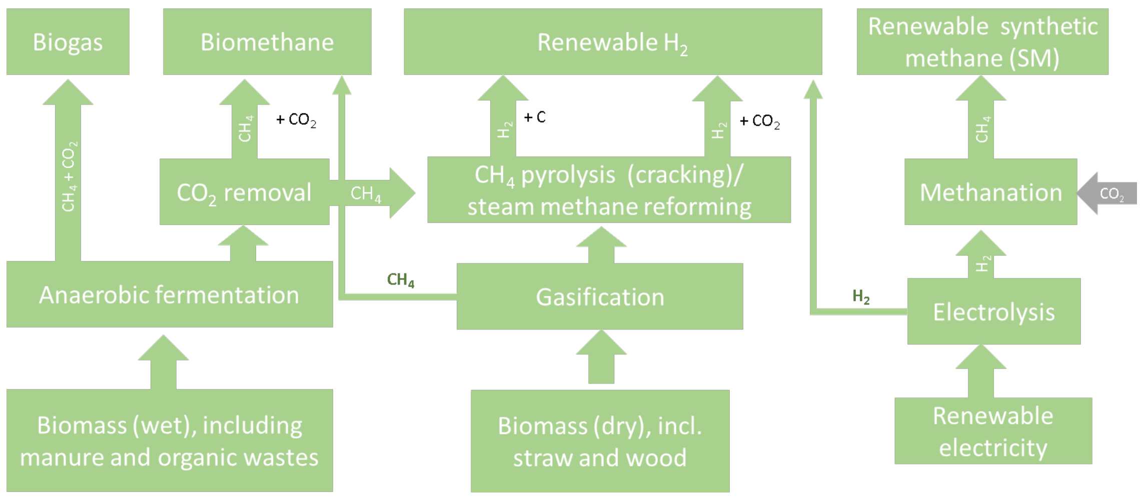
Renewable gas - deployment, markets and sustainable trade

Summary Report of the IEA Bioenergy Intertask project
Renewable Gas: Deployment, markets and sustainable trade

March 2022



Renewable gas - deployment, markets and sustainable trade

Summary Report of the IEA Bioenergy Intertask project
"Renewable Gas: Deployment, markets and sustainable trade"

Authors:

Uwe R. Fritsche & Hans Werner Gress, IEA Bioenergy Task 40

with inputs from Christiane Hennig (IEA Bioenergy Tasks 40 & 44), Jan Liebetrau (IEA Bioenergy Task 37), Rory Monaghan & Stefan Majer (IEA Bioenergy Task 45), Olle Olson (IEA Bioenergy Task 40)

IEA Bioenergy: Task 40

March 2022

Published by IEA Bioenergy

CONTENTS

LIST OF FIGURES

LIST OF TABLES

Abbreviations and Acronyms

BCM	billion cubic meters
BECCS	bioenergy with carbon capture and sequestration
BECCU	bioenergy carbon capture and utilization
Bio-SNG	Synthetic Natural Gas from biomass
BY	Belarus
CCS	carbon capture and sequestration
CCU	carbon capture and utilization
CH_4	methane
CO_2	carbon dioxide
DNV-GL	Det Norske Veritas group - German Lloyd
EBA	European Biogas Association
EC	European Commission
ERGaR	European Renewable Gas Registry
ERIG	European Research Institute for Gas and Energy Innovation
EU	European Union
GfC	Gas for Climate
GHG	greenhouse gas(es)
GO	Guarantee of Origin
H_2	(molecular) hydrogen
ICCT	International Council on Clean Transportation
IEA	International Energy Agency
IEA Bio	International Energy Agency Bioenergy Technology Collaboration Programme
IEA H2	International Energy Agency Hydrogen Technology Collaboration Programme
IPCC	Intergovernmental Panel on Climate Change
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
IRENA	International Renewable Energy Agency
ISO	International Standardization Organization
JRC	European Commission Joint Research Centre
LH2	liquefied hydrogen
LHV	lower heating value
LNG	liquefied natural gas
Mt	million tons
NZE	net zero emission
PtG	power-to-gas
REGATRACE	Renewable Gas Trade Centre in Europe
RG	renewable gas(es)
RU	Russian Federation
SM	synthetic renewable methane
SNG	Synthetic Natural Gas
TRL	Technology Readiness Level
vol%	per cent by volume
UA	Ukraine
UK	United Kingdom
US	United States of America

Objectives of the IEA Bioenergy Strategic Intertask Project "Renewable gases - deployment, markets and sustainable trade"

The IEA Intertask project concerns the prospects of implementing renewable gases (RG) in the energy markets of IEA countries, and beyond. The aims of the RG project are to

- provide state-of-the-art overviews on prospects, opportunities and challenges for various mechanisms that could help deploying biogas, biomethane and other renewable gases in energy markets in IEA countries (e.g., green gas certificates), and beyond
- discuss technological and sustainability issues of RG from a deployment perspective and derive respective recommendations for policymakers.

The project aims to provide decision makers and the research community with a comprehensive overview of what is currently known regarding renewable gases, considering both technology development/infrastructure and which mechanisms exist and are considered to fulfil the important role of renewables gases in global climate scenarios for a well-below 2°C world.

Overall summary of key findings

This summary report compiles the key findings from the RG Intertask project[1].

Biogas and biomethane

Renewable gases (RG) will be key components of a global energy system aiming at net zero greenhouse gas emissions by 2050 (IEA 2021a). IEA's World Energy Outlook (WEO) indicates that global gas demand will be decreasing in emission reduction scenarios. There is agreement that among renewable gases, biomethane and hydrogen (H_2) will be most critical. Biomethane is the largest contributor to low-carbon gas supply in the WEO scenarios. As biomethane is nearly pure methane, it can be used without any change in natural gas transmission and distribution infrastructure or end user equipment.

Regarding biomethane feedstocks, a survey within selected countries revealed that almost all countries which support anaerobic digestion (AD) incentivise the use of manure and waste materials. The use of energy crops is not as much common and even when eligible for incentives they are not utilized everywhere due to conditions of the incentive system. Energy crops are costly and discussed controversially, with sustainability aspects and land use being the main issues. Intercropping avoids some of the issues, and the trend is away from energy crops.

Biomethane provision based on AD processes is a proven technology with numerous applications worldwide – with a variety of substrates used and technologies for gas production, upgrading and utilization. In recent years major progress has been accomplished in the reliability and efficiency of the upgrading technologies. When looking at technology used for upgrading, an increasing market share of membrane separation technology in regards of number of plants is apparent.

With cost reduction achieved by wind and photovoltaics, the gap to electricity costs from biogas is getting bigger. As an effect, biogas-based electricity is more expensive and only

[1] https://www.ieabioenergy.com/blog/task/inter-task-projects/#renewable_gas_deployment_markets_and_sustainable_trade

economic with higher feed-in tariffs than for wind and solar. Currently, biogas use is dominated by combined heat and power units. Since upgrading and grid injection is costly for smaller-scale sites, CHP will remain the technology of choice for those aiming at high heat utilization and flexible electricity provision to balance market prices.

Under current market conditions, biomethane is not cost-competitive to most fossil energy carriers, e.g., natural gas. However, the basis of comparison for renewable energy carriers in the future needs to consider the necessary reduction of CO_2 emissions, and therefore, the long-term transition to a decarbonized economy requires CO_2 pricing. The transition process will change the overall demand in energy forms and carriers as e.g., electricity, gaseous and liquid fuels. Up to 2050, competition of technologies for producing gaseous energy carriers will be driven by overall demand, production costs (including CO_2 price), and availability of technical alternatives. Any support should consider the availability of necessary infrastructure and technology options for gas utilization.

Due to the current lack of a comprehensive and cross-sectoral CO_2 pricing, support for developing renewable gas needs to balance the shortfall between the revenues for the product and the financial effort for the production. There are numerous systems and approaches to incentivise the production or the utilization of biomethane. With an obligatory development target for renewable fraction of the market, set e.g., by a quota, a defined market share for renewables can force a development. Yet, a proper timing of the shift from protected technology development phase to competition is crucial to avoid “lock in” effects. In the long-term, any support mechanism shall be replaced by a competitive market scheme.

Strategies and incentives to develop the sector need to reflect the available substrates for biomethane production, the specific costs for the improved access of substrates and gas provision. Since the investment has usually long amortisation periods, the duration of temporal guarantee of the incentive is highly important. Biomethane can contribute but not satisfy the demand for renewable gas completely. Therefore, the interaction and compatibility with other renewable gases such as H_2 is highly recommended. Technologies which can be combined with biomethane plants as Power-to-gas need to be included in the strategy to capitalize on synergies and enable most benefit in regards of greenhouse gas abatement, considering existing and needed infrastructure (e.g., natural gas grids).

Biogas upgrading to biomethane is also a valid source of CO_2 for bioenergy with carbon capture and sequestration (BECCS) which achieves **negative** CO_2 balances, and for bioenergy with carbon capture and utilization (BECCU) which delivers CO_2-neutral products.

Non-biogenic renewable gases

Non-biogenic renewable gas (NBRG), encompassing hydrogen (H_2) produced by electrolysis powered by renewable electricity and potential subsequent methanation with capture of CO_2, are potential routes to decarbonize energy and chemical feedstock use, especially in hard-to-abate sectors. A growing number of countries developed national H_2 strategies to position H_2 in their decarbonization plans, some include non-biogenic renewable methane (RM). Most strategies focused on green H_2 expect that its first deployment will be in industries that already consume fossil-derived H_2 such as oil refining, and fertilizer and chemicals production; a focus on aviation, shipping, and long-range heavy duty trucks; a focus on the co-benefits of H_2 use including reduced GHG emissions, improved air quality, reduced reliance on fossil fuel imports.

The analysis conducted in this report considers regional case examples in the North Sea, Texas, and Brazil to illustrate how local factors such as renewable electricity resource, electricity grid GHG intensity, potential CO_2 source type, and other factors affect NBRG economic feasibility (measured by levelized cost of gas), environmental sustainability (measured by GHG intensity of gas), and the cost of abating CO_2 emissions using NBRG. The use of excess electricity to power electrolysis is cost-ineffective due to low electrolyser capacity factors caused by the infrequent availability of excess electricity. On the other hand, the economic and environmental feasibility of using grid electricity to maintain high electrolyser capacity factor show strong dependences on regional factors including the price of grid electricity and its GHG intensity.

In the North Sea, H_2 produced from grid electricity has the lowest carbon abatement cost in 2030 (170 $/t CO_2), but by 2050 is overtaken by H_2 produced by dedicated offshore wind (140 $/t CO_2). This is mostly due to the expected decrease in offshore wind electricity price and simultaneous increase in grid electricity price. In Texas, which possesses abundant wind and solar resources with high combined capacity factor, H_2 produced from dedicated renewables achieves abatement costs of 180 $/t CO_2 in 2030 and 110 $/t CO_2 in 2050. Similar trends are seen in Brazil, with H_2 produced from dedicated biomass electricity achieving abatement costs of 130 $/tCO2 in 2030 and 100 $/t CO_2 in 2050. Expected ranges of levelized costs of H_2 by region are: 4-7 $/kg in 2030 and 3-6 $/kg in 2050 for the North Sea; 4-10 $/kg in 2030 and 3-8 $/kg in 2050 for Texas; and 8-12 $/kg in 2030 and 6-12 $/kg in 2050 for Brazil.

In all cases, methanation of H_2 using captured CO_2 to **renewable methane (RM) significantly increases abatement costs**, but this must be balanced against the benefits of being able to use existing natural gas infrastructure and appliances. For methanation using CO_2 sourced from direct air carbon capture (DACC), high capital and operating costs of DACC lead to high CO_2 prices and, thus, to high abatement costs for RM. **The lowest abatement costs for RM are seen for CO_2 captured from biomethane and bioethanol plants**, which combine CO_2 of renewable origin with relatively low CO_2 capture price due to high CO_2 concentration in off-gases.

Another finding is that situating electrolysers close to renewable electricity sources **is more cost effective** than situating them close to H_2 demand centres since it is cheaper to move energy via new H_2 transmission pipelines than via electricity transmission lines. Finally, the analysis shows that the lower ends of carbon abatement cost ranges are similar to carbon tax proposals in several of countries, indicating the feasibility of NBRG in national decarbonisation strategies.

Sustainable trade of renewable gases

Renewable gases will be key components of a global energy system aiming at net zero greenhouse gas emissions by 2050. RG will have to strongly increase, and **international trade** may become an important component of decarbonizing the global energy system. International trade of RG can be either **physical** through gas pipelines (or as liquefied gases in ships), or **virtual** through the exchange of certificates such as Guarantees of Origin.

In the short- and medium term, **biomethane is the major RG being traded** internationally, and prospects for further growth are significant in Europe but also in Latin and North America and South-East Asia, where current trading is rather low.

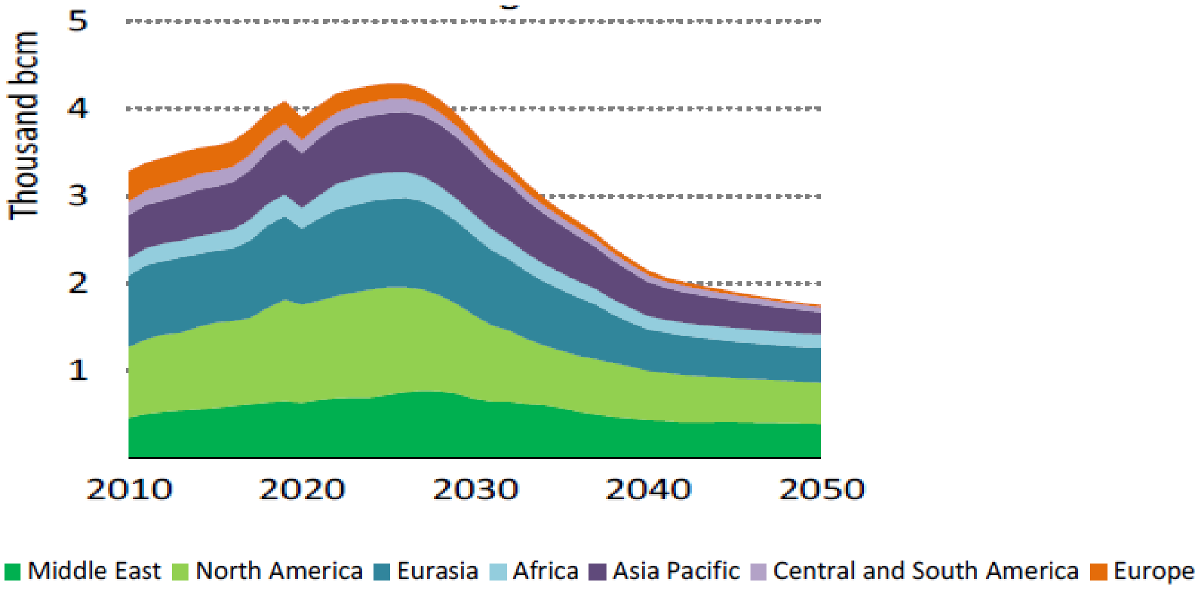
In the longer-term, “green” H_2 has a high potential for international RG trade. The 2050 potential green H_2 exporting countries are seen as those offering low-cost renewable electricity for H_2 production, i.e., wind- and sun-rich regions with access to international pipelines and/or ports in Africa (e.g., Morocco), Europe (Portugal, Spain), Latin America (e.g., Chile), Middle East (e.g., Saudi-Arabia), and Oceania (Australia and New Zealand). H_2 trade will rely on existing gas pipelines and new dedicated H_2 pipelines, or transport with ships (ammonia, LH_2). Up to **1/3 of green H_2 will be traded internationally by 2050**, a share slightly higher than the current share of natural gas traded globally.

For trade of green H_2 and its derivatives, regulatory hurdles remain, especially the definition of “greenness” and respective GHG emission thresholds, but ongoing work in the EU and internationally aims to address these issues.

Introduction

Renewable gases (RG) will be key components of a global energy system aiming at net zero greenhouse gas emissions by 2050 (IEA 2021a). With fossil gas supply peaking in the mid-2020ies and shrinking fast up to 2050 (Figure 1), RG will have to strongly increase, and international trade may become an important component of decarbonizing the global energy system (Daioglou et al. 2020).

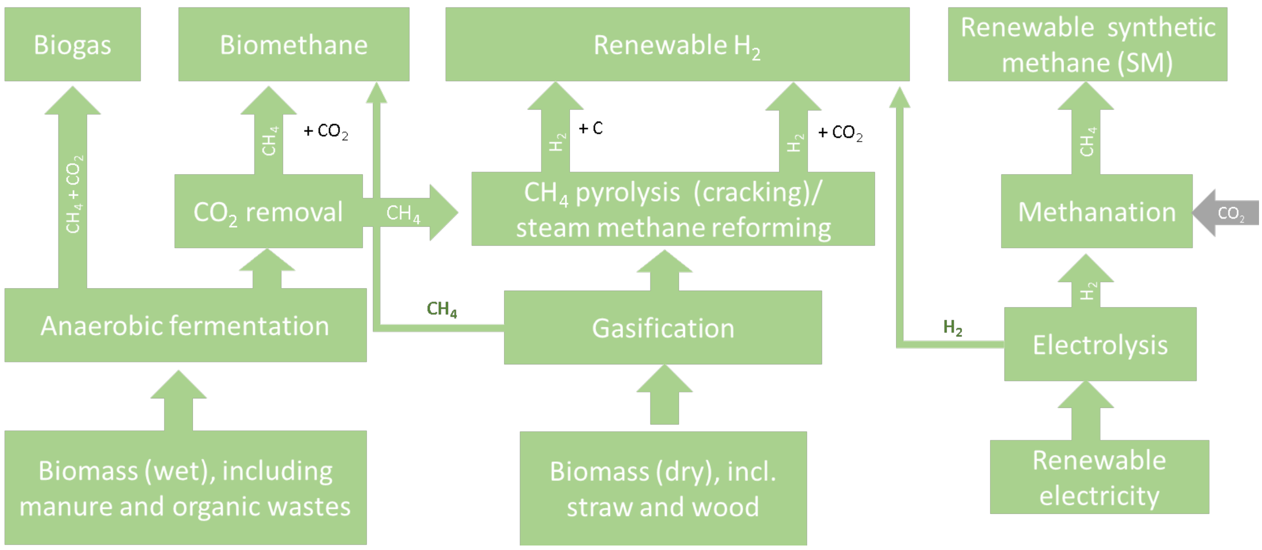
Figure 1 Global natural gas production in the IEA Net Zero Emission Scenario



Source: IEA (2021a); bcm = billion cubic meters (approx. 40 PJ)

Several pathways exist to provide renewable gases, as depicted in Figure 2.

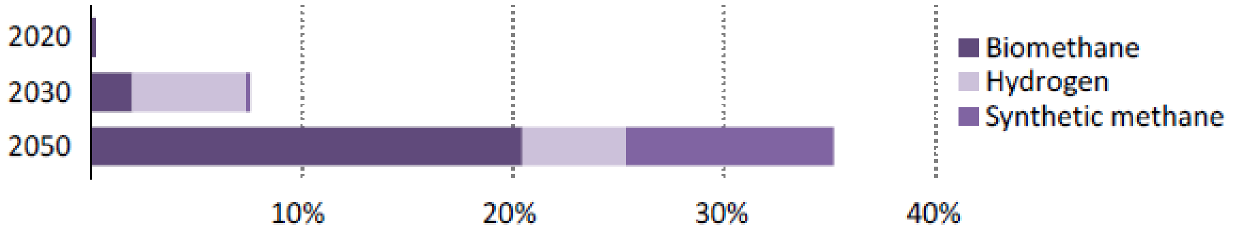
Figure 2 Simplified overview of renewable gases production pathways



Source: Fritsche (2022); renewable synthetic methane (SM) is also referred to as renewable methane (RM)

The IEA NZE scenario assumes a major role for renewable gases, especially for biomethane, but also for H_2, and H_2-based synthetic methane (Figure 3).

Figure 3 Gas grid shares of renewable gases in the IEA NZE Scenario



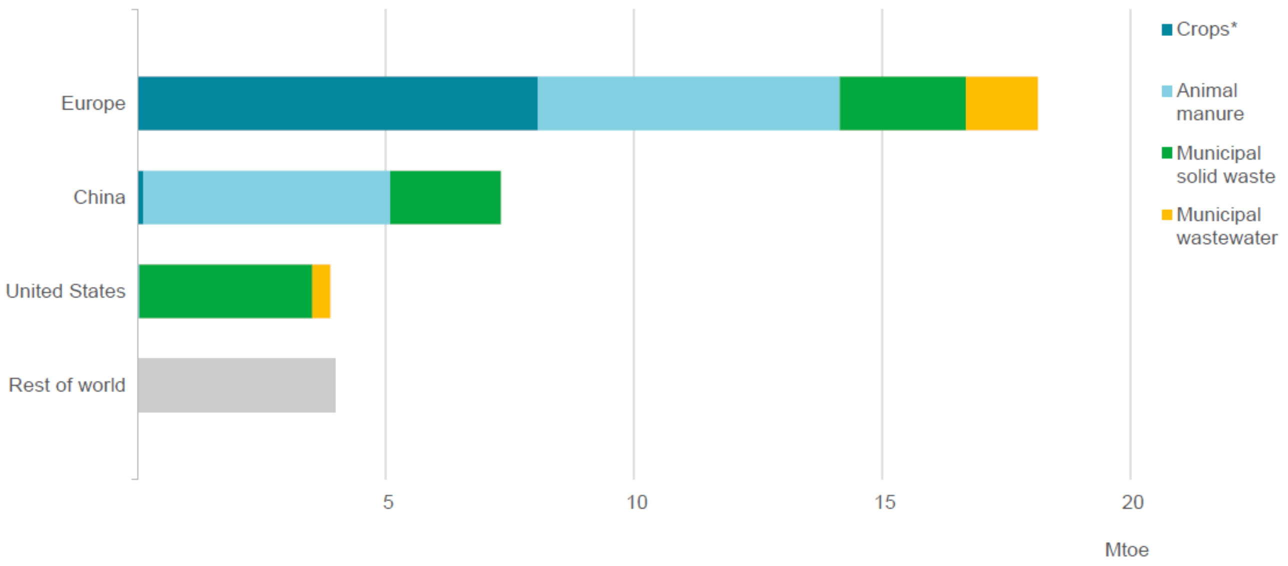
Source: IEA (2021a)

1. Biomethane

Biomethane is the largest contributor to low-carbon gas supply in IEA's World Energy Outlook Scenarios (IEA 2020a) and a key component of future energy technology developments (IEA 2020b + 2021).

Currently, biogenic gases only play a small role in the global system, with Europe and China being the largest suppliers, followed by the US (Figure 4).

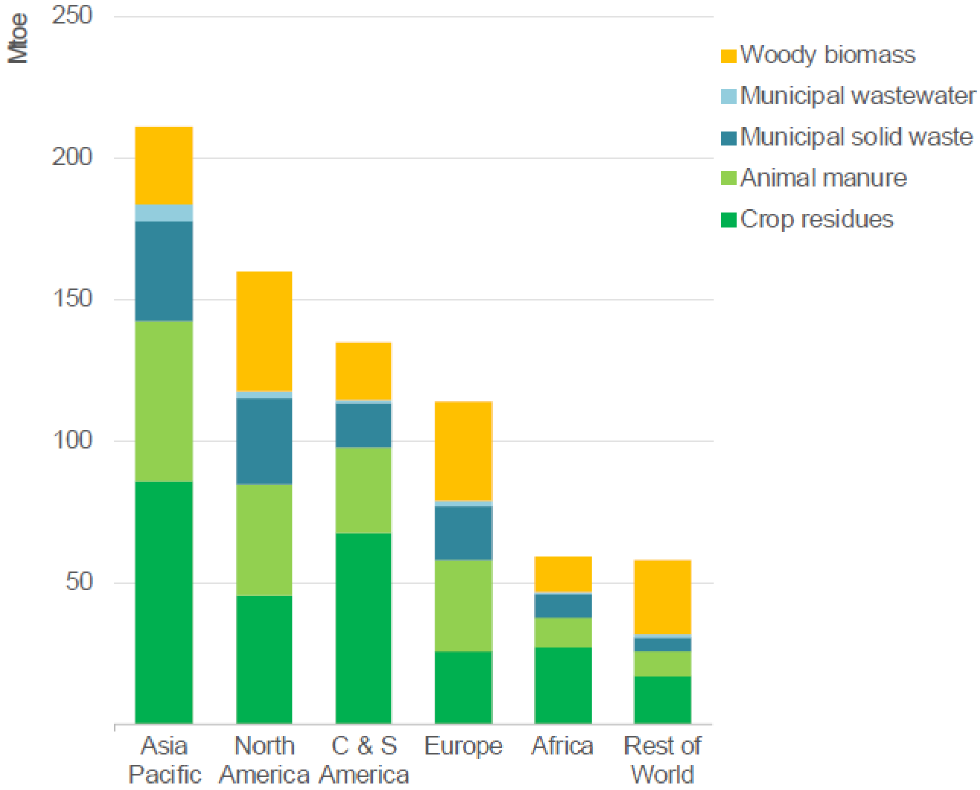
Figure 4 Biogenic gas production by feedstock type, 2018



*Source: IEA (2020b); Mtoe = million tons of oil equivalent (41.9 PJ); * = Crops include energy crops, crop residues and sequential crops*

The potential for biogenic gases, excluding dedicated annual crops, is shown in Figure 5 – Asian and American countries dominate, followed by Europe and Africa. More regionalized analysis on biogas is available (Dale et al. 2020; GBEP 2020).

Figure 5 Production potential for biogenic gases by feedstock source, 2018



Source: IEA (2020c); Mtoe = million tons of oil equivalent (41.9 PJ); C&S America = Central and South America. Woody biomass feedstocks are available only for biomethane production (through gasification or pyrolysis). Note that the potentials do not reflect mobilization restrictions, nor cost issues

Biomethane is nearly pure methane and can be used without needing any changes in transmission and distribution infrastructure or end user equipment (FE & IAEW 2019; Fritsche 2022; IEA 2020b).

1.1 Technologies for the production of biomethane

Technologies for production of biomethane as a renewable gas are anaerobic digestion (AD) and gasification processes. Biomethane provision based on anaerobic digestion processes is a proven technology with numerous applications worldwide – with a variety of substrates used and technologies for gas production, upgrading and utilization. In recent years, major progress has been accomplished in the reliability and efficiency of the upgrading technologies. Increasingly, membrane separation is applied in EU countries.

Since biogas plants are highly individual and represent many components and contractors, and as they are limited in size due to substrate supply and digestate logistics, the future overall cost reduction potential based on higher efficiency of components is limited.

With cost reduction achieved by wind and photovoltaics, the gap to electricity production costs from biogas is getting bigger. As an effect, biogas-based electricity is more expensive and only economic with higher feed-in tariffs than for wind and solar. Within the renewable gas sector, the situation is different, currently available alternatives are not necessarily cheaper and consequently the trend of biogas utilization is moving towards renewable gas applications.

Due to different and in the course of time changing incentive systems, the development of the sector has been neither temporal steady nor evenly spread in the regions of the world. However, whenever conditions are in favour for biogas or biomethane sector, plants have been quickly built and the sector has been developing since experience and knowledge for reliable technology with a predictable constructions and operational costs are available.

1.3 Support mechanisms

Under the current market conditions the provision of renewable biomethane is not cost competitive to the provision of e.g., natural gas. However, the basis of comparison for renewable energy carriers in the future needs to be different than sole production costs. The necessary reduction of CO_2 emissions requires additional instruments and therefore in the long-term the transition to a decarbonized economy requires a pricing of CO_2 of any kind.

Many countries apply several mechanisms – either specific to a region or an energy sector – yet, developing successful biomethane applications is independent from the specific support mechanism. The support mechanism or incentive come into action at different points of the productions process – starting with the support of specific substrate utilization (e.g., incentives for manure utilization), the production process itself (investment support, feed-in tariff for the gas, quota systems for gas in the grid) and/or the final gas utilization (quota systems in specific sectors for gas utilization as transport, feed-in tariffs for electricity, tax exemption for target sector etc.). The support systems differ additionally in the resulting financial compensation, the one-time (mostly investment support) or operation related grant and in the latter case very important- the guaranteed period of the grant.

The decision for or against the investment are made by weighing potential financial profit, positive co-benefits, legislative hurdles, and technical risks. Major driver for the success of a support scheme is the chance for the entrepreneur to make a profitable business case. Technical risk and legislative hurdles might have a certain impact but are usually to be overcome if interest of stakeholders to build plants is given.

Most participants of a survey vote for economics when asked what hinders the market development most. Combining this statement with the abovementioned incentive systems, it becomes obvious that for the development of a national industry the type of mechanism is not decisive, it is the fact if an economic business case is possible or not. In countries where the support for the installation is based on a realistic cost assessment and the legislative conditions do not represent a unbreachable obstacle, the sector develops.

Table 1 Major obstacles for further biomethane market development

	Australia	Canada	China	Estonia	Finland	Germany	India	Norway	Sweden	Switzerland	UK
Financial	x	x		x	x	x	x	x	x	x	x
Legislative (regulations regarding technology and plant operation)	x		x		x		x				x
Legislative (framework conditions other than financial and technological)	x	x	x		x	x					x

Source: own compilation: x = agreed

Some countries decide to target - based on national, sectoral abatement targets - a specific gas utilization sector (e.g., transportation or electricity). The gas is directed with the incentive system and technical requirements to the desired sector. One aspect of the implementation is the certification or proof of eligibility measures specific to the target sector. Due to the specific arrangement of these systems and a certain complexity, a quick redirection of produced biomethane to other sectors requires new procedures and conditions for eligibility – although technically the gas can be applied in many sectors. In order to avoid "lock in" effects, any certification system shall be compatible to other sectors of use.

1.4 Strategies and actions for biomethane development

Many countries recognize the need for renewable gas as a major energy carrier for future energy systems, often with a focus on H_2, although many countries update their incentive systems for biomethane as well. In all countries, the potential of available biomass (excluding energy crops) exceeds currently used sustainable substrates by far, i.e., biomethane production can increase. Yet, biomethane cannot satisfy the demand for renewable gas completely. Therefore, the interaction and compatibility with the development of hydrogen is highly recommended. Last but not least, existing and new infrastructure (e.g., gas grids) shall be part of the strategies.

The main fields of action for the development of biomethane as a renewable gas are:

- Create strategies for biomethane sector development, including the consideration of available substrates and development costs, defined development targets and consideration of needed infrastructure
- Obligatory market implementation by means of a quota is the most effective way of introducing renewable gas under the current conditions
- Incentives which reflect costs and long-term operation (amortisation) conditions and provide a secure market environment for the run up of technologies
- Dismantling of inhibiting regulations on technical and regulatory level
- Compatibility with other measures to develop renewable gas sector and downstream technologies (e.g., PtG)

In the long-term, the technology and sector specific support schemes need to be transferred into an overall market scheme resp. an economy where CO_2 emissions have a monetary value. According to reduction targets and technology development the price for CO_2 will develop and drive the transformation.

Such a system will include competition of technologies and shifts between energy sectors and consequently the phase out of specific incentives. Any incentive system set today shall be scrutinized for transferability into such a future economy.

1.5 Biogas, biomethane, and CCU

Building renewable fuels, chemicals and materials based on CO_2 and H_2 is a rapidly expanding field. One of the basic carbon capture and utilization (CCU) products is also one with the largest current market, namely methane (CH_4) which is the main component in natural gas and a widely used feedstock in the chemical industry.

There are some volumes of renewable methane being produced already today, although not primarily via the CCU route but as a key component of different renewable gases produced from biomass.

Biogas upgrading to biomethane and syngas from biomass gasification are valid sources of CO_2 for bioenergy with carbon capture and sequestration (BECCS) which achieves **negative** CO_2 balances, and for bioenergy with carbon capture and utilization (BECCU) which delivers CO_2-neutral products.

2. Non-biogenic renewable gases

Non-biogenic renewable gases (NBRGs) encompass **hydrogen** produced from electrolysis powered by renewable electricity, or from direct solar water-splitting, or **methane** produced by combining H_2 with CO_2.

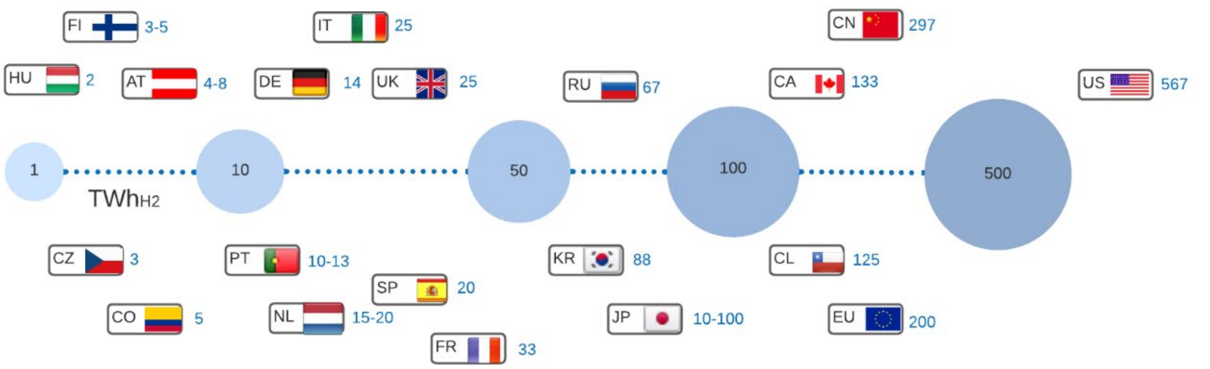
If this NBRG incorporates H_2 produced by electrolysis powered by renewable energy (green H_2), it can enable sector integration, and enable indirect electrification of hard-to-abate sectors. Sector integration is key to decarbonising energy use beyond the electricity sector. The potential of NBRG to meet decarbonisation objectives has been recognised in the EU's *Hydrogen Strategy for a Climate Neutral Europe*, which envisions 40 GW of green H_2 production in the EU by 2030, with a further 40 GW in neighbouring countries supplying the EU (EC 2020). Methane produced from CO_2 captured from the atmosphere or a biogenic process is renewable methane (RM).

Demand for hydrogen in 2020 was approximately 90 Mt, of which roughly 5% was produced by electrolysis. Of the electrolytic share, only a small portion was green hydrogen (IEA 2021b). The IEA projects that global consumption of hydrogen could exceed 200 Mt in 2030 and 500 Mt by 2050, in a zero-emissions scenario.

2.1 National strategies for NBRG

No country or region has an explicit strategy for NBRG, but many have developed, or are developing, hydrogen strategies. The planned estimated scale of H_2 production for selected countries is shown in Figure 6. Countries that have large scale hydrogen production for export plans in their strategies and roadmaps are Australia, Canada, Chile, Portugal and Spain.

Figure 6 Estimated scale of H_2 production for selected countries by 2030



Source: adapted from Fritsche et al. (2022)

Most H_2 strategies focus on zero- or low-carbon, with green H_2 from water electrolysis powered by renewable electricity, and blue H_2 from natural gas reforming with CO_2 capture and storage, as the main technologies. Only Canada explicitly references biomass gasification as a H_2 route.

Most of the strategies/roadmaps except for Russia show H_2 use in the transport sector. Other uses are industry (including chemicals and steel for some countries), electricity, refining and buildings. A few strategies consider aviation and shipping, with only 2 strategies (Canada and Chile) mentioning the use of H_2 in mining.

It is estimated that by 2030, about USD 50 billion of global investment and 65 GW of electrolyser capacity will be required to bridge the cost gap between grey and green H_2, equivalent to 6.6 Mt of H_2 (WEC 2021).

2.2 Assessing the State of the Art

H_2 and methane are two common compounds used in many industrial sectors around the world. They can be produced in different ways and the pathway selected for their production determines if they are considered renewable or not. For H_2, it will be renewable if it is produced from water by means of electrolysis driven by renewable electricity, or from biomass. H_2 end uses include combustion or electrochemical conversion in a fuel cell, or conversion to a chemical product. In the case of non-biogenic methane, it can be generated by the Sabatier methanation reaction, which combines H_2 and CO_2. If the H_2 is renewable and the CO_2 originates from a renewable, non-fossil source, e.g., direct air capture (powered by renewables) or biogenic CO_2, the resulting methane can also be considered renewable.

To better identify the most relevant topics related to NBRG, a survey and a workshop were carried out to summarize the technological, environmental, social, and political issues that NBRG chains entail. The key environmental sustainability issues raised by respondents that are relevant for the assessment of H_2 pathways are: the additionality and certification of renewable electricity for green H_2 and the climate effects of CO_2 used for PtX production. Freshwater availability, land-use concerns for greater renewable electricity requirements, and the global warming potential of H_2 itself were also raised.

2.2.1 Renewable hydrogen from electrolysis and photocatalysis

The two most commercialised electrolyser technologies that are projected to dominate the future of this hydrogen production route are alkaline and polymer electrolyte membrane (PEM).

Direct H_2 production from solar irradiation has a TRL of 7, which is lower than electrolysis (FSR 2021), and has lower efficiencies than PV generation and electrolysis of water (Nishiyama et al. 2021). On the other side, it presents promising characteristics for scaling up, being potentially cheaper and simpler than other H_2 production systems (Nishiyama et al. 2021).

2.2.3 Methanation in Renewable Methane production

Methanation is the process of producing methane using carbon dioxide and hydrogen as feedstocks. The process can be driven by biological or chemical systems, but since the biological process is slower and less developed, this report is focused on the chemical route.

The origin of CO_2 is an important parameter for assessing the GHG intensity of RM. The carbon source can be classified as renewable if it is biogenic CO_2 or from direct air capture, while non-renewable CO_2 comes from fossil sources such as powerplants or steel works fuelled by fossil energy, and cement production flue gases. The origin of CO_2 will also influence the cost of the carbon capture process. The use of renewable energies in the carbon capture process is crucial to ensure a low carbon footprint of the CO_2 used as feedstock for methanation.

Some studies indicate that RM Methane can be economically competitive in 2030 if electricity prices are low enough (30 EUR/MWh), and if CAPEX and OPEX decrease due to technology development (Gorre et al. 2019). Thus, the methanation field is expanding with several projects planning to be in operation by the end of this decade (Thema et al. 2019).

2.2.4 Renewable hydrogen and methane end-use

Currently, H_2 is mainly used in the chemical industry and refineries (IEA 2021b). This means, that the first sector in which green hydrogen can help to abate GHG emissions. In parallel, H_2 can be used to store renewable electricity and reduce curtailment (IEA 2021b). Long range heavy-duty transport, including trucking, shipping, and aviation, are hard-to-abate sectors with high operating costs that represent major opportunities for H_2. Supply of high-temperature heat and feedstock to industry represents a further route to market. There is also a potential role for H_2 to supply heat to the built environment, although in this sector, it faces very stiff competition from other decarbonisation options, especially heat pumps.

2.3 Production costs and commercial readiness

The levelized costs of production of renewable H_2 and RM depend strongly on location and time factors. Electricity is a significant portion of the cost of NBRG, accounting for 50-90% of the total production costs (IEA 2021b). Projections for the future cost of methanation are not widespread, since this will depend directly on the hydrogen production costs. For example, Gorre et al. (2019), calculated the production cost of Renewable Methane in 2030 and 2050 for different scenarios at 20-200 EUR/MWh of methane. This illustrates that the production cost of NBRG is an open issue.

The main electrolysis technologies of alkaline and PEM have TRLs of 9, meaning that they are commercially deployed. Other technologies, such as Solid Oxide Electrolyser Cells, have TRLs of 6-7. The power-to-gas process is also in a lower commercial readiness with a TRL of ~6.

2.4 Sustainability aspects of NBRG

NBRG can contribute to abate GHG, however, the actual GHG mitigation effects depend on the GHG intensity of the inputs of the system. As for the production of NBRG, the electricity used in the production processes and the carbon source for the methanation are the two main sources that are key for abating carbon emissions with NBRG.

The production of NBRG can be driven mainly by two types of systems, 100% renewable electricity (dedicated or curtailed), or connected to the electricity grid. For the latter case, the energy mix of the grid varies with place and time, which means that the carbon intensity of the electricity is not necessarily constant and difficult to predict.

The various certification schemes have suggested limits or thresholds for GHG emissions of NBRG production to declare those gases "low carbon" products (Fritsche 2022).

In the case of methane produced from CO_2 and H_2, the CO_2 used will carry emissions by itself as a potential direct emission after the burning of the produced methane, and due to the process of capture and purification. The direct emissions can be considered as net-zero if the CO_2 comes from a renewable source. In addition to the emissions from the production and the conversion of NBRGs, incomplete conversion processes (e.g., combustion) or leakage from infrastructure or slip in conversion processes can lead to direct emissions of NBRGs. Depending on the type of the NBRG, this can result in direct or indirect climate effects.

Table 2 Different carbon sources' carbon capture energy requirements.

Carbon source	Energy required (kJ/kgCO_2)	References and notes
Direct air carbon capture	3500-9900	Value depends on the type of technology (Chatterjee & Huang 2020)
Biomethanol upgrading	288-432	Assuming post-combustion carbon capture technologies (Jackson & Brodal 2019)
Bioethanol production	432	(Moreira et al. 2016; Pace & Sheehan 2021)
Natural gas power plant flue gas	288-432	Assuming post-combustion carbon capture technologies (Jackson & Brodal 2019)
Cement plant	288-432	Assuming post-combustion carbon capture technologies (Jackson & Brodal 2019)

Source: own compilation

Since methane is a potent greenhouse gas and methane emissions are a key contributor to climate change, aspects of direct emissions from methane slip or leakage are of high relevance for the development of future NBRG capacities and infrastructure. Furthermore, besides the identification and quantification of direct methane emissions, the selection of the time frame and the climate metrics can have a strong impact on assessment results.

Contrary to methane, hydrogen is not a direct greenhouse gas. Besides emissions related to the production of hydrogen as an energy carrier, a complete conversion of hydrogen to energy would result only in water vapour. However, incomplete hydrogen combustion as well as hydrogen emissions from distribution infrastructure and throughout the value chain can potentially cause climate impacts (Bond et al. 2011; Weger et al. 2021). Hydrogen is considered an indirect greenhouse gas. (Derwent et al. 2006 + 2020; IPCC 2007; Schultz et al. 2003). Furthermore, hydrogen emissions can influence O_3 concentrations, leading to additional potential impacts on air pollution and a potential contribution to the depletion of the O_3 layer in the stratosphere (Sand et al. 2020)

Electrolysis, consumes 9 kg of water per kg of H_2 versus 13-18 kg of water per kg of "blue" H_2 for SMR with CCS (IEA 2021b). Nevertheless, availability of freshwater for electrolysis is a concern in several places that are rich in renewable sources but suffer from water scarcity or stress, such as Northwest Texas, the Atacama and Sahara Deserts, or Australia. In regions that are near the sea, reverse osmosis seawater is a non-expensive option, because it affects the levelized cost of H_2 by less than 1% (Gallardo et al. 2021; IEA 2021b).

The land footprint of NBRG production will depend on the electricity source and the electrolysis and methanation installation. The land use of the renewable electricity used for the NBRG production varies according to the source, wind being the least intensive in land-use terms with around 1 m^2/MWh delivered, followed by geothermal with 2.5, solar PV and hydropower with 10.15 for concentrated solar power, and 500 m^2/MWh for biomass (Fritsche et al. 2017).

With H_2 production driven mainly by onshore and off-shore wind farms, the respective land footprint is not a main issue to be considered. Even if the projected global H_2 production of 530 Mt were driven by onshore wind, a surface of just 25.000 km^2 would be needed.

2.5 Regulatory barriers

Certification

Ensuring that NBRG are low in emissions is one of the key points of the production and trade of these goods. A standardized methodology that allows entities to certify low GHG emissions of NBRG is crucial for the development of the market. Some countries, such as Australia, the UK, and the EU, are working on certification schemes for H_2 (Bermudez et al. 2020), and IPHE works on methodology for determining the GHG emissions of H_2 production. An important element of the certification for NBRGs is to establish coherent instruments that allow traceability of product information (e.g., the guarantee of origin of the electricity used, the origin and climate effects of CO_2) throughout the value chain elements.

Additionality

Achieving ambitious targets for renewable gases will require a significant amount of renewable electricity, which is also needed for the decarbonization of several other industrial sectors. So, in order to avoid that the electricity demand for hydrogen becoming a drain on existing renewables in the energy system, the growing demand needs to be matched with new capacities of renewable electricity (Fritsche 2022). Thus, the EU framework for the support of renewable energy (EU Renewable Energy Directive) requires that to be accounted as renewable, electricity used for the production of renewable energy carriers has to be "additional". In that sense, Pototschnig (2021) defines the concept of additionality as "the requirement that renewables-based electricity used in electrolysers for the production of renewable hydrogen is additional to the renewables-based electricity which is used to meet the renewable penetration target with respect to final electricity consumption”.

In practice, the proof of compliance with the additionality concept, which is an important factor for the GHG mitigation potential of the energy carrier and thus, the respective sustainability criterion of the RED, is verified by means of a certification process. Fritsche (2022) argues for the need of additional delegated regulations under the RED II which shall provide stakeholders more clearance on how to understand which scenarios for electricity supply (direct connection to an installation producing renewable electricity, grid connection, etc.) can be considered additional and thus, be accounted as renewable electricity in the calculation of the GHG intensity of the Hydrogen produced from it.

2.6 NBRG in specific regional contexts

All cases are selected so that NBRG is produced and used in the same country, or within the EU. We are therefore omitting international trade of NBRG, which, as stated above, is covered in Section 3. The cases consider renewable electricity generation, water electrolysis, H_2 storage, possible CO_2 capture and methanation, electricity/ H_2/methane transmission and delivery to end-users. Three possible classifications of electricity source are considered in the analysis:

1. **Excess renewables:** In this classification, only renewable electricity that would otherwise be wasted or curtailed is used to power the electrolyser.
2. **Dedicated renewables:** In this classification, the sole purpose of a renewable energy generator is to supply hydrogen as opposed to electricity.
3. **Grid electricity:** In this classification, the capacity of the electrolyser is maximized by connecting it directly to the electricity grid.

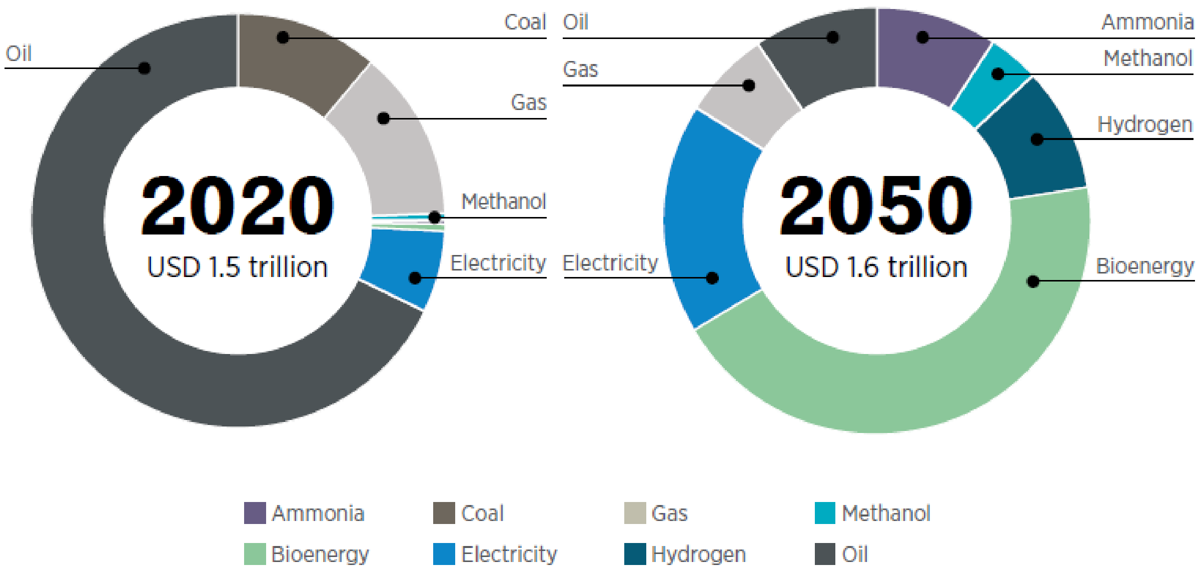
The key findings can be summarized as:

- Use of dedicated offshore wind in the North Sea and an onshore wind-solar mix in Texas results in high electrolyser capacity factors and delivered hydrogen costs of 4-6 USD/kg in 2030, which is highly dependent on the cost trajectory of wind. By 2050 in the North Sea and Texas, dedicated renewable hydrogen production is the cheapest option studied.
- For the Brazil case example, the lowest delivered cost hydrogen production route was for biomass-generated electricity, which has lower electricity price and decent capacity factors, resulting in a greater dependency on electrolyser cost reductions. By 2050, biomass-generated electricity hydrogen in this case study is the most competitive option.
- Use of excess electricity alone results in high levelized costs and abatement costs, despite having a very favorable GHG intensity.
- Renewable H_2 GHG abatement costs in some scenarios are comparable to proposed carbon taxes in some countries.
- Renewable methane produced using CO_2 from DACC results in unfeasibly high levelized carbon abatement costs. Renewable methane produced using non-renewable CO_2 has greater GHG intensity than fossil natural gas, but this finding depends strongly on the method of GHG emissions accounting employed.
- Using existing natural gas pipelines could decrease the levelized cost of renewable methane, but it remains significantly more expensive than hydrogen for all scenarios and case examples studied.
- Situating electrolysers close to renewable electricity generation sites is desirable since it is more cost effective to transmit hydrogen in pipelines that it is to transmit electricity in high voltage cables.

3. Renewable gas trade options and potentials

The two main RG options for trade are biomethane and "green" hydrogen[2]. Trade is a vital component of the current global energy system, and the transformation towards a renewable, zero-carbon system will affect future trade patterns drastically, yet with only a small change in overall amount, as shown in Figure 7.

Figure 7 Shifts in the value of trade in energy commodities, 2020 to 2050



Source: IRENA (2022)

Trading of RG between countries or regions requires the physical movement of the respective gases, or the virtual transfer of RG quantities from one country to its trade partner country through certificates, either per "book & claim", or mass balancing approaches.

The **physical** trade of RG can have two modes:

Domestic RG is injected into gas pipeline within the exporting country, and transport between countries is carried out through high-pressure pipelines, or in liquefied form through shipping (Bio-LNG or LH_2). In the latter case, the liquefied RG is regasified in the receiving port and injected into the national gas grid of the importing country[3]. Biomethane and SM can be used without limitation in natural gas infrastructure, including liquefaction plants (IEA 2020).

In contrast, there is currently not much infrastructure for H_2 transport, but when blending H_2 with natural gas, existing systems could be used, within a limit of max. 20 vol% (Fritsche 2022).

The **virtual** trade of RG through certificates is not hindered by infrastructure constrains but by lacking agreements on requirements and governance of systems used to certify RG. Several systems not fully compatible nor being agreed internationally were developed, but standardization bodies such as CEN and ISO are working on it (Fritsche 2022). For the sustainable RG trade potentials, the mode of trade is not relevant, though.

---

2 Either as gaseous or liquefied H_2 resp. synthetic renewable methane.

3 Note that for small quantities and distances, liquefied RG can also be transported in specialized trucks.

3.1 Potentials for renewable gas trade

Trading of RG is still in an early stage – yet, as Thrän et al. (2014) indicated and Junginger et al. (2019) confirmed, there is growing trade in **biomethane** especially in Europe[4], and much interest in that in other parts of the world (see Section 3.1.1).

For **hydrogen** and derived products, IRENA (2022) discusses global and Wang et al. (2021) European perspectives for respective trade in the 2050 timeframe (see Section 3.1.2). The analysis of H_2 strategies and roadmaps given by Fritsche (2022) provides perspectives of countries' ambitions. The 2050 potential green H_2 exporting countries are seen as those offering low-cost renewable electricity for green H_2 production via electrolysis, i.e., wind- and sun-rich regions with access to international pipelines and/or ports in Africa (e.g., Morocco), Europe (Portugal, Spain), Latin America (e.g., Chile), Middle East (e.g., Saudi-Arabia), and Oceania (Australia and New Zealand). Yet, the quantification of future H_2 trade potentials is still at the beginning.

3.1.1 Biomethane

Today, Europe is the main producer of biomethane (IGU 2021; Liebetrau, Fritsche & Gress 2021). Europe also holds significant biomethane domestic potential (Birman et al. 2021). Several studies calculated the biomethane potential in the European Union (EU27) for 2030 and 2050 and estimated the potential to be around 350 TWh by 2030, and up to nearly 1,000 TWh in 2050 (Birman 2021; GfC 2021). These figures show the total methane potential from anaerobic digestion and gasification without considering whether the gas is used domestically as biogas for on-site electricity production, or whether it is upgraded to biomethane and injected into the gas grid. In 2020, biomethane production (32 TWh) accounted for only 17% of total biogas production (191 TWh) in the EU (EBA 2021).

So far, the volumes of biomethane traded among EU countries are rather small - about 3 TWh in 2020 (dena 2021), corresponding to 0.06 % of natural gas consumption in the EU. Given the extensive natural gas infrastructure existing in Europe, the ambition of the EU to increase its renewable energy share and decrease GHG emissions on the one hand, and the significant agricultural and forest resources of Eastern European countries and Russia on the other hand, several studies tried to identify the export potential for biomethane from this region (Angelova 2012; Angelova et al. 2012; Fritsche & Iriarte 2016; GfC 2021).

Recent work for the German National Energy and Climate Plan estimated global export potentials for biomethane (Kemmler et al. 2020), building on earlier work (Fritsche & Iriarte 2016), and identified biomethane export potentials for 2030 from (Western) Russia of about 1250 PJ, and for UA of 500 PJ. In a projection towards 2050, these export potentials were reduced due to rising domestic demands to about 950 PJ (RU), and 400 PJ (UA). These potentials considered only biomethane from abandoned/marginal land, and future domestic uses were subtracted from the export potential. For the Ukraine, BAU (2021) expects biomethane exports as an option, but the current political situation in this country and in Russia does not allow to assume much by 2030. In a **post-war long-term perspective**, economic cooperation of the EU with Russia and the Ukraine may include biomethane trade to avoid "stranded assets" in the gas transmission infrastructure.

Outside Europe, grid-based international biomethane trade has not started yet[5], but interest in e.g., Africa (for city grids), and Latin America as well as parts of Asia is rising (Junginger et al.

[4] The EU is supporting the Renewable Gas Trade Centre in Europe (REGATRACE) to foster such developments, see https://www.regatrace.eu/

[5] There is some inter-state trade within Canada and the US, though.

2019). The state of biomethane development in selected IEA member countries is reported regularly[6], and an overview of biomethane potentials from manure are available in Liebetrau et al. (2021) for Austria, Australia, Canada, Germany, Ireland, Norway, and the UK.

3.1.2 Trade of H_2 and RM

Currently, H_2 production and use are quite localized – some 85% of H_2 is produced and consumed on-site than bought and sold on the wider market (IEA 2019). H_2 is already in use but is predominantly produced from fossil fuels. As of now, the sustainable trade potential of H_2 and RM cannot be quantified due to the early development of the technologies and logistics.

Yet, several countries have ambitions to ex- or import significant amounts of H_2 in the future (see Table 3).

Table 3 Overview of national H_2 targets and trade perspectives

	H_2 targets [TWh_{LHV}]		H_2 trade	
Country/Region	2030	2050	export	import
Austria	4 - 8			x
Australia			x	
Canada	133	667	x	
Chile	125		x	
Colombia	5		x	
China	297		n/a	
Czech Republic	3		n/a	
European Union	200			x
Finland	3	5		x
France	33			x
Germany	14			x
Hungary	2			x
Italy	25			x
Japan	10 - 100	667		x
Korea	88			x
Netherlands	15 - 20			x
Norway			x	
New Zealand			x	
Poland	10		n/a	
Portugal	10 - 13	25	x	
Russia	67		x	
Spain	20		x	
United Kingdom	25			x
total	1088 - 1192	1363		

Source: own compilation based on Fritsche (2022) and IEA (2021b); n/a = information not available

[6] https://task37.ieabioenergy.com/country-reports.html

IRENA (2022) estimates that roughly 1/3 of green H_2 will be traded internationally by 2050, a share slightly higher than the current share of natural gas traded globally.

Several countries are very active in creating bi- and multilateral agreements on H_2 trade, as reported in IEA (2021b). The potential export "clusters" identified by IRENA are in Africa[7], Latin America, the Middle East, and Australia, Canada, New Zealand, Russia, and Southern European countries. This fits rather well with the country trade ambitions given in Table 2.

For the EU27 + UK, Wang et al. (2021) estimated a **domestic** green H_2 supply potential of 4,000 TWh by 2050, and green H_2 **import** potentials from Northern Africa and the Ukraine of 1,700 TWh by 2050. Imports would be transported mainly through pipelines.

Given the very early stage of H_2 trade on the one hand and the rather large potentials on the other hand, the future dynamics of H_2 ex- and imports will depend on realizing cost reductions for electrolysers, investments in renewable electricity and H_2 transport infrastructure as well as success in market introduction schemes which factor in (rising) CO_2 prices.

The lead time of respective policies and market developments imply that substantial "green" H_2 trade cannot be expected before 2030 – yet there will be some forerunner countries such as e.g., Australia, Chile, the EU, Japan, Saudi Arabia, the UK, and the US.

In that context, several countries such as Norway and Russia see a role of low-carbon H_2 from natural gas ("blue" or "turquoise") as a means to start investments and bring down cost of transport infrastructure, as indicated in IEA (2019), Fritsche (2022), and IRENA (2022).

3.2 Regulatory issues of RG trade

Trade in biomethane passed various regulatory hurdles in the last years so that further growth and market development using existing natural gas infrastructure can be expected (IEA 2020).

For "green" H_2 and its derivatives, though, trade hurdles remain. Besides the challenge of reducing production cost, international trade faces unresolved regulatory issues, especially in the definition of "greenness" and respective GHG emission thresholds, and the so-called **additionality** requirements for green H_2 (Fritsche 2022; Heinemann et al. 2021).

The **EC proposal** for a Directive on common rules for the internal markets in renewable and natural gases and in hydrogen (EC 2021a+b) includes the **mandatory certification** of H_2 to demonstrate a GHG emission reduction of at least 70%, compared to fossil gas. This obligation would apply also for H_2 imports to the EU. Given the importance of the issue for international trade, several countries agreed on a *Hydrogen Production Analysis Task Force* to reach consensus on a methodology and analytical framework for determining H_2-related GHG emissions (IEA 2021b). This group operates under the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) and is expected to deliver a proposal in 2022.

The work of the IPHE Task Force and the negotiations on the EU proposal for renewable gases will determine if the regulatory trade barriers for "green" H_2 can be overcome in the next years.

[7] The project H2ATLAS-AFRICA - a joint initiative of Germany and African partners – explores H_2 production potentials from renewable energy sources in the Sub-Saharan region (SADC and ECOWAS countries), see https://www.h2atlas.de/en/.

References

Abhyankar, N. et al. (2021) POWERING AMERICA'S CLEAN ECONOMY https://www.ourenergypolicy.org/resources/2030-report-powering-americas-clean-economy-a-supplemental-analysis-to-the-2035-report/

Ahmadi, E. et al. (2020) An Integrated Planning Framework for Sustainable Water and Energy Supply. Sustainability 12 (10): 4295 https://doi.org/10.3390/SU12104295

Angelova, Elena (2012) Nachhaltige europäische Biomethanstrategie. Deutsches Biomasseforschungszentrum. Leipzig https://doi.org/10.2314/GBV:729279723

Angelova, Elena et al. (2012) Potential in Eastern Europe - Case study for the Russian Federation, Ukraine and Belarus. In: Thrän, Daniela et al. (eds.) Focus on Biomethane - Biomass for Energy. DBFZ. Leipzig: 46-47 https://www.energetische-biomassenutzung.de/fileadmin/user_upload/Downloads/Ver%c3%b6ffentlichungen/fh_biomethane_engl_2.pdf

Balcombe, P. et al. (2018) Methane emissions: choosing the right climate metric and time horizon. https://doi.org/10.1039/c8em00414e

Barth, F. et al. (2019) Towards a Dual Hydrogen Certification System for Guarantees of Origin and for the Certification of Renewable Hydrogen in Transport and for Heating & Cooling Final Report of Phase 2 https://doi.org/10.2843/46282

BAU (2021) Vision for Ukrainian biogas/biomethane sector development. Bioenergy Association of Ukraine & REGATRACE https://uabio.org/wp-content/uploads/2021/02/Visio-Ukrainian-Biogas-sector-2021-EN.pdf

Baylin-Stern, A. & Berghout, N. (2021) Is carbon capture too expensive? – Analysis – IEA. International Energy Agency. Paris [Preprint] https://www.iea.org/commentaries/is-carbon-capture-too-expensive

Bermudez, J.; Hasegawa, T. & Bennett, S. (2020) Hydrogen – Analysis - IEA, Tracking report. https://www.iea.org/reports/hydrogen

Bhandari, R.; Kumar, B. & Mayer, F. (2020) Life cycle greenhouse gas emission from wind farms in reference to turbine sizes and capacity factors. Journal of Cleaner Production 277: 123385 https://doi.org/10.1016/J.JCLEPRO.2020.123385

Birman, Jessie et al. (2021) Geographical analysis of biomethane potential and costs in Europe in 2050. ENGIE https://www.engie.com/sites/default/files/assets/documents/2021-07/ENGIE_20210618_Biogas_potential_and_costs_in_2050_report_1.pdf

Blanco, H. et al. (2020) Life cycle assessment integration into energy system models: An application for Power-to-Methane in the EU. Applied Energy 259 https://doi.org/10.1016/J.APENERGY.2019.114160

Bloomberg New Energy Finance (2020) Hydrogen Economy Outlook https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf

Bond, S.; Alvarez, R. & Weilenmann, M. (2011) Hydrogen emissions to the atmosphere from industry and transportation. Transition to hydrogen: pathways toward clean transportation [Preprint]

Brinkman, G. et al. (2021) The North American Renewable Integration Study (NARIS): A Canadian Perspective https://www.nrel.gov/docs/fy21osti/79224.pdf

Caldera, U. & Breyer, C. (2020) Strengthening the global water supply through a decarbonised global desalination sector and improved irrigation systems. Energy 200: 117507 https://doi.org/10.1016/J.ENERGY.2020.117507

Cater, H. (2021) Incorporating used water into hydrogen production to develop a more sustainable energy source. Monash University https://www.monash.edu/news/articles/incorporating-used-water-into-hydrogen-production-to-develop-a-more-sustainable-energy-source

CEDIGAZ (2021) GLOBAL BIOMETHANE MARKET – 2021 ASSESSMENT – Executive Summary https://www.cedigaz.org/wp-content/uploads/EXECUTIVE-SUMMARY-1.pdf

CertifHy (2014) Developing a European Framework for the generation of guarantees of origin for green hydrogen Definition of Green Hydrogen https://www.fch.europa.eu/sites/default/files/POSTER%20PANEL%2006-221116%20%28ID%202891260%29.pdf

Chardonnet, C. et al. (2017) Study on Early Business Cases for H2 in Energy Storage and More Broadly Power To H2 Applications. EU Commission https://www.fch.europa.eu/publications/study-early-business-cases-h2-energy-storage-and-more-broadly-power-h2-applications

Chatterjee, S. & Huang, K.-W. (2020) Unrealistic energy and materials requirement for direct air capture in deep mitigation pathways. Nature Communications 11 (1): 1–3 https://doi.org/10.1038/s41467-020-17203-7

Climate Transparency (2021) BRAZIL: CLIMATE TRANSPARENCY REPORT: COMPARING G20 CLIMATE ACTION TOWARDS NET ZERO. Climate Analytics https://www.climate-transparency.org/g20-climate-performance/g20report2021

Corredor, J. et al. (2019) Comprehensive review and future perspectives on the photocatalytic hydrogen production. Journal of Chemical Technology and Biotechnology 94 (10): 3049–3063 https://doi.org/10.1002/JCTB.6123

Cosín, Carlos (2019) The evolution of rates in desalination (Part I). Almar water solutions https://smartwatermagazine.com/blogs/carlos-cosin/evolution-rates-desalination-part-i

Coutanceau, C.; Baranton, S. & Audichon, T. (2018) Hydrogen Production From Water Electrolysis. Hydrogen Electrochemical Production 17–62 https://doi.org/10.1016/B978-0-12-811250-2.00003-0

Cristina, C. et al. (2017) The Brazilian Electricity Supply for 2030: A Projection Based on Economic, Environmental and Technical Criteria. Environment and Natural Resources Research 7 (4) https://doi.org/10.5539/enrr.v7n4p17

Daioglou, Vassilis et al. (2020) Implications of climate change mitigation strategies on international bioenergy trade. Climatic Change https://doi.org/10.1007/s10584-020-02877-1

Dale, Bruce et al. (2020) The potential for expanding sustainable biogas production and some possible impacts in specific countries. Biofuels, Bioproducts & Biorefining 14 (6): 1335-1347 https://doi.org/10.1002/bbb.2134

Daprato, M. (2019) Texas' Power Price Spike and Designing Markets for a Carbon-Free Grid. Greentech Media https://www.greentechmedia.com/articles/read/texas-power-price-spike-and-designing-markets-for-a-carbon-free-grid

dena (2021) Branchenbarometer Biomethan 2021. Deutsche Energie-Agentur GmbH. Berlin https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2021/dena-ANALYSE_Branchenbarometer_Biomethan_2021.pdf

Derwent, R. et al. (2006) Global environmental impacts of the hydrogen economy. International Journal of Nuclear Hydrogen Production and Application 1 (1): 57–67 https://doi.org/10.1504/IJNHPA.2006.009869

Derwent, R. et al. (2020) Global modelling studies of hydrogen and its isotopomers using STOCHEM-CRI: Likely radiative forcing consequences of a future hydrogen economy. International Journal of Hydrogen Energy 45 (15): 9211–9221 https://doi.org/10.1016/J.IJHYDENE.2020.01.125

Earthjustice (2021) RECLAIMING HYDROGEN FOR A RENEWABLE FUTURE https://earthjustice.org/sites/default/files/files/hydrogen_earthjustice_2021.pdf

EBA (2021) EBA Statistical Report 2021. European Biogas Association. Brussels https://www.europeanbiogas.eu/eba-statistical-report-2021/

EC (2014) Technology readiness levels (TRL). European Commission https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

EC (2021a) Proposal for a Regulation of the European Parliament and of the Council on the internal markets for renewable and natural gases and for hydrogen (recast). European Commission COM(2021) 804 final - 2021/0424 (COD). Brussels https://ec.europa.eu/energy/sites/default/files/proposal-revised-gas-markets-and-hydrogen-regulation.pdf

EC (2021b) Proposal for a Directive of the European Parliament and of the Council on common rules for the internal markets in renewable and natural gases and in hydrogen. European Commission COM(2021) 803 final - 2021/0425 (COD). Brussels https://ec.europa.eu/energy/sites/default/files/proposal-revised-gas-markets-and-hydrogen-directive.pdf

EEA (2021) Greenhouse gas emission intensity of electricity generation - country level - 2018. European Environment Agency https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-3/assessment

EIA (2020) The Annual Energy Outlook explores long-term energy trends in the United States https://www.eia.gov/outlooks/aeo/

EPA (2012) Clean Power Plan: State at a Glance Texas https://archive.epa.gov/epa/sites/production/files/2016-09/documents/texas.pdf

EPE (2021) Cardeno de precos da geracao www.mme.gov.br

EU (2018) Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources. Official Journal of the European Union L 328/82 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&from=EN

Eurelectric (2015) Power statistics and trends: The five dimensions of the energy union. Eurelectric https://www.eurelectric.org/media/1992/power-statistics-and-trends-the-five-dimentions-of-the-energy-union-lr-2015-030-0641-01-e.pdf

EC (2020) A hydrogen strategy for a climate-neutral Europe. European Commission COM(2020) 301 final. Brussels https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

Eurostat (2014) Electricity and natural gas price statistics https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Natural_gas_price_statistics#Natural_gas_prices_for_non-household_consumers

European Parliament (2019) European Parliament resolution of 15 January 2020 on the European Green Deal (2019/2956(RSP)) https://www.europarl.europa.eu/doceo/document/TA-9-2020-0005_EN.html

Falcone, P.; Hiete, M. & Sapio, A. (2021) Hydrogen economy and sustainable development goals: Review and policy insights. Current Opinion in Green and Sustainable Chemistry 31: 100506 https://doi.org/10.1016/J.COGSC.2021.100506

FCH (2020) State-of-the-art and Future Targets (KPIs) https://www.fch.europa.eu/soa-and-targets

FE & IAEW (2019) The value of gas infrastructure in a climate-neutral Europe. Frontier Economics & Institute of Power Systems and Power Economics (IAEW), RWTH Aachen https://www.frontier-economics.com/media/3120/value-of-gas-infrastructure-report.pdf

Fredershausen, S. et al. (2021) Towards an Understanding of Hydrogen Supply Chains: A Structured Literature Review Regarding Sustainability Evaluation. Sustainability 13 (21): 11652 https://doi.org/10.3390/SU132111652

Fritsche, Uwe et al. (2017) Energy and land use. Working Paper for the UNCCD Global Land Outlook. Darmstadt etc. https://knowledge.unccd.int/publications/energy-and-land-usent

Fritsche, Uwe & Iriarte, Leire (2016) Sustainable Imports - Cost supply curves for medium- to longer-sustainable biomass and bioenergy (pellets, biomethane, liquid biofuels) imports to the EU-28. Deliverable 2.5 of the Biomass Policies project. Darmstadt http://iinas.org/tl_files/iinas/downloads/bio/biomasspolicies/IINAS_2016_Sustainable_Imports_D2.5_Biomass_Policies.pdf

Fritsche, Uwe (2022) Renewable Gases – Hydrogen in the Grid. Synthesis Report of the IEA Bioenergy Task 41 Special Project. Darmstadt https://www.ieabioenergy.com/wp-content/uploads/2022/02/Renewable-Gases-H2-in-the-grid.pdf

FSR (2021) Technology neutrality in hydrogen, opportunities and challenges: photocatalysis https://fsr.eui.eu/technology-neutrality-in-hydrogen-opportunities-and-challenges-photocatalysis

Fulwood, Mike (2021) Energy Transition: Modelling the Impact on Natural Gas. Oxford Institute for Energy Studies OIES PAPER: NG 169. Oxford, UK https://www.oxfordenergy.org/wpcms/wp-content/uploads/2021/07/Energy-Transition-Modelling-the-Impact-on-Natural-Gas-NG-169.pdf

Gallardo, F. et al. (2021) A Techno-Economic Analysis of solar hydrogen production by electrolysis in the north of Chile and the case of exportation from Atacama Desert to Japan. International Journal of Hydrogen Energy 46 (26): 13709–13728 https://doi.org/10.1016/j.ijhydene.2020.07.050

GasNaturally (2019) Making a clean future real - Long-term Vision of the European Gas Industry. Brussels https://gasnaturally.eu/wp-content/uploads/2018/11/long-term-vision-of-the-european-gas-industry.pdf

GBEP (2020) Biogas Stocktaking Paper – Regional analysis of biogas value chains. Global Bioenergy Partnership, Working Group on Capacity Building, Activity Group 7. Rome http://www.globalbioenergy.org/fileadmin/user_upload/gbep/docs/AG7/Stocktaking_AG7_Biogas_06.04.2020.pdf

GfC (2021) The future role of biomethane. Gas for climate - Guidehouse. Utrecht https://gasforclimate2050.eu/wp-content/uploads/2021/12/The_future_role_of_biomethane-December_2021.pdf

Ghaib, K.; Nitz, K. & Ben-Fares, F. (2016) Chemical methanation of CO2: A review. ChemBioEng Reviews 3 (6): 266–275 https://doi.org/10.1002/CBEN.201600022

Gorre, J.; Ortloff, F. & van Leeuwen, C. (2019) Production costs for synthetic methane in 2030 and 2050 of an optimized Power-to-Gas plant with intermediate hydrogen storage. Applied Energy 253 https://doi.org/10.1016/j.apenergy.2019.113594

Guandalini, G.; Campanari, S. & Valenti, G. (2016) Comparative assessment and safety issues in state-of-the-art hydrogen production technologies. International Journal of Hydrogen Energy https://doi.org/10.1016/j.ijhydene.2016.08.015

Guo, M.; Song, W. & Buhain, J. (2015) Bioenergy and biofuels: History, status, and perspective. Renewable and Sustainable Energy Reviews [Preprint] https://doi.org/10.1016/j.rser.2014.10.013

Guo, Y. et al. (2019) Comparison between hydrogen production by alkaline water electrolysis and hydrogen production by PEM electrolysis. IOP Conference Series: Earth and Environmental Science https://doi.org/10.1088/1755-1315/371/4/042022

Harmse, Mathijs et al. (2019) The role of methane in future climate strategies: mitigation potentials and climate impacts. Climatic Change https://doi.org/10.1007/s10584-019-02437-2

Heinemann, Christoph et al. (2021) Sustainability dimensions of imported hydrogen. Oeko-Institut Working Paper 8/2021. Freiburg www.oeko.de/fileadmin/oekodoc/WP-imported-hydrogen.pdf

Howarth, R. & Jacobson, M. (2021) How green is blue hydrogen? Energy Science and Engineering 9 (10): 1676–1687 https://doi.org/10.1002/ese3.956

Hydrogen Council (2020) Path to hydrogen competitiveness: a cost perspective https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf

IEA (2019) The Future of Hydrogen. International Energy Agency. Paris https://doi.org/10.1787/1e0514c4-en

IEA (2020a) World Energy Outlook 2020. International Energy Agency. Paris https://doi.org/10.1787/557a761b-en

IEA (2020b) Outlook for biogas and biomethane - Prospects for organic growth. World Energy Outlook Special Report. International Energy Agency. Paris https://doi.org/10.1787/040c8cd2-en

IEA (2021a) Net Zero by 2050: A Roadmap for the Global Energy Sector. International Energy Agency. Paris https://www.iea.org/reports/net-zero-by-2050

IEA (2021b) Global Hydrogen Review 2021. International Energy Agency. Paris https://doi.org/10.1787/39351842-en

IGU (2021) Global Renewable and Low-Carbon Gas Report 2021 edition. International Gas Union. Surrey, UK https://www.igu.org/wp-content/uploads/2021/11/IGU_RenewableGasReport2021_V5.pdf

IPCC (2007) Climate change 2007: the physical science basis : contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, New York

IPHE (2021) Methodology for Determining the Greenhouse Gas Emissions Associated With the Production of Hydrogen https://www.iphe.net/iphe-working-paper-methodology-doc-oct-2021

IRENA (2019a) Future of solar photovoltaic. International Renewable Energy Agency. Abu Dhabi https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Nov/IRENA_Future_of_Solar_PV_2019.pdf

IRENA (2019b) Future of wind. International Renewable Energy Agency. Abu Dhabi https://www.irena.org/-/media/files/irena/agency/publication/2019/oct/irena_future_of_wind_2019.pdf

IRENA (2020) Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5 C Climate Goal, /publications/2020/Dec/Green-hydrogen-cost-reduction.

IRENA (2021) Renewable Power Generation Costs in 2020. International Renewable Energy Agency. Abu Dhabi https://irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jun/IRENA_Power_Generation_Costs_2020.pdf

IRENA (2022) Geopolitics of the Energy Transformation: The Hydrogen Factor. International Renewable Energy Agency. Abu Dhabi https://irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jan/IRENA_Geopolitics_Hydrogen_2022.pdf

Jackson, S. & Brodal, E. (2019) Optimization of the Energy Consumption of a Carbon Capture and Sequestration Related Carbon Dioxide Compression Processes. Energies 12 (9): 1603 https://doi.org/10.3390/EN12091603

JRC (2021) Assessment of Hydrogen Delivery Options. EC Joint Research Centre Policy Science for Policy Briefs RC124206 https://ec.europa.eu/jrc/sites/default/files/jrc124206_assessment_of_hydrogen_delivery_options.pdf

Junginger, Martin et al. (2019) The future of biomass and bioenergy deployment and trade: a synthesis of 15 years IEA Bioenergy Task 40 on sustainable bioenergy trade. Biofuels. Bioprod. Bioref. 13: 247-266 https://doi.org/10.1002/bbb.1993

Keçebaş, A.; Kayfeci, M. & Bayat, M. (2019) Electrochemical hydrogen generation. Solar Hydrogen Production: Processes, Systems and Technologies: 299–317 https://doi.org/10.1016/B978-0-12-814853-2.00009-6

Kemmler, Andreas et al. (2020) Energiewirtschaftliche Projektionen und Folgenabschätzungen 2030/2050. Studie von Prognos AG, Fraunhofer ISI, GWS & IINAS i.A. des BMWi. Basel https://www.bmwi.de/Redaktion/DE/Publikationen/Wirtschaft/klimagutachten.pdf

Koivisto, M. et al. (2020) North Sea region energy system towards 2050: Integrated offshore grid and sector coupling drive offshore wind power installations. Wind Energy Science 5 (4): 1705–1712 https://doi.org/10.5194/WES-5-1705-2020

Lee, W. et al. (2021) Recent trend in thermal catalytic low temperature CO2 methanation: A critical review. Catalysis Today 368: 2–19 https://doi.org/10.1016/J.CATTOD.2020.02.017

Liebetrau, Jan et al. (2021a) Renewable Gas - discussion on the state of the industry and its future in a decarbonised world. IEA Bioenergy Task 37, 2021:11 http://task37.ieabioenergy.com/files/daten-redaktion/bilder/publications/Renewable%20Gas%20Report_2.pdf

Liebetrau, Jan et al. (2021b) Potential and utilization of manure to generate biogas in seven countries. Murphy, Jerry (ed.) IEA Bioenergy Task 37 2021:6

http://task37.ieabioenergy.com/files/daten-redaktion/download/Technical%20Brochures/Potential%20utilization_WEB_END_NEW_2.pdf

Liebetrau, Jan; Fritsche, Uwe & Gress, Hans Werner (2021) Biomethane - factors for a successful sector development. Synthesis Report of WP1 of the IEA Bioenergy Intertask project Renewable gas - deployment, markets and sustainable trade https://www.ieabioenergy.com/blog/task/inter-task-projects/

Lotrič, A. et al. (2021) Life-cycle assessment of hydrogen technologies with the focus on EU critical raw materials and end-of-life strategies. International Journal of Hydrogen Energy 46 (16): 10143–10160 https://doi.org/10.1016/J.IJHYDENE.2020.06.190

Majer, S. et al. (2015) D5.3 Calculation of GHG emission caused by biomethane http://www.biosurf.eu/wordpress/wp-content/uploads/2015/07/BIOSURF-D5.3.pdf

McKinsey & Company (2020) Perspective on Hydrogen https://energia.gob.cl/sites/default/files/clemens_muller-falcke_de_mckinseyco.pdf

Mehmeti, A. et al. (2018) Life Cycle Assessment and Water Footprint of Hydrogen Production Methods: From Conventional to Emerging Technologies. Environments 5 (2): 24 https://doi.org/10.3390/ENVIRONMENTS5020024

MNRE (2021) Annual Report 2020-2021. Ministry for New and Renewable Energy, Government of India. New Delhi https://mnre.gov.in/img/documents/uploads/file_f-1618564141288.pdf

Moreira, J. et al. (2016) BECCS potential in Brazil: Achieving negative emissions in ethanol and electricity production based on sugar cane bagasse and other residues. Applied Energy 179: 55–63 https://doi.org/10.1016/j.apenergy.2016.06.044

Nishiyama, H. et al. (2021) Photocatalytic solar hydrogen production from water on a 100-m 2 scale. Nature 598 https://doi.org/10.1038/s41586-021-03907-3

OIES (2021) Transitioning to Net-Zero: CCUS and the Role of Oil and Gas Producing Countries. Oxford Institute for Energy Studies Energy Insight 90. Oxford, UK https://www.oxfordenergy.org/wpcms/wp-content/uploads/2021/06/Insight-90-Transitioning-to-Net-Zero-CCUS-and-the-Role-of-Oil-and-Gas-Producing-Countries-.pdf

Pace, G. & Sheehan, S. (2021) Scaling CO2 Capture With Downstream Flow CO2 Conversion to Ethanol. Frontiers in Climate 3: 35 https://doi.org/10.3389/fclim.2021.656108

Papadias, D. & Ahluwalia, R. (2021) Bulk storage of hydrogen. International Journal of Hydrogen Energy 46 (70): 34527–34541 https://doi.org/10.1016/J.IJHYDENE.2021.08.028

Perez-Linkenheil, C. (2019) Update December 2019 – EU Energy Outlook 2050 https://blog.energybrainpool.com/en/update-december-2019-eu-energy-outlook-2050/

Plaza, M.; Martínez, S. & Rubiera, F. (2020) Co2 capture, use, and storage in the cement industry: State of the art and expectations. Energies https://doi.org/10.3390/en13215692

Pototschnig, A. (2021) POLICY BRIEF: Renewable hydrogen and the 'additionality' requirement: why making it more complex than is needed? https://cadmus.eui.eu/handle/1814/72459

Princeton University (2021) Net Zero America Project https://netzeroamerica.princeton.edu/?explorer=year&state=texas&table=2030&limit=2000

Ram, M. et al. (2018) A comparative analysis of electricity generation costs from renewable, fossil fuel and nuclear sources in G20 countries for the period 2015-2030. Journal of Cleaner Production 199: 687–704 https://doi.org/10.1016/J.JCLEPRO.2018.07.159

Sánchez, Itzel & Jacobsen, Henrik (2021) Potentials for transborder green gas and hydrogen certificate markets. Technical University of Denmark, Report M1 for task 7.b SuperP2G project https://www.superp2g.eu/fileadmin/user_upload/Potential_for_renewable_gas_and_hydrogen_certificate_trade.pdf

Sand, M. et al. (2020) Atmospheric Impacts of Hydrogen as an Energy Carrier, CICERO Report. CICERO Center for International Climate and Environmental Research - Oslo. Available at: https://cicero.oslo.no/en/publications/internal/2913

Schiavo, M. & Georges, P. (2020) The Energy Transition: What It Means For European Power Prices And Producers https://www.spglobal.com/ratings/en/research/articles/210917-the-energy-transition-and-what-it-means-for-european-power-prices-and-producers-september-2021-update-12108381#

Schultz, M. et al. (2003) Air pollution and climate-forcing impacts of a global hydrogen economy https://doi.org/10.1126/science.1089527

Shell (2021) The Energy Transformation Scenarios https://www.shell.com/promos/energy-and-innovation/download-full-report/

Silva, W.F. da et al. (2018) Reverse osmosis desalination plants in Brazil: A cost analysis using three different energy sources. Sustainable Cities and Society 43: 134–143 https://doi.org/10.1016/J.SCS.2018.08.030

Singlitico, A.; Østergaard, J. & Chatzivasileiadis, S. (2021) Onshore, offshore or in-turbine electrolysis? Techno-economic overview of alternative integration designs for green hydrogen production into Offshore Wind Power Hubs https://doi.org/10.1016/j.rset.2021.100005

Speirs, Jamie et al. (2018) A greener gas grid: What are the options? Energy Policy 118: 291-297 https://doi.org/10.1016/j.enpol.2018.03.069

Terlouw, T. et al. (2021) Life Cycle Assessment of Direct Air Carbon Capture and Storage with Low-Carbon Energy Sources- Environmental Science and Technology 55 (16): 11397–11411 https://doi.org/10.1021/acs.est.1c03263

Thema, M.; Bauer, F. & Sterner, M. (2019) Power-to-Gas: Electrolysis and methanation status review. Renewable and Sustainable Energy Reviews 112: 775–787 https://doi.org/10.1016/J.RSER.2019.06.030

Thomson, C. & Harrison, G. (2015) Life Cycle Costs and Carbon Emissions of Offshore Wind Power https://www.climatexchange.org.uk/media/1461/main_report_-_life_cycle_costs_and_carbon_emissions_of_offshore_wind_power.pdf

Thrän, Daniela et al. (2014) Biomethane – status and factors affecting market development and trade. A Joint Study by IEA Bioenergy Task 40 and Task 37 https://task40.ieabioenergy.com/wp-content/uploads/sites/6/2013/09/t40-t37-biomethane-2014.pdf

Tlili, O.; de Rivaz, S. & Lucchese, P. (2020) Task 38 Final Report https://www.ieahydrogen.org/es/

Tröndle, T. (2020) Supply-side options to reduce land requirements of fully renewable electricity in Europe. PLoS ONE https://doi.org/10.1371/journal.pone.0236958

Valente, A.; Iribarren, D. & Dufour, J. (2016) Life cycle assessment of hydrogen energy systems: a review of methodological choices. The International Journal of Life Cycle Assessment 22 (3): 346–363 https://doi.org/10.1007/S11367-016-1156-Z

van Leeuwen, C. & Zauner, A. (2018) Innovative large-scale energy storage technologies and Power-to-Gas concepts after optimisation. D8.3 EU Horizon [Preprint] https://www.storeandgo.info/fileadmin/downloads/deliverables_2019/20190801-STOREandGO-D8.3-RUG-Report_on_the_costs_involved_with_PtG_technologies_and_their_potentials_across_the_EU.pdf

Voldsund, M. et al. (2019) Comparison of Technologies for CO2 Capture from Cement Production—Part 1: Technical Evaluation. Energies 12 (3): 559 https://doi.org/10.3390/EN12030559

Wang, Anthony et al. (2021) Analysing future demand, supply, and transport of hydrogen. Guidehouse. Utrecht https://gasforclimate2050.eu/wp-content/uploads/2021/06/EHB_Analysing-the-future-demand-supply-and-transport-of-hydrogen_June-2021_v3.pdf

Wang, X. and Song, C. (2020) Carbon Capture From Flue Gas and the Atmosphere: A Perspective. Frontiers in Energy Research https://doi.org/10.3389/fenrg.2020.560849

Weger, L.; Leitão, J. & Lawrence, M. (2021) Expected impacts on greenhouse gas and air pollutant emissions due to a possible transition towards a hydrogen economy in German road transport. International Journal of Hydrogen Energy 46 (7): 5875–5890 https://doi.org/10.1016/J.IJHYDENE.2020.11.014

Wernet, G. et al. (2016) The ecoinvent database version 3 (part I): overview and methodology. International Journal of Life Cycle Assessment 21 (9): 1218–1230 https://doi.org/10.1007/S11367-016-1087-8

World Bank (2021) State and Trends of Carbon Pricing 2021 [Preprint] https://doi.org/10.1596/978-1-4648-1728-1

WEC (2021) National Hydrogen Strategies. World Energy Council https://www.worldenergy.org/assets/downloads/Working_Paper_-_National_Hydrogen_Strategies_-_September_2021.pdf

Wouters, Carmen et al. (2020) Market state and trends in renewable and low-carbon gases in Europe https://gasforclimate2050.eu/publications

Zhang, J. et al. (2020) Recent progress for hydrogen production by photocatalytic natural or simulated seawater splitting. Nano Research https://doi.org/10.1007/s12274-020-2880-z

IEA Bioenergy

Technology Collaboration Programme