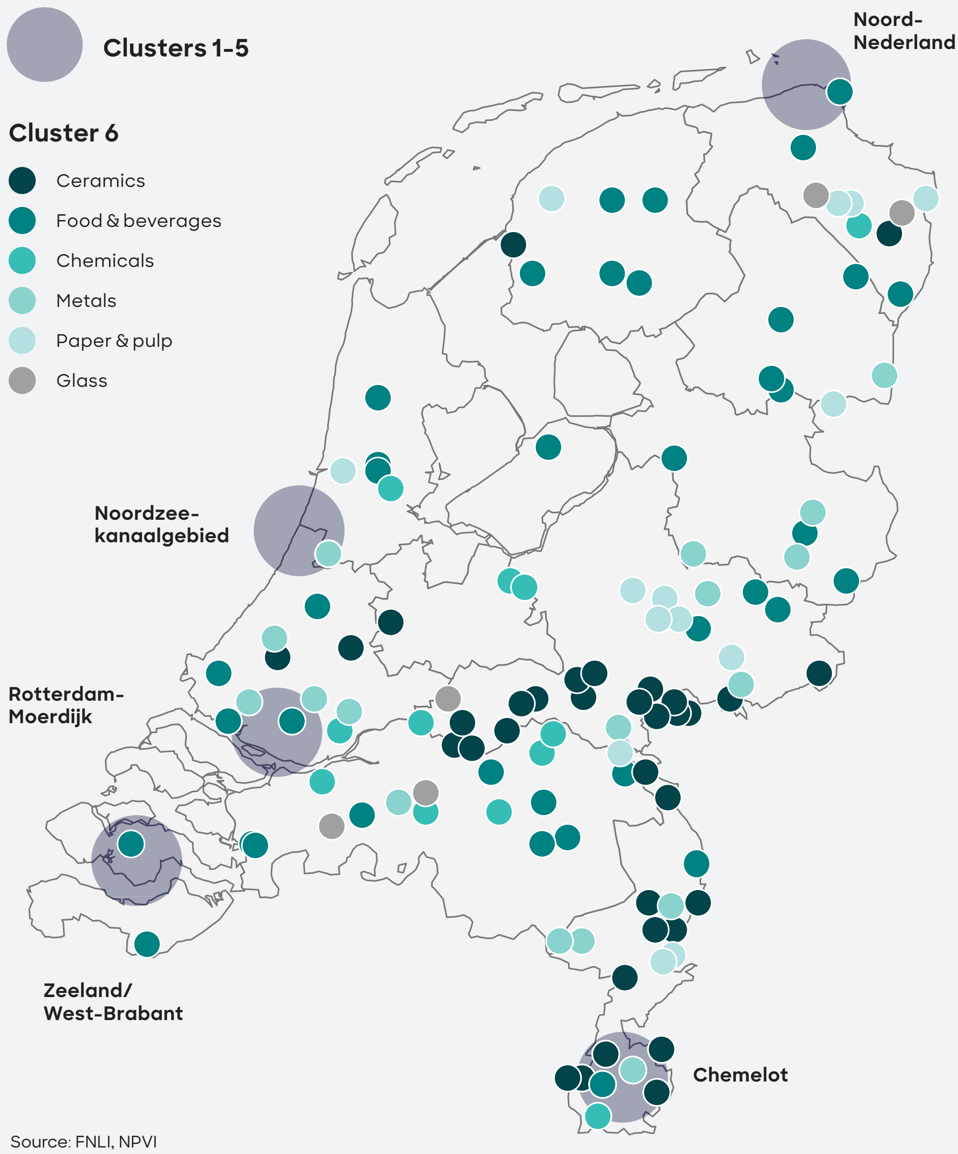
For the five selected use cases, e-methane and hydrogen are the primary energy vectors. Their roles in each value chain step are explored further.

21 Mobility is a relevant sector for e-methane; however, many use cases within this sector either have a smaller share of downstream costs in the total value chain (e.g. shipping) or would require similar new infrastructure for both e-methane and hydrogen (e.g. heavy-duty transport). Since the downstream value chain setup would not significantly differ between the two vectors, mobility use cases were not prioritized for comparison in this study

DEEP DIVE

In the Netherlands, industries are segmented into six clusters based on their geographical distribution. ▶| Clusters 1 to 5 consist of large, geographically concentrated industrial hubs that include sectors like refineries, chemicals and metallurgy. Example companies in these clusters include TATA Steel (iron and steel), OCI (chemicals), Shell (petrochemicals) and Nobian (chemicals). In contrast, cluster 6 is dispersed across the country and comprises industries such as ceramics, food and beverages, metals, paper and pulp and glass production. Examples of companies in this cluster are Wienerberger (ceramics), FrieslandCampina (dairy) and Ardagh Group (metal and glass packaging).

There are primarily six industrial clusters in the Netherlands



Source: FNLI, NPVI

Considerations of different value chain steps have been further defined for each use case for both e-methane and hydrogen

The five selected use cases are further detailed for the final value chain steps after reconversion – that is, transmission, seasonal storage, distribution and end-use conversion. ▶ J

In transmission, e-methane can utilize the existing natural gas infrastructure (HTL and RTL), while hydrogen will rely on the planned hydrogen backbone. In addition to the hydrogen backbone, some use cases, such as central dispatchable electricity production and process heat for cluster 6, may require additional pipelines to connect to the hydrogen backbone.

Seasonal storage requirements differ based on demand profiles: 40% of the demand for decentral heating is expected to go into long-term storage, ideally in depleted gas fields. For

J For the final value chain steps different considerations are relevant per use case

Produc-tion › Long-distance transportation › Recon-version › **National transmission:** Transmission › Seasonal storage › **Regional distribution & end-use:** Distribution › End-use conversion

Use case	Energy carrier	Transmission	Seasonal storage	Distribution	End-use conversion
Iron and steel	E-methane	• E-CH_4 transmission via the CH_4 HTL and RTL • H_2 transmission via the H_2 backbone1)	Assuming required storage capacity of 10% of annual demand	No distribution assumed due to direct connection to either CH_4 HTL/RTL pipeline or H_2 backbone	1 New asset
	Hydrogen				
Process heat for clusters 1-5	E-methane				2 Depreciated asset
	Hydrogen				
Process heat for cluster 6	E-methane				
	Hydrogen				
Electricity production	E-methane		Assuming required storage capacity of 30% of annual demand2)		3 Lifetime extension
	Hydrogen				
Decentral heating	E-methane		Assuming required storage capacity of 40% of annual demand3)	Via existing CH_4 distribution network	2 Depreciated asset
	Hydrogen			Via H_2 pipelines (assuming 50% refurbished)	1 New asset

1) Additional dedicated pipelines assumed to connect power plants and cluster 6 to the hydrogen backbone. Other options also exist, such as blending hydrogen and methane in existing pipelines; 2) To accommodate flexible electricity production in times of high electricity demand and low renewable electricity supply; 3) To accommodate storage of additional produced energy in summer for additional energy demand in winter

Source: Interviews with industry experts, Desk research central dispatchable electricity production, 30% is expected to be stored, with salt caverns being more suitable due to short-term availability needs. Industrial use cases (iron and steel, process heat) require only limited seasonal storage, with 10% expected to be stored in salt caverns[22].

Of the selected use cases, only decentral heating will require the distribution network, as the other use cases likely will be connected directly to the transmission network[23].

End-use conversion options include:

1. Purchasing new assets
2. Using existing assets that are financially depreciated but still functional
3. Investing in asset lifetime extensions

For iron and steel, only new assets are feasible as it requires moving from a blast furnace to a direct reduced iron process (option 1), while process heat and central dispatchable electricity production can use both new and existing assets with necessary adaptations for hydrogen use. It is assumed that most industrial boilers will be depreciated, but not yet at the end of their lifetime (option 2) for process heat, whereas for electricity it is assumed that most of the existing natural gas-fired power plants will require lifetime extension by 2040 (option 3). For decentral heating, e-methane can use existing natural gas boilers (option 2), while hydrogen will require new boiler installations (option 1) due to compatibility issues. For both e-methane and hydrogen, it is assumed that existing natural gas boilers are fully depreciated.

22 Storage percentage for each use case has been calculated based on input from industry experts. Central dispatchable electricity production and industrial applications are expected to require flexible, multi-cycle storage, making salt caverns the ideal choice. In contrast, depleted gas fields are better suited for long-term, single-cycle storage.

23 Some industries in cluster 6 are also connected via the distribution pipeline; however, for simplicity, this study assumes that cluster 6 is directly connected to either the HTL/RTL pipelines or the H_2 backbone

Key assumptions and boundary conditions

The study aims to provide a relative comparison of financial and non-financial parameters between energy vectors, rather than forecast absolute numbers. Standardized assumptions across energy vectors have been made to ensure a fair and consistent basis for comparison. The analysis assumes a mature, large-scale system with positive technological advancements and an optimized global supply chain by 2040

4

The Netherlands is expected to meet part of its renewable energy vector demand through imports from regions with ample, low-cost renewable energy resources capable of producing a surplus beyond local needs. These include areas like MENA, the US, southern Europe and northern Europe and, to some extent, Australia and South America. To streamline the study, the current analysis focuses on MENA, the US and southern and northern Europe as potential import hubs to meet Dutch renewable energy demands.

For medium to longer distances, transportation of the renewable energy vectors is primarily through pipelines or shipping. The choice of transportation method from these export locations is influenced by the proximity of the production region and its infrastructure. In this study, imports from southern Europe and northern Europe are assumed to utilize pipeline infrastructure. In contrast, imports from the US and MENA rely primarily on shipping. The report further assumes that all Dutch demand for renewable energy vectors will be met via these strategic import routes, ensuring a like-for-like comparison across the entire value chain.

For the selected end-use cases, energy delivered via renewable methane or hydrogen is compared

This analysis compares final energy delivered for selected end-use cases, using both methane and hydrogen as vectors. For methane, both e-methane and biomethane (in gaseous and liquid forms) are considered. For hydrogen, gaseous and liquid hydrogen are included, along with three hydrogen vectors: ammonia, methanol and LOHC, all converted back to hydrogen for end-use. Stoichiometric inputs have been assumed for each energy vector in the analysis to ensure consistency across scenarios. ▶ K

K Stochiometric inputs vary based on the type of energy vector [per MWh of energy vector produced]

Input required for 1 MWh of output						Output
Primary energy carrier	+	**Other feedstocks**	+	**Process energy input4)**	→	**Energy vector**
1.19 MWh of H_2	per MWh of e-methane	0.19 ton of CO_2	per MWh of e-methane	<0.01 MWh	per MWh of e-methane	**1 MWh of e-methane**
0.3 ton of biomass with 5 MWh/ton of energy density	per MWh of biomethane	n/a	per MWh of biomethane	0.01[1] MWh	per MWh of biomethane	**1 MWh of biomethane**
1.19 MWh of H_2	per MWh of methanol	0.26 ton of CO_2	per MWh of methanol	0.04 MWh	per MWh of methanol	**1 MWh of methanol**
1.13 MWh of H_2	per MWh of ammonia	0.16 ton of N_2	per MWh of ammonia	0.13[2] MWh	per MWh of ammonia	**1 MWh of ammonia**
1.03 MWh of H_2	per MWh of LOHC	0.47 ton of H_0-DBT[3]	per MWh of LOHC	0.01 MWh	per MWh of LOHC	**1 MWh of LOHC (DBT)[3]**

Example
- To **produce 1 MWh of e-methane,** 1.19 MWh of hydrogen is combined with 0.19 ton of CO_2, together with <0.01 MWh of process energy input
- More than 1 MWh of primary energy carrier is required to produce 1 MWh of energy vector, as **energy is lost during the conversion process**

1) Figure comprises electricity and heat used to produce biomethane; 2) Energy consumption includes electricity needed for nitrogen separation from air; 3) LOHC = liquid organic hydrogen carrier; DBT = dibenzyltoluene, a type of LOHC; H_0-DBT = dehydrogenated DBT, H_{18}-DBT = hydrogenated DBT; 4) Only the energy required to make the energy vector is included. Any energy required to synthesize feedstock is not included here

Source: Agora, CE Delft, HyDelta, EU LCA, IEA, IRENA, Desk research

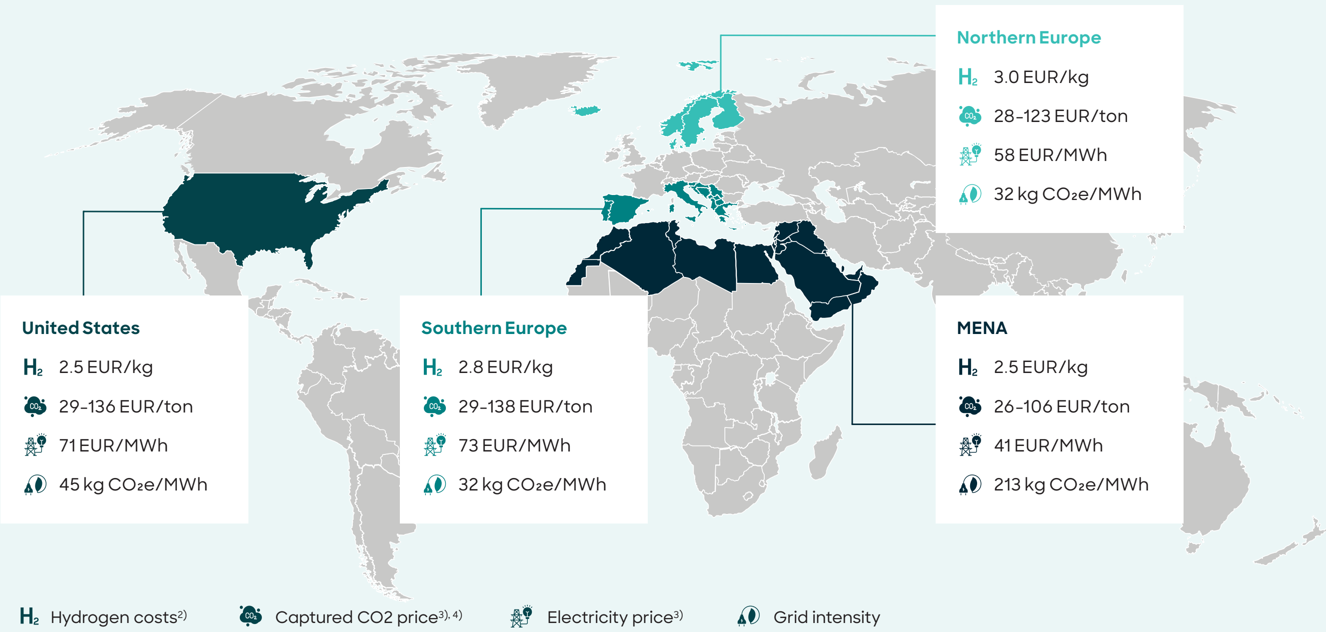
For the renewable energy vectors in scope, assumptions across the value chain have been made

This study aims to provide a relative comparison of financial and non-financial parameters between energy vectors, rather than forecast absolute numbers, as these depend on numerous factors outside the scope of the study. Most of the assumptions used throughout the value chain are based on public sources, providing a foundation for the analysis.

The renewable energy vectors evaluated also vary in maturity and are subject to technological and cost uncertainties, as some technologies have not yet been proven at an industrial scale. The analysis assumes a mature, large-scale system with positive technological advancements and an optimized global supply chain featuring centralized conversion/liquefaction and reconversion/gasification infrastructure by 2040. Consequently, assumptions for currently immature technologies are estimates of a future state and inherently carry lower confidence levels compared to those for already mature technologies. Key assumptions – such as the cost of renewable hydrogen, CO_2 capture price, electricity prices and grid emission intensity – are standardized across regions to enhance comparability[24]. ▶ L

24 For further details on assumption per energy vector per value chain step per use case, please refer to the appendix

L **MENA is expected to offer competitive costs across regions for renewable hydrogen and lowest price for captured CO2 and electricity in 2040 – Grid intensity of MENA is projected to be relatively high[1)]**



1) Renewable hydrogen costs for 2040 are based on the IEA forecast for 2030, with WACC at 6%, and underlying assumptions that 2030 assumptions are optimistic and forecasted price is expected to be closer to the latter half of the 2030s. CO_2 capture price estimates vary, with the lower bound representing capture from high-purity biogenic sources like bioethanol, and the upper bound reflecting DAC with energy consumption of 1 MWh per ton of CO_2 captured. In the absence of reliable electricity price data for MENA, the region's electricity price is assumed to be 60% of the US price; 2) Produced via captive renewable power; 3) Prices are based on baseload hours; 4) Study assumed TOTEX cost excl. electricity consumption of 25 EUR/ton for biogenic point-source and of 65 EUR/ton for DAC and an electricity consumption of 0.1 MWh/ton for biogenic point-source and 1 MWh/ton for DAC

Source: IEA, NETL, Natuur & Milieu, Bavarian industry association (VBW), E-bridge

The cost of renewable hydrogen follows IEA projections with a captive renewable setup, while grid electricity, with its associated emissions, is assumed for the rest of the value chain. Most of the upstream value chain – conversion to transportation (excluding pipelines) and reconversion – is modeled purely on operational costs without factoring in the cost of capital or margins. In contrast, pipeline transportation and the downstream segment, encompassing transmission, storage and distribution (regulated assets) incorporate tariffs calculated using the weighted average cost of capital (WACC), accurately reflecting regulatory conditions. WACC is excluded from the upstream segment due to varying regional risk profiles and investor return expectations, making reliable estimates challenging. This approach allows for a focused comparison of cost-competitiveness across energy vectors while respecting downstream regulatory contexts.

For long-distance maritime transportation, vessels carrying methane or liquid hydrogen are assumed to use boil-off gas as their primary fuel source, leveraging the evaporative losses from cryogenic storage to power the engines. In contrast, ships transporting ammonia and methanol will combust a portion of the cargo itself as fuel, balancing efficiency with fuel availability en route. For vessels transporting LOHC, it is assumed that e-methanol is used as fuel.

For downstream costs related to transmission, distribution via pipelines and seasonal storage within the Netherlands, bottom-up cost calculations have been conducted. These calculations are based on extensive literature reviews and stakeholder inputs to ensure that the assumptions are aligned with industry insights and the latest research. ▶ M

M Downstream costs have been assumed per value chain step [EUR/MWh][1),2)]

National transmission
Regional distribution & end-use

Production → Long-distance transportation → Reconversion → Transmission → Seasonal storage → Distribution (only for decentral heating) → End-use conversion

	Transmission	Seasonal storage: Depleted gas field	Seasonal storage: Salt cavern	Distribution (only for decentral heating)
E-methane	1.6	10	15	19
Hydrogen	1.7[3)]	35	51	55

Additional costs for pipelines to connect to the hydrogen backbone: 1.4 EUR/MWh for electricity production and 16 EUR/MWh for process heat for cluster 6

1) Power plants and industrial activities in cluster 6 will require dedicated pipelines to connect to the hydrogen network, adding significant costs. Especially for cluster 6, replacing natural gas pipelines with hydrogen-compatible infrastructure introduces complexities, making pipeline costs 2-3 times higher than standard pipelines. Additionally, the limited hydrogen volumes required in this cluster 6 exacerbate the per-unit cost, resulting in a high overall cost for pipeline infrastructure in cluster 6; 2) For the hydrogen backbone, 70% refurbishment of pipelines is assumed; for all other hydrogen pipelines (additional transmission pipelines and distribution pipelines), 50% refurbishment is assumed; 3) The hydrogen tariff was calculated before the new cost estimate for the proposed Dutch hydrogen pipeline network was made public, revealing a 2.5x increase from EUR 1.5 bn to EUR 3.8 bn

Source: Roland Berger comprehensive value chain model

E-methane *van put tot pit:* a financially viable renewable energy vector

E-methane's landed costs are competitive with other renewable energy vectors when delivered in their end-use state. For hydrogen-specific applications, ammonia and liquid hydrogen offer the lowest landed cost. E-methane is cost-competitive for specific end-use cases with high downstream costs, such as decentral heating, industrial process heat for cluster 6 and central dispatchable electricity production. Large-scale e-methane production will increasingly rely on DAC to ensure stable CO_2 supplies. Consequently, DAC costs will critically determine e-methane's cost-competitiveness relative to hydrogen

5

The study analyzes renewable energy vector competitiveness through a systematic approach, first identifying optimal transport modes per import region, then evaluating total landed costs of the vectors in their end-use state and when converted to hydrogen, and finally analyzing total value chain costs for selected end-use cases. To account for key uncertainties in the assumptions, a sensitivity analysis was conducted on key parameters affecting total value chain costs. The findings of this study are also more or less relevant to neighboring countries such as Belgium, Germany and others that share a similar reliance on natural gas and are likely to require substantial imports to meet their future renewable energy needs.

Transporting renewable energy vectors via pipelines is expected to be the most cost-competitive method for shorter distances, provided that sufficient volumes are transported. For medium to longer distances, shipping will be more cost-competitive

Long-distance transportation options depend mainly on the distance between export and import locations. Pipelines are more cost-competitive for shorter distances, while maritime shipping is more cost-competitive over medium to longer distances. Pipeline costs rise in line with distance, whereas the high initial costs of shipping (e.g. liquefaction, gasification) are offset over longer routes, with only fuel and operational expenses adding incrementally. According to model-based calculations, the tipping point[25] for methane transportation is around 1,500-2,000 km, while for hydrogen it is around 5,000-6,000 km, reflecting hydrogen's higher upfront costs for liquefaction or conversion (e.g. to ammonia). Liquid hydrogen is expected to have a lower upfront cost compared to other hydrogen derivatives, making it more cost-competitive for delivering hydrogen over short to medium distances. ▶ N

In practice, the tipping point is situation-specific and influenced by various factors. For example, shipping can be viable over shorter distances, as border crossings and intercontinental links can complicate pipelines and increase costs. Additionally, pipelines are typically cost-competitive only for large volumes, making shipping more attractive, particularly in the short term when volumes are lower. Conversely, if existing pipelines are already in place, the tipping point for pipeline transportation could be later than indicated.

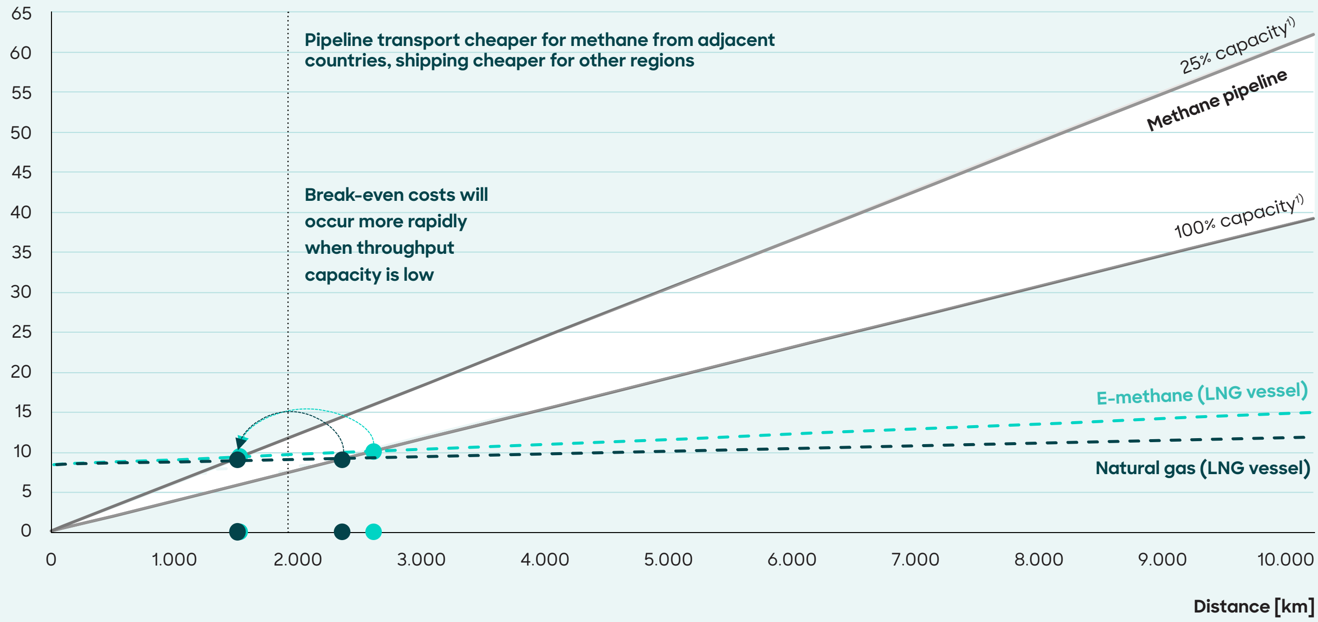
As a result, renewable energy vectors from southern Europe and northern Europe are likely to be shipped initially, with pipelines taking over in the long term, while those from MENA and the US are expected to use shipping in both the short and long term. Factoring in production and transportation, MENA and the US are anticipated to be the most cost-competitive sources of e-methane, while southern Europe likely to be the most cost-competitive for hydrogen. ▶ O

To mitigate risks like supply chain disruptions, political instability and feedstock limits, diversifying export regions is essential. To ensure consistency across different vectors, the remainder of this analysis will use MENA as the primary export region for renewable energy

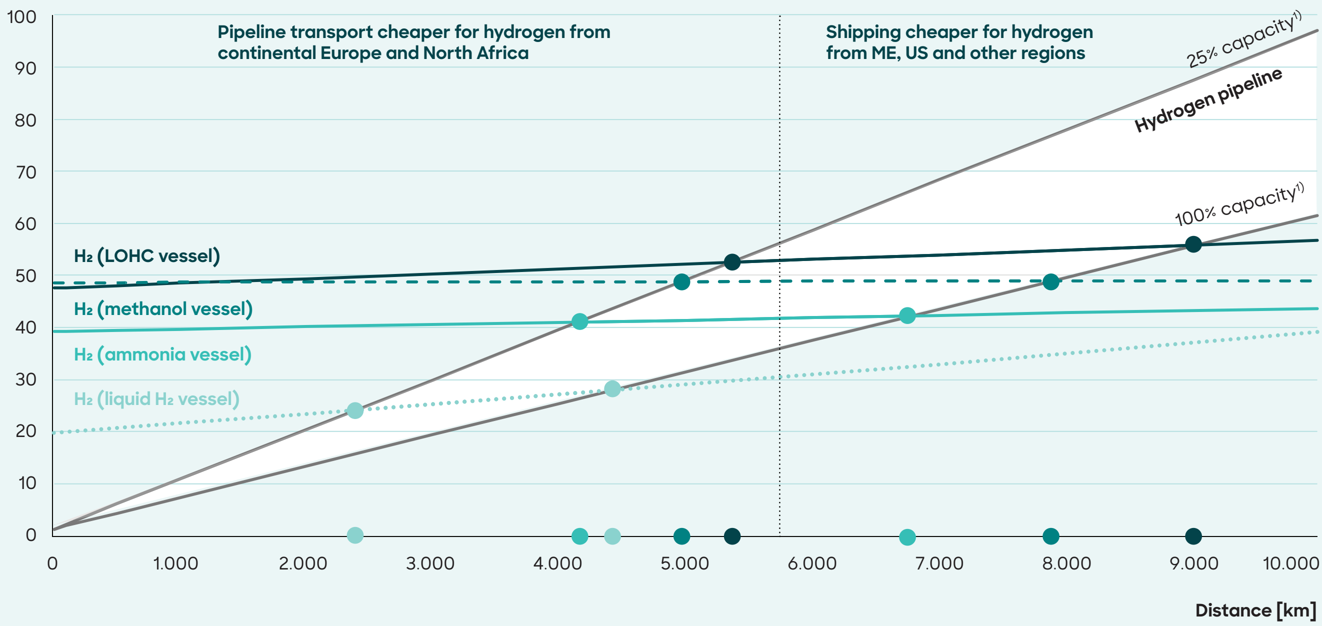
25 Shipping costs include conversion, storage, transportation and reconversion costs. Within conversion, it also accounts for the cost of the additional feedstock required compared to gaseous vector to deliver same amount of landed energy. As explained earlier, shipping costs are modeled purely on an operational cost basis without including WACC, whereas pipeline costs are tariff based and account for WACC as regulated assets. Accounting for WACC in shipping would slightly increase the tipping point

N Transporting renewable energy vectors via pipelines is more cost-competitive for shorter distances, whereas for medium to longer distances shipping becomes more cost-competitive

Projected transportation cost of methane [EUR/MWh output]



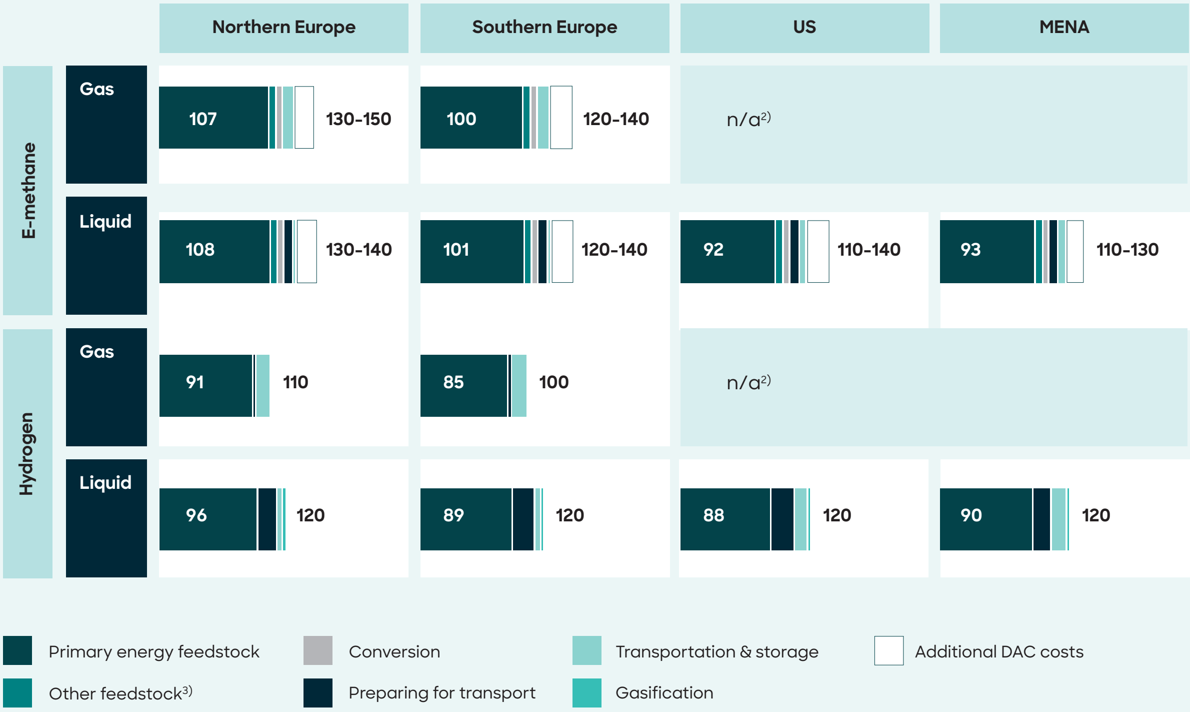
Projected transportation cost of hydrogen [EUR/MWh output]2)



1) Total pipeline capacity of 163 TWh for methane and 147 TWh for hydrogen; 2) Includes conversion and reconversion

Source: Roland Berger comprehensive value chain model

Liquid route from MENA and US is expected to be the most cost-competitive for e-methane whereas importing via pipelines from southern Europe seems to be most attractive for hydrogen [EUR/MWh output][1)]



1) Total costs are rounded to nearest multiple of 10 in all the financial comparison analyses; 2) Pipeline transport of gases not considered for the US and MENA, as the distance for gas pipelines is too long and in that situation pipeline transport becomes significantly more expensive than shipping of liquids; 3) Includes CO_2 for e-methane and methanol, N_2 for ammonia and dehydrogenated DBT for LOHC

Source: Roland Berger comprehensive value chain model

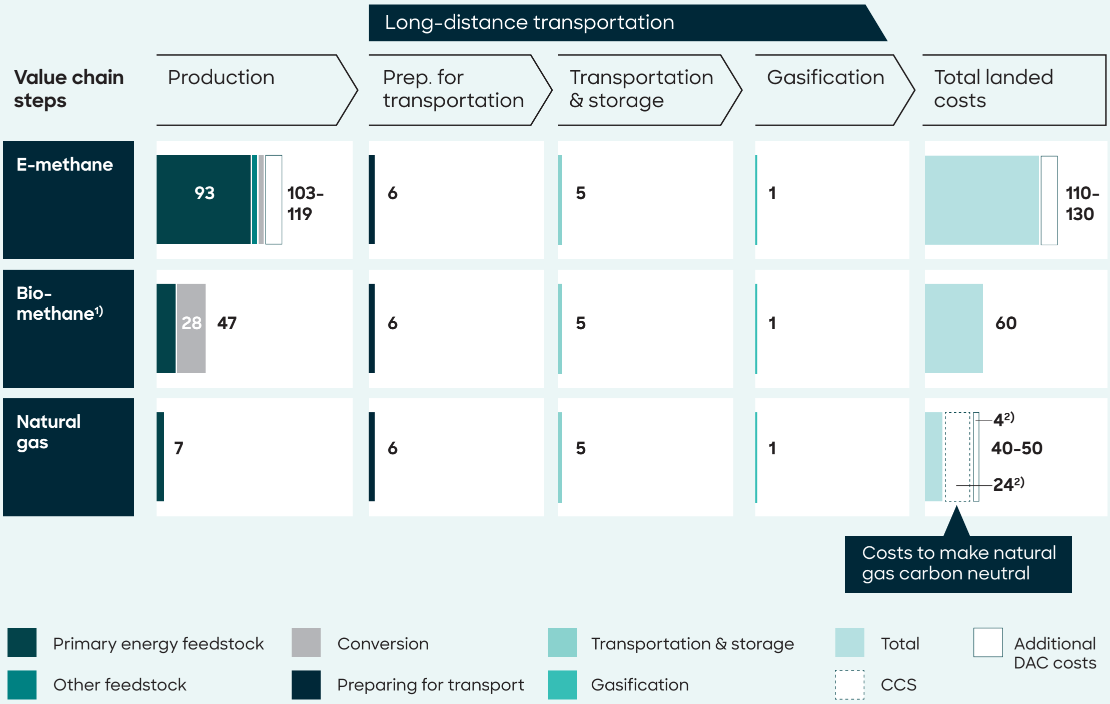
vectors, with shipping as the assumed transportation mode[26]. It is important to note that, for all remaining financial analyses in this chapter, costs are shown per MWh output at the last value chain step in the figure. Due to losses throughout the value chain, numbers might not correspond between figures. The different efficiencies at end-use conversion associated with different use cases also explain the varying costs per use case.

Importing e-methane will come at a premium compared to CO_2 compensated natural gas. Large-scale production of e-methane will increasingly need to rely on DAC to ensure stable CO_2 supplies, as biogenic CO_2 availability is expected to be limited in long term

Natural gas, with production costs typically well below 10 EUR/MWh, is expected to remain one of the most affordable energy vectors, also when considering the cost of capturing and

26 Total costs are rounded to nearest multiple of 10 in all the financial comparison analyses. All financial analyses show costs and efficiencies with biogenic CO_2. Additional DAC feedstock costs are shown separately in the production step. The overall efficiency of e-methane with DAC is about 10% lower than with biogenic CO_2

P Natural gas is expected to remain one of the most affordable energy vectors [EUR/MWh output]



1) Based on anaerobic digestion; 2) The combustion of 1 MWh of natural gas emits ~ 0.19 ton of CO_2 per MWh. CCS is assumed to occur at the end-use location in the Netherlands, while DAC is expected to take place at the export location in MENA. Costs to capture CO_2 in NL are expected to be ~66 EUR/ton for point source with additional transport & storage costs of 60 EUR/ton and DAC in MENA is expected to have a cost of 106 EUR/ton for capture with additional transport & storage costs of 40 EUR/ton

Source: Roland Berger comprehensive value chain model

storing the CO_2 created during combustion. ▶ P With rising demand for greener alternatives, biomethane and e-methane are emerging as viable options that utilize existing infrastructure. Biomethane is generally more cost-competitive due to lower feedstock costs, though its large-scale production is limited by feedstock availability, which competes with food production, animal feed and agriculture. Feedstock supply is also influenced by geography, seasonality and sustainability factors. In contrast, e-methane can be produced from virtually unlimited renewable sources like sun and wind, making it a scalable supplement to biomethane.

E-methane produced from biogenic CO_2 has lower production costs than CO_2 from DAC, but biogenic CO_2 availability is also limited. By 2040, global biogenic CO_2 supply is projected to be at 400-500 Mt[27]. Just meeting Dutch demand of 25 Mt of CO_2 for e-methane in 2040 would require 6–8% of expected global biogenic CO_2 supply, 12–15% of US and a staggering 150-160% of the expected MENA, illustrating the insufficiency of relying solely on biogenic sources. Therefore, while e-methane with biogenic CO_2 has potential, large-scale production will increasingly need to rely on DAC to ensure stable CO_2 supplies long term – the same applies to methanol.

27 IEA, Zero Carbon Shipping

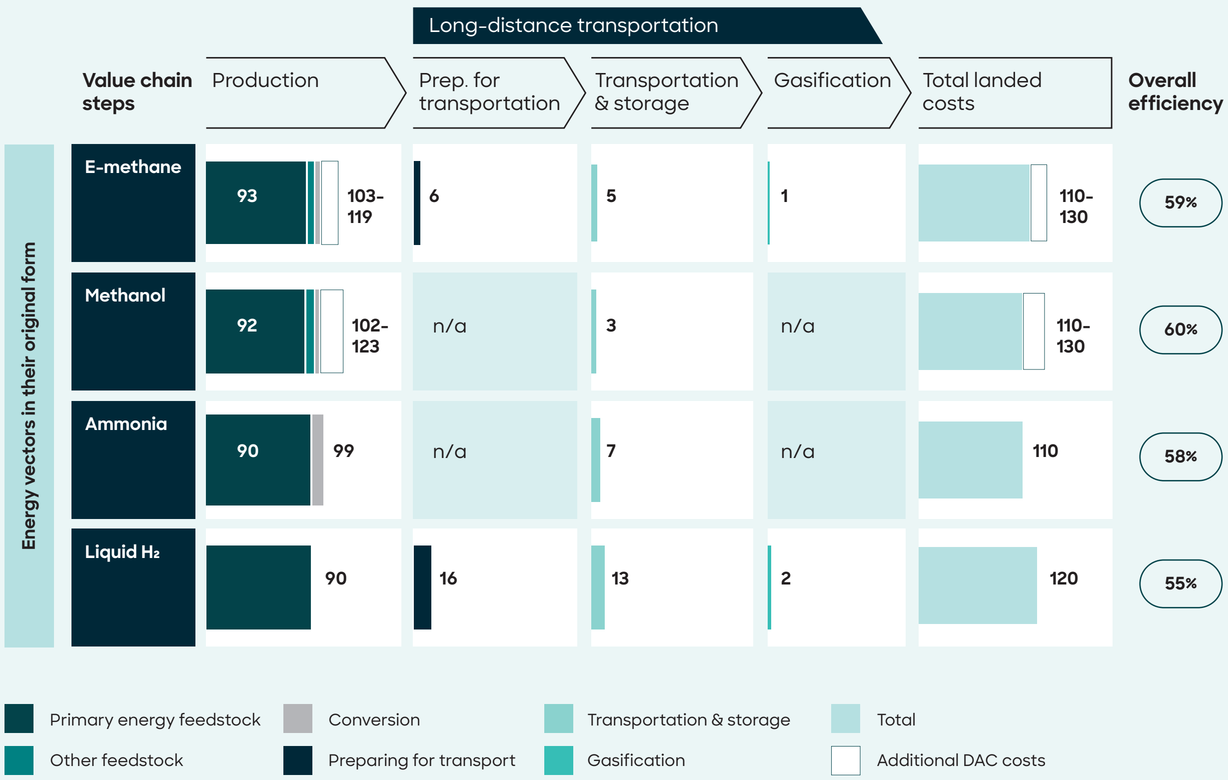
Landed cost of e-methane is in line with other renewable energy vectors. Production and shipping of renewable energy vectors most cost-competitive when already in end-use state

The landed cost[28] of e-methane is comparable to that of other renewable energy vectors. ▶ Q When produced with biogenic CO_2, e-methane costs are comparable to methanol and ammonia. However, sourcing CO_2 from DAC increases the cost of e-methane by 20-25% compared to ammonia. Despite this increase, e-methane remains cost-competitive with other renewable energy vectors as higher production costs are offset by relatively lower long-distance transportation cost.

Shipping renewable energy vectors in their original form is more cost-competitive than synthesizing them in the Netherlands from imported hydrogen, regardless of distance and the shipping method. This advantage arises because transportation costs typically account for only 5-10% of the total landed costs and are more than offset by the higher energy prices in the Netherlands compared to the production location. For instance, synthesizing ammonia or

28 Costs from production up to and including transportation to the import location

Q Landed cost of e-methane is cost-competitive with other renewable energy vectors [EUR/MWh output]



Source: Roland Berger comprehensive value chain model

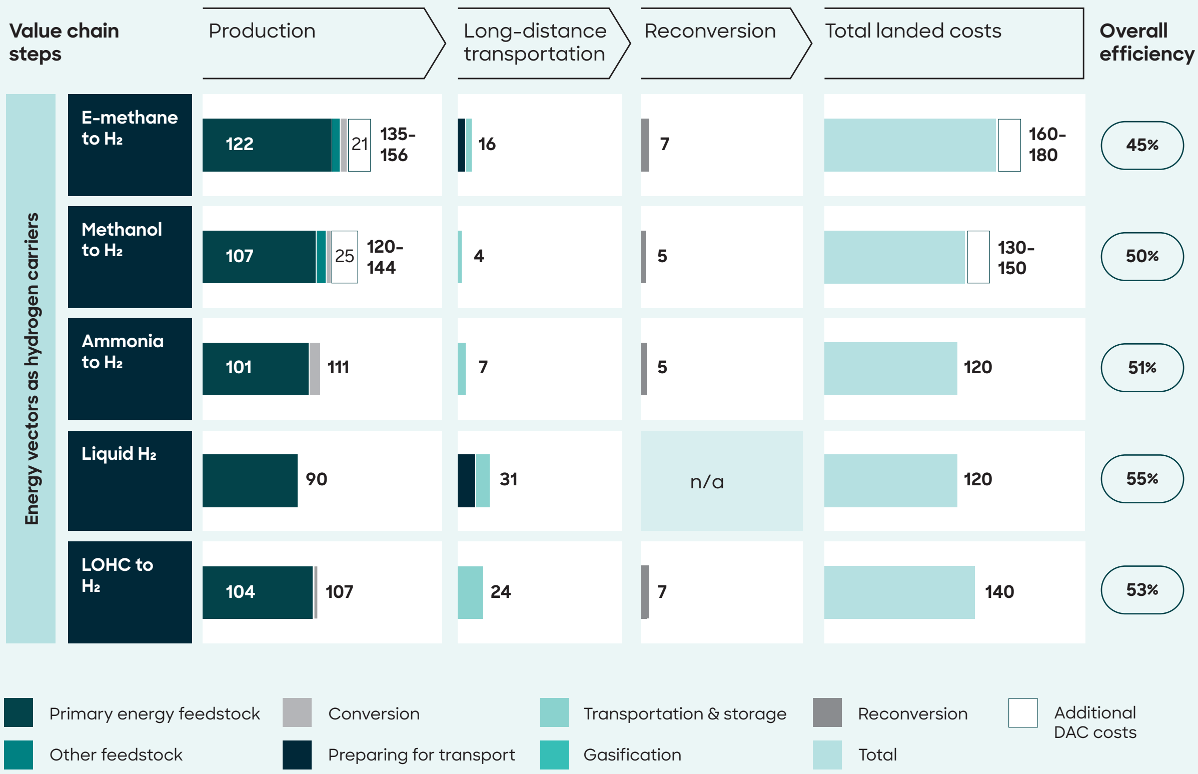
methanol in the Netherlands using imported hydrogen is 20-30% more expensive than importing the already synthesized vectors from regions like MENA. As a result, there is a possibility that production of these renewable energy vectors, such as ammonia and methanol, will shift from the Netherlands to regions where energy prices are lower, such as MENA.

If hydrogen is the required energy vector for end-use, ammonia and liquid hydrogen are expected to offer the lowest cost levels

As some sectors like refineries specifically require hydrogen for their operations, the procurement of renewable hydrogen for end-use will be necessary in the future. Comparing the landed costs of various energy vectors for hydrogen, ammonia and liquid hydrogen are projected to have comparable costs, followed by methanol and LOHC. ▶ R

The landed costs of ammonia and methanol are primarily driven by the production steps of each vector, with ammonia outperforming methanol due to its lower hydrogen feedstock requirements and the absence of the need for GHG-neutral CO_2. In contrast, the cost of

R If hydrogen is the end requirement, ammonia and liquid hydrogen are expected to have the lowest costs [EUR/MWh output]



Source: Roland Berger comprehensive value chain model

liquid hydrogen is predominantly influenced by long-distance transportation, including liquefaction and gasification. LOHC is relatively more expensive than ammonia and liquid hydrogen, primarily due to its lower volumetric energy density, which results in higher transportation costs per MWh. Additionally, the dehydrogenation process incurs high conversion losses and energy demands, further increasing its overall cost. Lastly, if used as a hydrogen carrier, e-methane is the least cost-competitive and energy-efficient carrier, primarily due to the costs associated with its synthesis. These high production costs, combined with its lower energy efficiency, make e-methane a less viable option if hydrogen is the required energy vector for end-use in the Netherlands.

Even with CO_2 from DAC, which is likely required due to the limited long term availability of biogenic CO_2, e-methane is still cost-competitive for certain use cases where downstream costs of storage, distribution, and end-use conversion make up a relatively higher share of total costs in the value chain

The comparison of the total costs includes the downstream value chain steps of transmission, seasonal storage, distribution and end-use conversion. ▶ S Comparison depends on the specific end-use case. For the five selected use cases, e-methane sourced as a liquid from MENA via vessels is compared with hydrogen transported from MENA. The analysis assumes hydrogen is delivered as ammonia but acknowledges that it could also be transported as liquid hydrogen, given the comparable landed costs of the two vectors.

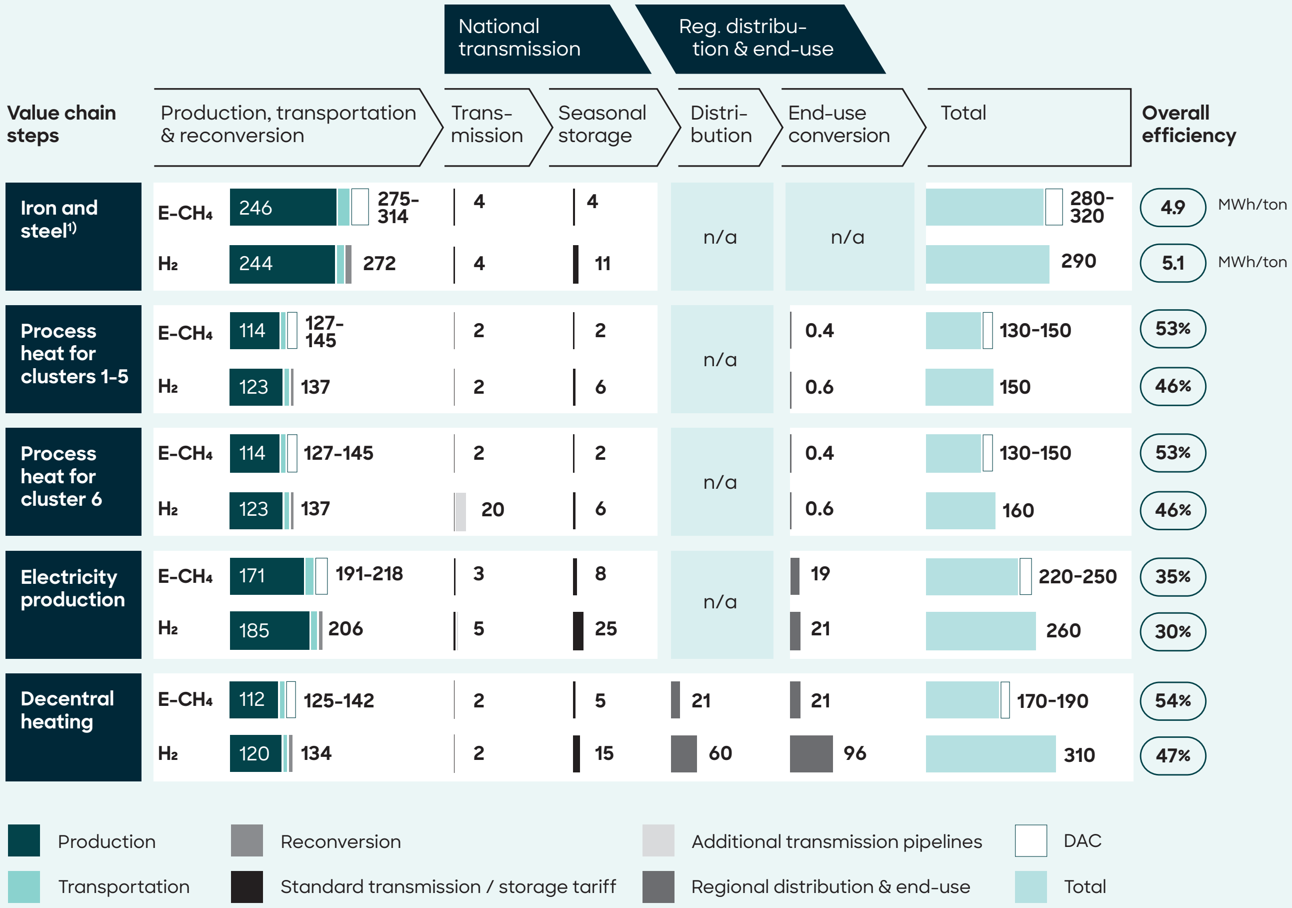
While e-methane with biogenic CO_2 is expected to be more cost-competitive than hydrogen across all shortlisted end-use cases, there are limitations. As mentioned earlier, biogenic CO_2 availability is limited due to feedstock constraints. This will likely restrict the scalability of e-methane with biogenic CO_2 for large-scale applications. Although e-methane from DAC incurs higher costs compared to biogenic CO_2, it still has a cost advantage over hydrogen for decentral heating, process heat for cluster 6 and central dispatchable electricity production. For process heat in clusters 1-5, e-methane with DAC is cost-comparable to hydrogen, while hydrogen remains more cost-competitive for iron and steel production.

E-methane mainly has a cost advantage over hydrogen in specific use cases with higher downstream value chain costs, as existing infrastructure can be leveraged, reducing associated expenses. For example, decentral heating with hydrogen would require adapting 80% of the existing distribution network (equivalent to 100,000 km[29]) and upgrading 2.5 m boilers[30], resulting in significant additional costs compared to e-methane, which can use the existing infrastructure. Seasonal storage costs for hydrogen are three times higher than for e-methane, primarily due to e-methane's three times higher volumetric energy density, which reduces storage costs for decentral heating and central dispatchable electricity production. In process heat for cluster 6, the hydrogen route would require an additional

29 Netbeheer Nederland indicates 136,000 km of gas network in the Netherlands, 11,000 km of which is for transmission, according to Gasunie. The remaining 125,000 km is distribution network and 80% of 125,000 km results in 100,000 km of distribution network remaining

30 Based on II3050, considering the International Trading (INT) scenario

S E-methane as an end-product with biogenic CO_2 is cost-competitive with hydrogen for all use cases, whereas with DAC it is cost-competitive in cluster 6, electricity production and decentral heating due to the lower infrastructure costs for e-methane [EUR/MWh output]



1) Values for iron and steel shown in EUR/ton steel

Source: Roland Berger comprehensive value chain model

400 km of dedicated pipeline[31], adding 18 EUR/MWh in transmission costs. E-methane, however, can utilize the existing transmission network without additional costs for new pipelines to connect to certain end-users.

The current analysis focuses on e-methane synthesized at the export location and transported to the Netherlands. Alternative routes include capturing CO_2 at the combustion site and returning it to the export location or capturing CO_2 at the end-use site and storing it

31 HyRegions: Approach for the possible roll-out of regional hydrogen infrastructure

in the Netherlands. Both alternatives are cost-comparable, but the latter may offer cost advantages when carbon deposit removal fees exceed 180-200 EUR/ton[32].

In the broader context of low-carbon energy vectors, fossil vectors with CCS are generally expected to be more cost-competitive than renewable energy vectors if they run at high utilization rates. When comparing different fossil vectors with CCS, natural gas combined with CCS is expected to be more cost-competitive than blue hydrogen, because it is cheaper to transport natural gas and CO_2 than to transport hydrogen. Consequently, even when considering low-carbon alternatives, hydrogen pathways remain less cost-competitive than low-carbon/renewable methane-based vectors, solidifying methane's role as a less costly option for selected use cases.

Since e-methane is expected to be more cost-competitive in certain use cases, it could reduce the total future demand for renewable hydrogen in the Netherlands, particularly in applications like decentral heating, process heat and central dispatchable electricity production. This reduction in the Dutch demand for hydrogen would in turn lead to higher transmission and distribution tariffs, as the infrastructure costs would need to be distributed across a smaller user volume. However, in practice, reduced hydrogen demand within the Netherlands could be offset by increased export capacity to neighboring regions like Germany, potentially minimizing the impact on tariffs.

The costs of DAC play a key role in determining the degree of cost-competitiveness of e-methane with respect to hydrogen

All renewable energy vectors in this study face uncertainties, including the costs for renewable hydrogen, prices for electricity and captured carbon, technology maturity and demand-related tariffs. A sensitivity analysis was conducted on key parameters affecting total value chain costs, such as hydrogen costs, DAC prices, electricity prices and transmission tariffs. Sensitivity on transmission tariffs reflects the uncertainty in the demand of e-methane and hydrogen. If the demand reduces by half, the tariffs will increase by factor of two (assuming pipelines are primarily used for domestic demand). ▶ T

Although uncertainty in renewable hydrogen costs significantly impacts total costs, it does not affect e-methane's cost-competitiveness in most cases, as the hydrogen costs make up over 55% of production costs of all of the renewable energy vectors. Uncertainty in DAC price has the biggest impact on cost-competitiveness; as DAC price doubles, hydrogen becomes more cost-competitive in all cases except decentral heating, where e-methane remains more cost-competitive due to high hydrogen-related costs at later stages of the value chain. Initially, e-methane can use the more cost-competitive biogenic CO_2, but as demand grows, the CO_2 from DAC will become a crucial feedstock, making DAC pricing a key factor in e-methane's long-term cost-competitiveness. With DAC still at a lower technological maturity level (TRL 6),

32 Alternative routes for electricity production and process heat in clusters 1-5 have been analyzed. For electricity production, it is assumed that the carbon capture unit increases the CAPEX and OPEX of the electricity plant by 75%. For process heat in clusters 1-5, the CAPEX for the carbon capture facility is assumed to be 250 EUR per ton of CO_2 captured, with an OPEX rate of 4%. Shipping costs are estimated at 40 EUR per ton of CO_2, while transportation and storage costs are estimated at 60 EUR per ton

its scalability and cost trajectory remain uncertain, underscoring the importance of investments in its technology to ensure e-methane's future cost-competitiveness.

The current analysis focuses on energy demand based on the INT scenario outlined in the II3050 report. When other scenarios are considered, the total demand for renewable energy vectors changes, which primarily influences transmission tariffs. However, these changes in transmission tariffs do not affect the relative cost-competitiveness of the energy vectors. Even when transmission tariffs are doubled, the conclusions regarding the comparison between e-methane and hydrogen remain unchanged. This suggests that selecting a different II3050 scenario with varying energy demand would not significantly affect the conclusions on the cost-competitiveness of renewable energy vectors.

T Cost of hydrogen has the highest impact on the total costs of energy vectors but has less effect on their competitiveness compared to the significant influence of DAC price on cost-competitiveness [EUR/MWh output][1)]

		Base case	Hydrogen costs (1.25 ← 2.5 → 5.0 EUR/kg)		Break-even	DAC price for CO_2 (80[5)] ← 106 → 212 EUR/ton)		Break-even	Electricity price[3)] (41-92 → 82-184 EUR/MWh)	Break-even	Transmission tariff[4)] (1.6-17.7 → 3.2-35.4 EUR/MWh) – Reflects demand uncertainty
Iron and steel[2)]	E-CH4	320	-35%	+69%		-4%	+16%		+1%		+1%
	H2	290	-39%	+77%		n/a	n/a		+8%		+1%
Process heat for clusters 1-5	E-CH4	150	-35%	+69%	3.7	-4%	+16%	88	+1%	58-132	+1%
	H2	150	-38%	+77%		n/a	n/a		+8%		+1%
Process heat for cluster 6	E-CH4	150	-35%	+69%		-4%	+16%	168	+1%		+1%
	H2	160	-34%	+69%		n/a	n/a		+7%		+12%
Electricity production	E-CH4	250	-31%	+63%		-4%	+14%	137	+2%		+1%
	H2	260	-33%	+65%		n/a	n/a		+7%		+2%
Decentral heating	E-CH4	190	-27%	+53%		-3%	+12%		+1%		+1%
	H2	310	-18%	+36%		n/a	n/a		+3%		+1%

Most cost-competitive option, **both** in base case and with changed parameter

Most cost-competitive option, **not** in base case but only with changed parameter

xx Break-even price/costs

1) Considering import of liquid e-methane with DAC and ammonia (to hydrogen) via shipping from MENA, 2040 forecast; 2) Values for iron and steel shown in EUR/ton steel; 3) 41 EUR/MWh in MENA and 92 EUR/MWh in the Netherlands; 4) Depending on energy vector and use case. If multiple tariffs were considered, which is the case for the additional pipelines for cluster 6 and central dispatched electricity production, all tariffs were multiplied by 2 for the sensitivity analysis; 5) Theoretical minimum of DAC costs

Source: Roland Berger comprehensive value chain model

Comparing e-methane with other energy vectors on criteria beyond cost

Given the capital-intensive nature of the energy transition, the adoption of e-methane allows for the reuse of existing infrastructure, conserving financial and human resources while minimizing delays. With lower upfront costs, e-methane enhances societal value and enables a more resource-efficient energy transition. Its viability is further bolstered by its positive emissions impact, safety advantages and efficiency in land use and logistics

6

In addition to the landed and total costs of energy vectors discussed in Chapter 5, this study also compares energy vectors across other key parameters, such as infrastructure needs and costs, emissions and safety to evaluate their long-term feasibility. Infrastructure costs and technology readiness levels are key to determine how to meet GHG targets sooner rather than later, influencing timelines and investment needs. Assessing GHG emissions across the value chain and the cost per ton of CO_2 saved identifies the most cost-competitive decarbonization pathways. Safety and land-use analyses highlight feasibility, costs and compliance requirements of the energy vectors.

In the Netherlands, for the selected use cases, the hydrogen route will require an additional EUR 63 billion in CAPEX compared to the e-methane route

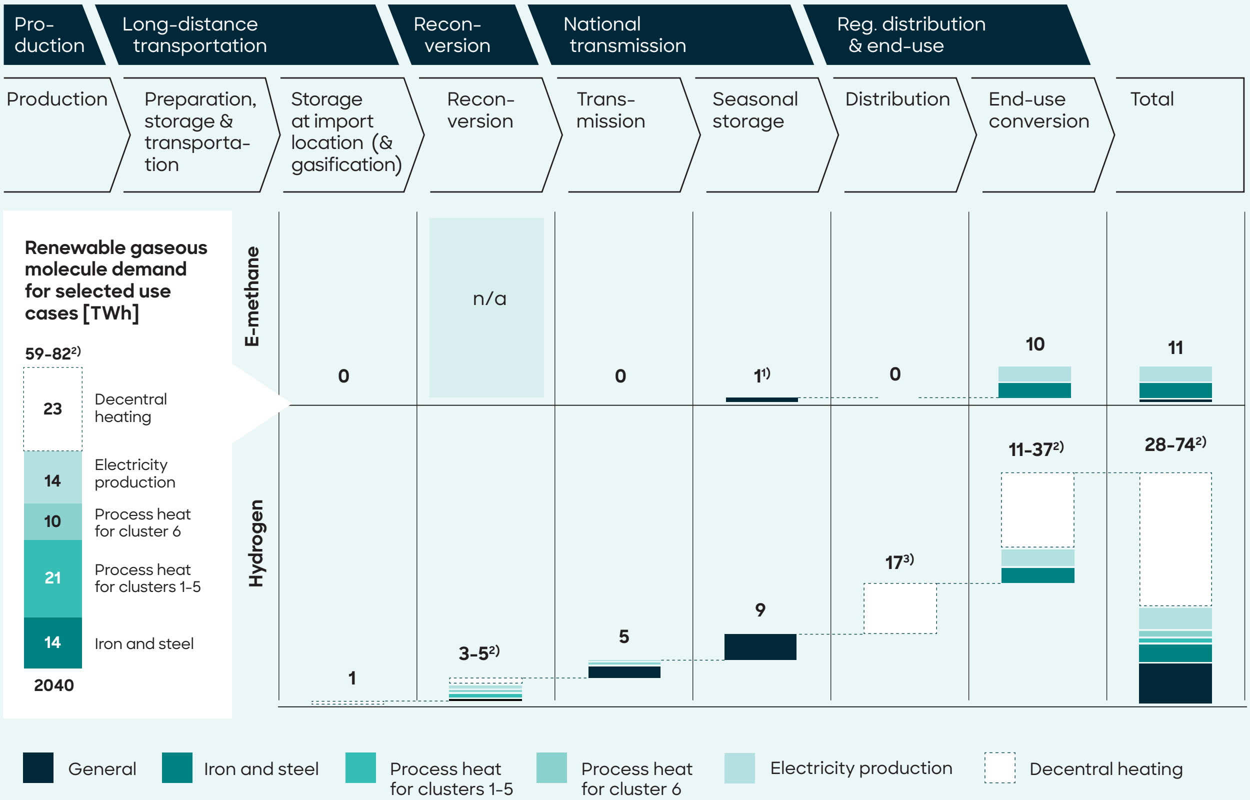
The total CAPEX investment required in the Netherlands to meet renewable energy vector consumption shows that hydrogen consumption costs are estimated at EUR 74 billion across the five selected use cases – significantly higher than the EUR 11 billion needed for e-methane (imported in liquid form). ▶U This cost disparity largely stems from the Netherlands' existing methane infrastructure, which spans the entire value chain from storage at import terminals to end-use conversion, whereas hydrogen infrastructure would need to be built almost entirely from scratch, except for the share of existing pipelines that can be repurposed for hydrogen. In regions with a less developed methane infrastructure, this cost disparity will likely be less pronounced.

For the use of hydrogen, decentral heating accounts for a substantial portion of CAPEX, totaling EUR 45 billion. Due to e-methane's significant cost advantage and the option to use biomethane and hybrid heat pumps, decentral heating is unlikely to transition to hydrogen. Excluding decentral heating from hydrogen's investment needs reduces total hydrogen CAPEX to EUR 28 billion, still almost triple the EUR 11 billion needed for e-methane.

In the remaining four use cases, most additional costs for hydrogen arise from seasonal storage, transmission and reconversion. For example, in seasonal storage, e-methane would require EUR 1 billion to expand flexible storage in salt caverns[33], increasing the current capacity of 3.6 TWh to 11 TWh. In contrast, hydrogen would require EUR 4 billion to adapt existing salt caverns and develop new hydrogen storage capacity. Also developing new hydrogen storage capacity for longer periods in depleted gas fields would cost EUR 5 billion, leading to a total investment cost of EUR 9 billion. The large difference in required investments is not only due to the fact that much of the methane storage infrastructure is already in place. Also, less TWh of hydrogen can be stored in a salt cavern than methane, as the volumetric energy density of hydrogen is only one-third that of methane. Therefore, relatively more salt caverns are required for hydrogen storage, increasing the hydrogen costs per MWh for seasonal storage.

33 While there is currently sufficient methane storage capacity in depleted gas fields (136 TWh), this type of storage is mainly suitable for long-term storage. It is expected that in the future, more short-term storage capacity is required, for which salt caverns would be more suitable; there is currently only 3.6 TWh capacity compared to the 11 TWh capacity expected to be required

U CAPEX intensity of meeting hydrogen demand in the Netherlands is three times higher than that of e-methane, even when excluding decentral heating costs [EUR bn]



1) Additional methane storage required specifically for salt caverns for higher flexibility; 2) Low end of the range shows total required CAPEX without decentral heating; 3) Distribution only required for decentral heating

Source: Roland Berger comprehensive value chain model

A recent study by the Dutch Ministry of Economic Affairs indicated that by 2050, up to 60 salt caverns will be required to accommodate the storage needs for hydrogen[34].

E-methane adoption enhances societal value, enabling a more resource-efficient energy transition

Given the capital-intensive nature of the energy transition, exploring alternatives that reduce the societal burden with lower upfront costs is crucial. The adoption of e-methane allows us to reuse existing infrastructure, conserving both financial and human resources and minimizing the risk of delay. In addition, e-methane can also serve as a transition energy vector in other use-cases by using it as a drop-in for natural gas. This facilitates the transition

34 Risk assessment for Underground Hydrogen Storage (UHS) in Salt Caverns and Interaction with other Underground Storage Locations, KEM, 2023

to renewable energy vectors through longer use of the existing natural gas infrastructure throughout the entire value chain. This efficient use of resources and infrastructure amplifies e-methane's societal value, freeing capital and attention for other critical strategic priorities.

Majority of the renewable energy vectors considered in the study are expected to achieve full commercial readiness by 2040

TRL scores indicate the development stage of a technology, from research and development (TRL 1-3) to full commercial deployment (TRL 11). Understanding these scores is needed for assessing when different energy vectors can be widely adopted. The technological maturity of different energy vectors varies by value chain step. ▶ V Renewable methane vectors are generally more mature than hydrogen vectors as they can leverage fully commercially mature existing gas infrastructure, apart from the production step, which has yet to achieve commercial maturity. For hydrogen, the ammonia vector is the most technologically mature, primarily due to the well-established infrastructure for ammonia synthesis, storage and transportation at scale. However, all renewable energy vectors face technological uncertainties and lower maturity in different parts of their value chains. E-methane, for example, still requires further development in areas like DAC and conversion processes. Similarly, further advances in ammonia cracking technology will be required to mature the ammonia route. Despite these technological uncertainties, all renewable energy carriers currently operate at a TRL level above the prototype stage (TRL 4) and for the purpose of this study are assumed to reach commercial technological readiness by 2040.

E-methane and renewable hydrogen have comparable GHG emission intensities

E-methane and renewable hydrogen have similar landed GHG emission intensities[35,36], ranging from 20 to 80 kg CO_2e/MWh, but the sources of these emissions vary. Emissions from methane-based vectors are both scope 1 and scope 2, where scope 1 emissions are due to methane and hydrogen slips, and emissions from hydrogen vectors are largely scope 2, influenced by grid CO_2 intensity. As the vectors are net-zero, scope 1 CO_2 emissions are not considered. Across both vectors, the production stage is the primary source of emissions, with minimal impact from transportation (except for liquid and gaseous hydrogen, where energy-intensive liquefaction and hydrogen leakage in pipeline transportation, based on current insights, significantly contribute to transportation emissions). ▶ W

Emissions for e-methane and methanol rise when CO_2 is sourced from DAC due to the energy intensity of the process. Similarly, ammonia emissions are driven by its energy-intensive synthesis. As a result, all three vectors have higher scope 2 CO_2 emissions as the grid

35 Emissions are converted to CO_2 equivalent using the 100-year Global Warming Potential (GWP_{100}); methane is assumed to have a GWP_{100} of 27, hydrogen of 11.6, N_2O of 273 and NOx of 8.5

36 In all emissions analyses in this chapter emissions are shown per MWh output at the last value chain step shown in the figure. Due to losses throughout the value chain, numbers might therefore not correspond between figures. Some value chain steps are relatively small compared to other steps, making them difficult to visualize in a graph. All emissions analyses show emissions with biogenic CO_2. Additional DAC feedstock emissions are shown separately in the production step and in the final totals

V Renewable methane vectors have relatively higher technology maturity level compared to hydrogen vectors[1]

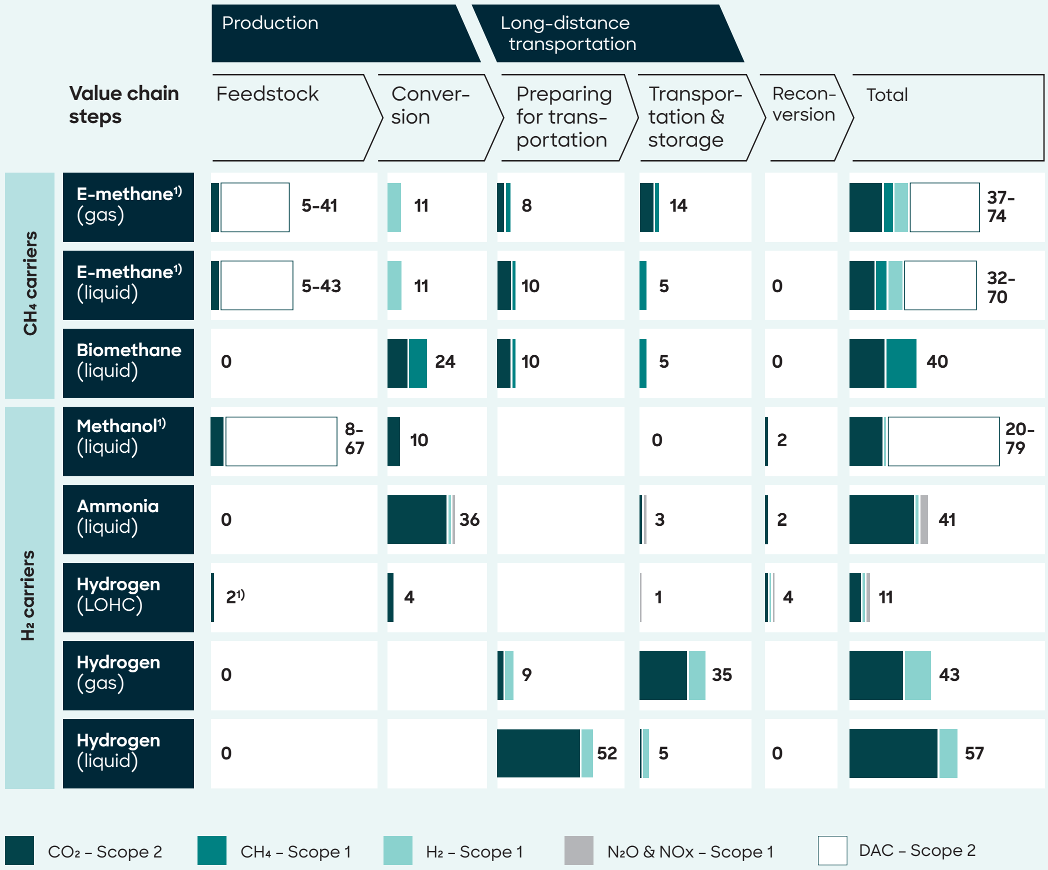
	Production			Long-distance transportation					Reconversion	National transmission		Reg. distribution & end-use	
Value chain steps	Production	Other feedstocks	Conversion	Preparing for transportation	Storage at production location	Transportation[6]	Storage at import location	Gasification	Reconversion	Transmission	Seasonal storage	Distribution	End-use conversion
Natural gas (liquid)	Extraction: **11**			Liquefaction: **11**	Storage at production: **11**	Shipping: **11**	Storage at import: **11**	Re-gasification: **11**	Conversion to H_2: **11**	National gas grid (HTL & RTL): **11**	Seasonal storage **11**	Local gas grid: **11**	Iron and steel: **9**
E-methane (gas)	Electrolysis: **9**	Carbon capture: **6-11**[2]	Methanation: **7**	Compression: **11**		Pipeline: **11**							
E-methane (liquid)				Liquefaction: **11**	Storage at production: **11**	Shipping: **11**	Storage at import: **11**	Re-gasification: **11**					Process heat, electricity production, Decentral heating: **11**
Biomethane (liquid)	Bio feestock		Methanation: **10-11**										
Methanol (liquid)	Electrolysis: **9**	Carbon capture: **6-11**[2]	Methanol synthesis: **9**[4]		Storage at production: **11**[3]	Shipping: **11**[5]	Storage at import: **11**[3]		Conversion to H_2: **4-6**[5]	Local H_2 grid: new **9**, refurbished **8**	Seasonal storage: **4-10** Depleted gas field storage: **4** Salt cavern storage: **9-10** We assume NL will make use of both storage types	Local H_2 grid: new **9**, refurbished **8**	Iron and steel: **6** Process heat, electricity production: **8** Decentral heating: **9**
Ammonia (liquid)		Nitrogen	Haber-Bosch: **11**		Storage at production: **11**	Shipping: **11**	Storage at import: **11**		Conversion to H_2: **4**				
Hydrogen (LOHC)		DBT	Hydrogenation: **6-7**		Storage at production: **9**[3]	Shipping: **11**	Storage at import: **9**[3]		De-hydrogenation: **6-7**				
Hydrogen (gas)				Compression: **6**		Pipeline: new **9**, refurbished **8**							
Hydrogen (liquid)				Liquefaction: **9**	Storage at production: **8-9**	Shipping: **7**	Storage at import: **8-9**	Re-gasification: **8**[4]					

TRL unknown TRL 1-6 TRL 7-8 TRL 9-10 TRL 11

1) The TRL at each value chain step only corresponds to the maturity of the main technology and not to the associated technologies of that value chain step; 2) DAC TRL of 6, point-source capture TRL of 11 (point-source TRL: EU technology report, 2019); 3) According to HydroHub HyChain, 2019; 4) According to IRENA; 5) According to Sterner et al, 2019; 6) Shipping TRL refers to tanker transporting relevant renewable energy vector

Source: IEA, IRENA, Desk research

W **Renewable methane and hydrogen vectors have comparable landed emissions [kg CO_2e/MWh output]**



1) CO_2 for e-methane and methanol synthesis is assumed to be captured as biogenic byproduct in the base case
2) LOHC feedstock emissions are scope 1 instead of scope 2

Source: Roland Berger comprehensive value chain model

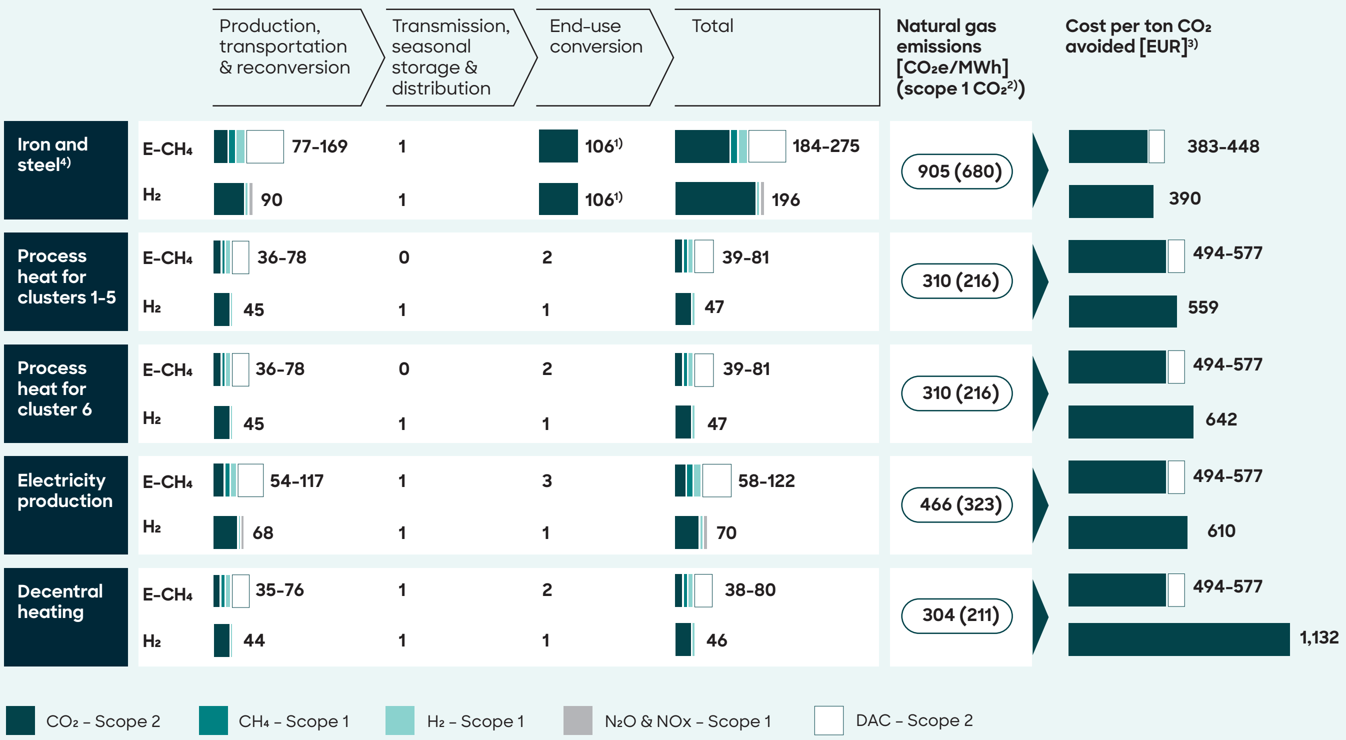
emissions intensity is assumed to be relatively higher in MENA compared to regions such as southern Europe. However, most of these projects are expected to use captive renewable electricity setups in the future, significantly reducing scope 2 emissions and leading to lower overall landed emissions.

For renewable energy vectors to become economically viable, the EU's Emissions Trading System price must exceed EUR 400 per ton CO_2

The total emissions of e-methane and hydrogen delivered via ammonia range from approximately 40 to 120 kg CO_2e/MWh across most use cases, except for iron and steel. ▶ X This represents a more than 70% reduction in GHG emissions for most use cases compared to fossil comparators, meeting the RFNBO requirements[37] even when assuming production in

37 The RED II defines a GHG emission reduction for RFNBOs of 70% below a fossil fuel comparator of 94 gCO_2eq/MJ, i.e. no more than 28.2 gCO_2eq/MJ (equivalent to 102 gCO_2e/kWh H_2)

X The cost per ton CO_2 avoided is higher than EUR 400 for both e-methane and hydrogen [kg CO_2e/MWh output]



1) Emissions due to coal component needed for steel production – These emissions are scope 1 instead of scope 2; 2) Refers to scope 1 CO_2 emissions at end-use conversion per MWh of output; 3) Only includes scope 1 CO_2 emissions at end-use conversion; 4) Values for Iron and steel shown in kg CO_2e/ton steel

Source: Roland Berger comprehensive value chain model

MENA and grid electricity use for processes post-hydrogen production. For iron and steel, emissions range from 200 to 300 kg CO_2e/MWh. However, these emissions include coal emissions, which are excluded from RFNBO requirements, ensuring that the iron and steel use case also meets compliance. While future RFNBO thresholds are expected to become stricter, the anticipated adoption of captive renewable electricity setups will significantly reduce scope 2 emissions, ensuring the continued compliance of e-methane and hydrogen vectors.

The emissions are comparable across use cases due to the limited impact of the downstream value chain steps on the GHG emissions. In large part this is because grid intensity is expected to be lower in the Netherlands by 2040, and leakage plays a smaller role in the downstream steps.

The cost per ton of CO_2 avoided[38] is also comparable for e-methane and renewable hydrogen, except in decentral heating, where the avoidance cost for hydrogen is two times that of e-methane due to the higher cost of energy delivered (the higher cost for decentral heating is primarily driven by the higher cost of energy, as discussed in Chapter 5.) The higher

38 Calculated by dividing the cost difference compared to natural gas by the difference in scope 1 CO_2 emissions during end-use conversion relative to natural gas

avoidance cost implies that the EU's Emissions Trading System (ETS) price would need to be in the EUR 400-600 range to make the business case for renewable vectors competitive.

Of the renewable energy vectors, e-methane is intrinsically a relatively safer vector

The safety characteristics of an energy vector can be determined based on its chemical properties like flammability, explosiveness and toxicity. (E)-methane scores relatively well on these metrics, with a relatively high auto-ignition temperature, narrow explosive range and low toxicity. ▶ Y

In contrast, hydrogen and methanol both present a significantly larger explosiveness bandwidth, which is measured by the explosive range between the lower explosive limit (LEL) and upper explosive limit (UEL), defining the concentrations at which ignition can occur. The explosive ranges are approximately seven and five times wider than (e)-methane, for hydrogen and methanol respectively, making them highly flammable across various air-fuel mixtures. However, it is important to note that hydrogen is much lighter than air, which makes it disperse more rapidly than other molecules. In addition, due to hydrogen's small size, it can escape more easily from indoor environments. Therefore, additional empirical evidence is required to better estimate the risk of hydrogen explosions in practice.

Ammonia has a higher toxicity, as indicated by its low life-threatening limit (*Levens-bedreigende waarde* or LBW) and Acute Exposure Guideline Level (AEGL) scores, meaning

Y Higher explosiveness risk of hydrogen and methanol, coupled with the greater toxicity of ammonia, makes (e)-methane in terms of measures a comparatively safer renewable energy vector

	General		Flammability		Explosiveness		Toxicity			
	Appearance	**Odor**	**Flash point [°C]**	**Auto-ignition temp. [°C]**	**LEL [%(V)]**	**UEL [%(V)]**	**AEGL 1 [mg/m3]**	**AEGL 2 [mg/m3]**	**AEGL 3 [mg/m3]**	**LBW1) [mg/m3]**
(E-) Methane	Colorless gas	Odorless	< -56	670	4.4	17	n/a	n/a	n/a	n/a
Methanol	Colorless liquid	Alcohol-like	9.7	455	5.5	44	690	2,800	9,400	15,000
Ammonia	Colorless gas	Ammonia-like	n/a	651	16	27	21	112	769	780
Hydrogen	Colorless gas	Odorless	n/a	560	4	77	n/a	n/a	n/a	3,300

1) At exposure of 1 hour

Source: Safety data sheets

even minor leaks can pose serious risks. These properties underscore the importance of stringent safety measures for hydrogen, methanol and ammonia handling.

Based on current safety guidelines, hydrogen infrastructure will potentially require additional safety measures compared to (e)-methane

The potential need for additional risk mitigation measures for infrastructure varies across the value chain and depends on legal risk thresholds. Risk is determined by the probability of an adverse event and its potential impact. While these factors are well-established for (e)-methane, limited empirical evidence for hydrogen makes them harder to define. Current regulations adopt a cautious approach with conservative assumptions, potentially leading to additional measures for hydrogen to achieve comparable risk levels to (e)-methane. However, as more data becomes available and understanding improves, regulations may evolve, potentially reducing these requirements.

For instance, a risk that is often considered for handling chemical substances is the site-specific risk *(plaatsgebonden risico)*, defined as the distance from the risk source at which the annual fatality risk is less than one in a million. In case of transportation via pipeline, the site-specific risk is based on the probability of pipeline failure, the probability that after a pipeline failure the released substance will ignite[39] and the impact when the released substance would ignite. While the impact and failure probability are probably comparable for (e)-methane and hydrogen, ignition probabilities differ significantly.

(E)-methane's ignition probability after pipeline failure ranges from 20-80%, depending on pipeline diameter, based on decades of experience. ▶ Z However, with limited data on hydrogen, the RIVM advises assuming a 100% ignition probability for now. This assumption necessitates additional safety measures for hydrogen pipelines if constructed now, to maintain equivalent site-specific risk levels to methane. Measures like increased supervision of digging activities or protective pipeline coverings can mitigate the higher assumed ignition probability. These measures are particularly relevant for smaller pipelines (less than 24-inch diameter) used for last-mile connections, where the ignition probability gap between hydrogen and (e)-methane is more pronounced.

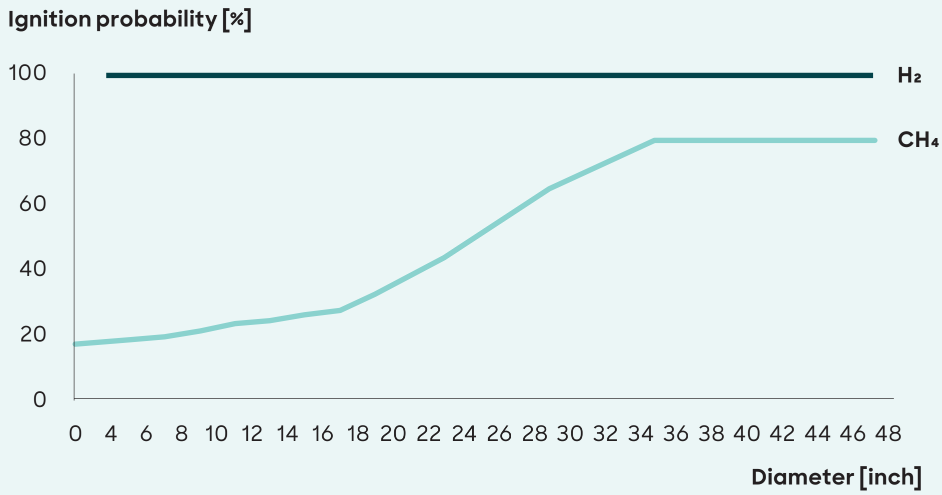
E-methane offers a more land-efficient and logistically manageable alternative to hydrogen

When comparing the land-use requirements of e-methane and hydrogen in the Netherlands,[40] for an equivalent annual energy flow of 100 TWh, e-methane is expected to be notably more land-efficient compared to hydrogen. Within the Netherlands, e-methane

39 Refers to the probability of ignition over a timeframe of 20 to 140 seconds. An equivalent energy amount escaping from a rupture for both hydrogen and methane is assumed

40 This analysis only considers land-use requirements inside the Netherlands. When comparing land-use requirements at the location of production, most of the land is required for renewable electricity generation. When assuming all renewable electricity comes from utility-scale solar PV panels, 100 TWh of hydrogen in the Netherlands would require 1,400 km^2 of land in the production region, compared to 1,600 km^2 for e-methane

Z **Based on current RIVM guidelines, hydrogen has a higher probability of ignition after a pipeline rupture than methane, especially for smaller pipelines**



Source: RIVM

requires only one-third of the total land use (47 km² vs. 128 km²)[41], covering areas needed for storage at import, seasonal storage, reconversion and end-use conversion. The most substantial land-use difference arises from seasonal storage, where e-methane needs 40 km² compared to hydrogen's 120 km² due to hydrogen's lower volumetric density. Although land requirements for storage at import and reconversion are also lower for e-methane (0.3 km² vs. 1.35 km²)[41], this difference is relatively minor.

In addition, e-methane demands fewer shipping resources. For a 100 TWh annual flow e-methane would require one LNG shipment (transporting an average of 1 TWh per ship) every 3-4 days, while hydrogen (assuming it is shipped via ammonia) would need almost daily shipments, each averaging 0.25 TWh. This increases the logistical intensity for hydrogen. Taken together, these factors make e-methane a more viable option for minimizing land and transportation demands associated with renewable energy use in the Netherlands.

41 Based on publicly available data from Gate Terminal and Port of Rotterdam, along with additional desk research and interviews with industry experts. Estimates for reconversion of hydrogen are based on land use reported by Port of Rotterdam for ammonia cracking

Conclusions & recommendations

E-methane is a feasible and promising renewable energy vector for specific use cases with high downstream costs in the future energy mix of the Netherlands, but its full potential can only be realized with advancement and cost reduction of technologies for renewable hydrogen production, e-methane synthesis and direct air capture

7

As the Netherlands and the broader EU work towards achieving climate neutrality by 2050, e-methane presents itself as a promising and practical energy vector within the renewable energy landscape when also considering the downstream part of the value chain, including transmission, storage, distribution and end-use. The analysis shows that e-methane not only aligns with the Netherlands' climate goals by facilitating the transition from fossil fuels to renewable energy, but also provides several key advantages for specific use cases in terms of cost, emissions, land use and safety. Synthesized from renewable hydrogen and CO_2, e-methane offers the Netherlands an additional feasible and potential option, next to other renewable energy vectors, to achieve net-zero carbon emissions by 2050 in hard-to-electrify use cases, and it does this while supporting decarbonization targets and minimizing the need for extensive new infrastructure.

One of the key benefits of e-methane is its compatibility with existing natural gas infrastructure. As a drop-in replacement for methane, it can make use of the extensive transport, storage and conversion infrastructure that is already in place. This reduces capital expenditures required to scale renewable energy adoption. This infrastructure advantage makes e-methane a particularly cost-competitive renewable energy vector for sectors with high downstream costs, such as decentral heating, industrial process heat for cluster 6 and central dispatchable electricity production. Additionally, certain industrial processes that will require a non-fossil carbon source can benefit from e-methane, as it contains carbon atoms - an advantage over hydrogen or ammonia. In the Netherlands and other similar regions with well-established natural gas networks, e-methane (combined with biomethane) can be deployed rapidly and at a lower cost for certain sectors, placing a much smaller financial and logistical burden on citizens compared to renewable hydrogen.

E-methane's cost-competitiveness in certain use cases is further bolstered by its emissions profile, safety characteristics and efficiency in land use and logistics. The GHG footprint of e-methane is comparable to that of renewable hydrogen vectors, making it a sustainable option for the energy transition. In terms of safety, e-methane is less hazardous than hydrogen and its derivatives and benefits from established safety protocols, whereas hydrogen infrastructure may require additional measures based on current regulations, which are informed by limited operational experience, to achieve comparable risk levels. Additionally, e-methane is more resource-efficient, with significantly lower land and logistical demands than hydrogen. This advantage could be crucial for large-scale deployment, especially in densely populated areas or areas with limited available land. These attributes collectively highlight the societal value of e-methane by reducing the financial burden on society, supporting sustainability goals and enabling a more inclusive transition to renewable energy.

Initially, e-methane could be produced using biogenic CO_2; however, due to feedstock limitations, large-scale adoption will rely on DAC for CO_2 sourcing. While DAC holds promise, uncertainties around its costs present challenges for e-methane's cost-competitiveness in the long term. Sensitivity analyses show that fluctuations in DAC costs could affect the cost of e-methane, making it essential to address these uncertainties through technological advancements and regulatory support. As DAC technology matures, it will be crucial for unlocking e-methane's potential as a large-scale, cost-competitive additional renewable energy vector.

Ultimately, e-methane is a promising renewable energy vector for specific use cases in the Netherlands and other similar regions, where established natural gas infrastructure can be leveraged for renewable energy distribution. Its efficiency in terms of capital and operational costs, emissions, safety, land use and transportation makes it a viable vector in the renewable energy mix. E-methane can play a role in decarbonizing cluster 6, decentral heating and central dispatchable electricity production – sectors where hydrogen adoption seems to face significant challenges.

However, to realize the full potential of e-methane, several key steps should be focused upon:

- **Strategic decarbonization planning**
  Develop specific end-use case strategies that evaluate the true costs of achieving net-zero emissions across the entire value chain *van put tot pit*. Recognize e-methane as a feasible and potential energy vector and integrate it into future energy mix evaluation alongside other renewable vectors.

- **Technological maturity**
  Invest in R&D and pilot/demonstration projects to validate and commercialize e-methane production processes. Demonstration projects can be initiated globally to provide proof of concept and establish scalability and efficiency.

- **Kickstarting e-methane with biogenic CO_2**
  Identify locations (e.g. northern Europe) with high biogenic CO_2 availability to kickstart e-methane production and import.

- **Cost reductions for renewable hydrogen**
  Support initiatives to lower the production costs of renewable hydrogen through innovation in electrolysis technologies, economies of scale and renewable energy price reductions.

- **Scaling DAC solutions for e-methane production**
  Accelerate technological advancements to lower the costs of DAC and ensure economic viability. DAC is critical for scaling up e-methane, especially where biogenic feedstocks are constrained.

- **Utilizing CCS solutions to realize negative emissions**
  Utilizing CCS for high-emission, high-utilization end-use cases powered by e-methane offers the potential to achieve negative emissions. This option should be considered in the overall weighting of the transition paths of end-uses and associated carriers.

- **Leveraging existing gas infrastructure**
  Update and align plans for the existing gas infrastructure to ensure readiness to support e-methane, since e-methane can leverage existing gas infrastructure and

thus reduce the need for significant downstream infrastructure investments. To enable this transition, adequate pipeline capacity must be ensured for e-methane, alongside sufficient infrastructure for other molecules in the future energy mix.

- **Blending-in biomethane and e-methane**
  Implement blending mandates for biomethane and e-methane into natural gas supplies, especially for fragmented CO_2 emission use cases like decentral heating and transport to drive initial market demand.

- **Prioritizing optimal end-use cases**
  Identify and prioritize the most viable end-use cases for e-methane where it offers the highest cost-competitiveness and impact, such as industrial process heat for cluster 6, dispatchable electricity production and decentral heating.

- **Supportive policy and regulatory frameworks**
  Standardize cross-border CO_2 certification to facilitate trade and align regulatory frameworks. Implement supportive policies to attract investment in e-methane and other renewable energy vectors.

- **Public awareness**
  Raise public awareness about the role of renewable gases like e-methane in achieving climate goals to secure societal support for its development and use.

Definition of key terms and abbreviations

Definition of key terms

GHG-neutral CO_2: Refers to CO_2 obtained through DAC or from biogenic sources. CO_2 sourced from fossil sources is excluded

Hydrogen carriers: Molecules containing hydrogen atoms that can facilitate the transportation of hydrogen. Examples include LOHC, methanol and ammonia

Low-carbon energy vectors: Refers to molecules derived from non-renewable sources that meet a GHG emissions reduction threshold of 70% compared to fossil natural gas across the full lifecycle as defined by the EU

Methane carriers: Methane energy vector produced from different sources. Examples include e-methane, biomethane and natural gas

Renewable electricity: Refers to electricity generated from wind, solar (both solar thermal and solar PV), geothermal energy, ambient energy, tide, wave and other ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas, biogas and nuclear systems. Although nuclear energy is not classified as renewable in the EU, its carbon emissions are very low. Nuclear can thus be used for production of renewable energy vectors if the average emission intensity of the electricity grid is <18 g CO_2e/MJ

Renewable energy vectors: Refers to molecules from organic sources, such as biogas and biomethane, or non-biological renewable sources using electricity (which is at least 90% renewable), such as renewable hydrogen and derivatives like e-methane, renewable ammonia and renewable methanol as defined by the EU

Renewable gaseous molecules: Renewable methane and hydrogen, including green hydrogen, e-methane and biomethane

Abbreviations

AEGL: Acute Exposure Guideline Level
AEGL 1: Mild, reversible effects (discomfort)
AEGL 2: Serious but non-life-threatening effects (disability)
AEGL 3: Disability potentially causing death
CAPEX: Capital expenditure
CH_4: Methane
CH_3OH: Methanol
CO_2: Carbon dioxide
CO_2e: Carbon dioxide equivalent
CCS: Carbon capture and storage
DAC: Direct air capture
DEC scenario: Decentral Initiatives scenario (one of the II3050 report scenarios)
ETS: Emissions Trading System from the EU
EU: European Union
EUR scenario: European Integration scenario (one of the II3050 report scenarios)
GHG: Greenhouse gas
GW: Gigawatt
GWh: Gigawatt hour
H_2: Hydrogen
H_2O: Water
HTL: Main transmission pipelines (hoofdtransportleidingnet)
IA scenario: International Ambition Scenario (one of the EU scenarios – used for 2030 in the II3050 in the report, most similar to the II3050 INT scenario)
IEA: International Energy Agency
II3050: Integrale Infrastructuurverkenning 2030-2050 (Dutch) or Integrated Infrastructure Outlook 2030-2050 (English)
INT scenario: International Trading scenario (one of the II3050 report scenarios)
ISO: International Organization for Standardization
kg: Kilogram
LBW: Life-Threatening Value (Levensbedreigende Waarde)
LEL: Lower explosive limit
LNG: Liquid natural gas
LOHC: Liquid organic hydrogen carrier
MENA: Middle East and North Africa
MW: Megawatt
MWh: Megawatt hour
N_2: Nitrogen
n/a: Not applicable
NAT scenario: National Leadership scenario (one of the II3050 report scenarios)
NH_3: Ammonia
NL: The Netherlands
O_2: Oxygen
OPEX: Operational expenditure
PEM: Proton-exchange membrane
PVs: Photovoltaics
R&D: Research & development
RED: EU Renewable Energy Directive
RFNBO: Renewable fuel of non-biological origin
RTL: Regional transmission pipelines (regionale transportleidingnet)
SOEC: Solid oxide electrolyzer cell
TRL: Technology readiness level
TW: Terawatt
TWh: Terawatt hour
UEL: Upper explosive limit
US: United States
WACC: Weighted average cost of capital

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We are grateful for the contributions from numerous experts from GasTerra, Gasunie and the broader energy sector.

04.2025

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Publisher

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