THE ROLE OF NATURAL GAS IN EUROPE TOWARDS 2050

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EXECUTIVE SUMMARY

This report examines the role of natural gas in Europe towards 2050. The study has investigated drivers in the energy markets and relevant new technologies. The main drivers are the response to global warming with the ambition to cut greenhouse gas emissions by at least 55% by 2030 and to become climate-neutral by 2050, as well as the increased competition from renewable power generation. Currently we observe a significant growth in renewables, competing head-to-head with natural gas in some specific market segments. It is also an ongoing development towards increased integration and interaction across power, heat, industry and transport sectors. Europe's response to the impacts of global warming is the long-term strategy "A Clean Planet for all" (EC, 2018a). The European ambition is to lead the way to climate neutrality by investing in realistic technological solutions, empowering citizens, and aligning action in key areas such as industrial policy, finance, or research while ensuring social fairness for a just transition. The "Clean Energy for all" package highlights the need for a dramatically changed energy system. The European targets are a significant increase of the share of renewables, up to 27% by 2030 and 40-60% by 2050. The second step of the energy system transformation focuses on "putting active consumers at the center of the energy system".

The power sector: The large deployment of renewable energy sources has changed the power generation sector, leading to energy markets dominated by the high intermittency of renewable power generation. An increased need for flexibility will probably be the most fundamental characteristic of future energy systems. Several technologies to balance the grid with different advantages and disadvantages are currently available. However, there is not a unique solution and several storage and power generation technologies will be important to determine the reliance and efficiency of the future power sector including (natural) gas and electricity storage. Natural gas power with post-combustion CO_2 capture is an available technology for providing such flexibility and allows power generation from natural gas with relatively low greenhouse gas emissions. When carbon capture and storage (CCS) is available in the markets, its use expands with the scale of the carbon price.

The building sector: Natural gas is the primary source of energy in the building sector in Europe and it is the main source of the CO_2 footprint in European buildings. Substitution of natural gas by biofuels or biomass is the most direct approach to reduce the resulting CO_2 emissions. This would allow preserving and reusing the current infrastructure, and hence minimize the changes required in the sector. However, even if demand from other sectors is not considered, biofuels and biomass will probably not be capable to supply all the energy demand from the building sector. Hydrogen could be an alternative clean fuel if produced from electrolysis of water or natural gas reforming with CCS. A hydrogen infrastructure and economy could be a cost-efficient way to decarbonize the building sector in the long term. Electrification is an alternative that does not require new infrastructure. Heat pumps can provide the heating and cooling demand in the building sector and are a solution that can lead to a phase-out of natural gas. However, the massive deployment of heat pumps would require the decarbonization of the power sector in order to effectively mitigate climate change as well as significant upgrades of the power infrastructure.

The transport sector: The most positive outlook for future natural gas use comes from the transport sector where there is a potential increase of demand for compressed natural gas (CNG) in road traffic and liquefied natural gas (LNG) can be a future fuel for maritime transport. Hydrogen may play a central role for both of these segments. Unlike with road transport, the potential for electricity in the maritime sector is limited to short-sea and in-port operations. The fuel mix is set to switch from being nearly entirely oil-fuelled today to an even mix of natural gas (mostly LNG) and hydrogen in 2050, based on on an assumption of increasing carbon prices, as well as a host of regionally imposed decarbonization efforts.

The industry sector: For both the energy and industrial sector, the application of CCS remains an open issue just as well as improvements in energy efficiency. Steady growth in the use of CCS in hydrogen (H_2) production using natural gas feedstocks, the use of CCS in refining (including bio refining) and CCS use in conjunction with cement manufacture is foreseen in the modelling/scenarios developed in this study. Hydrogen can be supplied effectively to a large number of high-capacity users through pipelines. However, the energy required for compressing and pumping hydrogen is substantial.

Social trust: Trust is an important issue to address with respect to implementing new natural-gas technologies such as CCS and hydrogen into new applications and continue to use natural gas as an energy carrier. If this is pursued as a commercial endeavor, people affected by infrastructure need to be able to trust the companies' motivations and their ability to operate the infrastructure safely. Affected people also need to trust the fairness of the processes implemented in planning and operation, as well as see a benefit strong enough for them to justify the intrusion of their area.

Scenarios: Several scenarios for future energy demand and supply under different polices are developed and analyzed using the Global Change Assessment Model (GCAM). It is an integrated tool for exploring the dynamics of the coupled human-Earth system and the response of this system to global changes. GCAM is a global model that represents the behavior of, and interactions between five systems: the energy system, water, agriculture and land use, the economy, and the climate. Natural gas production and consumption continues to expand globally in all examined scenarios except one – the Paris Policy Scenario without CCS. If CCS is available, then natural gas markets continue to expand throughout the period of analysis. When CCS is unavailable and the world is on a trajectory leading towards 2 degrees average temperature rise in °C, the natural gas market peaks and declines as soon as the world increases ambition towards the Paris goals. The scenarios in this study show a robust future for natural gas even if Paris goals are pursued as long as CCS technology can be deployed at scale. To meet these consumption levels, natural gas trade is vital and an increase in LNG supplies is crucial to this growth.

Future role of natural gas: If society and industry succeed in implementing CCS at large scale and use H_2 as feedstock to reduce the carbon footprint in industrial processes the role of natural gas towards 2050 in a global context is robust. In Europe, model studies show that the demand for natural gas will probably decline, and Europe will become a less important consumer of natural gas. The European natural gas demand varies between studies, but the trend is clear and in many studies dramatic. The major factors that could influence the role of natural gas in Europe is the availability of CCS as a commercial and cost-efficient technology and the role of hydrogen in transport and industry.

In Europe the role of natural gas in the energy transition is under pressure. Below we list what we find to be the main areas that will have a high impact for the role of natural gas as a relevant and sustainable bridging fuel in Europe:

- Market design for providing sustainable and cost-efficient flexibility into power systems with an increasing share of intermittent renewables;
- Development of a European infrastructure for CO_2 transport and storage;
- Non-discriminating market design for hydrogen in Europe where clean hydrogen is defined by its carbon footprint;
- The future cost and efficiency of hydrogen fuel cells with applications in transport;
- Development of a European infrastructure for H_2 production, storage and transport.

The above are also areas where research is required to improve the knowledge base for future decisions. CCS and the market penetration of hydrogen are probably the two single factors with the highest impact on the future role of natural gas in Europe. Both of these technologies are immature in terms of commercialization and there is need for more research on business models and how to build markets for these technologies.

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This report aims to provide an understanding of the role of natural gas in a future decarbonized economy.

Photo: Gassco

1 INTRODUCTION AND BACKGROUND

This report examines the role of natural gas in Europe towards 2050 and investigates current knowledge on drivers in the energy markets and relevant new technologies. The main drivers are the response to global warming and the ambition to cut greenhouse gas (GHG) emissions by at least 55% by 2030 and to become climate neutral by 2050. This report aims to provide an understanding of the role of natural gas in such a future decarbonized economy.

This report takes as a starting point that natural gas today plays a central role in sectors like heat, power, industry, transport both in Europe and globally. We discuss this role towards 2030 and 2050 and how it is likely to change. The role of natural gas as a bridging technology until and potentially beyond 2050 (when society has to be emission-free) depends on the ability to remove carbon dioxide emissions in the transformation process. We look at different pathways for the energy transition and discuss the role of natural gas with and without this technology.

Hydrogen production produced from natural gas or electrolysis is a potential future game-changer in the energy transition. The report briefly discusses hydrogen from a natural gas perspective, but does not go into details on the hydrogen economy or the role of hydrogen in the energy transition. This is a topic that will be discussed in a forthcoming position paper.

The main topics discussed in the position paper are:

- Fundamental drivers in the change of energy systems (Chapter 2)
- The potential role of natural gas in decarbonizing the sectors (Chapter 3)
- Consumer engagement and natural gas (Chapter 4)
- Scenarios of future natural gas demand and supply (Chapter 5)
- The role of natural gas in Europe (Chapter 6)

This report builds on research carried out by research groups cooperating in the NTNU Energy Transition Initiative: NTNU, DIW Berlin, PNNL, TU Berlin and University of Maryland.

2 FUNDAMENTAL DRIVERS OF CHANGE IN ENERGY SYSTEMS

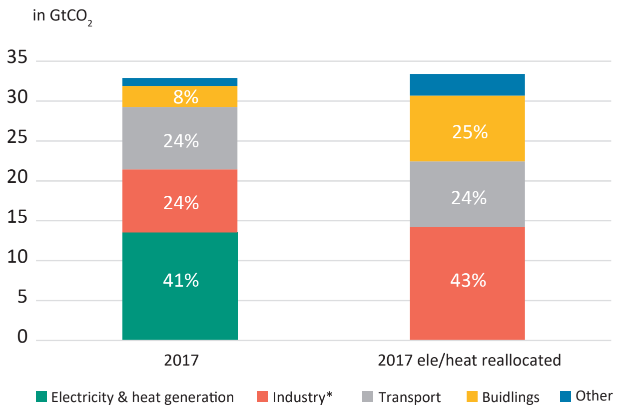
This section will illustrate that natural gas is a substantial contributor to global CO_2 emissions, albeit at lower per-energy content level than coal or oil. The current debate on using natural gas as a bridging technology until and potentially beyond 2050 (when it has to be emission free) depends on the ability to remove carbon dioxide emissions in the transformation process. The speed of finding large-scale technological solutions will determine the future role of natural gas in all sectors of the economy.

Europe's answer to the IPCC report on the impacts of global warming (IPCC, 2018) is the long-term strategy "A Clean Planet for All" (EC, 2018a). This strategy presents Europe's long term vision on how "Europe can lead the way to climate neutrality by investing into realistic technological solutions, empowering citizens, and aligning action in key areas such as industrial policy, finance, or research while ensuring social fairness for a just transition."

The "Clean Planet for All" package highlights the need for a dramatically changed energy system: On top of the agenda are the EU targets for reduction of GHG emissions and the increase of the share of renewables up to 27% by 2030 and 40-60% by 2050. Large-scale wind and PV farms have little flexibility and provide intermittent generation, making it challenging to forecast precisely the amount of energy that is going to be produced. This increases the need for balancing services while at the same time capacity of traditional sources of flexibility, i.e., fossil-fuel based power plants is being reduced. The second step of the energy system transformation focuses on "putting active consumers at the center of the energy system". This will involve the integration of technological advances (smart technologies) such as innovative distributed flexibility services. Also, new business models are developing and will bring forward the most competitive innovations for increased system flexibility. One central element in European policy making for combating climate change is the European Strategic Energy Technology Plan (SET Plan). Among the key actions identified is the reduction of technology costs.

Several analyses of future energy projections are similar in their general outlook for growth in total energy demand and degree of electrification. However, they are significantly different in how these demands will be met, i.e., which role fossil fuels, renewable energies, energy efficiency, future modes of transportation or new technologies will play. The incumbents of the fossil fuel industry regularly stress the importance of natural gas in supporting a global coal phase-out and projects carbon capture, utilization and storage a bright future.

Currently a significant growth in renewables is seen, competing head-to-head with natural gas in some specific market segments. It is also an ongoing development towards increased integration and interaction across the power, heat and transport sectors. At the same time, there is a growing renewable share in the electricity sector, calling for more intermittent power and demand control services in the power sector. Globally, the share of natural gas remained at around 20% of total primary energy supply which accounted for 20% of global CO_2 emissions. Emissions from natural gas grew across all regions by 170 Mt CO_2. In Europe, coal, oil and natural gas almost equally contributed to total emissions. The share of CO_2 emissions from fuel combustion from gas in the EU28 accounted for 28% (IEA, 2019).



* Industry includes also energy industries own use

Source: IEA (2019)

Figure 1: Global emissions by sector - 2017

Two thirds of total CO_2 emissions globally come from electricity/heat generation and transport (Figure 1), the rest is split equally between industry and buildings. The shares differ across countries: emissions from transport are dominant in North and South American countries whereas in Asia about half of the emissions comes from power generation according to IEA (2019). After reallocating emissions from power generation, industry accounts for slightly less than half of total emissions, buildings and transport for one quarter each. It is interesting to note that most of the emissions from the building sector stems from OECD countries while most from industry comes from Asia.

Availability of natural gas globally is not a constraint and most projections foresee an increasing number of LNG exports. As for demand, industry is likely to be an important driver of gas demand since it is – as of now and without substantial cost reductions in new technologies – an essential input for production of cement or steel. With growing electrification across Europe, substantial cost reductions in renewable power generation put natural gas at a disadvantage. International carbon pricing will also impact the future of natural gas in electricity production. In the transportation sector (individual mobility, freight transport and maritime shipping) CNG/LNG may be an option (but it would not suffice to meet sectoral emission reduction targets). Bio-based synthetic gas, hydrogen (blue or green), carbon capture, utilization and storage (CCUS) are potential other contributors to a decarbonized Europe. However, substantial cost reductions are required (for hydrogen use), competition for biomass needs to take into account other Sustainability Development Goals (SDG) (food-water-energy nexus) and the development of CCTS infrastructure (transport and storage) needs to be financed (Egging et al., 2019).

In 2019, 57 carbon pricing initiatives were in place or scheduled for implementation. In total, they cover 11 gigatons of carbon dioxide equivalent ($GtCO_2e$), which is roughly 20 percent of GHG emissions. Prices for carbon within the initiatives (Emission trading schemes (ETS) and carbon taxes) vary from less than US\$1/tCO_2e to maximum US\$127/tCO_2e. Whereas tax levels remained constant recently (except for in Portugal and Iceland), prices in many ETS increased. The effectiveness of carbon pricing crucially hinges on the overall climate policy environment put in place (World Bank Group, 2019).

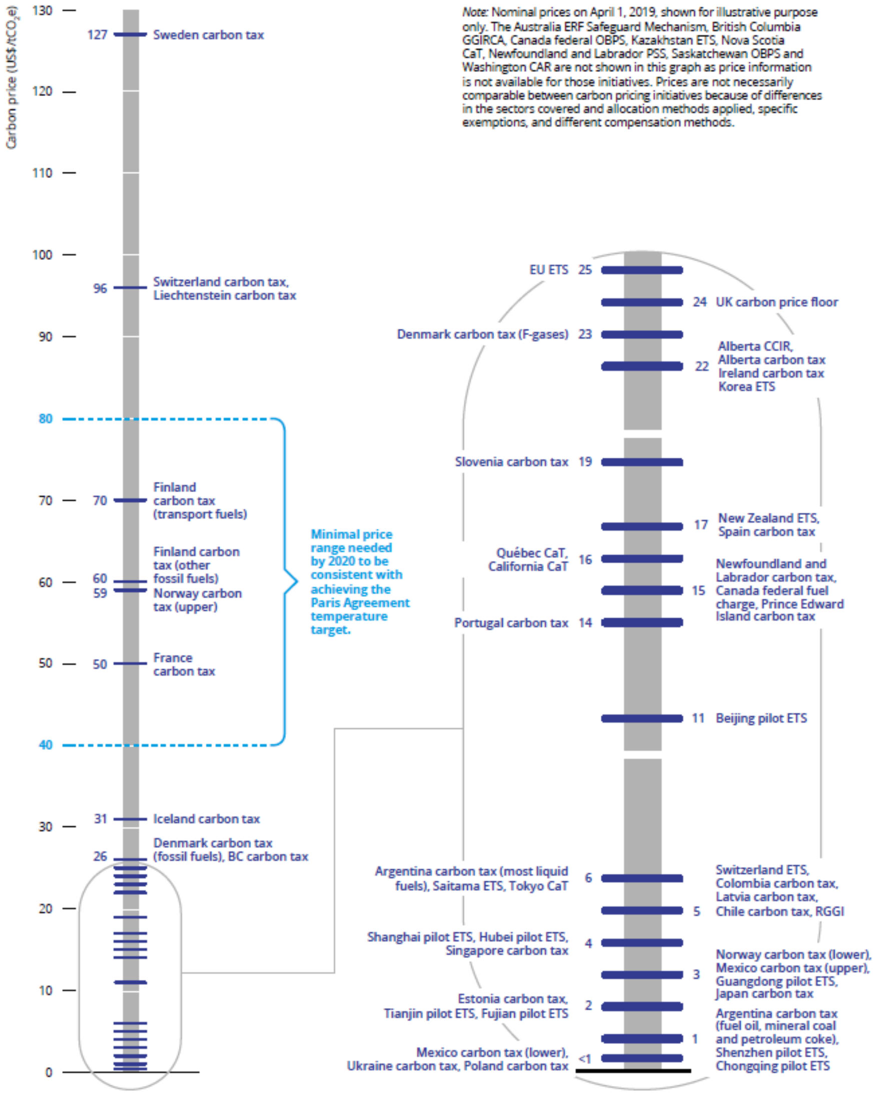
The European Union allowances grew after the establishment of the market stability reserve and expectations for a more certain development of future trading. Since the start of the EU-ETS, revenues from auctioning off allowances have added up to more than 35 billion Euros (revenues go to member states, and at least 50% should be used for climate- and energy-related purposes). For Phase 3 (2013-2020) 300 million allowances are reserved for auction to fund the demonstration of environmentally safe carbon capture and storage and innovative renewable energy technologies through the NER300. This (NER300) will be replaced in Phase 4 (2021-2030) by the innovation and modernization fund. The former will serve the demonstration of innovative technologies to breakthrough innovation in industry, as well as carbon capture and storage/use and renewable energy. The latter will facilitate investments in modernizing the energy systems and supporting energy efficiency in lower-income Member States, including investments to support a socially just transition to a low-carbon economy (ICAP, 2019).

The current coverage of the energy sector, energy-intensive industries and intra-European aviation in the EU-ETS (accounting for roughly 40% of total emissions in Europe) will not achieve the prescribed reduction in emissions. Therefore, a debate has stirred up on the implementation of additional carbon pricing in the heating/building and transport sectors.

All fossil fuels, natural gas included, has a problem as they are in fact emitting CO_2. The role of natural gas will hence depend on our ability to decarbonize the resource or compensate by decarbonizing or avoiding use of other fossil fuels. How quickly society is able to do such a shift towards a low carbon energy mix is a key element in this analysis, hence determining how much gas that can be recovered before the energy system needs to become emission-free in 2050, or how quickly CCS and hydrogen technologies can be implemented.

In Europe this is reflected in the Green Deal package. A number of Commission proposals for revised energy and climate legislation is expected in the summer of 2021 to accommodate the expectations of a carbon neutral society. Here revisions are expected in directives order to establish a framework for renewable and decarbonised gases. This includes both the decarbonisation potential of natural gas, coal-to-gas switches as well as biogas and hydrogen.

Relevant for the role of natural gas is also the EU strategy to reduce methane emissions from 2020 (EC, 2020) and the ENTSO-G Ten-year network development plan (ENTSO-G, 2020). While the formal legislation is still not in place at the time of this writing, it is clear that infrastructure support for natural gas is increasingly under pressure. At the same time there is an increasing need for joint planning of natural gas infrastructure and electric infrastructure, based on the potential role of hydrogen and increased focus on coupling between heat and electricity. This would also benefit from increased system cooperation and long-term planning between ENTSO-E and ENTSO-G.



Note: Nominal prices on April 1, 2019, shown for illustrative purpose only. The Australia ERF Safeguard Mechanism, British Columbia GGIRCA, Canada federal OBPS, Kazakhstan ETS, Nova Scotia CaT, Newfoundland and Labrador PSS, Saskatchewan OBPS and Washington CAR are not shown in this graph as price information is not available for those initiatives. Prices are not necessarily comparable between carbon pricing initiatives because of differences in the sectors covered and allocation methods applied, specific exemptions, and different compensation methods.

Source: World Bank Group (2019)

Figure 2: Prices in implemented carbon-pricing initiatives

3 THE POTENTIAL ROLE OF NATURAL GAS IN DECARBONIZING THE SECTORS

Mitigation of climate change requires a technological and economic transition towards a sustainable society. Greenhouse gas (GHG) emissions must be reduced from the different economic sectors of society through research, development and deployment of more sustainable technologies. This section presents different technological solutions that could lead to a reduction of greenhouse emissions organized in different sectors, i.e. power, industry, transport, and building. The combination of these technologies and the interdependencies among sectors are also discussed. Hydrogen utilization and deployment is discussed in a separate section owing to its broad application range in all economic sectors. In particular for the Norwegian context this crucially depends on the successful (and economic viable) large scale utilization of CCS. For the future use of natural gas in the power sector, CCS technology would also need to be flexible. This may not address the full bandwidth of issues but rather provides a point of departure. An in-depth analysis of hydrogen (taking into account several hydrogen roadmaps, strategies and interaction with natural gas infrastructure) will be provided in a future position paper.

3.1 Technical solutions by sector

This section describes several technologies that can reduce the CO_2 emissions in different sectors, the main bottlenecks for their deployment, and their role in a future energy system. A summary of these technologies including their level of development and deployment, relation with natural gas, and volume of emissions is also included.

3.1.1 Power

Fossil fuels play a fundamental role in the power sector in Europe. Historically, natural gas and coal have been the main fuels used to generate electricity in traditional thermal power plants. In the last decade, wind (onshore and offshore) and solar (thermal and PV) have increased their power generation by more than 250% since 2000 (IEA, 2018). The large deployment of renewable energy sources has changed the power generation scenario, leading to energy markets dominated by the high intermittency of renewable power generation (Kondziella and Bruckner, 2016; Bertsch et al., 2016).

Traditional thermal power plants must thus operate flexibly to accommodate their electricity production to the variability of these renewable energy sources (Gonzáles-Salazar et al., 2017; Eser, 2017). In this context, renewables replace and foster simultaneously the utilization of natural gas in combined cycles. The replacement occurs because of the increased installed capacity of wind and solar energy sources, which offsets the share of traditional fossil-fuel based power plants. However, the growth of renewables also requires mechanisms and technologies to balance the grid. Natural gas combined cycles (NGCC) are a good complement owing to their flexibility, which is characterized by fast-ramping rates and short start-up and shut-down times (Eser et al.), 2017; Alobaid et al., 2017). In addition, NGCC with post-combustion CO_2 capture is the most mature and flexible technology in the CCS field and allows power generation from natural gas with low greenhouse gas emissions (Montañés et al., 2017; Bui et al., 2018; Rúa, 2020).

In contrast, biomass and derivative biofuels are substitutes for natural gas as a main power generation fuel (Cumicheo et al., 2019). These types of fuels offer low or even neutral greenhouse gas emissions due to the removal of CO_2 during the vegetation growth and can reach negative emissions if combined with CO_2 capture plants in what is known as BECCS technology (Bio-Energy CCS) (Bui et al., 2018; Cabral et al., 2019). However, the capacity to produce biomass and biofuels at a commercial scale large enough to replace the entire fleet of power plants relying on natural gas must be demonstrated.

The Allam cycle is a novel power generation capacity based on oxy-combustion CCS (Allam et al., 2014: Allam et al., 2017). Natural gas is burned with pure oxygen originating water and CO_2 as exhaust gases. Pure CO_2 is obtained after condensing the water. Most of this CO_2 stream is recycled in a supercritical CO_2 cycle to produce power, whilse the remaining is compressed, transported and stored. Therefore, the Allam cycle does not emit greenhouse gases during its operation. Since efficiencies up to 60% can be achieved without emissions, the Allam cycle may become a game-changing technology for base-load power generation with natural gas, thus boosting the utilization of this fuel (Khallaghi et al., 2020). Compared to the previously discussed technologies, the Allam cycle is not fully developed and research is being conducted worldwide to gain understanding on the production of key pieces of equipment (turbine, combustor, and heat exchangers) and deploy this power generation technology.

Sources of Flexibility in Power Production

In the last decade, the investment in renewable energy sources has notably increased to reduce CO_2 emissions in the power generation sector. Wind (onshore and offshore) and solar (thermal and PV) installed capacity is continuously growing, and their share in the energy mix is only expected to increase (IEA, 2018). Hence, balance of the power grid becomes a challenge because of the intermittency of the renewable energy sources. In this transition to a cleaner electricity sector, flexibility is the cornerstone to ensure safe, reliable and efficient power generation (Bertsch et al., 2016; Huber et al., 2014; Kondziella and Bruckner, 2016). There are several alternatives and technologies to reduce the CO_2 emissions whilse meeting an increasing electricity demand. There is not a unique solution that will balance the grid alone, but rather a combination of them.

Pumped storage, i.e. pumping water back to a dam during low. demand periods, is currently the most mature storage technology available. Because of the size of dams, large amounts of energy can be stored. However, this storage technology highly depends on the geography of the region and it is not applicable to all countries. Furthermore, its utilization is restricted to cases where excess of clean energy is available, otherwise the net emissions of pumped storage can increase substantially.

Batteries are a direct solution to store the intermittent power generation from non-dispatchable renewable energy sources such wind or PV solar. This technology does not affect the operation of the wind farms or solar power plants as it is a supplementary and external component, and therefore its deployment does not impose any extra constraints. However, batteries cannot balance the grid by themselves as providing high power generation over a long period of time would require extremely big units (IEA, 2014). Therefore, the capacity to provide large amounts of energy limits the utilization of this technology to balance an entire grid. Furthermore, the production and recycling of batteries involves mining and treatments that generate large amounts of CO_2 emissions. A life cycle assessment is thus necessary in each case to guarantee that the utilization of this technology leads to a reduction in the net CO_2 emissions.

Thermal energy storage adds flexibility to the operation of thermal solar power plants and combined heat and power (CHP) plants. This technology allows storage of excess energy produced in these thermal power plants in the form of latent or sensible heat, to utilize it whenever required (Sharma et al., 2009). In addition to the advantage of balancing the grid, thermal energy storage also allows operating the power plant more steadily and efficiently. By storing or releasing some energy, the power plant can compensate disturbances to improve its operation, e.g., solar radiation changes in thermal solar plants and changes in heat demand but not power, or vice-versa, in CHP plants. Storage size may also be an issue for the deployment of this technology, as enormous storage units would be required to balance the grid with thermal energy storage exclusively.

Power-to-gas is a promising technology to store energy in the form of a fuel. Hydrogen or methane can be produced when excess of clean power is available, leading to high-quality energy storage than can be used in a broader range of applications than the power or thermal energy stored with other technologies (Yao et al., 2019). The main disadvantage of this technology is its energy intensity, as large amounts of energy are required to produce the fuel. Therefore, energy sources with almost net zero emissions are necessary to implement this storage technology. This would require the major deployment of wind and solar power plants together with large contributions of hydro power. Thus, it is not a feasible storage technology in the short-term as generating clean power is still the biggest challenge.

Traditional thermal power plants may play a fundamental role to provide flexibility in the power generation sector. The deployment of renewables will significantly increase the cycling operation and number of start-ups and shut-downs of these thermal power plants (Montañés et al., 2016). Modern natural gas combined cycles (NGCC) are more efficient, less polluting and faster than current coal fired power plants (Alobaid et al.,

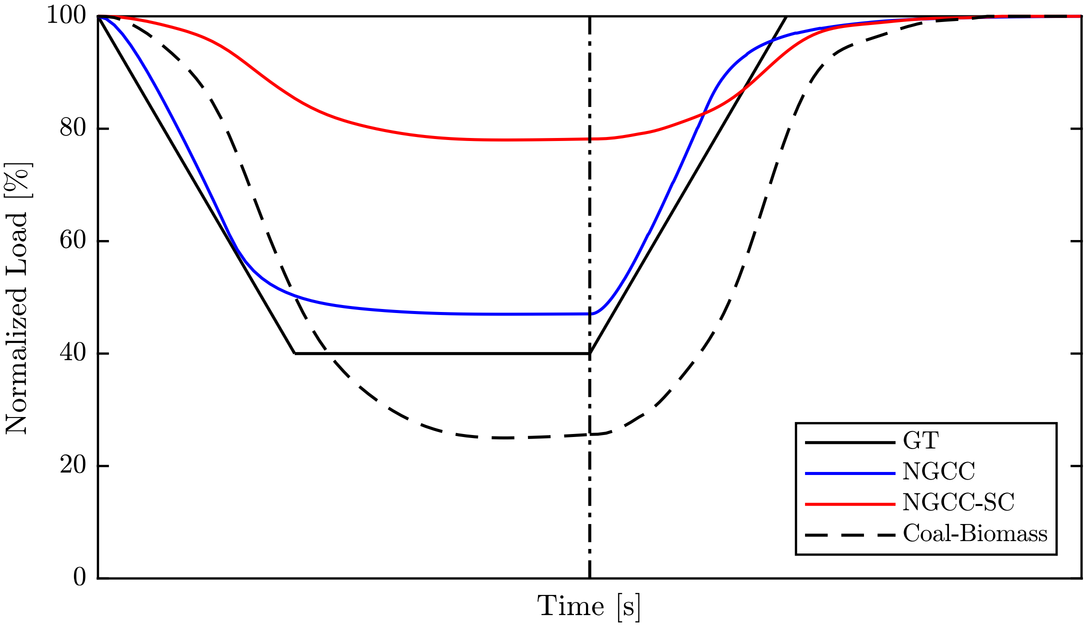


Figure 3: Generic dynamic behaviour of two types of thermal power plants for a decrease and an increase in the power load.

2017; González-Salazar et al., 2017). Therefore, the penetration of renewables in the power sector may foster the utilization of NGCCs because of their better performance and capacity to balance the grid over long periods of time, being the only current technology that offers this feature (González-Salazar et al, 2017; Eser et al. 2017). In contrast, coal power plants might be less competitive owing to their limited flexibility and longer start-up and shut-down times.

The steam cycles in traditional power plants are passive elements with large heat capacitance in the steam generator that slow down the response in power generation from the steam turbines (Kehlhofer et al., 2009). Gas turbines provide rapid ramp rates that allow NGCCs to decrease their power within seconds. Therefore, the slowness of the steam cycle may be compensated in NGCCs by over- or under-shooting the gas turbine load (Rúa et al., 2020). This factor enhances the flexibility of gas-based power plants over the more traditional coal-fired units. In addition, the start-up and shut-down times required by NGCCs are shortened owing to the fast ramp rates of the gas turbines, while coal power plants are limited by the steam generator. Figure 3 represents a generic dynamic behaviour of these two types of thermal power plants for a decrease and an increase in the power load.

Post-combustion CO_2 capture (PCC) may enhance the utilization of NGCCs as balancing technology in the power sector, since the integration of both technologies leads to fast and reliable power generation with reduced CO_2 emissions (Montañés et al., 2017). Chemisorption with MEA is the most mature technology for post-combustion CO_2 capture (Bui et al., 2018). This process is characterized by the slow response of the different process variables because of the delay introduced by heat exchangers, the large residence times in the solvent storage tanks, and the liquid hold-ups in the absorber and desorber columns. As a result, the stabilization of a capture plant for commercial applications may take several hours to completely stabilize all the process variables after a single disturbance (Montañés et al., 2017a; Montañés et al., 2018)).

Natural gas combined cycles and CO_2 capture plants based on absorption exhibit hence different dynamic behaviour. The power plant stabilizes completely after 10-20 minutes, with the power control being even faster, i.e., in a few minutes, because of the fast response of the gas turbine. In contrast, the post-combustion capture plant might need several hours owing to the interaction among its equipment and its intrinsic slow performance (Montañés et al., 2017b). This could suggest that the flexibility of NGCCs may be partially lost due to their integration with slow PCCs. However, the integrated system does not reduce the power generation flexibility of the NGCC albeit the slow performance of the PCC. Since the gas turbine is the major contributor to the total power generation of the NGCC, steam extraction from the steam turbine to provide heat to the post-combustion plant has a negligible effect of the dynamic power generation of the integrated system. Thus, power generation from NGCCs integrated with chemisorption PCCs can provide power generation flexibility to the grid with reduced emissions (Rúa et al., 2020).

The main penalty of the integration is hence the reduction of efficiency because of the steam extraction from the steam turbine. Nevertheless, NGCCs integrated with PCC plants can reach efficiencies up to 55% respect to the low heating value of the fuel (Jordahl et al., 2012). This loss of profitability can be offset however by the tax penalties that may be imposed on the CO_2 emissions. In this context, adequate planning and scheduling of the NGCCs integrated with PCCs can improve the economic performance of the system by prioritizing the electricity generation during peak demand, and enhancing the capture plant operation during low-price periods (Bankole et al., 2018). Future energy systems will most likely be balanced by a combination of these technologies. Batteries can also be combined with NGCC to provide fast responses in the short-time scales (order of seconds), whilst the thermal power plant balances the grid in the medium and long-time scales (order of minutes and hours). This would lead to tight balancing of the grid without the need of large batteries, as the major power demand variation would be met by the NGCC. A similar approach can be followed in CHP plants, where thermal energy storage can be used to balance the process heat demand whilst batteries might be installed to balance the power generation.

Flexibility will probably be the most fundamental characteristic of future energy systems. Several technologies of different nature and with different advantages and disadvantages are currently available. However, there is not a unique solution to balance the grid, and the symbiosis among the different available storage and power generation technologies will determine the reliance and efficiency of the future power sector.

3.1.2 Industry

Combustion of fossil fuels and process-related emissions from chemicals reactions are the main contributors to industry being one of the largest GHG-emitting sectors (IEA, 2018).[1] Natural gas and coal are the main fuels in the non-metallic mineral, steel and iron, and chemical industries. They are the main energy source of these industries, as their combustion can generate high temperatures required in several processes and produce steam and hot water (IEA, 2018). In addition, these fossil fuels are also feedstock of different products.

There are several approaches to reduce emissions in the industry sector. These are mainly distinguished by the deployment of CCS and the development of new processes and techniques, which strongly depend on the type of industry and its energy intensity. Efficiency is however common to all of them, as it allows reducing energy demand and improving production.

For the steel and iron industry and the non-metallic minerals sector, especially cement production, CCS may lead to large reductions of CO_2 emissions (Bui et al., 2018). In these industries, the gases emitted to the atmosphere are characterized by high CO_2 concentrations and steady mass flow and temperature. Post-combustion capture could be a solution for these conditions for several reasons:

- "end-of-pipe" solution: the post-combustion capture plant is a complement of the facility and does not impose any constraint on the operability. Therefore, its installation and operation does not affect the fabrication of the end-product.
- steady-operation: the industry sector tends to operate in steady-state to keep process variables stabilized and maximize productivity. This operation approach enhances the utilization of CCS as it allows to optimally design the capture plant for a specific operating regime. Furthermore,

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[1] Industry accounts for 23% of global CO_2 emissions.

post-combustion capture is characterized by slow dynamics, which normally limit its flexible operation. However, industry processes undergo slow modifications too, which is suitable to adapt the operation of the capture plant.
- high CO_2 concentrations: post-combustion capture performance improves with higher concentrations of CO_2 in the gas stream. In the steel and iron industries, CO_2 concentrations up to 50% can be reached (in comparison to 4% vol in natural gas combined cycles), which leads to improved energy intensities in the capture plant.

The CO_2 capture in the non-metallic and steel and iron industries can be further enhanced with fuel switching from natural gas to biomass. BECCS combines the suitability of CCS for the industry sector with the removal of CO_2 of the biomass during its lifetime (Cabral et al., 2019). Negative emissions can be obtained if the cycle of afforestation is implemented adequately and sufficiently high capture ratios are obtained in the capture plant (Fajardy et al., 2018; Fajardy and Mac Dowell, 2017)). As a result, it is considered by the IPCC as a key technology to not exceed the limit of 1.5°C increment respect to pre-industrial levels (IPCC, 2018). Fuel switching to biomass or biogas from natural gas would also lead to reduction of emissions, although the effect on the net emissions from the industry sector would not be as pronounced as if this fuel switch was combined with CCS.

Fuel switching from natural gas to hydrogen can also mitigate the emissions in the production of ammonia, ethylene and methanol. However, this solution requires changes in the process to adapt them to a hydrogen-based technology.

Electrification is also an alternative for any kind of industry due to its flexibility. For instance, electric arc furnaces can replace the traditional basic oxygen furnaces during steel production. Emissions may be reduced from this technology change if electricity is generated from clean energy sources. However, this alternative imposes bigger challenges to the power sector owing to the increase in electricity demand.

Heating and low-medium temperature water and steam can also be produced with electricity, but this approach should be avoided whenever possible. District heating can be used instead for heating purposes and to obtain low-temperature water, while combined heat and power (CHP) can produce medium temperature water or steam in a more efficient manner (Beiron et al., 2019).

Emissions in the petrochemical industry are highly related to the utilization of oil and natural gas feedstock and not so much to the direct energy utilization. Efficiency improvements in the upstream processes, including extraction, treatment and transport, can lead to a sizeable reduction in the CO_2 emissions of this industry. However, new processes, materials and technologies are necessary to significantly contribute to mitigate the impact of the petrochemical industry in global warming. Fuel switching to hydrogen can be a feasible alternative.

3.1.3 Transport

Natural gas has potential in the following transport sectors:
- light duty road transport i.e., cars, taxis, small vans etc.,
- public passenger road transport- primarily urban buses,
- freight transport,[2]
- marine, shipping and inland water way transport.

The share of global energy demand in transport is 28%, with road transport accounting for over 80% of that. The transport energy demand in 2017 was approximately 116 EJ, projected to decrease to 112 EJ by 2050 (DNV-GL, 2019a). The transport sector is identified as a key player in the energy transition, as electrification is rolled out and gains primacy over fossil fuels, at least for the road transport sector. The world's fleet of passenger road vehicles is 97.5% internal combustion and 2.5% electric. By 2050 the fleet will have transformed to 73% electric and 27% internal combustion (DNV-GL, 2019a). Natural gas has the potential to be adopted in some of the applications not suitable for electrification and many non-road sectors.

Natural gas usage as a transport fuel essentially means replacement of a liquid fuel; gasoline, diesel or some form of bunker fuel (fuel oil for maritime) for use in an internal combustion engine (ICE). Therefore, it is relevant to compare natural gas to these liquid fuels and consider some technical details about the internal combustion engine.

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[2] This sector can be subdivided into medium duty goods vehicles and heavy duty goods vehicles with the latter being split between urban uses such as refuse collection and inter-urban long distance transport.

Natural gas can be utilized as compressed natural gas (CNG) or liquefied natural gas (LNG). CNG is compressed and stored at pressures of 200 to 250 bar, requiring energy for the compression stage and the use of heavy, safe and in many applications crash tested storage vessels. LNG is cryogenically cooled to -160°C to liquefy the gas. This process requires energy and special insulated tanks. It would be extremely difficult to maintain -160°C in the vehicles´ storage tanks, hence the actual storage temperature is always slightly above this temperature. This results in some of the liquid evaporating. This is called boil-off, and in a closed vessel would lead to an unacceptable pressure increases. The evaporated, saturated LNG which boils off is used to control the temperature in the tank, utilizing latent heat to cool the remaining fuel, the boil-off is allowed to leave the tank and is used as a fuel; this is carried out on board LNG transport ships as a method to control boil-off and to power the vessel (Fernández et al., 2017).

In the transport sector, the specific energy or energy density (kJ/kg or kg/m^3) along with the cost, size and weight of onboard storage are extremely important characteristics because the vehicle in question is usually transporting the fuel on board. It is generally desirable to minimize the space taken up by the fuel system and maximize space for passengers or cargo.

	Specific Energy	Energy density
CNG @ 250 bar	53 MJ/kg	9 MJ/L
LNG @ -160°C	53 MJ/kg	22 MJ/L
Gasoline	46 MJ/kg	34 MJ/L
Diesel	45 MJ/kg	39 MJ/L
Hydrogen (Compressed)	120 MJ/kg	4,5 MJ/L
Hydrogen (Cooled)	120 MJ/kg	8,5 MJ/L

Table 1: Energy density in different gases

Compared to gasoline and diesel, natural gas may have higher specific energy, but not energy density, meaning that whilst getting more energy for each kilo of fuel you carry around, this will require a larger volumetric space on board the vehicle to carry the fuel around (Korakianitis et al., 2011). This analysis does not include the fuel system itself, the mass and complexity of the fuel system, nor the safety aspects of traveling with a compressed vessel or a cryogenically cooled vessel need to be considered as well. The same is true for hydrogen, which must either be cooled down to minus 253°C or compressed at 700 bar. High-pressure tanks and insulated tanks that will have a form of boil-off control require periodic inspection and certification. LNG operation is further complicated as the cryogenic tanks have specific hold time before the pressure build is relieved meaning the vehicle should be operated on a schedule to maintain a lower pressure in the tank or the boil off is going to need to be vented through some other mechanism (EIA, 2013).

For these reasons natural gas, CNG and LNG will have a limited role in light duty vehicles. There is some scope to use natural gas in larger vehicles though, where there is more room for storage. In general LNG is preferred for shipping and long-distance heavy-duty vehicles, whilst CNG is for smaller or shorter distance vehicles, especially commercial or public sector vehicles that will conduct short journeys and regularly go back to their depot. Shipping is really the sector that is expected to take up natural gas, in the form of LNG.

Engine considerations

Broadly speaking engines are broken down by their method of ignition and fuel. Spark ignition engines use gasoline fuel. The fuel and air mixture are ignited in the engines' combustion chamber by a spark. Compression ignition engines use diesel fuel. The fuel and air mixture are ignited by the high temperatures achieved during the compression of the air inside the engine's combustion chamber.

Natural gas has some features that make it a useable fuel for internal combustion engines. It can be compressed by quite a large degree before it ignites, meaning a high compression ratio can be used. For thermodynamic reasons, this results in higher thermal efficiencies. The low carbon content generally

Natural gas’ role in the energy mix depends on CCS, a developed hydrogen market and continued focus on reducing methane emissions.

Photo: Gassco

results in very low levels of CO_2, soot and hydrocarbon emissions. The low soot formation is one reason why natural gas has found some use in urban environments where local emissions are of primary concern. Other emissions, if the engine is operated correctly, can also be low or equivalent to other fuel types.

As natural gas is generally finding use in larger heavy-duty vehicles (HDV) it implies that it is being used primarily as a compression ignition engine fuel. The fact that natural gas does not ignite very well under compression alone means that the engines usually operate a dual fuel scheme. Under this operational mode, natural gas is either admitted to the engine in the intake port, or directly injected into the engines' combustion chamber and when ignition is desired, a small "pilot" injection of diesel fuel takes place, which acts as an ignition source and will ignite the natural gas and air mixture (Korakianitis et al., 2011). This method has found extensive use in the marine sector and some penetration into the heavy-duty market. For example, Volvo has introduced a truck that will utilize CNG and diesel, with both fuels injected though one injector. There has been a move away from admitting the natural gas into the engine's intake port towards direct injection. This is due to the need to reduce the amount of unburnt natural gas in the exhaust gases, commonly referred to as gas or methane slip.

Methane slip can occur when a well-mixed, air and natural gas mixture enters the combustion chamber and is not completely burnt due to some of the mixture being trapped in crevices, such as around the piston rings. As natural gas is a very powerful greenhouse gas with methane (CH4) estimated to have a global warming potential (GWP) of 28–36 over 100 years, and 84–87 over 20 years (EPA, 2017), any GHG advantage in the reduction of CO_2 can be mitigated. Hence it has been essential to reduce the methane slip to extremely low levels or to fit an after-treatment system such as a catalytic converter. Direct injection means the mixture is in-homogeneous and avoids unburnt natural gas from crevices in the combustion chamber. The pilot injection of the liquid diesel helps mix the natural gas and air in the chamber by creating some turbulence into the chamber. Direct injection (DI) natural gas engines will be carefully designed to maximize natural gas and air mixing and complex injection strategies of the liquid fuel may be utilized to "shape" the combustion for efficiency and emissions control.

The share of natural gas as a transportation fuel is expected to grow from 3% in 2012 to 11% in 2040. It is projected for the natural gas share of total energy use by large trucks, to grow from 1% in 2012 to 15% in 2040. In addition, 50% of bus energy consumption is projected to be natural gas in 2040, as well as 17% of freight rail, 7% of light-duty vehicles, and 6% of domestic marine vessels (EIA, 2016).

Maritime

Maritime transport is the most energy efficient mode of transport in terms of energy per tonne-kilometre. Approximately 2% of the world's energy is consumed by ships, mostly by international cargo shipping (Lion et al., 2020). The most common bunker fuel (fuel that used aboard a vessel) is heavy fuel oil (HFO), a residual oil containing sulphur[3]. Strict sulphur emissions regulations have come into effect in 2020 in some regions. Ship owners have three options to meet these regulations:

- use alternative fuels, e.g. natural gas (no sulphur),
- fit exhaust gas cleaning equipment (scrubbers) to remove exhaust sulphur,
- switch to distillate fuels such as marine diesel oil (MDO) (no sulphur).

Which is the most appropriate, will depend on many factors but will be principally determined by the relative costs of HFO, MDO and gas fuels, and the time spent in areas where sulphur emissions are severely limited. The International Maritime Organization (IMO) – supported by both shipowners and governments – has also targeted a 50% CO_2 emission reduction from 2008 to 2050 (DNV-GL, 2018). It is forecasted that a mixture of improved utilization and energy efficiencies, combined with a fuel decarbonization, including conversion from oil to gas and ammonia, electricity, and biofuel use, will enable this goal to be met (DNV-GL, 2019b).

Driven by the decarbonization push, the fuel mix will change dramatically. Unlike to road transport, the potential for elec-

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[3] Other emissions such as NOx, CO_2 or PM are not explicitly referred to here but need to be considered when, e.g. LNG is considered as alternative transport fuel.

tricity in the maritime sector is limited to short-sea and in-port operations. The fuel switch from being nearly entirely oil today to an even mix of natural gas (mostly LNG) and hydrogen in 2050, is based on increasing carbon prices, as well a host of successful, regionally imposed, decarbonization efforts.[4]

The adoption of LNG is currently underway with ships powered by LNG being built and operated in many countries around the world; the Norwegian passenger ship MV Glutra was the first LNG-fuelled ship, built in 2000. The Baltic and the North Sea countries have had to reduce emissions since 2005, which has resulted in them switching to LNG, with the port of Stockholm being the first LNG bunkering port and other European ports following, such as Rotterdam and Zeebrugge. LNG bunkering ports are now also in operation in the United States and the Asian ports in Singapore and Kochi; there are currently twenty one LNG ports operating worldwide with ten more confirmed to operate by 2020 (Anezerisi et al., 2020).

Ammonia is currently under investigation as an alternative, carbon free maritime fuel. MAN is developing ammonia engines and there is current forecast projecting a massive surge in its use up to 2050 (DNV-GL, 2019b). The ammonia is likely to be produced from a mixture of green sources and natural gas utilizing CCS, hence its relevance to the future use of natural gas in the transport sector.

3.1.4 Heating

Emissions of CO_2 from the building sector account for 10% of the global total emissions. This sector corresponds to a large share of the power and heat demand, increasing its total emissions up to 26% if the CO_2 produced in the power and heating sector is reallocated (IEA, 2018). Thus, severe changes in the building sector should be included as part of the portfolio of solutions to mitigate climate changes.

Energy efficiency improvements in old buildings and higher energy standards in new constructions are expected to be the pillars of the future building sector (Lund et al., 2014; Bribián et al., 2011). Emissions can be thus reduced by decreasing the energy demand. Therefore, passive strategies such good ventilation, maximization of heat gains, and optimal illuminance, will play a fundamental role minimizing the energy demand of future buildings (Baetens et al., 2010; Raman et al., 2014; Sadineni et al. 2011; Soares et al., 2013). In addition, active strategies such power generation from PV panels or hot water production from thermal solar energy may further reduce the demand.

Currently, natural gas is the primary source of energy in the building sector in Europe and the main producer of its CO_2 footprint. The substitution of natural gas by biofuels or biomass is the most direct approach to reduce the CO_2 emissions. This would permit preservation of the current infrastructure, and hence minimize the changes required in the sector. However, even if the demand from other sectors is not considered, biofuels and biomass might not supply all the energy demand from the building sector. Hydrogen could be an alternative clean fuel if produced from electrolysis of water or natural gas reforming with CCS (Ahmadi et al., 2013). Nevertheless, a hydrogen infrastructure and economy would be required. Thus, hydrogen can be considered as a possible long-term solution to decarbonize the building sector.

District heating is a technology widely spread in the Scandinavian countries, Germany, and other countries to provide hot water and heating. It is energy efficient as it is produced in specialized plants, primarily in CHP plants. District heating also has the advantage that waste can be used as fuel in some of the plants where the hot water and steam for heating are produced, which allows making use of waste that has to be burned anyway to avoid the generation of other gases with higher global warming potential. The deployment of this technology in other countries could lead to large reductions in the CO_2 emissions in the building sector, although the changes in infrastructure that would have to be carried out are a disadvantage (Lund et al., 2010).

Electrification is an alternative that does not require new infrastructure. Heat pumps can provide the heating and cooling demand in the building sector and are considered a solution to phase-out natural gas (Vanhoudt et al., 2014; Eyre and Baruah, 2015). The massive deployment of heat pumps would however require the decarbonization of the power sector in order to be

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[4] DNV-GL (2019b) provides more information concerning the Maritime segment's fuel mix and use.

Sector	Technology				
	Name	**Role of natural gas**	**Maturity**	**Deployment**	**Direct GHG emissions**
Power	Renewables	replace / coexist	high	medium	none
	Nuclear	coexist	high	decreasing	none
	Biomass	replace / coexist	high	low	neutral
	Natural gas + CCS	foster	medium	low	low
	BECCS	replace / coexist	low	none	negative
	Allam Cycle	foster	low	none	none
Transport	LNG	coexist	low	increasing	reduced
	Biofuels	coexist	high	medium	reduced
	Batteries	coexist	med	increasing	none
	Fuel Cells	coexist	low	none	reduced
Industry	CCS	foster	medium	low	low
	Biomass / Biofuels	replace	high	low	neutral
	Hydrogen	replace	low	none	none
	Electrification	replace	medium	low	none
Building	Biomass / Biofuels	replace	high	low	neutral
	Electrification	replace	high	low	none
	District Heating	replace	high	medium	none
	Hydrogen	replace	low	none	none

Table 2 : Technologies to reduce CO_2 emissions

effective mitigating climate change. Therefore, the expansion of heat pumps as heating and cooling technology for the building sector would require the increase of installed capacity and power generation from renewable energy sources and traditional thermal power plants with CCS in the power sector.

3.1.5 Summary of interplay between technologies in different sectors

Different technological solutions can be implemented to decarbonize different sectors. Efficiency improvement is a common approach to reduce the energy demand, although the ease and implementation varies among the sectors and it is almost case-dependent. Table 2 summarizes the considered technologies that can mitigate climate change in each sector, including the effect they may have on the use of natural gas in the future, their emissions and their level of development.

For **natural gas** in the building sector the rate of refurbishment and the accompanying decrease in demand for heating is crucial. In the long-term there may be strongly increasing rollout of renewable heat (this is mainly driven by cost differences in heating from natural gas and renewable energies). For low-temperature heat and process, steam energy efficiency improvements and substitution of natural gas with electricity and renewable fuels may lead to a decrease of natural gas demand in the industry sector. For high-temperature heat (>500°) and use as feedstock the reduction of natural gas is more restricted due to processes. Increasing use of wind and PV leads to decreasing spot prices for peak-load electricity. In order to cover residual load in the energy sector natural gas may be needed, however this depends on differences in marginal costs of co-generation and other technologies (the use of which relies on the difference of marginal costs of power generation from Gas-CHP and district heat/electricity provided on renewable basis; for moderate carbon pricing this implies more use of natural gas than for high carbon prices). The most positive outlook for natural gas use comes from the transport sector: there is a potential increase of compressed natural gas (CNG) demand in road traffic depending on cost differences to other liquid fuels and establishment of fueling station infrastructure. Liquefied natural gas (LNG) can be a future fuel for maritime transport. For both the energy and industrial sector, the application of CCUS remains an open issue just as well as improvements in energy efficiency.

For **methane-based renewable gases** (biogas, bio-methane, e-methane) the picture is different. In the building sector these gases are not relevant since other options are less costly. For high-temperature heat and as feedstock a gaseous demand remains in the industry sector. The price differences of methanol-based fuels are drivers for substitutes from natural gas to other gases. In the energy sector there is some room for gases to cover residual load and other flexibility options. These flexibility requirements are main drivers for gaseous energy carriers, but price differences among them remains a crucial element. The main potential for renewable gases in the transport sector comes from maritime transport given the development of required infrastructure (to transport gases).

None of the proposed technologies can uniquely decarbonize an entire sector. Therefore, an optimal combination of different solutions is fundamental to mitigate climate change. It is also worth noting the interdependencies existing among sectors and the need to account for them, as some decarbonization technologies in one sector may limit the implementation of others in another sector or, on the contrary, may boost it. Thus, a global perspective of the different scenarios and technologies is required for adequate decision-making.

Biomass or biofuels may be used in different sectors because of their flexibility and carbon neutrality. The extent of their deployment in the industry sector might affect the power and building sectors due to the limited production capacity and the finite resources available. In contrast, the deployment of CCS in many sectors would boost the installation of this technology due to its increased relevance and its fast development. Similar consequences would have the broad utilization of hydrogen, as it would enhance the creation and growth of a hydrogen network and economy. The power sector is arguably the most dependent sector owing to the possible use of electricity and hydrogen-based technologies in the industry, transport and building sectors. Therefore, the decarbonization of the power sector is essential in the transition towards a sustainable society.

3.2 Hydrogen

Norway is endowed with abundant fossil fuels and renewable energy resources (mainly hydro, wind and thermal) and thus the introduction of hydrogen in the Norwegian energy system should be a major driver for export and internal use purposes. Despite Norway being the world's 3rd largest natural gas exporter, it is lacking a natural gas distribution grid. While hydrogen is already used in the Norwegian industry (e.g., steel, refining, ammonia used in fertilizers, methanol, etc.), by producing the fuel from natural gas and renewable electricity, it can play an important role in the Norwegian energy landscape. Electrolytic hydrogen can be an energy storage medium in combination with hydro, wind and thermal energy thus an option that should be under consideration to exploit excess (e.g. overnight) electricity generation in Norway. Moreover, as the Norwegian electricity price is competitive in Europe, this in turn should make hydrogen price competitive too. To add to this, electrolysers are now becoming competitive with SMR (steam methane reforming) technologies. According to NEL, the Norwegian world largest electrolyser manufacturer listed on the Oslo Stock Exchange, the cost of electrolysers is becoming fully competitive with fossil fuel alternatives (on a CapEx basis) representing a quarter of the total cost. However, three quarter of the cost for renewable hydrogen is directly linked to the price of electricity. In Norway, electricity prices are now at a level that makes renewable hydrogen fully competitive with fossil fuel solutions. The production and availability of cost-effective hydrogen could help the deployment and commercialisation of fuel cell passenger vehicles, fuel cell heavy duty vehicles and fuel cell ships in the maritime transport as well as the complete adoption of hydrogen in the Norwegian industry for power generation and heating.

3.2.1 Hydrogen production

There are many methods of producing hydrogen, although the most conventional ways are by *natural gas/biogas reforming and by water electrolysis*.

Natural gas/biogas reforming – Almost 96% of the total hydrogen production globally is based on fossil fuels. Worldwide 68 % of hydrogen is produced by steam reforming of natural gas with an efficiency range of 65–75%. Natural gas (mainly methane) steam reforming is a mature technology with large-scale industrial plants in operation and a commercial efficiency ranging from 70 to 85% (even higher if steam is available from other sources). Main technologies for hydrogen production in Norway include catalytic steam reforming (800–1,000°C) and partial oxidation (600–900°C) of hydrocarbons (e.g. natural gas) or renewable fuels (e.g. bioethanol); coal or biomass gasification. Coal gasification is a less used and less efficient (50–70%) process. All processes based on fossil fuels are to be associated with a *CO_2 capture and storage (CCS)* technology to produce carbon-free hydrogen and reduce CO_2 emissions.

Renewable hydrogen through electrolysis – Electrochemical water splitting i.e., water electrolysis at ca. 50–80°C and thermo-chemical water splitting at ca. 900°C are used to produce hydrogen. The overall energy efficiency of commercial systems for electrolytic hydrogen production ranges from 62% to 82%, equivalent to 47–77 kWhe/kg (high-temperature or high-pressure operational conditions can reduce the electrolysis energy use). Commercial electrolysers can meet hydrogen production demand from 1 to 1,000 Nm^3/h (from next year, electrolyser manufacturers will be rolling out 2-6 MW electrolysers delivering 10,000 – 30,000 Nm^3/h and trialing 20 MW electrolysers which could produce 8-10 tons of hydrogen per day – 1 kg H_2 = 11.126 Nm^3 H_2). Renewable energy can be used in relation to hydrogen in several ways, but there are four main chains of use: (i) convert surplus electricity into hydrogen (energy carrier) and convert it back into electricity when and where required. This entails hydrogen as storage for renewable electricity, (ii) mix electrolytic hydrogen with natural gas or convert it to methane, as this allows for the hydrogen to be stored in the existing gas grid (not possible in Norway), (iii) convert surplus electricity to hydrogen which can be feedstock for industry processes, and (iv) using surplus electricity for hydrogen production and using the hydrogen as a clean fuel for the transport sector. Most of these chains are of interest to the Norwegian hydrogen economy.

3.2.2 Hydrogen value chain: Storage, transportation and distribution

Hydrogen storage – Hydrogen can be stored as a compressed gas (up to 700 bar), as a liquid at cryogenic temperature (–253 °C), as well as trapped in solid materials such as metal hydrides. Hydrogen storage by compression and liquefaction are mature technologies but are energy-intensive processes, while solid storage is not yet a commercial option. Current R&D focuses on liquid organic hydrogen carriers (LOHCs) as an alternative hydrogen storage technology. Compressed hydrogen can be transported by tube trailers and pipelines, while liquid hydrogen is transported by tankers.

Hydrogen transportation & distribution – Gaseous hydrogen is usually transported by either tube trailers or pipelines while liquid hydrogen is moved by road tankers. For short distances and small amounts, delivery of gaseous hydrogen by tube trailers is usually the option of choice. For medium amounts and long distances liquid tankers are likely preferred, while large amounts over long distances are usually moved by pipelines, if available (d'Amore-Domenech et al., 2021).

- **Tankers** for large quantities and distances have typically a capacity of 400 to 4,000 kg of liquid hydrogen. If hydrogen becomes a widely used fuel for transport, tankers could likely be used for hydrogen refueling stations (RES) though liquid supply would be significantly costly to end-users.
- **Tube trailers** typically contain 300 kg of gas, stored at a pressure of up to 200 bar. They are used for small deliveries to end-users who usually are close to the hydrogen production plant in order to reduce the high cost of carrying small amounts of product.
- **Pipelines** for hydrogen transportation are typically 30 cm in diameter and operate at a pressure of 10-20 bar. They are based on steel pipes, but there is potential for cost reduction and better performance using fibre-reinforced polymer pipes. Pipeline supply can be effective for delivering hydrogen to a large number of high capacity users. However, the energy required for compressing and pumping hydrogen is large. It is also possible to mix up to 20% hydrogen in natural gas pipelines (by volume; equivalent to 6% by energy content), without important supply and end use modifications (Dentons, 2019). For Norway´s case, a semi-centralized hydrogen production with a new and more efficient transport solution should be implemented. Although, centralized against onsite hydrogen production depends upon power availability/pricing in the specific market and distribution cost/distance. Currently hydrogen transport container can move up to 1,500 kg of hydrogen in each run, making it very efficient – enough to fuel 75 buses in one load in a distance no longer than 2.5-hour travel time each way for optimal distribution cost in turn fully supporting a renewable hydrogen solution that is competing with diesel. Moreover, Norway needs between 50 and 100 RES in 2025 to reach the zero emissions goals of the national transport plan 2018–2029.

3.2.3 Cost

Costs and storage issues have hindered the use of hydrogen as a fuel. At the present time, the hydrogen retail price in Norway is ca. 90 NOK/kg. Hydrogen production costs depend on the process, feedstock and production capacity. In general, production from fossil fuels offers competitive prices and large-scale potential but cannot be considered a viable option for large scale production in the absence of effective CCS. In contrast, electrolysis is costly, but involves no or negligible emissions (apart from those from electricity generation) and produces high-purity hydrogen (99.999%). For hydrogen storage, compression energy amounts to 10-15% of the hydrogen energy content (up to 30% for very high pressure) with an electricity consumption of 3–5 NOK/kg. For the equipment, a 300-bar compressor with a capacity of 20 Nm^3/h would cost typically between 0.5-1 mNOK, yielding a hydrogen cost of 6.5–13 NOK/kg. In this case, electricity cost and capital costs make up a total compression cost of ca. 9-17.5 NOK/kg while liquefaction absorbs between 30%-40% of the energy content. Transportation costs range from 3-15 NOK/kg for liquid tankers, 1.5-3 NOK/kg for pipeline and 5-6 NOK/kg for tube trailers (100 km). Renewable hydrogen at the pump could reach 50 NOK/kg equaling diesel price of ~10 NOK/litre excl. VAT. In Norway, when comparing small- and large-scale hydrogen production systems the lowest feasible hydrogen costs could be in the range of 0.4 NOK/kWh to 1.2 NOK/kWh. The development of electricity prices is vital for the price development of hydrogen. Due to higher quantities of surplus electricity generated from renewable generation electricity, the wholesale market prices could decrease from 0.40 NOK/kWh to 0.15 NOK/kWh.

There are several technological options available for decarbonization of industry, heat and transport including CCS and hydrogen. In the power sector we will need CCS to continue to use natural gas as a flexibility tool, as well as baseload electricity generation. In the industry sector hydrogen can substitute natural gas in many applications and hence cut emissions significantly. Natural gas can also play a significant role in the transport sector, as LNG, CNG or converted to hydrogen by use CCS and used in fuel cells. The heating sector can also be decarbonized through electrification or use of hydrogen distributed through the current gas network. Electrification may be based on Natural Gas power with CCS. Cost efficient and flexible solutions to decarbonize these sectors will require successful deployment of CCS and hydrogen technologies.

> Trust is an important issue to address with respect to implementing new natural gas technologies such as CCS and hydrogen.

Photo: shutterstock.com

4 CONSUMER BEHAVIOUR

The question in which way consumer decisions affect the use of natural gas in the energy system, has many facets that need to be analysed. The following sections will therefore briefly present some of the key findings from social sciences that can be of importance for successfully transitioning the energy system towards carbon neutrality and have active consumers in central positions. This complex topic will be addressed in four steps, first asking, what consumer decisions in relation to natural gas are actually about, before diving deeper into questions of public acceptance of natural gas, infrastructure projects, CCS technology, and trust and safety issues connected to using natural gas in the household sphere. Following, the drivers of the use of natural gas by consumers will be discussed in relation to investment decisions (such as natural gas heating or warm water boilers, natural gas driven cars) and use in everyday life (e.g., warm water use). The section will end with some conclusions on the consumers position in the energy system based on findings presented.

4.1 What are consumers concerned with in relation to natural gas?

Before diving more deeply into an analysis of natural gas related consumer behaviour, it is important to highlight, that consumers do not make decisions about natural gas use per se. Instead they use services that natural gas can provide in competition with other energy carriers. Consumers aim to satisfy needs such as warmth in the home, warm water, warm food, or mobility by using an energy carrier such as natural gas, but usually do not have a relation to the energy carrier itself. The energy carrier consumers chose is determined by a large set of variables, including regulations (such as phasing out of oil stoves), availability of technological alternatives, ease of access to and relative costs of the energy carrier (e.g., availability of a gas infrastructure, prices and price stability of different energy carriers), social and cultural influences (e.g., prevailing heating systems in a region), and perceived characteristics of the technology (e.g., perceived ease of use, safety issues, health effects, etc.) (Mahapatra and Gustavsson, 2008; Sopha et al., 2010). Often, the majority of consumers is reluctant to explore new technologies and technological change is prevented by a preference for the status quo (Rogers, 2003; Sopha et al., 2010), which also applies to substitution of energy carriers.

4.2 Acceptance of natural gas as a resource

So, what are important factors to analyse when consumers relate to natural gas? On the one hand, people's relation (and use) of natural gas will be affected by the way they perceive it and its image in society. Furthermore, consumers might be affected directly or indirectly by gas production and distribution infrastructure (e.g., gas production plants, refineries, pipelines, etc.). If natural gas is supposed to play a role in the future energy system, CCS technology will need to play an important role, which raises the question of the publics relation to CCS. Finally, questions of trust in producers and the safety of the gas system itself cannot be ignored.

The public image of natural gas

Natural gas is a resource that has been exploited for decades and has recently experienced a change in the public image based on two international trends: On the one hand, being a fossil fuel, use of natural gas has received criticism as a contributor to global climate change. One of the few studies analysing the image of different energy carriers found that in Canada natural gas performed considerably better than oil and coal with respect to being perceived as green (about 18% of the respondents referred to natural gas as green energy as compared to 1-2% for oil and coal), but compared to wind or solar power where about 95% perceived the energy as green, natural gas performed clearly worse in the public image (Rowlands et al., 2002).

On the other hand, new and potentially more invasive production technologies such as shale gas production through fracking have raised new opposition. Theodori (2012) studies the public image of the gas industry in two counties in Texas and finds that shale gas production had a more negative image when it was more matured and more visible in a county. Boudet et al. (2014) find that fracking has a more negative image, the more people are informed about it, the more egalitarian worldviews a person holds, and the more they expect environmental impacts. Also, Davis and Fisk (2014) find strong relations between environmental and political orientations (favouring the Democrats) and opposition to fracking technology. Such findings highlight, that a person's relation to natural gas production and use is part of their worldview and connected to overarching values and beliefs, especially in polarized societies like the US.

Resistance to infrastructure projects

A related topic is to explore drivers of resistance to natural gas related infrastructure projects. Opposition to shale gas is as indicated above strongly linked to political orientations, worldviews, and perception of environmental issues connected to the issue (Boudet et al., 2014; Davis and Fisk, 2014). However, also geographic distance (the closer the more critical) and personal benefit (people working in the industry or owning mineral rights are less critical) have also been shown to impact the degree of opposition (Theodori, 2012). Studies of open resistance to fracking projects indicate that the local historical context might play a role if and how opposition manifests in open resistance. Vesalon and Crețan (2015) find for example in a study on resistance against fracking in Romania, that the extreme post-communist focus on privatisation contributed to fostering counter-movements against neoliberalization of natural resources. Also Riffo (2017) links the resistance against fracking in Argentina to more general movements about democratization of the energy sector.

In addition, resistance to other infrastructure projects like pipelines for natural gas has been studied, and a similar mix of factors were identified. Park et al. (2017) finds seven types of drivers of natural gas pipelines: (1) anticipated disturbances during the construction process, (2) anticipated economic loss (e.g., reduced property value), (3) location-based concerns (affecting local emotional issues), (4) poor planning and design (violating rights, affecting ecosystems), (5) sociopolitical issues (e.g., differences between political levels), (6) feasibility concerns, and (7) safety concerns. Even though the categorization of drivers of resistance in this study is not very clear, it shows that a mixture of local motivations (loosing value of your property, being disturbed in the construction stage, having to face safety issues) and more general societal issues (environmental concerns, political context) determine if open conflict arises.

Citizen acceptance of natural gas with CCS

Public perception of CCS technology is a current topic in social science. In a review of 42 published studies, L'Orange Seigo et al. (2014) report that in most studies, people report rather neutral levels of acceptance, which is not surprising for a new technology, hardly known to the public. People balance obviously the need to CO_2 reduction with CCS being a technology fixing the outcome of using fossil fuel, not the use of fossil fuel. Key factors for acceptance are perceived risks, costs, and benefits of the technology, and people see both sides. Previous experience with the gas industry or other large industry projects seems to affect acceptance of CCS (and this can go both ways, depending on the experience). Most reviewed studies show that providing information about CCS did not change people's acceptance, whereas trust in the actors behind CCS is a decisive factor: Here private industry actors suffer from considerably lower trust levels than researchers, NGOs, or governmental actors. Fairness considerations regarding procedures for decision making and distribution of benefits and costs have been shown to increase acceptance in the few studies that L'Orange Seigo et al. (2014) found on this topic. They conclude that risks, benefits, and trust in the actors' ability to operate and control the technology are decisive for acceptance, and that the social context of the project site is important for blooming of resistance or support.

Trust and safety issues

The previous sections have already highlighted, that trust is an important issue with respect to implementing natural gas technology and continued use of natural gas as an energy carrier. If this is pursued as a commercial endeavor, people affected by infrastructure need to be able to trust the companies' motivations and their ability to operate the infrastructure safely. Furthermore, they also need to trust the fairness of the processes implemented in planning and operation, as well as see a benefit strong enough for them to justify the intrusion of their area (L'Orange Seigo et al., 2014). However, there are also safety concerns connected to the use of natural gas itself (as a highly flameable gas with high energy density). Sopha et al. (2017), for example, identified safety considerations as an important component for the diffusion of natural gas conversion kits for cars in Indonesia.

4.3 Investment decisions in households involving natural gas

Whereas the previous section mainly focused on acceptance-related issues, it remains unclear how people make decisions about implementing natural gas-based technologies such as heaters, warm water boilers, or cars.

Natural gas-based heating and warm water

The main investment decisions involving natural gas technology in private households are gas heaters (either as central heating or as mobile devices), gas-driven warm water boilers, and to a lesser degree cooking and baking devices. Other appliances like gas-powered fridges are niche products for special applications. A number of studies have analysed decisions for heating systems (Mahapatra and Gustavsson, 2008; Sopha and Klöckner, 2011; Sopha et al., 2013). They identify some psychological drivers of changing heating systems: First, people do not change their heating system without there being a necessity. Often a new heating system is installed when the old breaks down, and then there is the need for quick decisions. This puts the salesperson in an important gate-keeper position. The default in such a situation is to stay with the system one has been using before unless there is a sufficient degree of dissatisfaction with it. Then, different strategies can be applied: (1) Engaging in a process of evaluating different alternatives along a list of criteria such as costs, maintenance costs and effort, safety, compatibility with the existing infrastructure, degree of uncertainty about future development of technologies or costs, health and well-being impacts, comfort, etc. (2) Observing what other people do, thus probing the social context for information about "normal" or "recommendable" heating systems. Under the "social influence" condition, the market share a technology has and the narratives around the technology are of high importance. High market share and success stories increase the probability for adoption of the technology, if people follow this decisional path. When the deliberate decision-making path is chosen, the different attributes of the technology alternatives are evaluated against each other weighted by their importance and the overall most beneficial technology is chosen (which does not necessarily mean the most economically beneficial alternative).

Natural gas-based mobility

Natural gas can also play a role as fuel for private transportation, although the market share is not particularly high. The purchase of a natural gas vehicle (NGV) or a kit for converting a standard gasoline engine to an NG-powered engine has been studied in the Indonesian context by Sopha et al. (2017). Many of the processes outlined in the previous section are also relevant here, especially access to refueling infrastructure, safety perceptions, compatibility with existing infrastructure and use patterns, costs, uncertainty about cost developments or convenience. Different scenarios for policies packages improving the market share of NGVs were tested in the study by utilizing agent-based simulation models. The authors find that a combination of tax increases on gasoline combined with increased perceived safety of NGVs and a time-limited subsidy schedule for NGVs or conversion kits was able to increase the predicted market share above the target of 12% NGVs in the Indonesian fleet and keep it there. In a study on acceptance of NGVs and converter kits in Malaysia (Teoh and Khoo, 2019) find that the price, perceived risk of engine damage, vehicle performance, perceived safety and payback period all were significant predictors of the decision to adopt this technology.

4.4 Everyday use of natural gas as an energy carrier

As the final aspect of this consumer behaviour-related section, the question of how natural gas is used (and saved) in everyday life will be addressed in more detail. As any energy carrier, energy efficiency and energy saving apply also to natural gas. Literally thousands of studies have been conducted on drivers of energy saving in private households. In a comprehensive review Frederiks et al. (2015) identify a long list of demographic, psychological and situational predictors that have been shown to impact energy-related household behaviours and thus consequently also energy use (including gas). On the demographic side, is has been shown that age, gender, education, employment status, socio-economic status, characteristics of the dwelling, and geographical location impact energy use. On the psychological side, knowledge and awareness about energy issues, values, beliefs and attitudes, motives, goals and intentions, personal norms, perceived responsibility, personality, social influence, and group membership have been linked to energy behaviour. On the contextual and structural side, laws, regulations, policies, availability of technology, pricing, design of infrastructure, media, neighbourhood aspects (community spirit, cohesion), cultures, and traditions have been identified. In this complex system decisions how to use energy manifest.

4.5 Some conclusions from the consumer perspective

People clearly see natural gas as a fossil fuel with the according negative impacts on climate change, but also with a clearly better profile than coal or oil. People's relation to natural gas is to a large extend a question of worldviews and beliefs, strongly linked also to political preferences. When gas production or infrastructure comes into the picture, public resistance may occur, especially when people feel that the decision procedures are unfair and they do not benefit from the infrastructure. It thus makes sense to seek collaboration with local populations around planned infrastructure projects to identify potentials for win-win situations and build trust. With respect to people's change towards natural gas-powered appliances and vehicles, a number of factors have shown to be important including compatibility of the new technology with existing technology and behaviour patterns, a beneficial cost structure and little uncertainty about future payoff rates, comfort and health aspects, safety issues, and social influence. If environmental concerns are relevant for people they usually work against natural gas, rather than for it.

5 SCENARIOS OF FUTURE NATURAL GAS DEMAND AND SUPPLY IN AN INTEGRATED ASSESSMENT MODEL (IAM)

In this chapter we explore the long-term, potential future of natural gas at global scales using the Global Change Assessment Model (GCAM). We consider a series of scenarios to explore alternative policy backgrounds as well as alternative technology developments. All scenarios are based on the Shared Socioeconomic Pathways (SSP) "Middle of the Road" scenario that was developed to provide researchers with a well-established point of reference. The Middle of the Road scenario, as its name implies, utilizes current best guess values for all key drivers—population, economic development, technology, and current environmental policies. The policy backgrounds are a **Reference** and **Paris Policies**.

In the **Reference Scenario** we assume that current policies continue indefinitely into the future. These include modest climate policies, but do not facilitate the goals of the Paris Agreement of 2015. In the **Paris Policies** scenario, we assume that in the year 2030 nations will have achieved their Nationally Determined Contributions **(NDCs)** and thereafter increase their ambition to a level that would limit average earth surface temperature change to two degrees or less with at least a 50-percent likelihood.

The future of natural gas depends on **technological developments** as well as socio-economic and policy developments. We will explore two technologies, CO_2 capture and storage **(CCS)** and an advanced fuel cell that can be used in mobile applications **(FCEV)**. Other technology developments were highlighted in the previous section. We chose CCS and FCEV because they illustrate two potential developments that could directly affect gas markets. CCS only affects gas markets in the Paris Policy scenario. In the Reference scenario it has no effect as its deployment adds both cost and risk with no increase (and in most cases a decrease) in output. But, in the context of climate policy, it puts a cap on the cost of fossil fuels that are used in facilities capable of capturing and storing CO_2. The IPCC fifth assessment report (IPCC, 2014) finds that CCS plays a critical role in enabling pathways consistent with Paris goals. When CCS was unavailable, only pathways that included large-scale global afforestation could reach the Paris target. It also has the potential to enable continued use of natural gas, both in large point-source applications such as power plants but also as a means of delivering cost-effective hydrogen derived from it.

Since the combustion byproduct of hydrogen is water, hydrogen is a potentially important technology in a climate-constrained world. The FCEV scenario is therefore an interesting technology scenario because it begins to explore a pathway for large-scale utilization of hydrogen (H_2) that extends beyond its direct use as a combustion technology. Table 3 outlines the four scenarios we explore in this chapter.

	No CCS	CCS	CCS+FCEV
Reference	1		
Paris Policies	2	3	4

Table 3: Policy and technology scenarios

5.1 GCAM 32 Geopolitical and energy market regional disaggregation

The GCAM model is global in scope and contains regional disaggregation of the energy and economy sectors at a 32 geopolitical region scale as shown in Figure 4. GCAM captures interactions between European markets and other international markets including interactions between and among all energy markets. Europe is disaggregated into 5 sub-regions: EU-12, EU-15, EFTA, Eastern Europe, and Other Europe.

5.2 The Reference Scenario (Scenario 1)

Scenario 1 is the Reference scenario. It is the starting point against which we compare both our policy and technology sensitivities. It is driven by population and economic growth assumptions. These assumptions are external to GCAM. They are taken from the SSP "Middle of the Road" scenario and are thus comparable to a wide range of other open literature scenarios. Assumptions for population and GDP are shown in Fig-

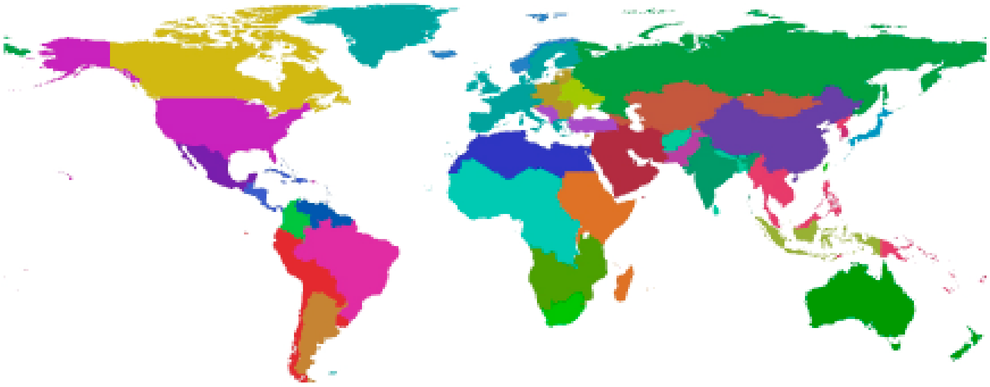
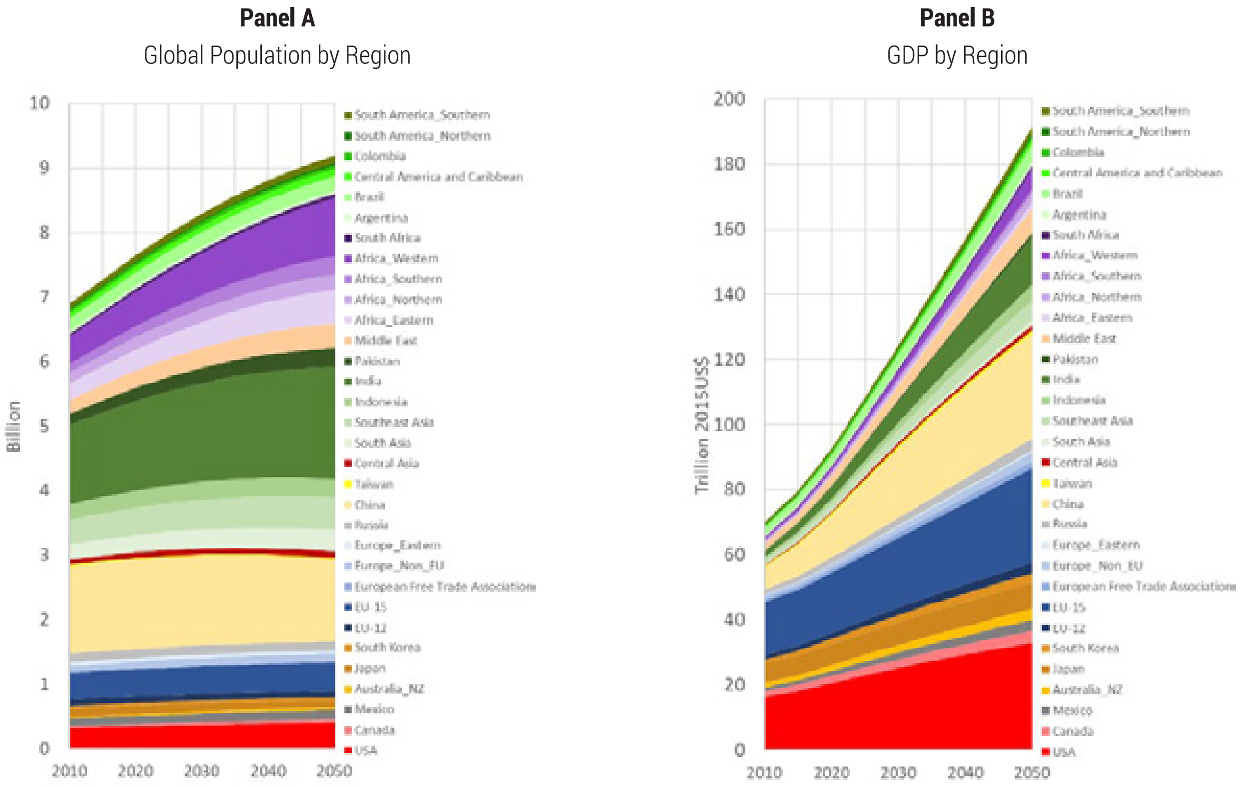


Figure 4: The 32 Geopolitical Regions of GCAM

EU-12
EU-15
European Free Trade Association
Europe_Non_EU
Europe_Eastern
Colombia
Canada
South Korea
Taiwan
Brazil
Central Asia
Japan
USA
Australia_NZ
China
Argentina
Russia
Mexico
South America_Northern
Indonesia
Africa_Northern
South Africa
South America_Southern
Central America and Caribbean
India
Middle East
Africa_Western
Southeast Asia
Africa_Southern
Africa_Eastern
South Asia
Pakistan

ure 5 showing all 32 geopolitical-energy market regions. These are grouped and color coded to make regional trends more obvious. Brighter green regions at the top of each figure are the seven Latin America and Caribbean regions. Regions in the purple shades are the five African regions. Sand color denotes the Middle East region. The darker green regions are located in South and East Asia. China is colored light gold. European regions are colored in the blue range. The Western Pacific OECD regions are colored in the amber tones. And North American regions are in the red shades. Panels A and B show that the current differentials between population size and income are anticipated to remain in place. Developing economies have the highest rates of population growth and higher rates of economic growth, but do not catch up to the current developed economies in terms of per capita income by 2050. Global population and the scale of the global economy both are expected to grow throughout the period to 2050 driving demands for energy services.

While continued improvements in energy efficiency reduce the rate of growth of energy, the energy system continues to grow, as shown in Figure 6, which shows global energy use in primary energy equivalent (Panel A) and final energy consumption (Panel B). Several important trends continue in the Reference scenario: Fossil fuels not only continue to provide the primary source of energy, but production and use continues to grow, though at a slower rate than GDP. This is even though renew-



Panel A

Global Population by Region

Panel B

GDP by Region

Figure 5: Population and GDP assumptions

able energy forms grow substantially in percentage terms. The growing global economy and population drive increasing demands for final energy. Fossil fuel demands grow throughout the period to 2050. Electricity demand also grows taking an increasing share of the final energy market.

Demands for energy drive growth in demands for natural gas (Figure 6 Panel C), and elicits a growing supply (Figure 6, Panel D). The reference world also produces almost 50 billion tons of CO_2 per year in 2050. Extending the scenario to 2100 produces an increase in average Earth temperature relative to pre-industrial of roughly 3.5 degrees (assuming a climate sensitivity of three-degrees). This is substantially higher than the maximum two-degrees change in Earth surface temperature goal articulated in the Paris Agreement.

5.3 Paris Policies (Scenario 2)

Our Paris Policies scenario begins with the Reference scenario. In order to limit climate change to two degrees in 2100 we assume that in the period to 2030 nations successfully implement their NDCs. NDCs are a heterogeneous set of near-term goals established by nations as national contributions to reaching Paris goals. We assume that each region implements its NDC independently of other regions.[5] If implemented successfully, current NDCs roughly stabilize greenhouse gas emissions. Stabilization of climate change requires that CO_2 emissions decline to zero.

Therefore, subsequent to 2030 we assume that the world moves to both comprehensive coverage of emissions and a common carbon price. While it is hard to argue that this is a likely scenario, all transition pathways that lead to climate sta-

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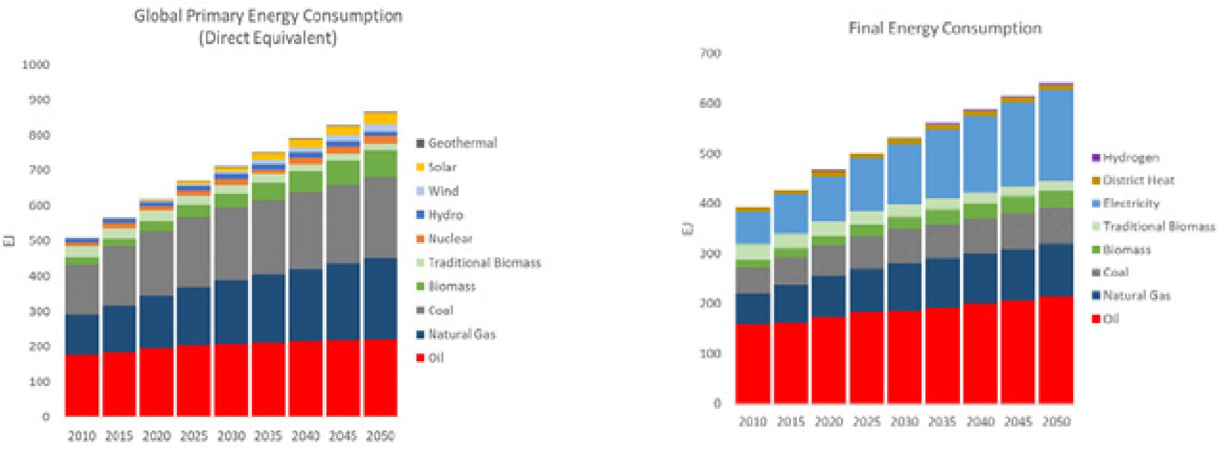
[5] In principle Article 6 of the Paris Agreement would allow countries to implement their NDCs cooperatively, but the heterogeneity in coverage and character of national goals coupled with the fact that rules for implementing Article 6 have not been established, at least as of November 2019, lead us to assume independent implementation of NDCs.

Panel A

Global primary energy consumption

Panel B

Final energy consumption (All Scenarios)



Panel C

Natural Gas Consumption (Reference Scenario 1)

Panel D

Natural Gas Production (Reference Scenario 1)

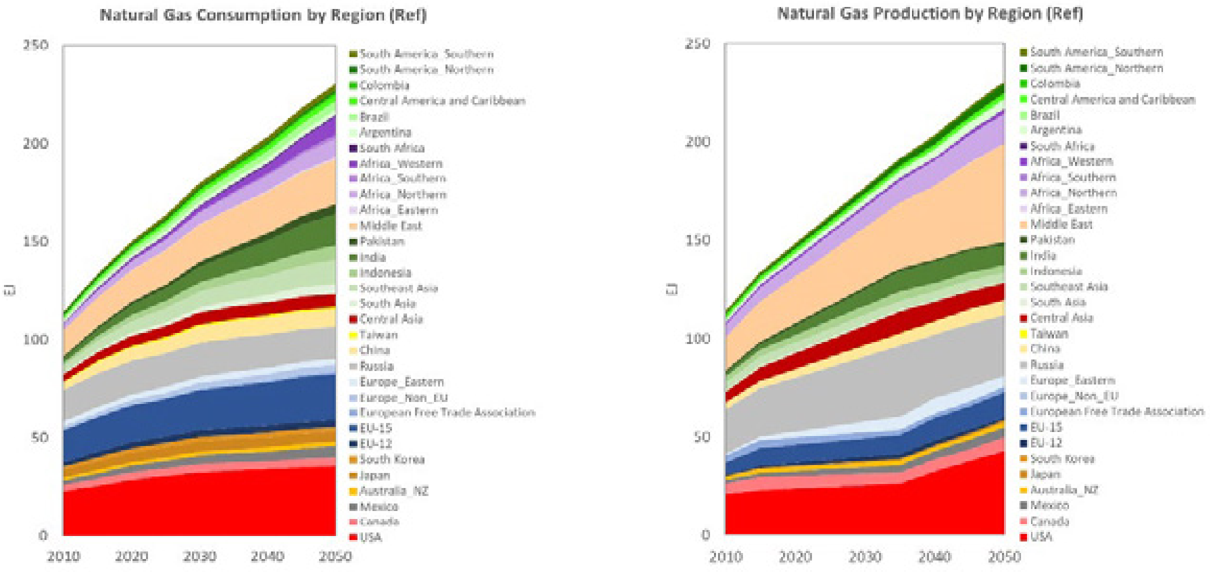


Figure 6: Reference scenario energy

bilization at two degrees require that all countries' emissions are approaching zero or going net negative in the 2065 to 2075 timeframe. This in turn implies that global energy and technology regimes have transitioned to non-emitting or negative-emission technologies in that time frame. By 2050 then global carbon emissions must be substantially lower than in 2020.

First we investigate a situation where CCS is not available. Not everyone supports the development and deployment of CCS. There are varying reason ranging from concerns about ancillary costs associated with, for example induced seismicity.

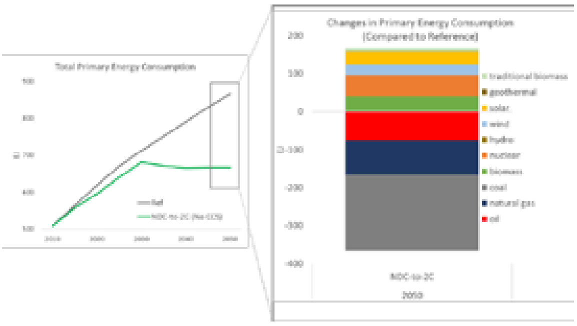
Others are concerned about permanence of storage reservoirs. And still others do not want it because it enables fossil fuels to continue to be used in a deeply decarbonizing world.

Changes to the global energy system for fuels and power driven by the NDCs are shown in Figure 7. While implementing NDCs reduces the rate of growth of global primary energy, growth remains positive. Figure 7 shows both the change in total energy consumption for primary equivalent energy (Panel A) and final energy (Panel B). Changes relative to the Reference scenario are shown to the right and absolute energy consumption are shown on the left side of each panel. The largest changes are reductions in energy for all fossil fuels. Coal use declines most. Oil and natural gas consumption also decline. Partially offsetting reductions in fossil fuel use, are increases in the use of bioenergy, nuclear and renewable energy forms.

The impact on natural gas markets is shown in Figure 7 Panel C. Overall natural gas demand grows relative to 2010. Only the rate of growth is smaller. Natural gas consumption in the NDC 2-degree scenario is substantially smaller than in the reference scenario. Slower growth is distributed roughly evenly across all end use sectors. The continued growth in natural gas use is in part a reflection of the fact that in the near-term natural gas has a lower carbon to energy ratio than coal or oil. (This is partially offset by the fact that natural gas losses in production, transport and distribution are in the form of methane, which has a higher global warming potential than CO_2.)

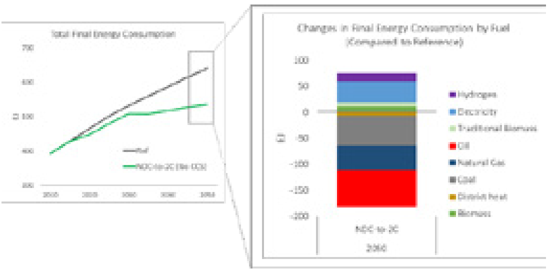
Panel A

Primary Energy Scenario 2



Panel B

Final Energy Scenario 2



Panel C

Natural Gas Consumption Comparing Scenarios 1 and 2, 2050

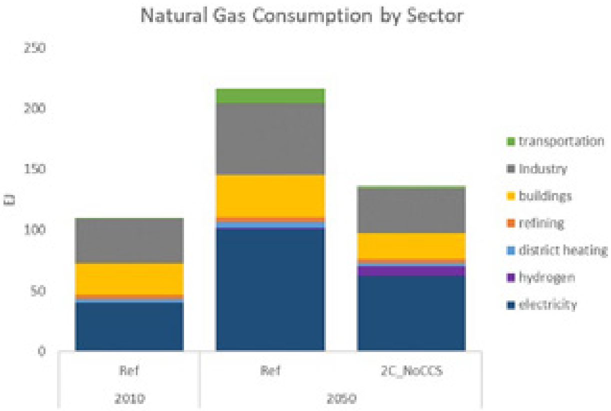


Figure 7: Changes in global energy from limiting climate change to 2 degrees, Compared to Reference, 2050 (Scenario 2)

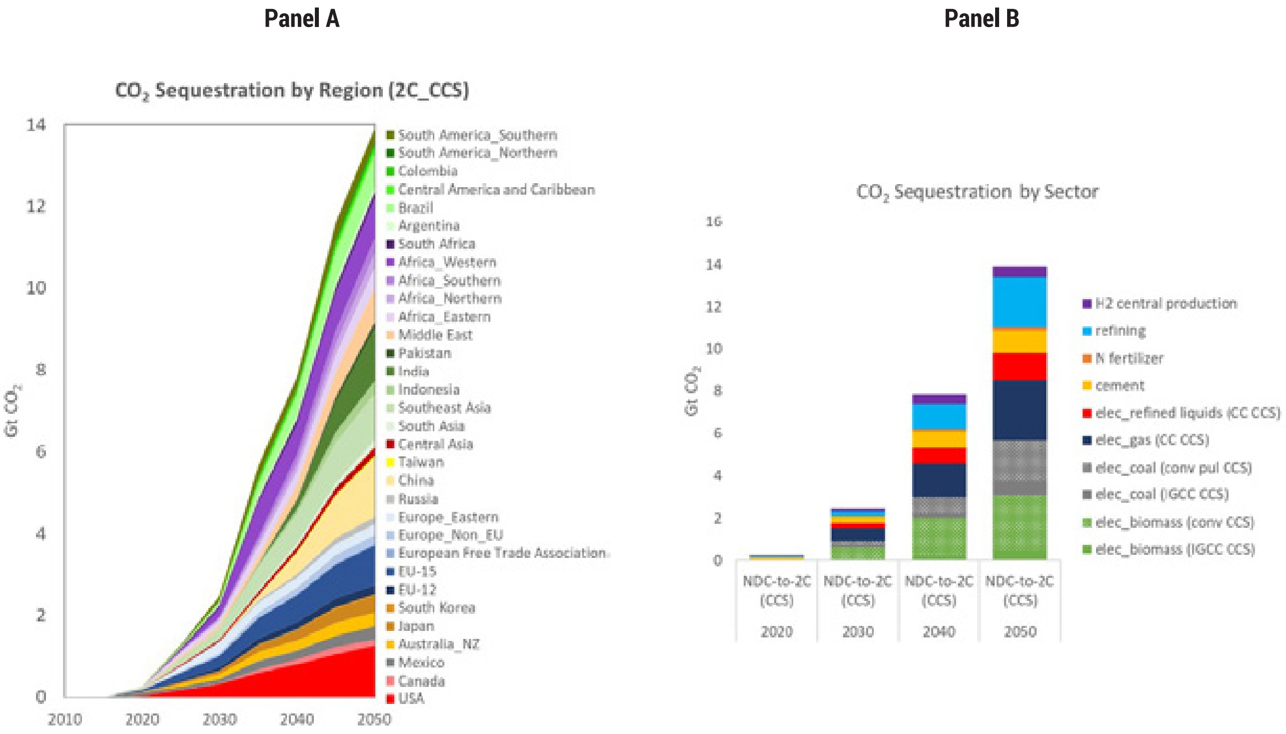


Figure 8: CCS in the Paris Policy Scenario by region and sector to 2050, Scenario 3

5.4 CCS in the Paris Policy Scenario (Scenario 3)

This extension to the Paris Policy scenario assumes that CCS is available worldwide. CCS can be used to decarbonize some sectors and also to enable negative emissions when deployed in combination with bioenergy — either for power production or in fuel production.

When CCS is available its use expands with the scale of the carbon price. Figure 8 Panel A shows that when driven by a rapidly rising common carbon price that the technology deploys rapidly throughout the world. Figure 8 Panel B shows the sectors using the technology. Power generation accounts for more than half. Note that the use of CCS with natural gas power production is the largest application of CCS among sectors. Over time use of CCS with natural gas has a comparative advantage over use with other fossil fuels because where capture is incomplete and carbon prices are high, the uncaptured portion of the emissions stream becomes an increasing burden on the system. CCS in combination with bioenergy power production is a major use of CCS technology as it produces power with negative emissions. Note also the growing use of CCS in hydrogen (H_2) production using natural gas feedstocks and the use of CCS in refining, including bioenergy refining. Finally, CCS use in conjunction with cement manufacture grows steadily.

The effects of CCS availability on energy markets are shown in Figure 9. Compared to a Paris Policy scenario without CCS (Scenario 2), the availability of CCS expands the use of all fossil fuels and decreases the use of biofuels and renewable energy. This in turn means reduced stranding of assets. Natural gas demand is particularly benefitted.

5.5 Advanced fuel cells and Paris Policies (Scenario 4)

To explore the implications of an advanced fuel cell (FCEV), we construct a scenario with CCS and FCEV. The advanced fuel cell sensitivity hypothesizes the development of a hydrogen fuel cell that is more efficient. That efficiency leads to both increased penetration in the transport market, displacing other mobility energy carriers, and reduced need for energy in aggregate as compared with our reference technology suite in the Paris Policy scenario. These effects are shown in Figure 10. In Panel A both the displacement and efficiency effects are evident. Total energy demand is reduced. Natural gas and coal demands are increased, while oil and bioenergy use decline.

In Panel B, use of hydrogen as a final energy carrier increases while oil use declines. Higher efficiency in fuel cells leads to less energy use in transport, and through lower overall energy prices, a slight increase in energy use in buildings and industry (not shown).

5.6 Natural gas markets across the scenarios

Production and consumption of natural gas continues to expand in all scenarios we examined except one – the Paris Policy Scenario without CCS (Scenario 2). If CCS is available, then natural gas markets continue to expand throughout the period of analysis. However, when CCS is unavailable and the world is on a trajectory leading through NDCs to 2 degrees, the natural gas market peaks and declines as soon as the world increases ambition towards the Paris goals (Figure 11).

While the four scenarios we have explored here describe a set of possible futures, they are far from comprehensive either in exploring the range of potential socioeconomic backgrounds that might evolve, or the range of technologies that might evolve, or in the range of policies that might be employed to achieve Paris goals. These scenarios show a robust future for natural gas even if Paris goals are pursued as long as CCS technology can be deployed at scale.

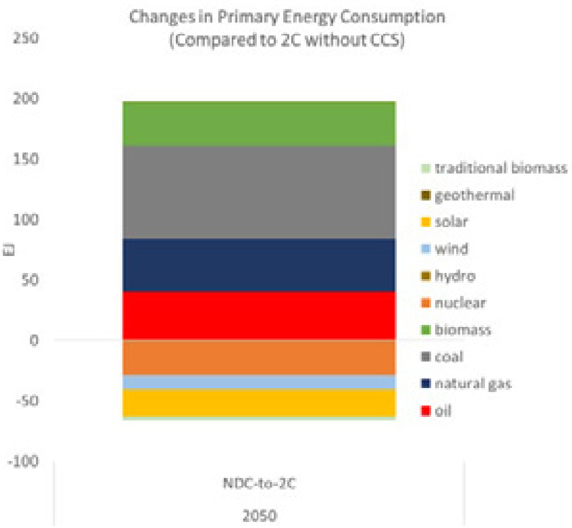
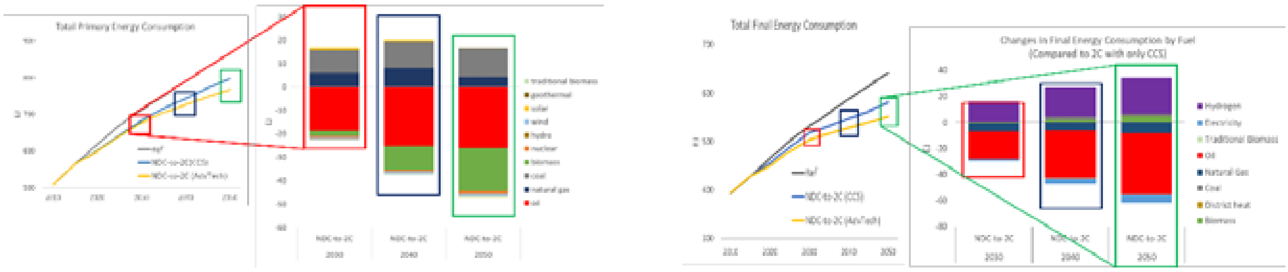


Figure 9: Paris Policy Energy Scenarios with and without CCS: Comparing Scenarios 3 and 2

5.7 Comparison with scenarios from other models

Whereas the results from GCAM (an integrated assessment model) provide insights at a global scale, more specific energy system models can deliver more specific details. In particular, the role of international trade of natural gas via LNG and pipelines and regional specifics can be addressed. In order to place the GCAM results into a broader perspective this section aims to explore the current and potential future of natural gas from several industry and agency-level reports. For this we will presents results for forecasted global and European natural gas demand by 2050 and focus.

Figure 12 illustrates that the overwhelming majority of these outlooks envisage a relatively robust share of 20-25% for natural gas in the global primary energy demand by mid-century. The only drastically deviating scenarios are deliberately “green” (renewable-intensive) scenarios such the green cooperation scenario of DIW-REM (Ansari et al., 2019) or the most recent Sky 1.5-scenario from Shell (2021). Using energy system models illustrating the technical feasibility of 100% renewables scenario (i.e. of the EWG (Ram et al., 2019)) naturally do not see any demand for natural gas by 2050 and are thus not shown. An excellent overview of different developments over



Panel A
Change in Primary Energy Use

Panel B
Change in Final Energy Use

Figure 10: Impact of advanced hydrogen fuel cell on Paris Policies: Comparing Scenarios 3 and 4

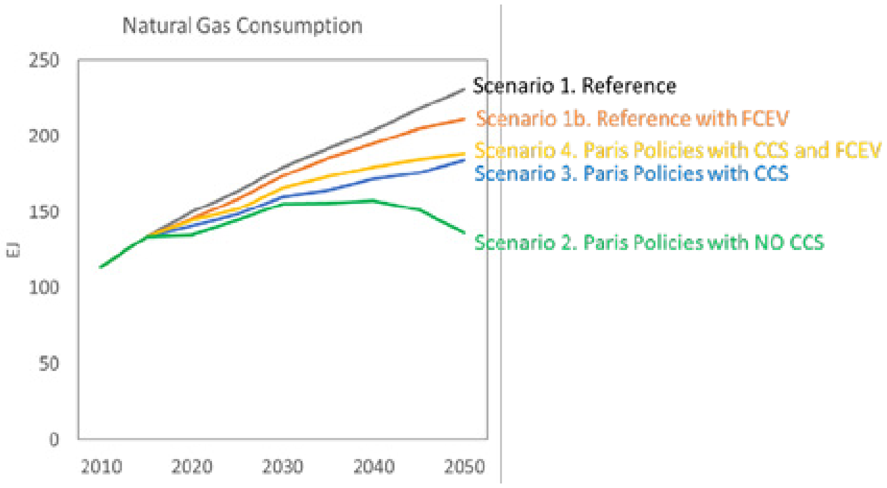


Figure 11: Natural gas consumption across scenarios

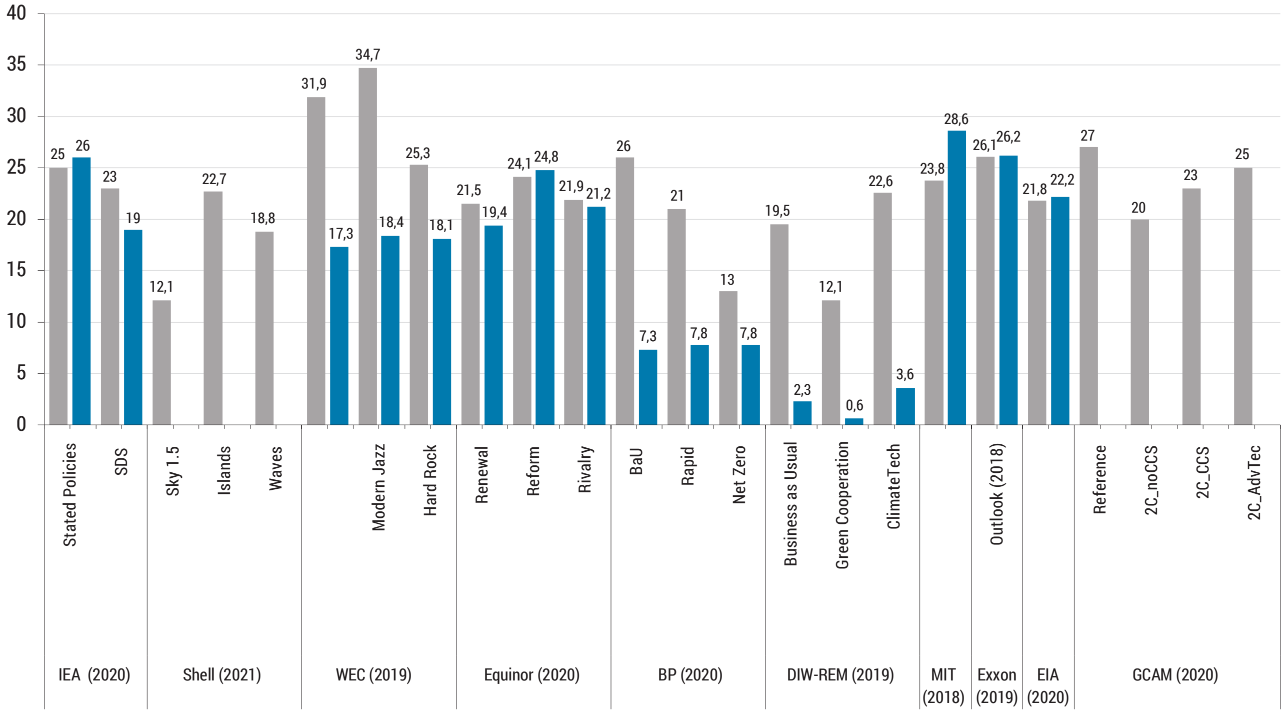
time of natural gas demand across different outlooks can be found in CEPS (2019).

For all scenarios, we note that the definition of "gas" or "natural gas" is not clear. In other words, it is unclear whether in the numbers used for Figure 13 biogas is included (probable in most scenarios) or whether alternative gases from power-to-X processes (hydrogen, methane) are included. Indeed, the outlooks reflect to a large extent a bias towards traditional fossil fuel industry thinking (Ansari et al., 2019). The regional disaggregation also differs across outlooks, hence what is considered as "Europe" in Figure 12 might not be consistent. For the overall findings, however, this does not weigh in for this report. ExxonMobil's outlook stops in 2040 thereby avoiding the question of complying with the Paris Agreement which set 2050 as target date. Others go to 2060 (World Energy Council) or even 2100 (Shell) which allows them to allocate the bulk of the decarbonization efforts to later periods after 2050. This must be kept in mind when comparing and contrasting some outlooks in detail to get insight into what might actually materialize for global natural gas markets and LNG in particular.

Figure 12 illustrates that on global level, natural gas demand remains on high levels in terms of its share in total primary energy demand. Some outlooks, like NetZero (BP) or Green Cooperation (DIW-REM) foresee a share of natural gas of around 12% globally but as low as 7.8% and 0.6% in Europe. This is a substantial reduction to the current 24% (globally and European) share (BP, 2020a).

Obviously, there are differences, but the main message is that natural gas demand will shift geographically, hence producers will have to find their counterparts in other parts of the world but Europe. Nearly all outlooks foresee a demand increase in Asia and (Sub-Saharan) Africa which will be met by more LNG traded internationally. Equinor's (2020) model indicates a rise in European import dependency which will be matched by Norwegian supplies including CCUS. According to EIA's AEO (2020) the US will rely heavily on LNG exports midterm (2050) becoming no longer competitive after that with new entrants in the global industry. ExxonMobil forecasts demand growth globally (~38%), but Europe only accounting for 3% of that and with Asia as the future destination of natural gas consumption. The WEO from IEA (2020) in its SDS Scenario also indicates an absolute reduction of European natural gas consumption (down to 19%) and identifies industry in Asia to be driving global demand.

Taken together, the majority of these scenarios indicate a growing demand for natural gas globally with Europe potentially becoming a less important consumer. This in fact heavily relies on the available production technology (competitiveness of CCUS compared to energy systems based on renewable energy sources) and the development path of hydrogen.



Note: IEA, BP, and ExxonMobil numbers are for 2040, DIW-REM numbers are for 2055.

Figure 12: Share of natural gas in primary energy demand in percentage (%) in various outlooks by 2050 for the world (grey) and Europe (blue)

6 THE ROLE OF NATURAL GAS IN EUROPE

This final section is dedicated to a closer look at the European perspective on natural gas demand in general and its potential role as a provider of flexibility in a European context. This is mainly motivated by the recent policy discussion of natural gas "as a bridge" and relates to the different findings from the outlook comparison in the previous section. However, it does not explicitly take into account the hydrogen vision that has come into place on a European level lately. We will address this in a forthcoming policy report. In the following we will consider 15 energy system models to first produce pathways scenarios for European natural gas and second identify the effect on power production using the power market model (EMPIRE).

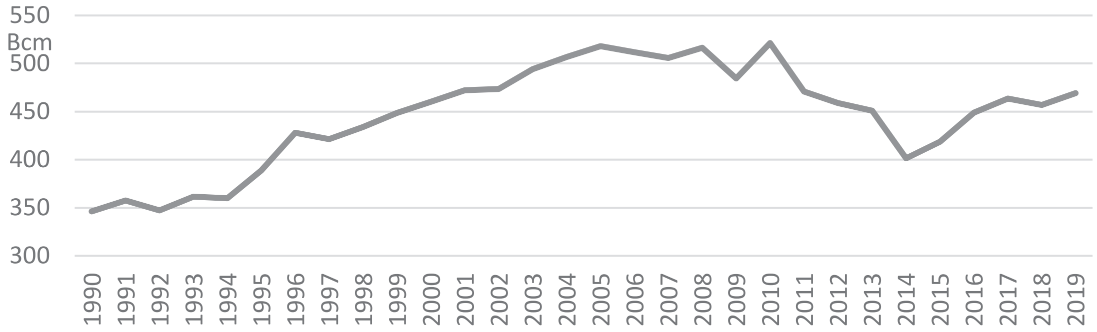
6.1 Current natural gas consumption in Europe

Natural gas consumption in Europe has been somewhat volatile in the past 30 years (Figure 13). After a steady increase of natural gas consumption until the mid-2000s, we have seen a relatively strong decrease by more than 20% between 2009 and 2019. This decrease was, to a large extent, due to relatively low natural gas utilization levels in the power sector in a period of low CO_2 certificate prices which provided a comparative advantage to coal and lignite. With rising CO_2 prices, medium-term outlooks of stable demand have become more credible until the pandemic has hit natural gas demand again in 2020. Low prices and economic downturn has meant a loss of demand of 40 bcm in 2020 compared to 2019 (IEA, 2020a).

6.2 Future (natural) gas consumption in Europe: an uncertain outlook

Future EU consumption is still subject to considerable uncertainty which becomes evident when comparing some industry and EC projections such as by the European Network of Transmission System Operators (e.g., ENTSO-G and ENTSO-E, 2018) or the EU Reference Scenario 2016 (EC, 2016), etc.) with other outlooks. Indeed, industry projections have been sluggish in acknowledging that the Paris Agreement will require the European Union to substantially reduce its consumption of fossil energy resources, including natural gas. However, as the IEA notes, Europe is the only region where in any scenario natural gas production and consumption are set to decrease (e.g., IEA, 2020b).

In the SET-Nav project, with participants from NTNU, SINTEF, DIW Berlin, TU Berlin, Fraunhofer ISI, TU Vienna and others, four pathways for the EU energy system were developed and quantified (Crespo del Granado et al., (2019). These are comprehensive scenarios that are unique by their coverage of all energy demand sectors (transportation, buildings, industry) as



Source: BP (2020b)

Figure 13: Natural gas consumption in the EU 28 (1990-2019 in bcm)

well as the various energy supply sectors (electricity, renewables, natural gas). For the quantification, sectoral models were used and linked with each other. Figure 14 shows the natural gas demand in each of the four pathways which is the aggregated demand from the electricity, industry, buildings and transportation sectors.

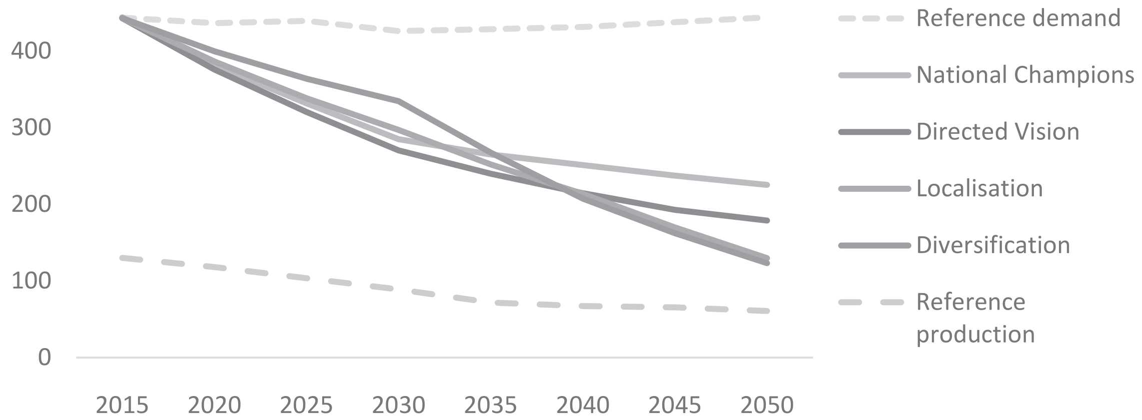
As a general pattern, pathways scenarios show a decreasing, and compared to the Reference scenario, a lower demand level for the EU28 (Crespo del Granado et al., 2019). In some countries, however, 2030-2040 natural gas consumption increases compared to the 2020 levels, namely in the Baltic countries, Scandinavia and Greece. There, demand decreases at the latest by the mid-2040s and 2050s. The demand surge is driven by the power sector; all other sectors show a monotonically decreasing (building, industry) or increasing (transport) pattern across Europe.

Of course, a natural gas phase out comes with the challenge of finding remuneration to existing natural gas infrastructure (production capacities, pipelines and LNG terminals, underground storage facilities). If assets become stranded, asset owners might request a compensation for stopping using their assets. Alternative uses may also be an option (maybe more likely than compensation payments) and there are currently several research initiatives to investigate the feasibility of power-to-gas which could use the existing natural gas transport and use infrastructure, but also of substituting natural gas with hydrogen in transport and storage infrastructure.

We note however, that a number of regulatory challenges are looming from the integration with the power sector and decarbonization efforts in Europe. For example, it is by no means clear whether the markets and infrastructure for other gases such as hydrogen should be regulated in the same way as natural gas (e.g. with third-party access to pipelines). Moreover, the use of natural gas infrastructure by biogas and e-gas must be clarified (for technical, quality and safety reasons). The next section will focus of the role of natural gas in the European power sector.

6.3 The role of natural gas as a flexibility provider in the European power sector

In August 2019 the report “Havvind – En industriell mulighet” was published by FME NTRANS. The first chapter in this report featured an analysis of a cost-efficient decarbonization pathway for the European power sector using the power market model EMPIRE. As the focus of the report was the role of offshore wind in the North Sea in the analysis, other technologies were not discussed in detail. In the following, we present an elaborate discussion on the role of natural gas in the EMPIRE analysis, taking into account an increase of the role of offshore wind.



Source: Crespo del Granado et al. (2019)

Figure 14: EU natural gas demand projections in the SET-Nav pathways and the EU Reference Scenario 2016 (in bcm/year)

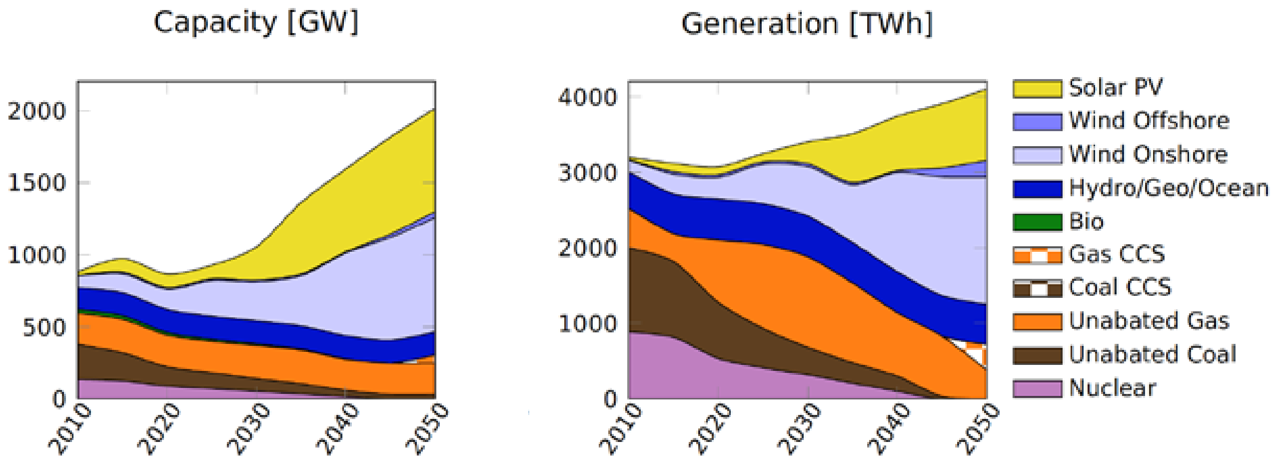


Figure 15: Baseline scenario with CCS. European power generation capacity and production using EMPIRE

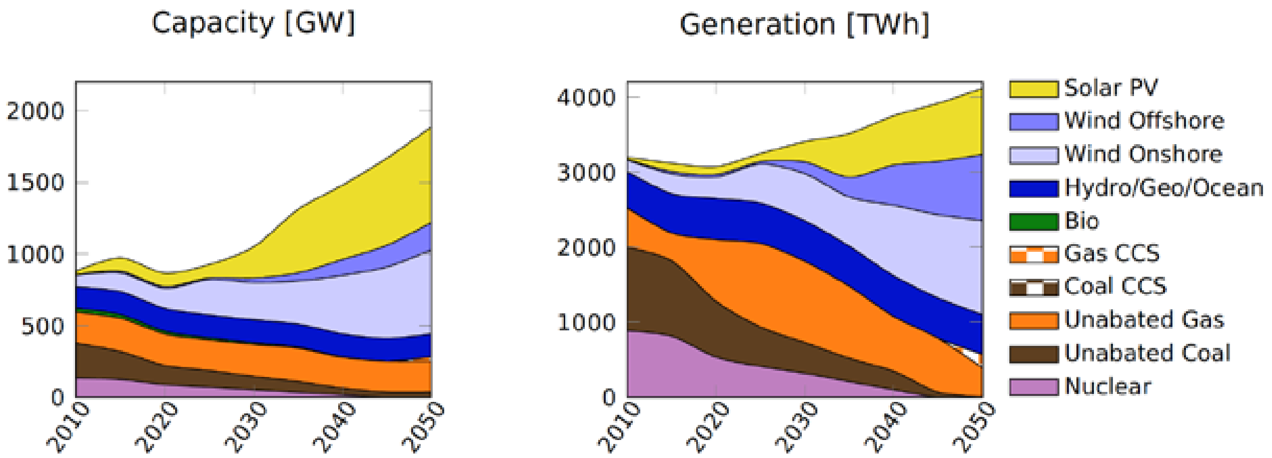


Figure 16: Sensitivity scenario: 30 % reduction of offshore wind capital cost relative to Baseline with CCS. European power generation capacity and production using EMPIRE

There are several key drivers impacting the European power generation technology mix optimized by EMPIRE. Particularly important are assumptions regarding future projected use of electricity, technology costs, fossil fuel prices and choice of climate policy. In the present analysis, future demand for electricity is taken from the EU reference scenario 2016 and fossil fuel prices are from the 2DS scenario of IEA Energy Technology Perspectives 2016. Assumptions regarding future costs and operational characteristics of power generation technologies are collected from several sources which have been described in the offshore wind report. In order to ensure a progressively less carbon intensive power sector a limit on total European emission is enforced every year. This limit is linearly decreasing from the historical emission level of 2010 until it reaches a 90% reduction by 2050. Although this target falls short of any reasonable interpretation of the European Commission's 2050 strategy of a carbon neutral energy system (ref "Clean Planet For All"), a 90% reduction of power sector emissions by 2050 from 2010 still entails a formidable transformation of the power system.

Figures 21 and 22 show the European aggregated capacity and production by technology from 2010 to 2050 in the two scenarios first presented in the offshore wind report. As can be seen these results are characterized by a rapid phase of coal and nuclear power from the production mix, which is at the same time accompanied by a wide-scale deployment of renewables, starting with land based wind, followed by solar PV and then lastly, beyond 2035, offshore wind.

Natural gas power generation increases from 2010 levels in the period from 2025 until 2045. In 2050, there is also some natural gas power generation with carbon capture and storage (CCS). In the sensitivity scenario with reduced offshore wind costs, the use of natural gas CCS is displaced relative to the baseline by increased offshore wind generation. As can be observed, the level of unabated gas production in 2050 is the same for both scenarios. This indicates that still with the assumed improved competitiveness for offshore wind the system value of having dispatchable natural gas generation capacity is high. If the limit for carbon emissions from the power sector is set to zero, either this natural gas needs to be replaced in the mix, or negative emission technologies would need to be included.

Photo: shutterstock.com

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