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Fossil natural gas exit – A new narrative for the European energy transformation towards decarbonization

Christian von Hirschhausen[1,2], Claudia Kemfert[1,3], and Fabian Praeger[2]

This paper discusses the potential role of fossil natural gas (and other gases) in the process of the energy transformation in Europe on its way to complete decarbonization. Mainstream conventional wisdom has it that natural gas, perhaps in combination with other gases, should maintain an important role in the energy mix, first, as a "bridge fuel", and then through a gradual transition toward decarbonized gases. This is most comprehensively rolled out in three consecutive discussion papers by Jonathan Stern from the Oxford Institute for Energy Studies (2017b, 2017a, 2019). Based on an in-depth assessment of the ambitious climate targets of the EU and the subsequent need for far-reaching decarbonization, as well as on results from energy system modeling, a contrasting result emerges, where the disappearance of fossil natural gas and its corresponding infrastructure is the next logical step of the transformation process in Europe. The lack of an economic perspective for nuclear power and the absence of a plausible deployment of large-scale carbon-dioxide removal technologies (CDR) imply that natural gas has no "sweet spot" any longer in the decarbonization process. In other words: Fossil natural gas is no longer part of the solution to the challenge of climate change, but has become part of the problem. Over the last years, the phasing out of natural gas in Europe has already started, and will continue until its complete phase-out, most likely in the 2040s, i.e. only two decades from now. The decline of natural gas in Europe has implications for the short- and longer-term aggregate and sectoral energy mix, but also for the future of the lumpy infrastructure, that has been developed over the last decades for a growing market. Today, investments into natural gas infrastructure are likely to produce stranded assets, as we show in three concrete cases: The € 10 bn. investment into the North Stream 2 pipeline are not necessary to assure European supply security, nor to make a return on investment; projects of new LNG terminals on the shore of the German North Sea (Brunsbuettel, Stade, Wilhelmshaven) lack a business case; and new natural gas power plants are likely to be unprofitable. The paper proposes to replace the dominant narrative ("natural gas in decarbonizing European energy markets") with what we consider a more coherent narrative in the context of decarbonization: Fossil natural gas exit.

Keywords: Europe, decarbonization, fossil natural gas, energy gases

JEL-codes: Q48, Q54, L52, L95

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1 Introduction

Fossil natural gas has an illustrious, but relatively marginal role in the European energy systems. It was only after the discovery of large natural gas fields in the North Seat that natural gas found its way into the energy mix of some European countries, such as the UK, the Netherlands, and Germany, from the 1960s/70s onwards. With the liberalization and completion of the European Single Market, spearheaded by the UK in the 1980s, natural gas gained a more significant share of the electricity market. Yet, the share of natural gas in European primary energy production and consumption peaked in 2000 (22.2%) and in 2010 (25.4%), respectively, in 2017 it was 13.6% and 23.8%, respectively (Eurostat 2019).[1]

The need for deep decarbonization of the European energy system has for a long time not been identified as an existential threat by the industry. Rather, the European natural gas industry has joined international narratives of a "golden age" of natural gas, as expressed in IEA's (2011) World Energy Outlook, as an integral part of the low-carbon transformation. Even against the evident decline of natural gas consumption in the EU 27 after 2010, the European Commission's EU reference forecasts continued to be optimistic about European production and consumption (EC 2013, 2016). The assessment was accompanied by even more optimistic growth perspective by the industry itself, Eurogas.[2]

Environmental groups and natural scientists had already identified the potential danger of large-scale use of natural gas to true decarbonization early on, e.g. Howarth (2014, 2015, 2019). Yet it has taken professional industry analysts relatively long to come to grips with the incompatibility between strong climate ambition and continued fossil natural gas use. The most comprehensive and thought-through analysis has been carried out by Jonathan Stern (2017a, 2017b, 2019) from the Oxford Institute for Energy Studies (OIES) in a series of three papers in which he urges the natural gas industry to take decarbonization serious, and to deploy a new approach to prove that "methane can decarbonize" (Stern 2017b, 24, Footnote 1). In an attempt to secure the survival of the natural gas industry and its capital-intensive infrastructure, Stern urges the industry to move away from blunt pro-natural gas advocacy, and instead to adopt a decarbonization narrative to accompany the transformation of the industry, to save what can be saved, in a gradual, but in fact rather long process that provides plenty of time to use the (well-remunerated) existing capital and infrastructure.[3]

[1] This paper results from a keynote lecture given at the 2nd International Conference "The Economics of Natural Gas - New Research Perspectives for Rapidly Changing World", held June 21, 2019, in Paris by the „"Chair Natural Gaz"; it has been appended by up-to-date research on the sector, and some historic references. We thank the organizing committee for the invitation and the audience for fruitful, controversial discussions, in particular with the other keynote lectures, Professor Ruud Egging (NTNU, Trondheim) and Dr. Robert Ritz (University of Cambridge, EPRG) as well as Prof. Francois Levêque, co-organizer of the Chair (Ecole des Mines de Paris). Thanks also to other colleagues in our cloud for internal discussions and/or research assistance and/or other forms of cooperation, mainly Hanna Brauers, Isabell Braunger, Louise Fitzgerald, Franziska Holz, Leonard Goeke, and Elmar Zozmann, and Anne Neumann for editorial support. This research has been supported by the research project "Future of Fossil Fuels – FFF", funded by the German Ministry for Research in the program "Economics of Climate Change (https://www.diw.de/fff); the usual disclaimer applies.

[2] See regular forecasts and other publications by Eurogas https://eurogas.org.

[3] "A 20-year horizon prior to significant global decline qualifies gas to be regarded as a "transition fuel (Stern 2017a, 32). Thus, the new narrative should include "the size and timing of developing commercial scale projects for biogas, biomethane, and hydrogen from power to gas (electrolysis), and reformed methane" (Stern 2019, 1), allowing the networks to survive an existential threat because then "they can maintain throughput while simultaneously adapting to decarbonization products" (Stern 2019, 1).

In this paper, we challenge the narrative that "methane can decarbonize" and that therefore fossil natural gas is an ideal transition fuel in the European decarbonization process. Instead, we develop an alternative narrative called "fossil natural gas exit", which is the logical consequence of a truly decarbonized energy system. We argue that when taking the decarbonization challenge serious, natural gas is no longer a solution, but becomes a major problem, and that it will disappear from the fuel mix within the next two decades.[4]

The paper is structured in the following way: The next section describes the transformation process of the European energy system in the context of decarbonization, sometimes also called "net zero", which is the official goal defined by the European Union. This has implications for the natural gas industry: From a focus on market restructuring, liberalization, and competition, the focus has shifted to environmental aspects and decarbonization. Clearly, while the former benefitted the natural gas industry, the latter disfavors it, due to its relatively large contribution to greenhouse gas emissions through CO_2 and also the climate impacts of methane (CH_4) in its raw form. In Section 3 we provide a technical overview about energy gases, and find that arguments to decarbonize methane are flawed, if not simply wrong. The new narrative has invented a "theory of colors" that is spreading, including "green", "blue", "turqoise" and other colors. In our narrative, neither methane nor other gases have any color, but should be analyzed with structured economic, technical, and environmental parameters. In Section 4, we provide model-based evidence that without (un-economic) nuclear power and without plausible carbon-dioxide removal technologies (CDR), natural gas has no place in a decarbonized European energy system but is likely to disappear from the energy mix, most likely towards 2040s. We then highlight the implications of these results for investments and the longer term dynamics of the system (Section 5): Investing in new natural gas infrastructure is not necessary anymore and would most likely to lead to "stranded assets", e.g. the North Stream 2 pipeline from Russia to Germany, LNG-import terminals, or natural gas power plants in some major European countries. In Section 6 we suggest changing the narrative, i.e. to move from a "decarbonize to survive" narrative for fossil natural gas to a truly decarbonizing solution: fossil natural gas exit. Section 7 concludes.

2 Framework conditions: Full decarbonization of the European energy system

2.1 From a focus on competition …

Natural gas has had an illustrious, though overall marginal role in the European energy systems. Synthetic "town gas" had lost its dominant role in lighting to electricity in the late 19th century, and was almost completely absent from energy conversion in the first half of the last century. It was only after the discovery of large natural gas fields in the North Sea that it found its way into the energy mix of some European countries, such as the UK, the Netherlands, and Germany (Lévêque et al. 2010). The big, largely politically motivated natural gas pipe deal with the Soviet Union in the 1970s ("Erdgasröhrengeschäft"), and the gradual emergence of internationally traded liquefied natural gas

[4] In an analysis focusing on sustainable energy transformations in Germany, Fitzgerald, Braunger, and Brauers (2019, 17) have come to a quite similar conclusion: "Natural gas is a dirty, GHG-intensive fossil fuel that cannot play a role beyond 2050 and needs to be drastically reduced in the upcoming years."

(LNG) were drivers towards higher utilization of natural gas in Europe. Yet the traditional, coal-based utilities always watched the new competition with suspicion, and often argued that natural gas was too valuable to be burnt for electricity generation, instead it should be used for heating only. Thus, in Germany legislation prevented large-scale deployment of natural gas until the mid-1990s.[5]

Liberalization and the restructuring of the industry, including third party access to the network and the construction of merchant, independent power plants (IPPs) gave another impetus to natural gas in the 1980s to the UK and the entire continent after the first natural gas liberalization Directive (98/32) in 1998. The breakthrough of natural gas in European energy mix in the last part of the 20th century was largely based on a competition narrative: Important European resources, discovered in the 1950s, and large-scale import infrastructure, both pipeline and LNG, had been developed since the 1960s. However, until the 1980s, natural gas had remained a marginal supplier, and was kept as the "small brother" of big coal (Mendelevitch et al. 2018). It took ambitious restructuring efforts in the Anglo-Saxon world, mainly the UK and the US in the 1980s, followed by Europe in the 1990s to make natural gas a real competitor to coal (Stern 1997; Leveque 2006; von Hirschhausen 2006; Joskow 2013). The introduction of carbon pricing through the European Emission Trading System (ETS) contributed to the switch, in particular in the UK where a carbon floor price had been established early on (Newbery, Reiner, and Ritz 2019).

In the first decade of this century, a gradual shift of the natural gas narrative can be observed from the initial focus on "competition" towards environmental issues. The narratives of European gas supply strategies were based on a broad coal-to-gas switch and the liberalization of the market. Key issues were the opening of the markets and transport infrastructure for other participants to create competition, the development and construction of import infrastructure such as pipelines and LNG terminals and the emergence of short-term contracts for short-term trading of gas on the exchange markets. Or, as Jonathan Stern (2019, 18) observed, "the cornerstone and ultimate priority of the EU liberalization experiment which has been ongoing for several decades through several EU "energy packages" has been the unbundling of networks, allowing access for all potential users in order to create competition, promote efficiency, and reduce prices for consumers." In addition to the competition narrative, supply security was a second pillar, in particular with respect to the role of Russia. However, after the Russia-Ukrainian gas crisis of 2006 and 2009, diversification of imports, and a rapid extension of the LNG infrastructure, were supposed to stabilize the role of fossil natural gas in the European energy mix.

2.2 … to a "bridge fuel" …

In parallel to the decline of fossil natural gas production and consumption in Europe (see Box 1), and growing environmental and climate concerns, the narrative started to be less focused on competition and more on environmental issues. First attempts were made to establish natural gas as a "clean" fuel, with respect to "dirty" coal, and to designate it as a "bridge fuel" towards a lower-carbon economy. First voices in this direction were Podesta and Wirth (2009) and Brown, et al. (2009).

[5] The third German law on electricity generation (Verstromungsgesetz, 1974) made the expansion of existing or the construction of new natural gas (and mineral fuel oil) power plants de facto impossible (for details, see Matthes, Felix Christian. 2000. Stromwirtschaft und deutsche Einheit: Eine Fallstudie zur Transformation der Elektrizitätswirtschaft in Ost-Deutschland. Berlin, Germany (p. 126)

Natural gas was long considered to be an ideal partner in electricity generation for variable renewables due to its high flexibility, versatility, as well as the diversified supply sources. In 2012, natural gas was expected to become a "key for the energy future of Europe".[6] The International Energy Agency's idea of a "golden age" (IEA 2011) was also based on the understanding that natural gas was the natural complement to variable renewable energy: when the wind is not blowing and the sun is not shining, natural gas—a relatively low-carbon fuel—can take the lead in a low-carbon merit order. Neumann and von Hirschhausen (2015, 3) have described this narrative of natural gas as a "transformation fuel": "Cleaner than coal, more flexible than oil in power generation, it can serve as a backup to renewables", an ideal transformation fuel.

Some evidence favoring the possibility of a natural-gas-driven low-carbon transformation came from the USA and Japan. With the idea that natural gas could play a key role, European transmission system operators conceived bold development plans for pan-European network development—similar to their plans for the electricity sector—in response to the perceived need for more natural gas supplies. These were supported by generous calculations of natural gas needs by the European Commission. At least €70 bn. were expected to be invested in pipelines, LNG terminals, and the necessary connecting infrastructure up to 2020 (ENTSO-G 2013).[7]

Box 1: Fossil natural gas on a declining path.

Natural gas was on a long-term decline, long before the decision on full decarbonization, and even longer before the Corona pandemic. The predicted "golden age" (IEA 2011) for natural gas, which was based on the narrative of the ideal partner for renewable energies, has not become reality. Since 2000, natural gas production in the EU is on a continuously declining path. As shown in Figure 1, total natural gas production in Europe decreased from a maximum of 323 Mtoe in 2004 to 223 Mtoe in 2018. While the consumption quantities show a higher fluctuation than production, they still depict a similar trend to decline to a relatively low level, not reaching the numbers of 2000 – 2005 again. Total natural gas consumption decreased from a maximum of 371 Mtoe in 2005 to 316 Mtoe in 2018.

The last major active gas fields in Europe are in Norway, the Netherlands and the United Kingdom with a yearly production of 112, 29 and 38 Mtoe, respectively in 2019 (Eurostat 2019). However, this former triade of large European producers is currently collapsing to just one: Previously the biggest producer, the Netherlands have decided to phase out gas production completely by 2030 after the acceptance of the Dutch population has steadily decreased due to earthquakes related to the natural gas production (Holz et al. 2017). The UK, too, is on a long-term decline of natural gas production. Figure 2 shows how the production of natural gas from the UK and the Netherlands was subsequently substituted by gas production of Norway (Egging and Tomasgard 2018). While production in the UK and the Netherlands decrease, Norway has continuously increased its production since 1990. The strategy of the Norwegian

[6] Speech of European Energy Commissioner G. Oettinger at the 10th Gas Infrastructure Europe Annual Conference in Krakow, Poland, May 24, 2012, quoted in the GIE article available at http://www.naturalgaseurope.com/oettinger-europe-gas-market.

[7] A recent survey of the challenges at European level is provided by Egging et al. (Egging et al. 2019).

future natural gas production reproduces the narrative of “decarbonizing natural gas”. Norway’s main gas production company is responsible for 70% of domestic natural gas exports, supplies about 25% of the natural gas demand in the EU and predicts a further future for gas production through decarbonization of the fossil fuel via CCOS (Carbon Capture and Offshore Storage).[8]

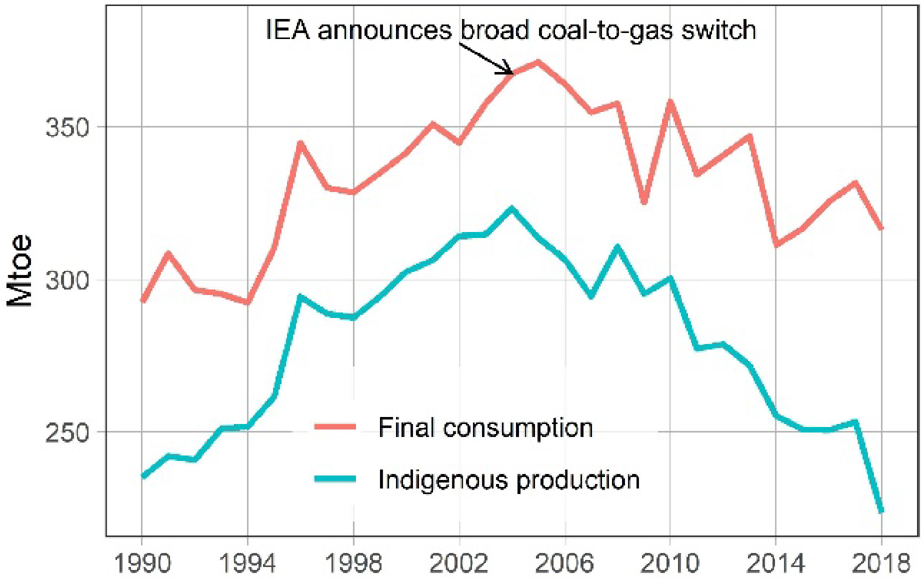

Figure 1: Fossil natural gas production and consumption in Europe.

Source: Eurostat (2019).

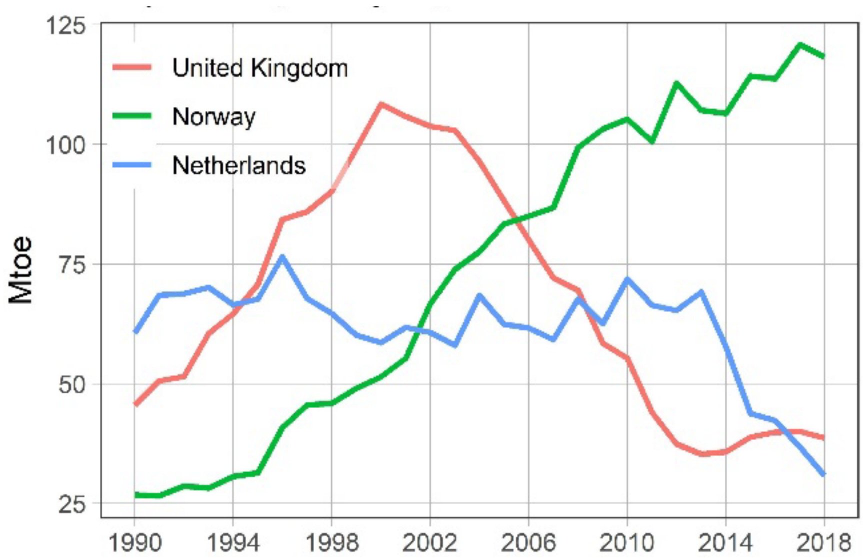

Figure 2: Fossil natural gas production in Europe and major producing countries.

Source: Eurostat (2019).

[8] See: https://www.equinor.com/en/what-we-do/low-carbon-solutions-in-equinor.html.

2.3 … to "methane can decarbonize" in a zero-carbon Europe

Clearly the framework conditions for fossil natural gas have changed with the ambitious decarbonization agenda of the European Union, and the signing of the Paris Agreement on Climate (UNFCCC 2015). From a rather general idea of long-term decarbonization in the 2011 Roadmap (European Commission 2011), a clear commitment to zero carbon now prevails in the policy framework. The framework conditions for the natural gas sector have changed with the commitment of the European Union to establish a climate-neutral Europe by 2050, sometimes referred to as "net zero carbon", in addition to the commitment to the objectives of the Paris climate agreement of 2015.[9] While the former objective ("net zero") targets are a state of emissions in 2050, the Paris agreement prescribes a pathway, including a budget for greenhouse gas emissions (see Box 2).

The old EU targets for greenhouse gas reduction until 2050 were set in the "2020 climate and energy package", the "2030 climate and energy framework" and the "2050 long term strategy".[10] As of 2020, the key reduction targets for greenhouse gas emissions for 2020, 2030 and 2050 are 20%, 40% and "climate-neutrality", respectively. These goals describe the cumulative emissions of a target year in relation to a base year (1990). Early on, it was clear that the targets were not stringent enough (Kemfert, Hirschhausen, and Lorenz 2014); today, it is once again clear that the intermediate target for 2030 (-40%, basis: 1990) is not ambitious enough to assure the 2050 target of net zero (Ecologic Institute 2019; Oei et al. 2019). Therefore, a further tightening of the CO_2 budget constraint is required.

Abiding by the rules of the United Nations Framework Convention on Climate Change (UNFCCC), the EU must present its 2050 long-term strategy for climate and energy policy by 2021. Also in adherence with the Paris Agreement, the first review of the long-term strategy (global stocktake) will occur in 2023. Whereas the previous long-term strategy foresaw a greenhouse-gas-reduction of "only" 80-95% by 2050 (basis: 1990), the target for 2050 is now clearly set at 0 for 2050, i.e. a 100% reduction, and has to comply with the Paris criteria in term of CO_2 budgets, too (see Box 2).

Under these conditions, both the "competition" and the "bridge fuel" narrative are outdated. Clearly, fossil natural gas is losing competitiveness with renewable energies (Stern 2017a).[11] Decarbonization, disruption and digitalization also imply the loss of competitiveness of the traditional natural gas cash-cows in the electricity and the heating sector. While a (high) price on carbon can temporarily help natural gas to crowd out coal, as shown by Newbery, et al. (2019) for the UK, natural gas will become unaffordable with stricter carbon constraints, and loose out in competitiveness with renewables and storage.

A new narrative is emerging. There seems to be a broad consensus that "decarbonization is the absolute priority of future energy regulation, and competition will need to be subordinated to that goal" (Stern

[9] I.e. keeping the increase in global average temperature to well below two degrees Celsius above pre-industrial levels and of pursuing efforts to limit the increase to 1.5 degrees Celsius in order to prevent more serious climate damage (IPCC 2018).

[10] See: https://ec.europa.eu/clima/policies/strategies_en.

[11] "Wind (both onshore and offshore) and solar power generation, combined with batteries storage, have substantially reduced in cost in the 2010s, and these trends are likely to continue (…) These sources are increasingly likely to have policy priority over gas-fired generation in the majority of countries for both environmental and security reasons." (Stern 2017a, 30).

2019, 18). However, there are different ways of dealing with this challenge: Rather than to call it quits for fossil natural gas, a new narrative is developed, called "methane can decarbonize".[12] In the next two sections, we test whether the new narrative of decarbonizing methane, mainly by introducing hydrogen from different origins, is consistent. Before that, we provide a brief picture of the fossil fuel natural gas industry in Europe.

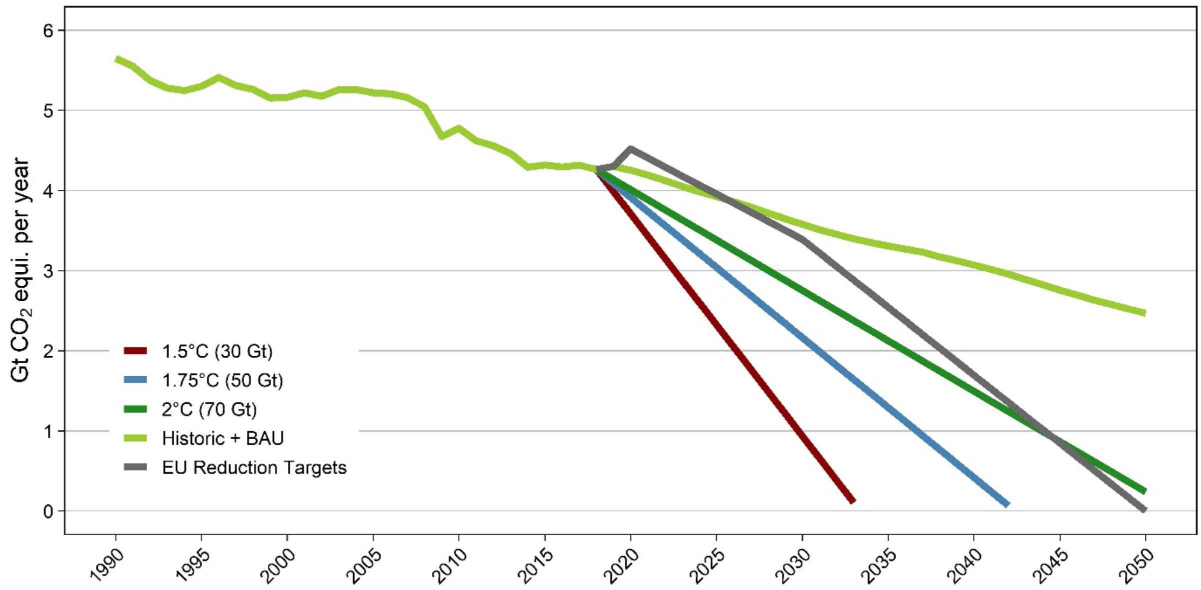

Figure 3: Historic emissions and pathways for the EU, compliant with CO_2 budgets.

Source: Own depiction, based on cited literature.

[12] "A paradigm shift in commercial time horizons and gas value chain cooperation will be necessary for the industry to embrace decarbonization technologies (such as carbon capture and storage), which will eventually be necessary if gas is to prolong its future in European energy markets" (Stern 2017b, vi).

Box 2: Tight CO_2-budgets in the wake of the Paris climate agreement.

This box "translates" the commitments of the Paris Agreement on Climate into concrete emission reduction figures for the EU, and suggest that they are very, very tight.

In terms of climate physics, there is an approximately linear relationship between the cumulated anthropogenic CO_2 emissions and the change in the global mean temperature (J. Rogelj et al. 2018, 105). Based on this phenomenon, which is described and proven by observations and measurements of the earth system as well as by numerical simulations, the IPCC report calculated the amount of CO_2 that can still be emitted in order to limit global warming to a certain level (J. Rogelj et al. 2018, 108). To keep global warming below 1.5°C, as claimed by the IPCC, to prevent the most catastrophic "climate-related risks for natural and human systems" (IPCC 2018, 5), total cumulative emissions which are released to the atmosphere are the crucial factor (Joeri Rogelj et al. 2019; Teske 2018). The critical question then becomes how the "Paris-compatible" CO_2-equivalent budget is calculated.

We follow a pragmatic methodology suggested by Rahmstorf (2019): The remaining CO_2-budget to attain 1.5° C, 1.75° C, and 2° C (with a certain probability) is 420 Gt (from 2019), 700 Gt, and 1,000 Gt, respectively. This budget is distributed on a per-capita basis, the simplest heuristic (though perhaps not "fair" to the emerging countries of the Global South): the EU represents approx. 7% of the world population. Thus, the remaining budget for the EU (from 2019 onwards) is 30 Gt (for 1.5° C), 50 Gt (1.75° C), and 70 Gt (2° C), respectively. The question of the national distribution of CO_2-budgets and how effort sharing will be fair is still to be discussed. Van den Berg et al. (2019) give a comprehensive overview of the different approaches.

To gain insights and draw a perspective of how a pathway for the full decarbonization of the EU must take place in order not to exceed the respective CO_2 budgets, a simplified calculation was made: Figure 3 shows the discrepancy between a 1.5°C-suitable linear reduction path (and a path for 1,75°C and 2°C), based on a CO_2-budget for all EU member states (EU-28) and a linear reduction path based on the current reduction targets set by the EU Commission. In order to illustrate the consequences of not-acting, a business-as-usual path (BAU) was calculated, which uses a trend function to show how emission reductions develop if we go on as in previous years. In all calculations, hopes and visions for CDR (e.g. (BE)CCTS) and negative emissions are excluded as these technologies will not be available in the foreseeable future (von Hirschhausen, Herold, and Oei 2012; Mendelevitch and Oei 2018).

The message is clear: the trend and the direction show a large deficit in the current EU targets for meeting any of the Paris targets. The CO_2-budget, following the current EU reduction targets and a linear progression, will be exceeded already by the year 2024. Following a linear, 1.5°C-path, staying within the limits of the given budget translates into fully decarbonization until the mid-2030s. This implies no less than zero emissions and a "100% renewable energy system" (RES) from the mid-2030s already. A 1.75° path would shift this towards the early 2040s.

3 Fossil natural gas and other energy gases: Methane cannot decarbonize

In this section, we challenge the hypothesis that "methane can decarbonize", and thus the fossil natural gas sector can be gradually adapted to the European decarbonization strategy. The section starts by spelling out the hypothesis explicitly. Then it is argued that methane is much more climate effective as generally acknowledged, and is detrimental to any climate balance. In a third step, we provide an overview of energy gases, and then explain why the current hydrogen and power-to-methane hype offers no sustainable solution. Carbon dioxide removal has neither technical nor economic perspectives. In concluding, we suggest to clarify fossil natural gas as "dirty" in the EU taxonomy.

3.1 The essence of "decarbonizing" fossil gases

Can the fossil natural gas industry still be saved, e.g. by referring to other gases as substitute? Despite forecasts of declining demand, the fossil natural gas industry is currently attempting a lifetime extension in the European energy mix with a larger narrative on the need to "decarbonize" natural gas (both pipeline gas and LNG), to strengthen the role of natural gas as a "transformation fuel". Stern provides advice to save the natural gas industry, by observing that the advocacy narrative of the European fossil gas community on coal to gas switching has failed to convince governments. Subsequently, he develops a "natural gas to other gases"-narrative, "the components of which are the size and timing of developing commercial scale projects for biogas, biomethane, and hydrogen from power to gas (electrolysis), and reformed methane" (Stern 2019, 1). Accepting that natural gas has a declining future in the European energy balance "unless it can be demonstrated that decarbonization of gas will be a commercially viable option which the gas community intends to actively pursue", Stern suggests to implement the narrative of "a lower carbon content" to decarbonized gas (Stern 2017b, 24). The incumbent narrative rests on three pillars:

i. Moving from fossil natural gas" to "other" gases, in order to save as much as possible of the existing infrastructures and allow for a gradual switching to "clean-green-etc." gases
ii. The success of carbon capture, transport, and storage (CCTS) as a condition (sine qua non) for a successful transformation process
iii. Large-scale industry investments into large-scale infrastructure and global trade structures, along the lines of global LNG-trading, e.g. for hydrogen from CH_4 through steam reforming.

This narrative of the "decarbonized green gases" is now increasingly adopted and implemented by the gas industry to justify the continuation and expansion of fossil natural gas infrastructure such as fossil natural gas-fired power plants, pipelines and LNG-terminals, and to maintain old, centralized energy supply systems and related business models.

3.2 Methane (CH_4) and climate change

Environmental groups, such as Muttit et al. (2016) and Stockman et al. (2018) as well as natural scientists, such as Howarth (2014, 2015, 2019), Shindell et al. (2009), Nisbet et al. (2019), Hughes (2011), Cremonese and Gusev (2016) and Alvarez (2018) had already identified the potential danger of large-scale use of natural gas to true decarbonization early on. Yet it has taken professional industry analysts relatively long to come to grips with the incompatibility between strong climate ambition and continued fossil natural gas use. Among the early warning signs about the decline of natural gas in the wake of deep decarbonization, Aoun and Cornot-Gandolphe (2015, 83) suggested that while the industry was looking for the golden age, “the gas market has to deal with a new operating context, dominated by uncertainty over the evolution of supply and demand.”

Methane, which is emitted directly to the atmosphere through leaks and vents (upstream and midstream emissions), has a particularly higher damaging effect on the climate than CO_2, as it has the ability to retain heat more effectively in the atmosphere. After approximately a decade, methane decays to additional CO_2 in the atmosphere, which is mostly absorbed by the oceans and the terrestrial biosphere but partly remains up to a hundred years as additional CO_2 in the atmosphere and further contributes to the warming of the planet (Cremonese and Gusev 2016). In addition to global warming, methane also contributes to the formation of ground-level ozone, which has negative health impacts on the human organism and agricultural systems (Drew T. Shindell 2015).

The climate physical relations have implications on the climate debate, in particular on available carbon budgets. In fact, for reporting and balancing global greenhouse gas emissions, the UNFCCC sets international and uniform standards as to how corresponding greenhouse gases must be calculated (Strogies and Gniffke 2019). The methodology used, developed by the Intergovernmental Panel on Climate Change (IPCC) and the United Nations Economic Commission for Europe (UNECE), multiplies the total emission activities identified by specific emission factors. The calculation basis for methane, the GWP over a time-frame of 100 years, is given as 25 (Strogies and Gniffke 2019, 89) based on the Fourth Assessment Report (AR4). This value has been updated by the “Fifth Assessment Report” (AR5) (Myhre et al. 2013, 56), which corrects the GWP_{100} to 34 and GWP_{20} to 86. Latest scientific findings even give a GWP_{20} of 105. An overview of the studies can be found in Howarth (2014, 7). The main reasons for the correction upwards is the inclusion of gas-aerosol interactions, which were examined e.g. in studies from Shindell et al. (2009), Howarth (2014) and Hughes (2011).[13]

If one takes tackling climate change and the corresponding need for decarbonization serious and does not rely on future CO_2-free technologies (such as CCTS, see 3.5), then one has to consider the 20-year perspective due to the perturbation lifetime of methane, leading to substantially higher CO_2-equivalents of the methane emissions. It is necessary to include the 20-year time frame in the calculations and balancing of global greenhouse gas inventories and modelling exercises in order to avoid exceeding the tipping points of the climate system that we will face in the coming decades (Schellnhuber, Rahmstorf, and Winkelmann 2016). On the other hand, the immediate, drastic reduction of short-lived methane emissions provides an opportunity of a short-term positive effect in the climate system, as the temperature of the atmosphere responds more quickly to methane reductions than to merely reduction of the long-lived CO_2 in the atmosphere (D. Shindell et al. 2012).

Recent changes in the amounts of methane in the atmosphere are alarming, since the quantity of methane doubled in the time from 2014 to the end of 2018, compared to observed values in 2007 (the

[13] Howarth (2014, 53) suggests that the 20-year GWP is not only in the range of about three times the 100-year GWP, but that the absolute figures also have to be updated recently on the basis of the AR5. It should also be noted, that the AR5 does not explicitly state, that the 100-year value should be preferred to the 20-year value and that “there is no scientific argument for selecting 100 years compared with other choices” (Myhre et al. 2013, 53).

start of observing increasing CH_4 levels) (Fletcher and Schaefer 2019). While scientists still debate whether the increase is based on anthropogenic measures or already caused as climate feedback, there is strong consensus that the high values endanger the achievement of the goals of the Paris agreement (IPCC 2018).[14] Depending on the origin of the methane, e.g. shale or conventional natural gas, coal (surface mining, vs. deep mining) and other energy sources, fossil natural gas turns out to be more climate damaging than both coal and oil in many cases.[15] Thus, instead of treating natural gas as clean, it needs to be treated as “dirty“, e.g. for the EU taxonomy on green finance (Box 3).

Box 3: EU Taxonomy on green finance: Natural gas has become a “dirty” fuel.

Tightening greenhouse gas emission budgets have prompted discussion on the taxonomy within the European Union, i.e. what should be considered “clean” technologies for sustainable financing. In order to steer private investment towards "green technologies" and avoid greenwashing, the EU Taxonomy, a central part of the EU “action plan on sustainable finance” in the course of the EU Green deal, is developed. The EU sustainable finance taxonomy excluded natural gas for power generation in its 2020 draft from getting cheap money from the capital markets to ensure sustainable financing (EU TEG 2020). Reacting on this announcement, the fossil natural gas industry was concerned about the development and called for corrections to be made. They raised up the discussion again whether switching a fossil-sourced fuel (diesel, coal etc.) installation to natural gas can be designated as “green” and should therefore be listed as “green” in the EU taxonomy list.[16] Based on these developments within the EU and how ambitious the natural gas industry is in the discourse, it becomes clear that the fossil industry is making attempts to maintain its business models and infrastructures which is expressed in highlighting the introduction of a new category of “transitional activities” (EU TEG 2020, 56) in the taxonomy. The taxonomy “may be open to interpretation in some cases”, as stated by the Technical Expert Group in the technical report. Also the tier of making “neither substantial contribution nor significant harm” to the climate targets of the EU clearly bears the signature of the fossil fuel industry.

The tighter climate budgets have also accelerated decisions within the European Investment Bank (EIB) not to finance fossil-based fuels anymore.[17] Even though the fossil natural gas industry is contesting this trend, it shows that the framework conditions for the industry have substantially changed. However, one success for the extension of the fossil era can already be demonstrated. It has been enforced that CCTS is qualified as green in the EU taxonomy, which opens the door for so called “decarbonized gases”.

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[14] Already in 2012, Shindell et al. (2012) highlighted the importance of reducing methane emissions in relation to global warming. They found that the average global mean temperature will “increase by 1.5 degrees by about 2030 and 2 degrees by 2045” regardless of the development of the CO_2-emissions, if methane and black carbon emissions are not immediately reduced significantly”. In addition to coal and methane, black carbon emissions also need to be reduced.

[15] Howarth (2014, 2015) provides a range of estimates of the greenhouse gas footprint indicating that taking into account the entire value chain, shale and conventional natural gas have higher CO_2 equivalents per MJ than coal or diesel oil for heat generation and electricity production, respectively.

[16] See: https://www.euractiv.com/section/energy-environment/news/gas-industry-storms-into-eu-green-finance-taxonomy-debate/

[17] See: https://www.euractiv.com/section/energy-environment/news/eib-begins-metamorphosis-into-climate-bank/

3.3 Overview of fossil natural gas and other colorless energy gases

Can the fossil natural gas industry still be saved, e.g. by referring to other gases as substitute? This narrative of the "decarbonized green gas" is now increasingly adopted and implemented by the gas industry to justify the continuation and expansion of fossil natural gas infrastructure such as fossil natural gas-fired power plants, pipelines and LNG-terminals, and to maintain old, centralized energy supply systems and related business models. The narrative of decarbonizing the fuel itself and step-by-step displacing fossil natural gas by hydrogen-blended or decarbonized gases, while relying on established and existing infrastructure and business models, was established in pathways strategies for reaching 80-95% GHG reductions or even "climate neutrality". Such attempts can be observed, among others, in the calculations of the latest dena-study scenarios (dena 2018) for meeting the German climate targets[18], which states by far the highest shares of synthetic methane until 2050.[19] A report by the Energy Watch Group which used updated values for methane emissions from Howarth (2019) has shown that the methane emissions in the natural gas system have been drastically underestimated and that fossil natural gas does not contribute to climate protection (Traber and Fell 2019).[20] This also implies that the use of methane, whether it is from fossil natural gas or synthetic is not compatible with effective climate protection because upstream- and downstream emissions will remain.

The debate about "decarbonized" gases and their role in the future energy system is often very vague. The reason for this is that there is often no clear distinction between hydrogen, synthetic methane or hydrogen blended fossil natural gas when dealing with the term "green gases". However, the gases differ significantly in terms of both use and production as well as their impact on the climate. Figure 4 shows an overview of energy gases, including their extraction and production. Hydrogen, as the basis for synthetic methane, is produced from fossil hydrocarbons (mainly via steam reformation of natural gas) or by electrolysis of water (with fossil or renewable electricity). Methane, the main component of fossil natural gas, has its origin in natural gas reserves or can be produced by methanation of hydrogen or by the fermentation or gasification of biogenic substances. Another attempt to decarbonize gas is the steam reformation with fossil fuels: For this, fossil natural gas is reformed (or thermal cracked in the future[21]) and the resulting CO_2 is (not completely) captured and injected into old offshore gas fields. This process is also known as CCOS (Carbon Capture and Offshore Storage) (Kim et al. 2016; Cumming et al. 2017).

The conventional fossil natural gas industry has successfully invented a nomenclature of colors to support its argumentation that gases can become "green", i.e. decarbonize. Thus, when the term "green

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[18] 80-95% emission reduction in 2050 compared to 1990, defined by the German government in 2010 (BMWi and BMUB 2010).

[19] When calculating the energy- and processed-based emissions, upstream emissions are not even included. Further, the CO_2-factor for imported synthetic fuels is considered as 0 and thus, emissions from synthetic fuels (production and transportation) are outsourced and not included, because they are considered as CO_2-neutral. Even if (not yet existing) direct air capture (DAC) is used for the provision of the CO_2, needed for the methanation, direct methane emissions to the atmosphere from leakages and process-based ventilations will remain.

[20] According to the estimates of the Energy Watch Group, three to 4.5 percent of the gas is lost in fracking gas, while other researchers consider a loss of six percent possible. It is only more climate-friendly than coal piles if less than 3.2 percent of the gas escapes.

[21] See: https://www.springerprofessional.de/betriebsstoffe/verfahrenstechnik/kit-forscher-wollen-methanpyrolyse-industrialisieren-/17334598

gas" is used by decisions-makers and in future strategies, they mainly consider both, methane and hydrogen, which are synthesized via electrolysis and subsequent methanation with the use of renewable energies and is therefore framed as "green". This two-step procedure is referred as Power-to-Gas (PtG) process (Götz et al. 2016). In a third process, the synthetic gas can be converted to a liquid fuel by Fischer-Tropsch synthesis, known as Power-to-liquid (PtL). Likewise, hydrogen from natural gas steam reforming is named "blue" hydrogen. However, the discussion about the "50 shades of gas" is misleading, and often misused to argue for a dominant role for the incumbent natural gas industry. We suggest to refrain from this taxonomy, and to rely on a technical description of the origin and the processes of the gas in question.

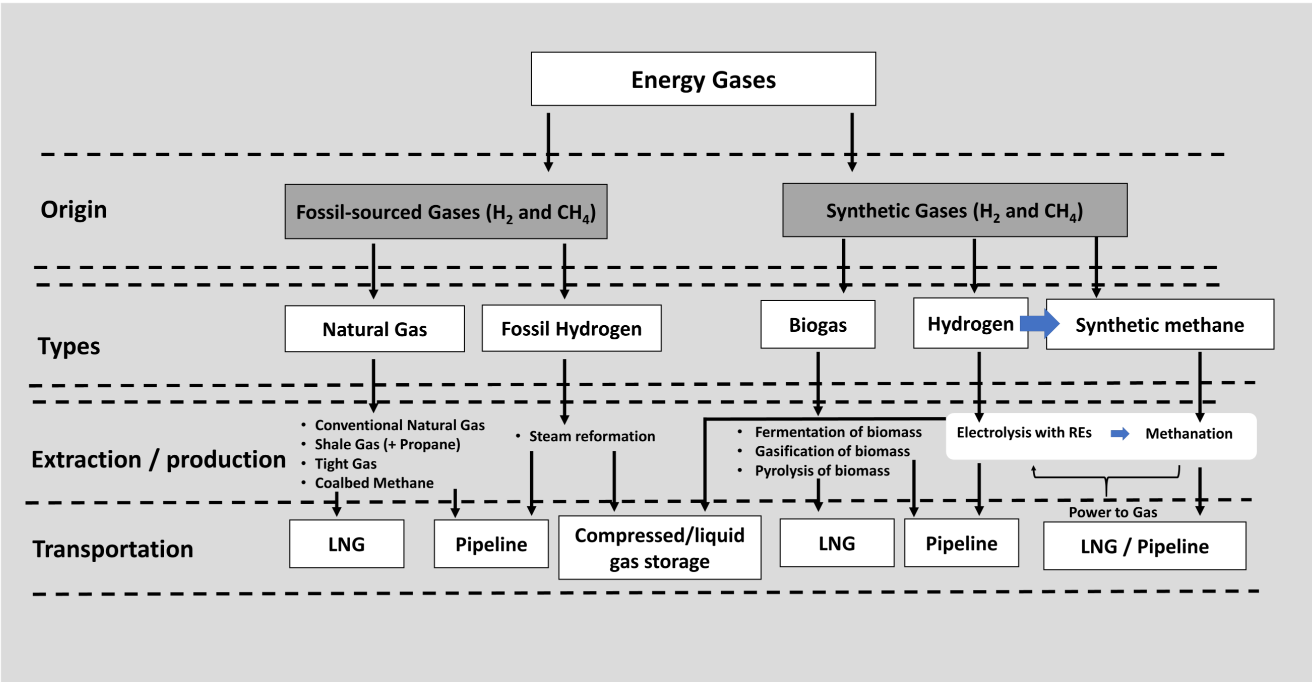

Figure 4: Overview of energy gases.

Source: Own illustration.

3.4 Hydrogen-strategies or Power-to-methane

Let us take a look at a concrete example of an energy gas, produced from electricity and "X", and called "power-to-X", here with a focus on methane. We look at synthesized methane from the power-to-gas (PtG) processes, a gas omnipresent in the decarbonization strategies of the European energy system (EEA 2018; EC 2016; European Commission 2018; ENTSOG and ENTSO-E 2019). A major problem of PtG processes is that the efficiencies of the processing steps are very low.[22] As an overview of the

[22] The electrolysis processes have efficiencies of 67 – 82%, depending on applied technology; chemical methanation processes have a maximum efficiency of 86%, while in practice rather efficiencies of 80% are achieved. Overall efficiency of PtG processes (excluding reconversion) are given with 53% (median from literature) and 55% (median from pilot projects), see Milanzi, Sarah, Carla Spiller, Benjamin Grosse, Lisa Hermann, and Joachim Müller-Kirchenbauer. 2018. "Technischer Stand und Flexibilität des Power-to-Gas-Verfahrens," August, 30.

energy intensity, Sterner et al. (2015) give a range of methane yield from power-to-gas from 0.24 – 0.84 kWh per 1 kWh of electricity.

The high energy conversion losses are a reason for preferring and prioritizing the direct use of electricity, e.g. battery electric vehicles (BEV) or electrical heat pumps to PtG and PtL.[23] Against this it is usually argued that low efficiencies are compensated using excess electricity, which is generated by the increasing renewable energies capacities. A look on the German electricity system, which is characterized by a high share of renewable energies, yields a different picture: Different studies related to the German energy system show that PtG-facilities cannot be run economically just by the use of excess electricity (Brynolf et al. 2018).[24] These facilities need high annual full load hours and thus high and continuous shares of excess electricity.[25] Absent significant overcapacities of renewables, prominent European and German scenarios for reaching CO_2-emission reduction targets are based on considerable amounts of imported synthetic gases and fuels from third countries (ENTSO-G 2019, 101, 132; ENTSOG and ENTSO-E 2019; EC 2016; BCG and Prognos AG 2018; dena 2018).

Clearly technical, economic and geopolitical challenges are immense. PtG is very expensive, and non-European countries have no capacities, and often not the political will to produce energy-intensively synthetic fuels to provide energy to Europe. Export potentials are low, or inexistent, in North Africa, South America, and Asia. The conversion process also plays an important role. For the electrolysis, only water and electricity are needed. The methanation process requires in addition to renewable electricity (for the required heat generation) pure CO_2. In order for the process to be theoretically CO_2-neutral, the CO_2 used has to be taken from the air (direct air capturing, DAC) (Goeppert et al. 2012) or from biogenic sources that have to regrow to the same extent in order to bind the same amount of CO_2 from the atmosphere. The energy balances of the whole life-cycle process as well as potentials for biogenic sources and upcoming conflicts with agricultural lands are rather at the beginning of the discussion but not implemented in the evaluation of these technologies. This is to be seen critically in so far as synthetic fuels are treated as CO_2-neutral in decarbonizing scenarios (see e.g. European Commission 2018, 54, 65, 67, 70).

3.5 Carbon Dioxide Removal (CDR) no technical nor economic solution

The narrative of “decarbonizing methane” strongly relies on the hope that some form of carbon dioxide removal (CDR) becomes available in the near future. The Stern papers state this condition several times,

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[23] See: https://www.zeit.de/mobilitaet/2020-03/e-fuels-treibstoff-synthetik-nachhaltigkeit-umweltschutz based on Kasten, Peter. 2020. “E-Fuels im Verkehrssektor.” Kurzstudie über den Stand des Wissens und die mögliche Bedeutung von E-Fuels für den Klimaschutz im Verkehrssektor.“ "To replace one percent of today's consumption of fossil fuel in the transport sector (30 PJ) with e-fuels, 2,300 onshore wind turbines would be needed for its production in Germany”. "To produce synthetic fuel for a distance of 100 kilometers, we need the same amount of electricity as is needed for 700 kilometers in a battery-powered car"

[24] For Germany, see also Agora Verkehrswende, Agora Energiewende, and Frontier Economics. 2018. “Die zukünftigen Kosten strombasierter synthetischer Brennstoffe,” March, 100; and Drünert, Sebastian, Ulf Neuling, Sebastian Timmerberg, and Martin Kaltschmitt. 2019. “Power-to-X (PtX) aus „Überschussstrom“ in Deutschland – Ökonomische Analyse.” Zeitschrift für Energiewirtschaft, August 2019.

[25] The large amounts which would be needed for large-scale production of synthetic fuels are simply not existing. In 2017, excess electricity in Germany accounted for 5.5 TWh (0.8% of total electricity generation) and is projected to 10 – 20 TWh/a and 20 – 50 TWh/a in 2030 and 2050, respectively (BMWI Energiestatistik).

quite clearly: “To maintain anything close to the scale of the gas market in the late 2010s, even the highest estimates of biogas, biomethane, and power to gas would need to be supplemented with the reforming of methane into hydrogen, accompanied by carbon capture, utilization, and storage“ (Stern 2019, 8).[26] Until recently, this hope focused on carbon capture, transport, and storage (CCTS), before diversifying into bio-CCTS, CCTS with carbon use (CCTUS), and other forms.

However, the high hopes placed on CDR technologies are technically unfounded, economically out of reach, and can only be explained by the desire to maintain fossil fuels alive as long as possible. In fact, since the beginning of this century, CCTS has been highly traded for the solving of problems with fossil fuel CO_2 emissions while not making any notable progress in reality. A decade ago, we have identified the first decade of the 21st century as a “lost decade” (von Hirschhausen, Herold, and Oei 2012). This exercise can now be repeated for the second decade of the 21st century: Until today, the step from small-scale pilot projects to large-scale demonstration plants never succeeded. Contrary to the rather poor performance of CCTS projects in Europe (Table 2), and globally (GCCSI 2018), the concept gained new momentum in the European energy strategies. Most recently as the basis of BECCTS (bioenergy), it also plays an important role in IPCC 1.5°C scenarios, which assume that CDR (mainly BECCTS in previous scenarios) will be used on a large scale from mid-century onwards. Faced with these two failures, instead of giving up the illusion of large-scale CO_2-separation, the most recent invention is direct air capture, transport, and storage (DACTS): Though much more complex and energy consuming than CCTS, DACTS is now considered as the new form of reducing CO_2-concentration (Creutzig et al. 2019).

Table 1 summarizes four phases of the (illusive) quest for CDRs. A narrative taking decarbonization serious should not be built on an inexistent technology with a very low probability of technical and economic success.

At the European level, the European Energy Programme for Recovery (EEPR) and the New Entrants' Reserve (NER300) were set up in 2009 to support the development of CCTS and renewable energies with several billion euros. The European Court of Auditors concludes in a report presented in 2018 that "neither of the programs succeeded to deploy CCS in the EU" (European Court of Auditors 2018, 9). Table 2 gives an overview of European CCTS projects. All 19 projects, with the exception of one planned in 2011, have been discontinued (see also Holz et al. 2018; Mendelevitch et al. 2018). Among the reasons for failing or cancelation were investment uncertainty (European Court of Auditors 2018), technical difficulties, and, most of all, no serious interest from the energy industry (von Hirschhausen, Herold, and Oei 2012). The only two operating large scale CCTS projects in Europe are at the natural gas production facilities Sleipner and Snøhvit in Norway (GCCSI 2018, 22).[27] Even with a very positive view on CCTS (assuming that CC is also included in enhanced oil recovery (EOR) and if new funding

[26] “Large capacity offshore structures - with pipelines leading to those structures - will be required. … Large scale CCS must take place pre-combustion rather than post-combustion “ (Stern 2019, 10); however, “large-scale methane reforming with carbon capture to produce hydrogen for network distribution to residential and commercial customers would be a completely new development“ (Stern 2019, 8).

[27] At both sites, the produced natural gas has a high CO_2 content which is reduced in order to meet export standards in the processing facilities; the separated CO_2 is captured and re-injected into offshore geological formations.

programs are set up), the building rates are way to slow (up to 100 times) with a projected capturing potential of 0.7 Gt per year (Haszeldine et al. 2018) which is just "a drop in the ocean".

Table 1: Four phases of the illusive quest for (Bio-)CCTS.

	1/ Pre-2000 "clean coal"	2/ 2000-2010 "lost decade" for CCTS	3/ 2010 - 2020 "lost decade" for BE-CCTS	4/ 2020 - … DACCTS + geoengineering
CDR-S technology	~ fossil fuel industry, coal dominant ~ IEA program "Clean Coal"	~ failed attempts ~ illusion of CCTS maintained (von Hirschhausen, Herold, and Oei 2012)	~ emergence of BE-CCTS in climate scenarios (Fuss et al. 2018) ~ but: if CCTS does not work, how can BECCTS?	~ Direct air capture: technically possible, but implausible at scale ~ Geoengineering: organizational model unclear
Energy system, renewables as alternatives	~ alternatives inexistent (e.g. low-cost renewables)	~ emerging, but not at large scale	~ breakthrough of renewables, though facing political opposition	~ perhaps well-meaning coalition of climate modelers and engineers (Creutzig et al. 2019)

Source: Own depiction, based on the cited literature.

The focus of the remaining, respectively new, CCTS development projects in Europe is less on conventional power plants with CCTS (exceptions Caledonia Clean Energy and Ervia Cork CCS), but increasingly on industrial applications and hydrogen production. However, almost all these projects are currently in an early planning phase only. According to GCCSI (2018, 19) no further commercial large-scale CCTS projects are planned worldwide until 2024. Despite this rather sobering balance of CCTS in the EU, the hope for a future use of CCTS still receives support in the European Commission (Simon 2019; Keating 2019). CCTS as the basis for BECCTS and DACCTS has an important role in the 1.5°C scenarios of the IPCC but also in this area, implementation cannot be observed (IPCC 2018) and hardly found in the political agenda (Geden, Peters, and Scott 2019).

Today, there is as little perspective for a breakthrough of carbon dioxide removal as there was two decades ago, for which there are several explanations.[28] The implications are clear, though: Even though CDR technologies have not yet disappeared completely from the political agenda, particularly at EU and international level, little has changed in a positive sense in recent years from a technical and economic point of view. The idea of "decarbonizing methane" through carbon dioxide removal is purposely wishful thinking.

4 Insights from energy system models in Europe

Energy system models can provide insights into the dynamics of decarbonization, by allowing scenario analysis, and by comparing results with other models using other assumptions, such as the EU Reference Scenario. Thus, beyond the concrete numbers, we can look at different models for insights

[28] For a detailed discussion see Gibbins and Chalmers (2008) and Braunger and Hauenstein (2020).

on the role of natural gas in the European energy mix. In particular, there is a stark contrast between the use of fossil gas in the “workhorse” of the EU modeling exercises, the “Reference Scenarios” (EC 2013, 2016), and our own energy system modeling analysis (Hainsch et al. 2018, 2020; Oei et al. 2019). Interestingly, this difference focusses less on natural gas itself, but on a difference of assessment of two other elements of the energy system: Nuclear power and carbon dioxide removal (CDR) technologies. If one assumes that nuclear power is very expensive and that CDR technologies are also expensive and the technologies will not be available at scale within the next two decades, then the natural conclusion is that fossil natural gas has no place in a decarbonized European energy system.

4.1 The EU Reference Scenarios

4.1.1 High remaining levels of fossil natural gas …

In the EU Reference Scenarios, which are produced every three years or so by the European Commission to inform the EU energy and climate debate, natural gas plays an important role in the energy mix up to 2050, though it is somewhat diminishing over the past exercises. The two most recent available and fully documented Reference Scenarios (EC 2013, 2016) both include a slight decline in natural gas consumption. However, when compared to the ambition of full decarbonization, this decline is negligible (Figure 5): In the 2013 Reference Scenario, fossil natural gas consumption almost remains constant between 2030 and 2040 (~ 400 Mtoe), before marginally declining towards 2050 (~ 380 Mtoe). The Reference Scenario of 2016 even includes an increase of fossil natural gas consumption in the 2030s.

Figure 6 shows the total energy mix in the 2016 Reference Scenario (EC 2016), in relative terms. Even though the share of fossil natural gas decreases in relative terms (from 14% in 2020 to 8% in 2050), the absolute values remain almost constant, from about 16 TJ (2020) to 15.8 TJ (2050).

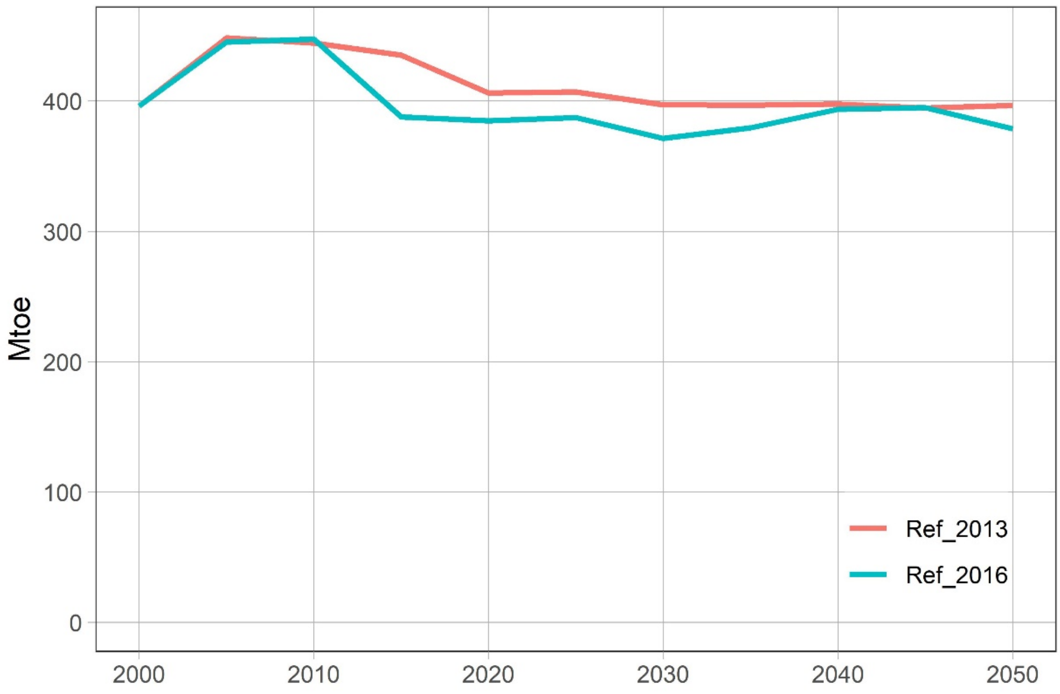

Figure 5: Fossil natural gas consumption in the European energy mix in the EU Reference Scenarios of 2013 and 2016.

Source: European Commission (2013, 2016).

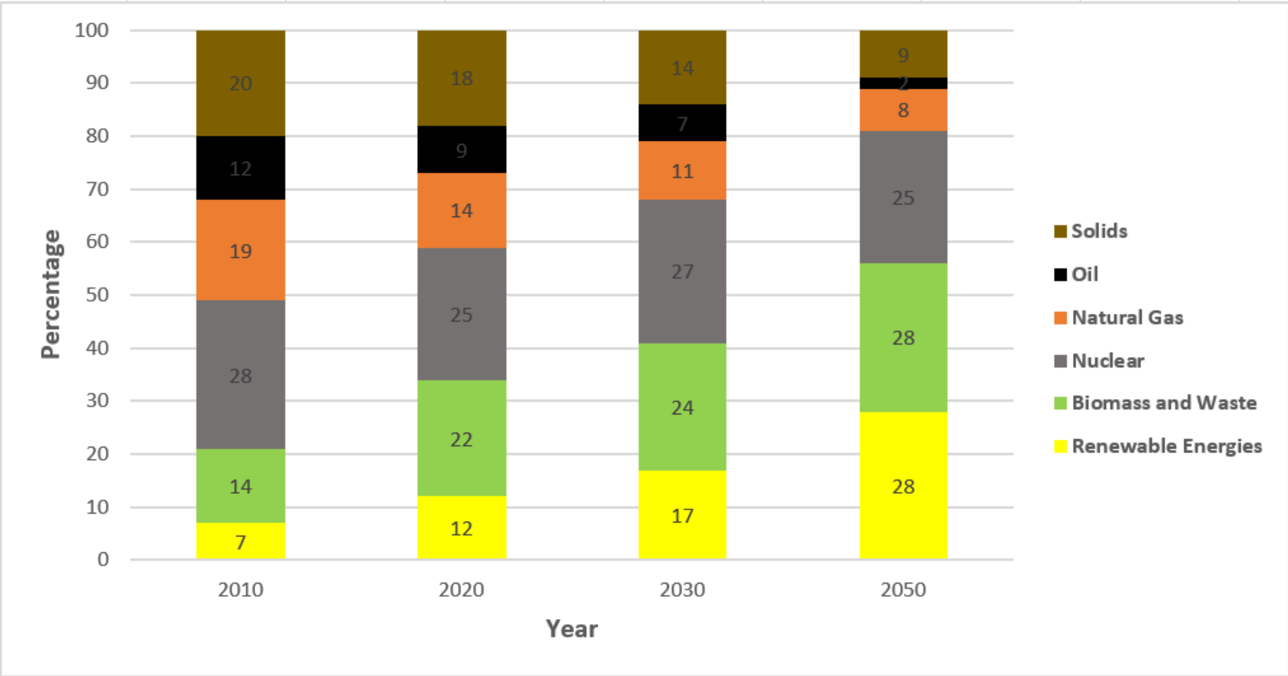

Figure 6: Shares of primary energy production by fuel in the EU Reference Scenario 2016.

Source: EC (2016).

4.1.2 …result from upstream political choices

The EU Reference Scenario is certainly the most sophisticated and comprehensive piece of modeling, the technicalities of which are well recognized in the community (Capros et al. 1998; E3MLab 2018). However, it has always suffered from a serious policy bias that limits its relevance in the current debate on decarbonization: Instead of providing a straight forward optimization of the European energy mix (under certain constraints), the underlying model exercise caters to the institutional setting in which the national energy mix is the sovereignty of the member states, and the EU has no saying about it (Art. 194 paragraph 2 of the TFEU). Thus, the model exercise tries to emulate national priorities as far as possible, to establish a political compromise between member states: Very roughly speaking, this compromise consists of a "triade", three pillars that make up the European "low-carbon" energy mix (Mendelevitch et al. 2018):

- Some remaining fossil fuels, mainly to cater to Central and South Eastern countries hanging on to coal and natural gas (biggest importers are Germany, Italy, Netherlands, France and UK) and - in order to justify this - the ex-nihilo introduction of carbon dioxide removal technologies, here concretely carbon capture, transport, and storage (CCTS), in its pure form, and extended to bioenergy (BE-CCTS),

- a major role for nuclear power in the electricity mix, to cater to the political preferences of the European nuclear powers (UK and France) and some "followers", mainly in Central and Eastern Europe, e.g. the Czech Republic and Hungary,
- a certain share of renewable energies, to cater to the ambitions of countries wanting to rely largely on renewable energy sources, such as Denmark and Germany.

While this modeling exercise cannot be praised highly enough for its technicalities, the political mistake was to have kept this political compromise behind a non-transparent curtain of complex modeling, algorithms, and data. Thus, until today, nobody outside the modelling team itself can trace results of the triade of EU Reference Scenarios (fossil fuels - nuclear - renewables) to the assumptions made upstream. Consequently, the exercise has been criticized for quite some time now (von Hirschhausen et al. 2013; Mendelevitch et al. 2018).

To understand why forecasts for the European energy mix are still showing significant shares of fossil natural gas, despite the fact that the actual consumption was always considerably lower than the forecasts from the Reference Scenarios (European Court of Auditors 2015; Neumann et al. 2018, 246), two results stand out that we have called the "nuclear energy paradox" and the "CCTS-paradox" of the Reference Scenarios. These paradoxes explain how the Reference Scenarios succeed in achieving high levels of decarbonization, while keeping significant amounts of fossil fuels in the system.

4.1.2.1 The nuclear power paradox

The nuclear power paradox consists of establishing quite high rates for this technology going forward, even in the light of its lack of economic competitiveness. There is a broad consensus in the economic literature that nuclear power has never been competitive in economic terms (MIT 2003; Davis 2012; Wealer et al. 2020). Thus, an economic optimization of the European energy system would yield gradually declining nuclear power, with a decrease of 50% by 2025 (Figure 7). By 2050, only the plants built in the 2010s might still be online (Kemfert et al. 2017).

By contrast, the Reference Scenario regularly suggests massive additions of nuclear power capacities in Europe, in addition to lifetime extensions (Figure 8). This result can be explained by the assumption of rapidly decreasing capital costs, and a segment "reserved" for nuclear power in the baseload electricity supply.[29]

[29] For details, see von Hirschhausen Christian von. 2017. "Nuclear Power in the 21st Century – An Assessment (Part I)." DIW Discussion Paper 1700. Berlin, Germany: DIW Berlin (p. 28).

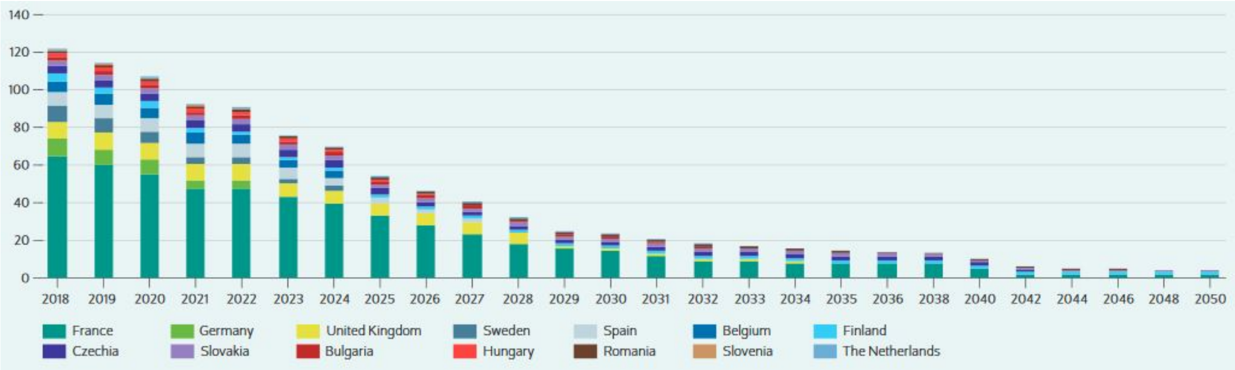

Figure 7: Installed capacities of nuclear power plants in EU-28 and development.

Source: Wealer (2019, 241).

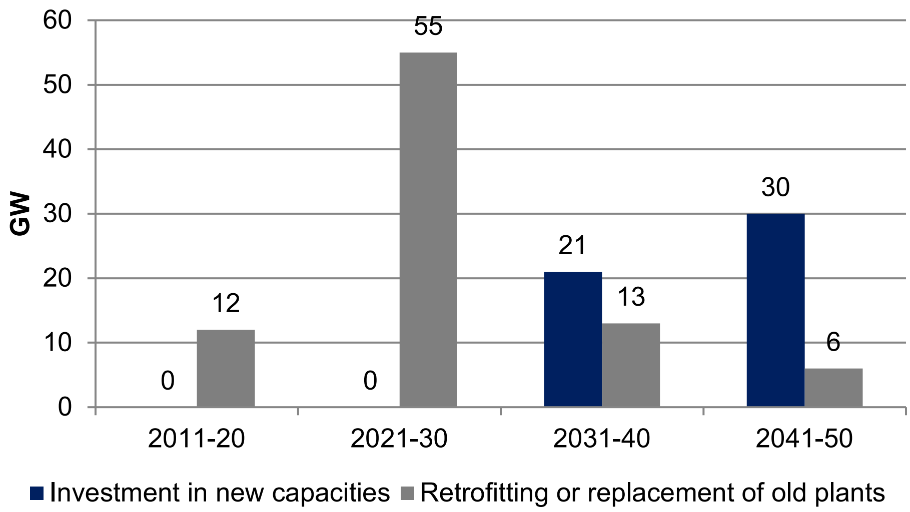

Figure 8: The nuclear power paradox: New-built and retrofit nuclear power plants in the EU 2016 Reference Scenario.

Source: EC (2016).

4.1.2.2 The CCTS paradox

The CCTS paradox consists of forcing a technology into national energy mixes that is neither technically nor economically available. As shown in the previous section, the idea of carbon dioxide removal technologies is wide spread for some time, but neither technologically nor economically founded. Nonetheless, the Reference Scenarios succeed in introducing CCTS somewhat "magically".

In this context, we identify a "CCTS paradox" in the Reference Scenario, which consists in defining – ex nihilo – some CCTS capacity for some Member States: Thus, in the 2013 exercise one finds CCTS capacities of 900 MW for 2020, and not less than 38,410 MW until 2050 (EC 2013, 87). Then, in 2016, the Netherlands and the UK were supposed to have a total of 833 MW by 2020, and 19,253 MW by 2050 (EC 2016, 144). Even the latest exercise, the "Clean Europe" package, includes CCTS in the 1.5° scenario (European Commission 2018).

Table 2: Failed CCTS projects in Europe.

Project	*Jänschwalde*	*Porto-Tolle*	*ROAD*	*Belchatow*	*Compostilla*	*Don Valley*	*Killingholm (C-GEN)*	*Longannet Project*	*Getica*	*ULCOS*	*Green Hydrogen*
Country	DE	IT	NL	PL	ES	UK	UK	UK	RO	FR	NL
Technology	Oxyfuel	Post	Post	Post	Oxyfuel	Pre	Pre	Post	Post	Post	Pre
Storage	Aquifer	Aquifer	Oil-/ gasfield	Aquifer	Aquifer	EOR	Aquifer	EOR	Aquifer	Aquifer	EGR
Capacity [MW]	250	250	250	260	320	650	450	330	250	Steel	H_2
Plan in 2011	2015	2015	2015	2015	2015	2015	2015	2015	2015	2016	2016
Status in 2018	canceled 2011	canceled 2014	canceled 2017	canceled 2013	canceled 2013	canceled 2015	canceled 2015	canceled 2011	canceled 2014	canceled 2012	canceled 2012
	White Rose (UK Oxy)	*Peel Energy*	*Peterhead*	*Teesside (Eston)*[30]	*Eemshaven*	*Pegasus*	*Maritsa*	*Mongstad*	*Caledonia Clean Energy*[31]	*Norway Full Chain CCS*	
Country	UK	UK	UK	UK	NL	NL	BG	NO	UK	NO	
Technology	Oxyfuel	Post	Post	Various	Post	Oxyfuel	Post	Post	Post	Various	
Storage	Aquifer	Oil-/ gasfield	Oil-/ gasfield	Aquifer	EOR	Oil-/ gasfield	Aquifer	Aquifer	Aquifer/EOR	Aquifer	
Capacity [MW]	430	400	400	0.8 Mtpa	250	340	120	630	3 Mtpa	1.3 Mtpa	
Plan in 2011	2016	2016	2016	2016	2017	2017	2020	2020	-	-	
Status in 2018	canceled 2016	canceled 2012	canceled 2015	mid 2020s	canceled 2013	canceled 2013	canceled 2013	canceled 2013	2024	2022	

[30] Power plant with CCTS canceled in 2014, now industrial park collective.

[31] Formerly Captain Clean Energy.

4.2 The European energy mix with full decarbonization

4.2.1 Energy system wide analysis

This subsection contrasts the EU Reference Scenarios (including plenty of remaining fossil natural gas) with results from a modeling exercise where decarbonization is fully implemented. We will show that assuming a zero carbon future is equivalent to exiting not only from fossil coal, but also from fossil natural gas and fossil oil. This raises the question when the fossil natural gas exit will occur.

In this section we report results generated from the Global Energy System Model (GENeSYS-MOD), a comprehensive linear optimization model determining lowest-cost energy mixes under provided pre-determined constraints (such as the amount of greenhouse gas emissions). GENeSYS-MOD was developed by a group of graduate students and researchers in Berlin, based on a predecessor model called OSeMOSYS, the Open Source Energy Modeling System (Howells et al. 2011). GENeSYS-MOD has adopted the open-source approach of OSeMOSYS, and, hence, provides both modeling code and results freely in an easily accessible form (Löffler et al. 2017). The results presented hereunder are obtained from the model version GENeSYS-MOD 2.0, as laid out in detail in the DIW Data Documentation (Burandt, Löffler, and Hainsch 2018), and applied in a recent study on the energy and macroeconomic implications of the European Green Deal (Hainsch et al. 2020). Concretely, a scenario compatible with the Paris Climate Agreement was developed, based on a storyline of "societal commitment" to a circular low carbon economy.[32]

As a generic energy system model, GENeSYS-MOD does not have any regional focus, but can be applied at the level of a rural community, as well as at a global level. The European version of GENeSYS-MOD that we refer to here was applied throughout the EU-27 countries plus the UK, Norway, Switzerland, Turkey and the Balkan region (Figure 9). The energy system modelled, shown in Figure 10 from which the use of natural gas can also be deducted, is structured as follows: Energy supply by conventional and renewable sources (column at the left) is linked to the demand sectors (electricity, heating, transportation) through a variety of conversion processes. A high-voltage electricity grid connects the nodes. Particular attention was given to the representation of storage technologies (center of the figure): The temporal disaggregation consists of 20 time slices, i.e. four seasons of the year, combined with four daily time brackets. Energy demand is exogenous; the model minimizes the costs of the energy system, in five-year time steps, from the base year 2015 to 2050.[33]

[32] The "Paris" scenario was developed and quantified in the process of the Horizon-2020 project "openENTRANCE", as explained in detail by Auer (2020) and summarized in Hainsch (2020, 3–5).

[33] An online manual is under preparation; an extension to 2100 is planned; the model does not (yet) cover the agriculture sector and non-energy use, e.g. of natural gas for fertilizers.

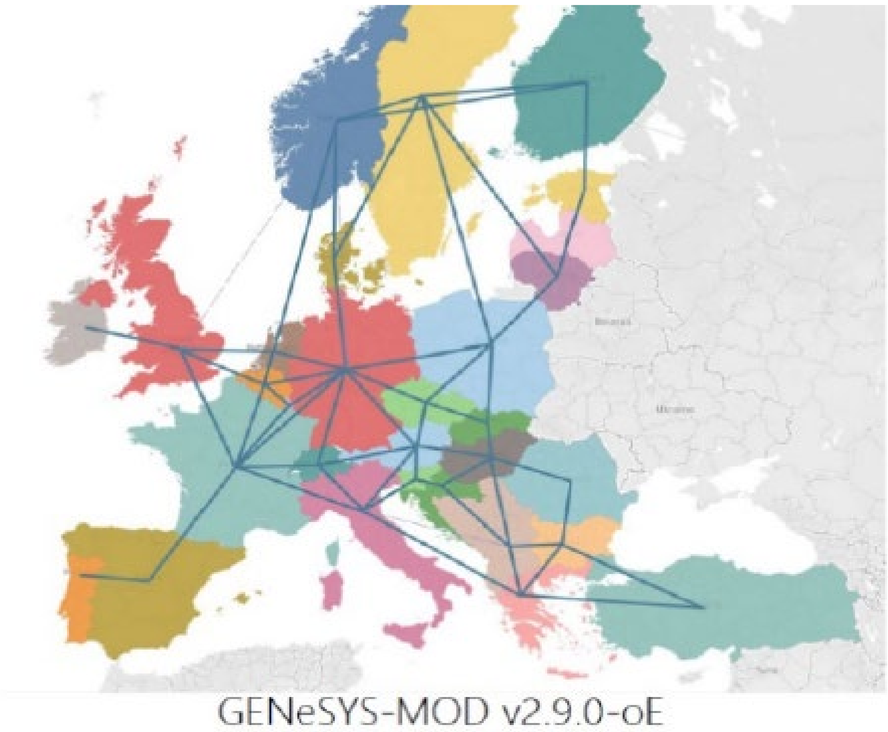

Figure 9: Regional specification of the European energy system in GENeSYS-MOD.

Source: Auer (2020, 25).

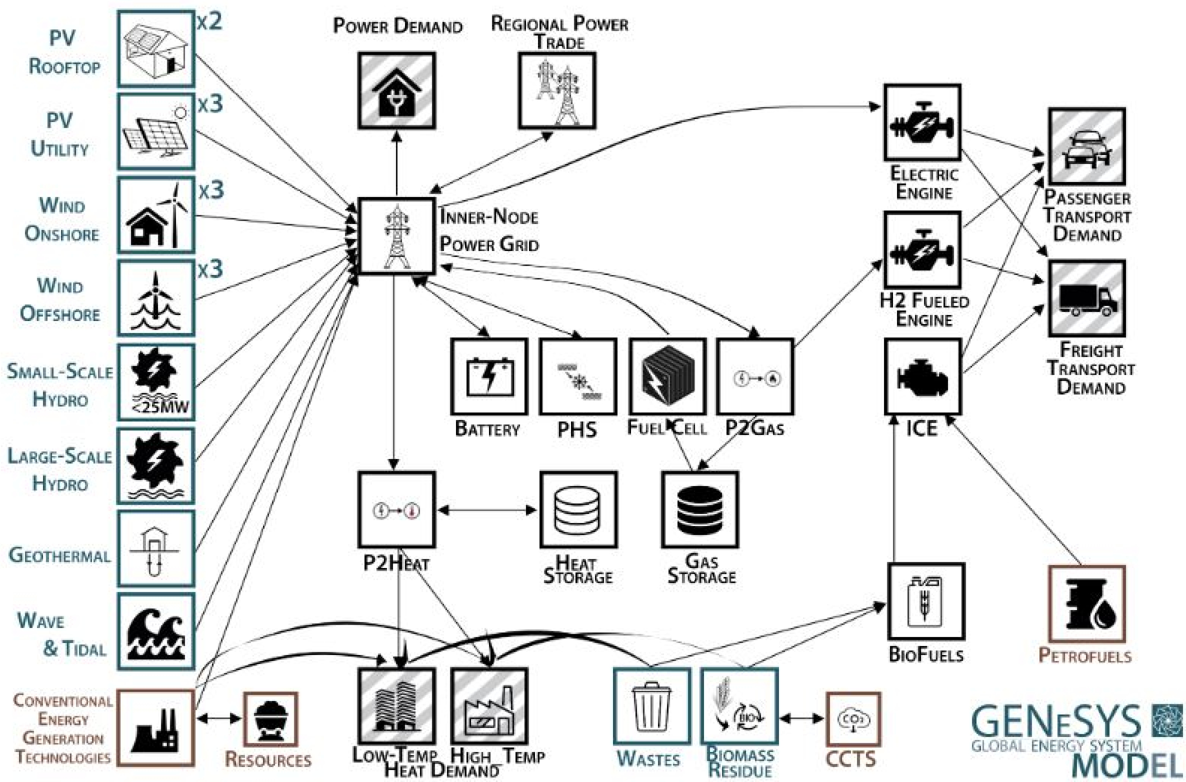

Figure 10: Stylized model structure of GENeSYS-MOD v2.0.

Source: Burandt, et al. (2018).

The modeling results are aligned to the European decarbonization strategy and to the objectives of the Paris Climate Agreement, targeting a reduction of the increase of the global mean temperature to below 2°, and as close as possible to 1.5°. This scenario will be called the “Paris”-scenario; it corresponds in the approach to a modeling exercise done for the next round of European infrastructure planning, the PAC-scenario (Paris Agreement Compatible, see (CAN Europe and EEB 2020)). The model optimizes the European energy system as an aggregate, so that national carbon objectives are not respected, and may be violated, for the benefit of overall cost minimization (“free distribution”). It is therefore assumed that the allocation of the remaining emissions is not predetermined and, in this ideal case, can be freely allocated to the individual generation sites by a central planner to find the cost optimal solutions.

Further it should be noted that the model calculations do not include upstream methane emissions (see Section 3) as far as just CO_2 emissions from stationary combustion are taken into account. If methane emissions from upstream processes over the entire life cycle were taken into account, natural gas exit would occur much earlier, as these emissions would additionally burden the available CO_2 budget (Howarth 2015). Since excluding greenhouse gas emissions over the entire life cycle is the weak point of all known integrated energy assessment models, there is still a considerable need for research and development in this area.

4.2.2 Rapid fossil natural gas exit

Figure 11 shows the European energy mix for the Paris-scenario, with exogenous (and inflexible) final energy demand, for the period 2015 - 2050. Fossil fuels are phased out at a significant rate and are replaced by renewable generation technologies, mainly wind and photovoltaics. Therefore, high degrees of electrification are required across all sectors with fuels produced through electricity (e.g. hydrogen, H_2) complementing where direct electric solutions are not available. This leads to an overall reduction of primary energy demand since electricity-based technologies offer higher efficiencies than the combustion of fossil fuels. Fossil gas remains as the last fossil energy carrier until as late as 2040, while wind onshore gains significantly in importance in early years and is complemented by increasing amounts of solar photovoltaics. Hydropower and biomass stay relevant across all periods, though their role does not change meaningfully since their potentials are already today almost being completely used.

Figure 12 zooms in on the trajectory of fossil natural gas consumption in Europe in the Paris-scenario, taken from the above primary energy consumption results. The trend is clear: From the 28 Exajoule used in the base year 2015, consumption is reduced linearly-hyperbolically in ten-year steps, to about 60% of it (16 EJ) in 2030, and down to 0 in 2040.[34] According to this scenario, by 2040 fossil natural gas will have disappeared from the energy mix.

[34] Note that these values refer to “Europe” (including Turkey) and therefore do not correspond to EU-consumption figures by Eurostat.

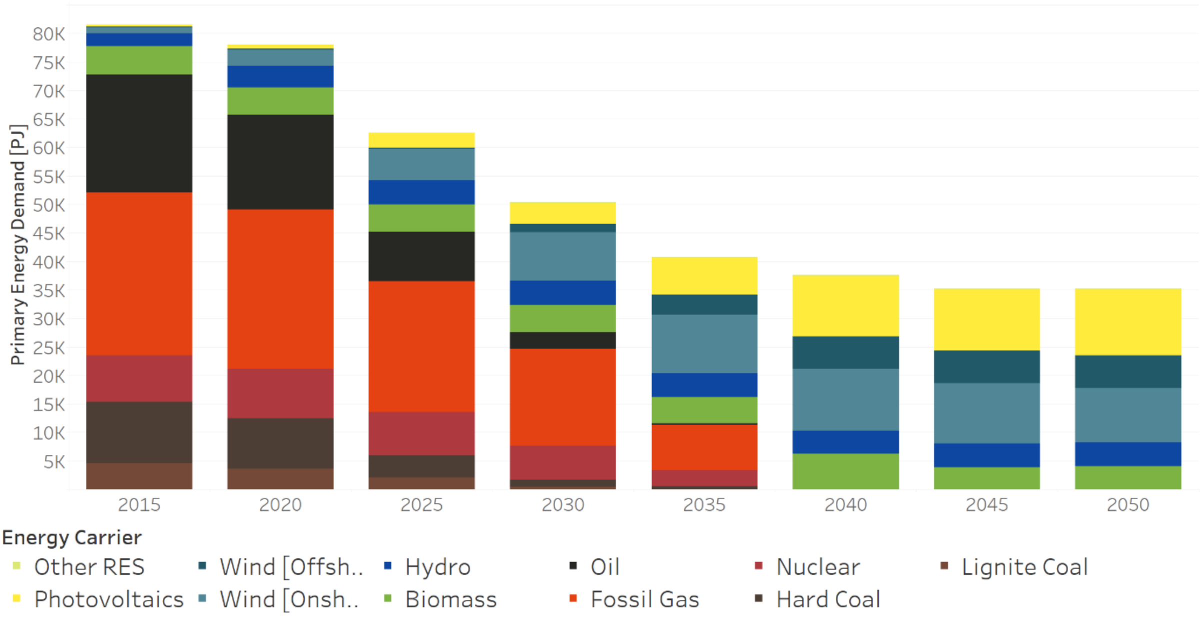

Figure 11: Primary energy demand in Europe in the climate scenario Paris (2015-2050).

Source: Hainsch et al. (2020, 9).

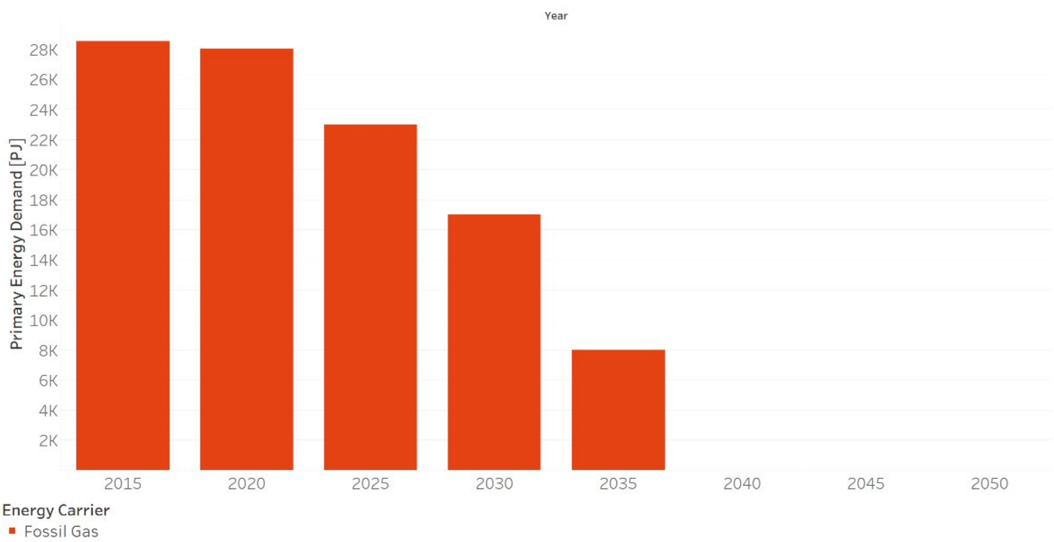

Figure 12: Total production of fossil gas in Europe in the Paris-scenario (2015 – 2050).

Source: Hainsch et al. (2020, 9).

CO_2 emissions decrease drastically, as compatible with the Paris Agreement, as shown in Figure 13. The electricity sector leads the way, followed by the industry, buildings, and transportation sector.

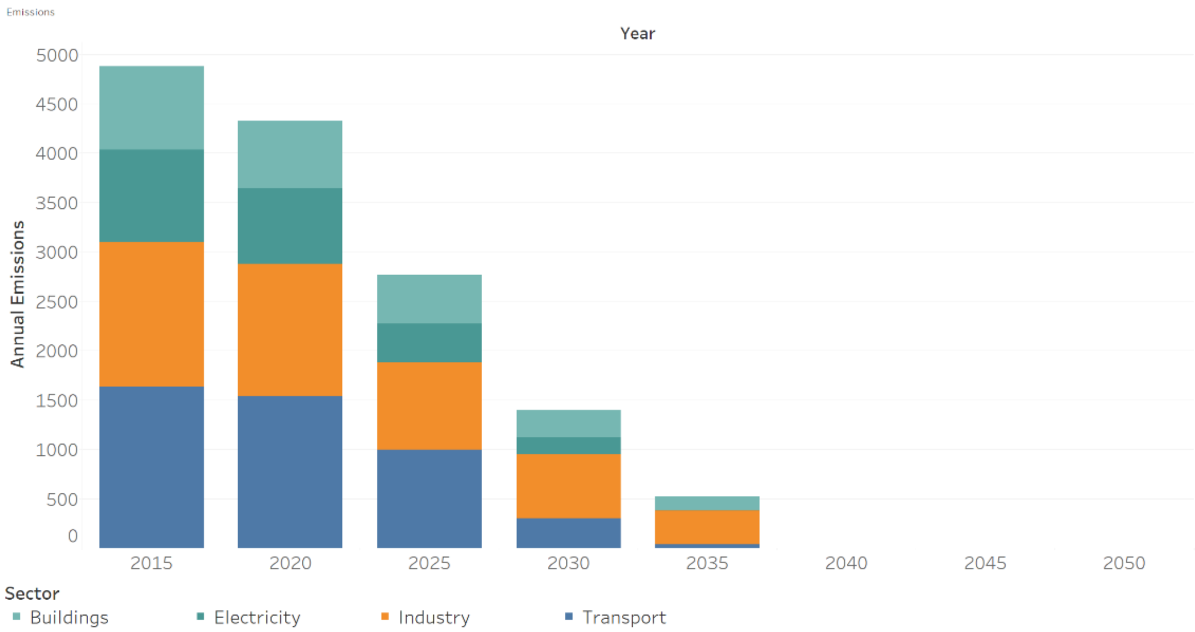

Figure 13: CO_2-emissions in the climate scenario „Paris".

Source: Hainsch et al. (2020, 10).

4.2.3 Fossil gas exit by sector

Without being fully comprehensive, the following charts provide some insights how the fossil natural gas exit may look like in each of the relevant sectors as it is in the concrete sectors where carbon (and other) constraints must be translated into transformed energy mix. Figure 14 shows the electricity mix in the Paris-scenario for Europe. Clearly, and confirming other modeling work, the decarbonization of the electricity sector is relatively "easy" (translated into "cost efficient"), so that the fossil fuels, including natural gas, disappear earlier, i.e. in the 2030s already. In the competition between the renewables, onshore wind dominates, particularly over offshore wind that comes in only marginally at the end of the period. Solar grows at similar rates as onshore wind, though from a lower basis, and thus trails behind onshore wind.

Figure 15 provides some evidence from what may become the most critical sector for the natural gas exit in some countries, the low-temperature heat sector. In fact, as evidenced in the 2015 base bar, fossil gas is by far the dominant incumbent, with almost two thirds of the total low-temperature heat demand. However, under a strict carbon constraint, electrification of the heating sector takes over rapidly: By 2030, the relation between natural gas and electricity is inversed, and natural gas is phased out completely by 2040. The model calculations also suggest that by 2050, about 15% of low-temperature heat will not be electrified and will come from bio-production and perhaps synthetic gas. High-temperature heating for the industry is largely produced by electricity, or to a small extent using biogas and hydrogen (Figure 16). This is a sector where natural gas exit is prominent, as there were high hopes to gain market shares.

Passenger transportation is quite easy to decarbonize, mainly by electric vehicles on rails and roads. Some hydrogen may be used for road traffic and aviation (Figure 17). Last but certainly not least, Figure 18 shows representative model results for freight transport services, besides residential heating the other segment in which proponents see significant growth potential for fossil gas. Similar to the heating sector, energy demand for freight transport is slightly reduced after 2025 (here expressed in ton-kilometers). There is a clear reduction of fossil oils, the share of which is reduced from over 60% in 2015, to below 50% in 2030, and to 0% in 2040 Road freight transport is largely electrified, and shipping is converted to biofuels.

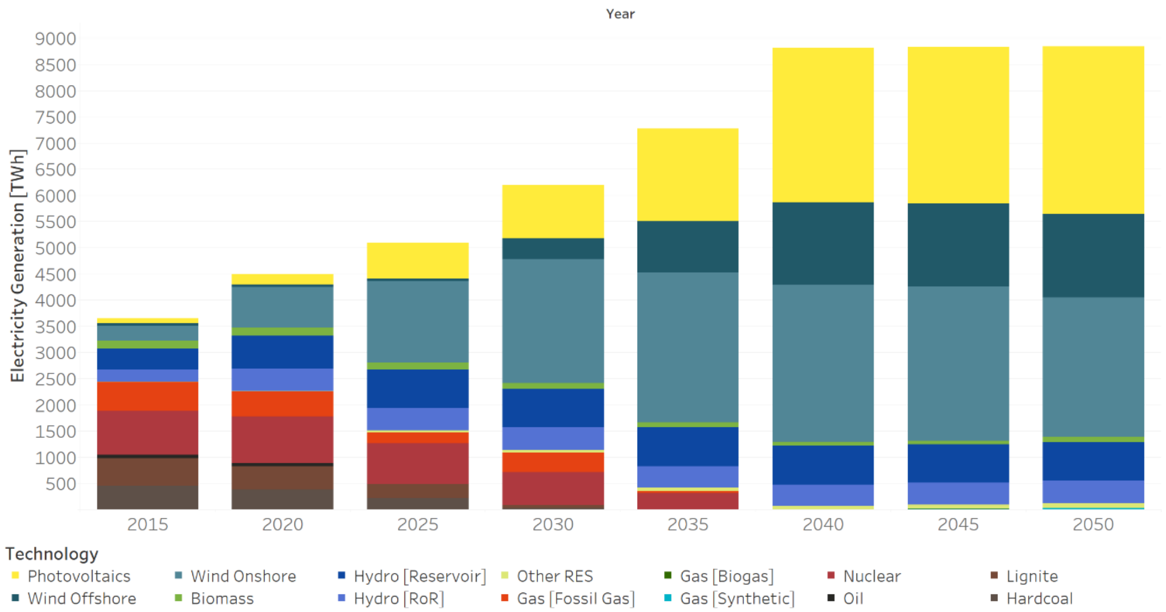

Figure 14: Electricity production in Europe in the Paris-scenario (2015 - 2050).

Source: Hainsch et al. (2020, 10).

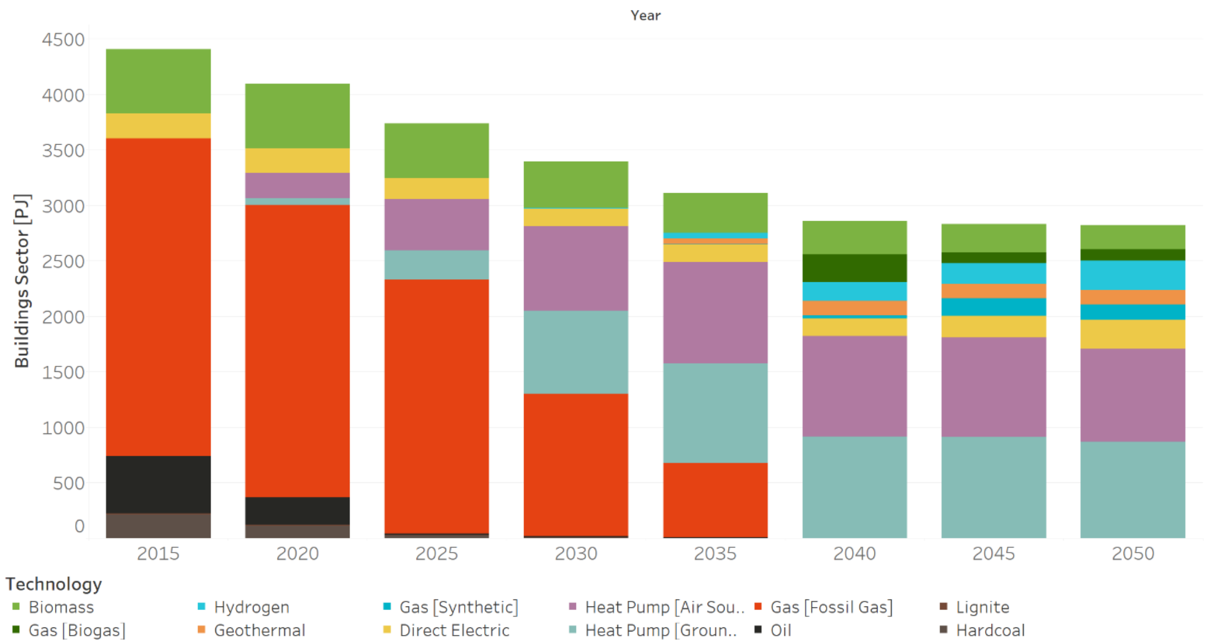

Figure 15: Yearly low-temperature heat production in the Paris- scenario (2015 - 2050).

Source: Hainsch et al. (2020, 13).

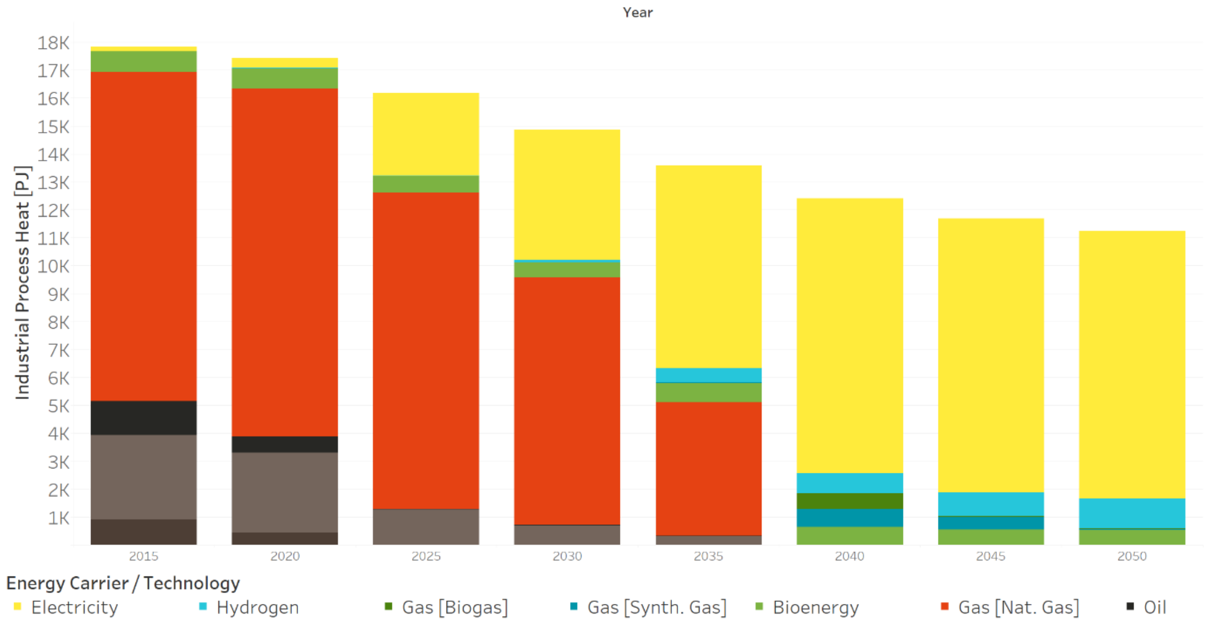

Figure 16: Energy demand for high-temperature heating (until 2050, by technology and fuel)

Source: Hainsch et al. (2020, 13).

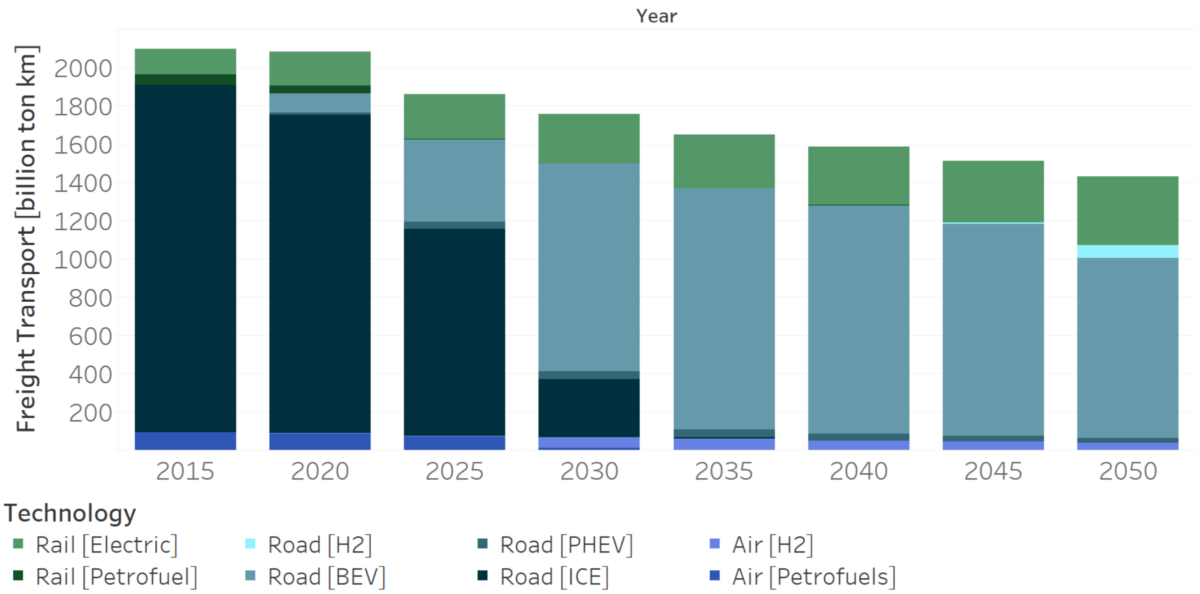

Figure 17: Energy demand for passenger transport (until 2050, by technology and fuel)

Source: Hainsch et al. (2020, 12).

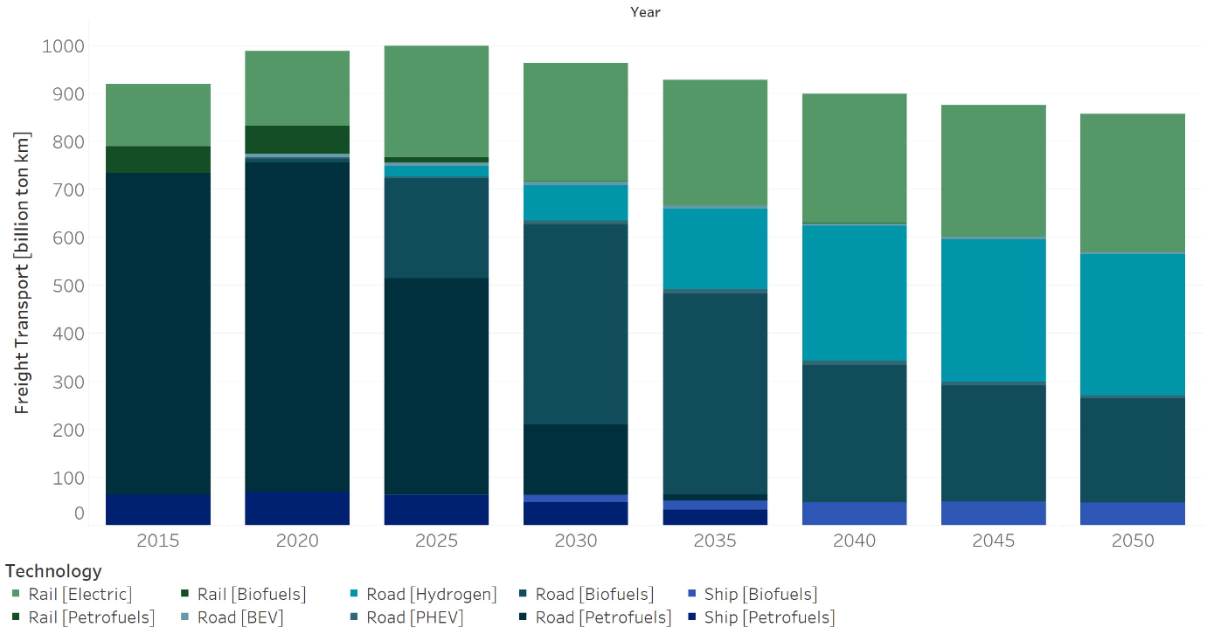

Figure 18: Freight transport services and corresponding energy sources in the 2° scenario (2015 - 2050).

Source: Hainsch et al. (2020, 12).

The model results indicate quite clearly that in a low-carbon energy future, natural gas has no sweet spot any longer in the European energy mix. However, contrary to fossil coal exit, which is relatively easy to target, the fossil gas sector is more complex, both in terms of sectoral use (electricity, heat, transport) and in potential alternatives, including "other" gases that do not rely on carbon. This has important implications on the regulatory accompaniment of the process, that will to a certain extent be sector specific, and in certain cases also country-specific, such as the natural gas phase-out in the Netherlands. Model results suggest that fossil natural gas exit in the electricity sector is easiest to achieve, and will not trail behind coal exit very much, i.e. somewhere between the 2030s and 2040s.

5 Three case studies on potential stranded fossil natural gas assets

If our assumption and model results from the precedent sections are taken as the benchmark, fossil natural gas exit is imminent. It comes as no surprise, therefore, that the fossil natural gas industry itself is searching for strategies to extend its business, and to maintain profits as long as possible. Different strategies exist to deal with assets as diverse as producing and trading of pipeline fossil natural gas and fossil LNG, transmission and distribution networks operation and investment, storage, and regasification. Yet the overall strategy is clearly one of establishing conditions and relations between industry, regulators, and national and European governments to work against the low-carbon transformation of the energy sector, mainly the natural gas sector, and "to create lock-in effects and path dependency to save fossil natural gas as long as possible" (Fitzgerald, Braunger, and Brauers 2019).

The current situation, where an industry doomed to disappear and starts to sink investments to assure short-term survival, is not new, but observed world-wide. The risk, however, both for an outside investor and the state/European regulators, is that the fossil natural gas industry invests in what will become stranded assets in the near future. In this section, we highlight that when taking the decarbonization challenge serious, investing in new natural gas infrastructure is not necessary anymore and is most likely to lead to such stranded assets.

5.1 Nord Stream 2 pipeline project

5.1.1 A controversial project based on natural gas as a "bridge"

The Nord Stream 2 pipeline project is perhaps the most evident case of a stranded asset, where billions of € are sunk in the Baltic Sea without economic justification, based on the idea of fossil natural gas as a "bridge fuel" for Europe.[35] The Nord Stream 2 project consists of the extension and new construction of inlet and outlet natural gas pipelines in Russia and Germany and the main line of two parallel offshore pipelines through the Baltic Sea (Figure 19).[36] The offshore pipeline is largely parallel to the Nord Stream pipeline (approx. 1,200 km). The investment needs for the entire Nord Stream 2 project are estimated at 17 billion USD, about USD 10 of which for the pipe through the Baltic Sea (Sberbank Investment Research 2018). The sole shareholder of this project is the state-controlled Russian natural gas company Gazprom.[37]

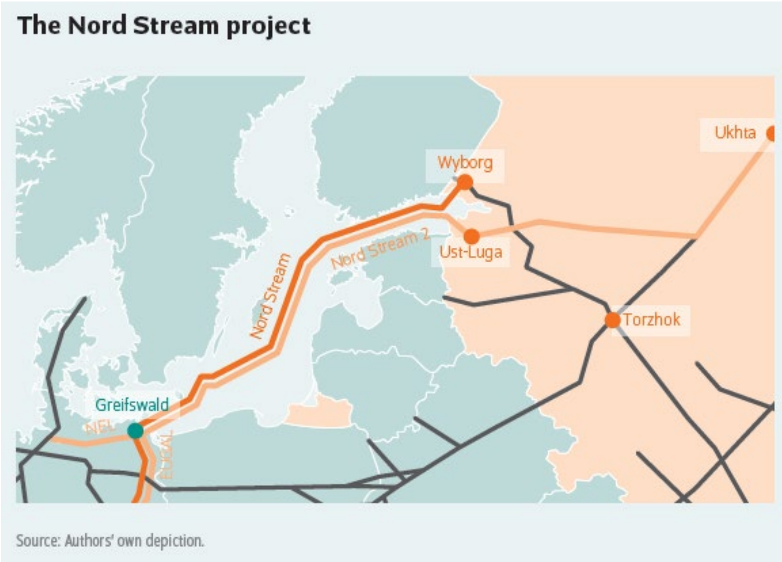

Figure 19: The Nord Stream project.

Source: Neumann, et al. (2018, 242).

The Nord Stream 2 project combines energy, environmental, and geopolitical aspects. Geopolitically, fossil natural gas exports from the Soviet Union to Central and Western Europe have been criticized by the United States since the very beginnings, i.e. the 1960s. After the collapse of the Soviet Union,

[35] This case study relies on Neumann, et al. (2018) and the literature cited.

[36] On the Russian side, a new pipeline from Ukhta to Gryazovets (970 km) and an extension of the Gryazovets-Volkhov connection to the Slavyanskaya compressor station, the entry point to the Nord Stream 2 offshore pipeline, are required.

[37] Although five Western energy suppliers were originally planned as minority shareholders, they were not included in the final ownership structure—unlike in Nord Stream 1 —and are now financial investors: ENGIE, OMV, Shell, Uniper, and Wintershall Dea.

Ukraine became an important transit country, which further increased the politicization of Russian natural gas exports. The dispute over appropriate transit fees has proved increasingly difficult with the growing political conflicts between Russia and Ukraine since 2006. Early on, Russia developed alternative transport corridors to circumvent Ukraine (von Hirschhausen, Meinhart, and Pavel 2005).[38] Since 2014, the disputes over natural gas exports have reached a new quality with the Russian annexation of Crimea and Southeastern Ukraine as well as the subsequent sanctions by the EU and the United States against Russia. Then, in 2019, the US even threatened sanctions on non-Russian companies involved in the project, which lead to a stop of the construction of the Nord Stream 2 pipeline.

While the geopolitical context is important, the analysis will focus on the economic aspects of what we consider a stranded investment. Initially, the justification for the pipeline was to fill a "natural gas gap" identified by several pro-Nord Stream 2 studies (Prognos 2017; ewi ER&S and EUCERS 2016). As laid out in the previous section, the EU-Reference Scenario (2016), too, identified high natural gas demand and import requirements. Thus, the planning documents submitted by the project company Nord Stream 2 argued that the pipeline would strengthen German and European energy security in the long term.[39]

5.1.2 Low revenues, high costs

Given the above model results on fossil natural gas exit, the economics of the Nord Stream project are ill founded and – independently of geopolitical considerations – will lead to stranding of the assets. In fact, the demand suggestions put forward do not at all correspond with the declining share of natural gas in the Paris-scenario sketched out above, where fossil natural gas consumption disappears around 2040. Aside from the broad reception in the scientific community, the structural errors in the EU reference scenario were also criticized by the European Court of Auditors with respect to lack of reliability: "… the Commission has persistently overestimated gas demand [...], and needs to restore the credibility of the forecasts it uses" (European Court of Auditors 2015). While Europe's natural gas supply is already crisis-proof and diversified, demand is likely to diminish, thus leaving no justification for the multi-billion € pipeline.

An accurate investment appraisal of the project is impossible, due to the lack of reliable data; however, both economic and commercial analyses indicate that the pipeline project is far from being profitable:

~ Finn et al. (2017) suggest that Nord Stream 2 cannot be profitable: building the pipeline will not increase Russian natural gas sales in Germany or the EU, and the additional low revenue Nord Stream 2 would bring is offset by very high costs. As a result, no profit can be made from the construction of Nord Stream 2.

~ An analysis from the Russian investment bank Sberbank concludes that Nord Stream 2 destroys rather than creates value (Sberbank Investment Research 2018). The costs of Nord Stream 2 of 17

[38] In 1999, the northern corridor through Belarus and Poland (the Yamal-Europe pipeline) was completed; in 2011, the Nord Stream pipeline, the first direct pipeline connection between Russia and the EU, opened, running from the St. Petersburg area through the Baltic Sea towards Germany.

[39] "The EU's domestic gas production is in rapid decline. To meet demand, the EU needs reliable, affordable and sustainable new gas supplies. The Nord Stream 2 Pipeline will provide this by transporting gas from the world's largest reserves in Russia to the EU internal market." (Nord Stream 2 Website: https://www.nord-stream2.com/company/rationale/).

billion USD, including the supply pipeline from the Russian natural gas network, will be compared with the savings of approximately 700 million USD per year from avoiding transit through Ukraine. Additionally, it is assumed that natural gas sales in Europe will not increase and that the pipeline is operating at 60 percent capacity. Based on these assumptions, the present value of the investment will be negative at six billion USD (approximately five billion EUR).

~ A further indication of the lack of economic viability of the project is the high average cost of transporting natural gas. Our own back of the envelope calculations suggests that the costs for the offshore pipeline would be approximately three to four euros per kilowatt-hour (kWh) for natural gas arriving in Germany. In the first half of 2018, the average price for natural gas in Germany was approximately 20 euros per megawatt hour (MWh); overall, it is assumed that it will increase in the coming years only slightly at most. As a result, the transport costs of Nord Stream 2 alone amounted to about 25 percent of the current price; it is not plausible that Gazprom can enforce these additional costs in a predominantly saturated European natural gas market.

5.1.3 A very likely candidate for stranded assets

Independent of the geopolitical context, which is all but favorable to the Nord Stream 2 project, the investments placed into this pipeline are economically unjustified. Europe has significantly diversified its natural gas supplies, and the demand for fossil natural gas will diminish under a strict decarbonization agenda. Whether the pipeline will eventually be finished or not, economically it has already stranded in the grounds of the Baltic Sea.[40]

5.2 Additional LNG-import terminals along the German North Sea

5.2.1 Three LNG-terminal projects…

The second case study analyzes attempts by the German government to site at least one LNG terminal on the North Sea shore. At present, three projects are being pursued actively, at the sites of Wilhelmshaven, Stade, and Brunsbuettel, respectively, all located on the German shore of the North Sea. The development of these capital-intensive terminals is justified, with supply security, but also with the opportunity to establish local value-added chains, e.g. the supply of fossil natural gas to energy intensive industries in the respective harbors.[41]

At the federal level, the traditional argument of supply security is used to justify a certain need for the first LNG-terminal in the country. In fact, plans to build one go back to the 1970s, but until now, neither the need nor an appropriate business model were in sight to make this happen. With regard to supply security, the German Minister for the Economy argued "the most important aspect is the independence from Russia; and that means LNG infrastructure in Germany."[42] At the local level, it seems that all the sites are pursuing the model of the port of Rotterdam, to become a nexus of resource supply and local

[40] A similar situation, though less drastic, prevails in almost all of the other Proects of Common Interest (PCI), contained in the latest EU list "Projects of common interests", with over 55 projects out of 173 are related to gas, see: https://ec.europa.eu/energy/topics/infrastructure/projects-common-interest/key-cross-border-infrastructure-projects_en.

[41] This case study builds on own research as well as Fitzgerald et al. (2019) and Brauers and Braunger (2019).

[42] Tweet by @peteraltmeier on Dec. 09, 2018.

industrial, resource-intensive activities. In that context, the conversion from fossil natural gas (methane, CH_4) to hydrogen (H_2) is sometimes mentioned as a potential success factor.

The following consortia are considering the construction of an LNG-terminal and the corresponding infrastructure (Fitzgerald, Braunger, and Brauers 2019, 6 sq.):

~ The Wilhelmshaven project is based on the electric utility UNIPERs daughter company Deutsche Flüssiggas GmbH, the port authority of Wilhelmshaven, and two oil and gas trading companies. Wilhelmshaven is by far the largest of the three projects (10 -14 bcm/a), but also the oldest one, being in discussion since the late 1960s.Two technical options exist: a fixed terminal (~ € 1–1.5 bn. invest) or a Floating Storage and Regasification Unit (FSRU, ~ € 150 mn.).

~ The Stade project is built around DOW Chemical Germany and the port operator, with the Australian Macquarie financial service company as a potential investor. With only 4 bcm/a, Stade is the smallest project, with an invest estimated at ~ € 500 mn.

~ The Brunsbuettel project is promoted by fossil fuel infrastructure companies Gasunie LNG holding, Vopak LNG holding (both from the Netherlands), and Oiltank (Germany). The project is also modest in size (5 bcm/a, several hundred millions of € invest), but has a strategic advantage of being connected to the big Hamburg port authority.[43]

5.2.2 …without a business case

The problem of all three projects is that none of them has a viable business model and – given significant overcapacities of LNG and pipeline gas in the region – there is no market demand for the services. Thus, all three are searching for direct and indirect subsidies by federal, state, and local authorities. The Federal Government has developed a "Mobility and Fuels Strategy" (MFS), by which fossil liquid natural gas can be subsidized, e.g. for transportation. Both states involved, i.e. Lower Saxony (for Wilhelmshaven and Stade) and Schleswig-Holstein (for Brunsbuettel) support the projects, e.g. through regional economic development funds. The state of Lower Saxony has even established an "LNG Support Agency", also supported with federal and state money.[44]

Under the decarbonization scenario sketched out above, there is no need for additional LNG import capacities in Europe, let alone on the German North Sea coast. Due to active diversification following the two Russia – Ukraine gas crises (2006, 2009), Europe is now well diversified (Neumann et al. 2018; Egging, Holz, and Czempinski 2020). LNG terminal utilization is at historically low rates, i.e. in the range of 20% only.[45] Close-by terminals such as Rotterdam (Netherlands), Zeebrugge (Belgium) and Swinoujscie (Poland) are available to receive plenty of LNG. Pipeline capacities in the region are unconstrained, so that all three sites can easily be supplied with such gas, or even with cheaper pipeline gas (Holz and Kemfert 2020).

[43] In addition to the three large projects, a small LNG-terminal is planned in Rostock (Baltic Sea), and one is already in operation in Duisburg (on the Rhine river).

[44] See https://www.mw.niedersachsen.de/startseite/aktuelles/presseinformationen/wirtschaftsministerium-fordert-neu-gegrundete-lng-agentur-niedersachsen-186208.html.

[45] See US-EIA summary of GIIGNL data: https://www.eia.gov/todayinenergy/detail.php?id=37354.

5.2.3 Avoiding stranded assets

Clearly, additional LNG infrastructure at the German North Sea shore is not required, neither economically feasible. Interestingly, these conclusions were drawn in the mid-2010s already, by both the Federal government and by the state legislature of Lower Saxony, but these assessments have been revised in the wake of the "natural gas as a bridge fuel"-debate (Fitzgerald, Braunger, and Brauers 2019). Given plenty of alternative supply, and diminishing demand, building new LNG terminals is clearly a stranding of unnecessary fossil infrastructure assets.

5.3 New fossil natural gas-fired power plants

5.3.1 Coal-to-gas switch…

Last but not least, the third case study focusses on fossil gas-fueled power plants generating electricity, or combined heat & power (CHP). In fact, with the accelerated coal exit in many European countries, one might be tempted to see fossil natural gas plants as the "natural" replacement for electricity generation, and in particular for combined heat and power generation. This narrative of the "coal-to-gas" switch can be observed in some European countries (and beyond). Thus, in the UK coal was replaced by fossil natural gas for electricity generation, strongly supported by carbon floor price (Newbery, Reiner, and Ritz 2019). A similar trend can be observed in the United States, where – even in the absence of stringent CO_2-policies – coal is losing out to natural gas big time (Mendelevitch, Hauenstein, and Holz 2019).

Another recent case of (subsidized) coal-to-gas switch is the German coal exit law of 2020. This law, which is the result of five-year negotiations between the incumbent industry and civil society, defines a staged closure of hard coal and lignite plants, to be finished the latest by 2038. In addition to ample compensations for closing down plants for electricity, it adds a "coal substitution bonus" for CHP plants, to favor the coal-to-gas switch and incentivize utilities to invest into fossil natural gas CHP. A coal replacement bonus of up to €390 per KW installed capacity is available for this changeover, in addition to the subsidies already provided for in the CHP-law.[46] In addition to the subsidies, the costs for a corresponding connection of the power plants to the natural gas grid could be added, at least for natural gas customers having to pay for the infrastructure.

Whether more market-driven or more administered, the coal-to-gas switch is considered by many as the next step of the energy transformation. In longer-term electricity market modeling with only minor greenhouse gas emission reductions, one observes indeed a wave of gas-fired power plants in the 2020s and 2030s. Thus a study by Gerbaulet, et al. (2019) suggests a need of 280 GW of new fossil gas-fired capacities between 2020 and 2040.

5.3.2 … not under carbon constraints

The situation looks very different under strict carbon constraints, i.e. rapid decarbonization and fulfilment of the Paris Agreement. In fact, given the need for rapid decarbonization until 2040, fossil natural gas

[46] The amount of the bonus payment is only linked to the age (first commissioning) of the existing plant and to the commissioning of the new plant. Other factors such as flexibility, efficiency, etc. are not taken into account.

will not be able to emerge as a “bridge fuel”, but will be rapidly replaced by renewable energies in combination with storage capacities. The existing capacities can still be used for some time, but as the carbon constraint becomes tighter, fossil natural gas loses its competitiveness. In fact, in the Paris-Agreement scenario model exercise, natural gas capacities disappear in the 2040s. As the lower part of Figure 20 shows, no new fossil natural gas plants are constructed, and the existing ones are not dispatched any more, towards 2040.

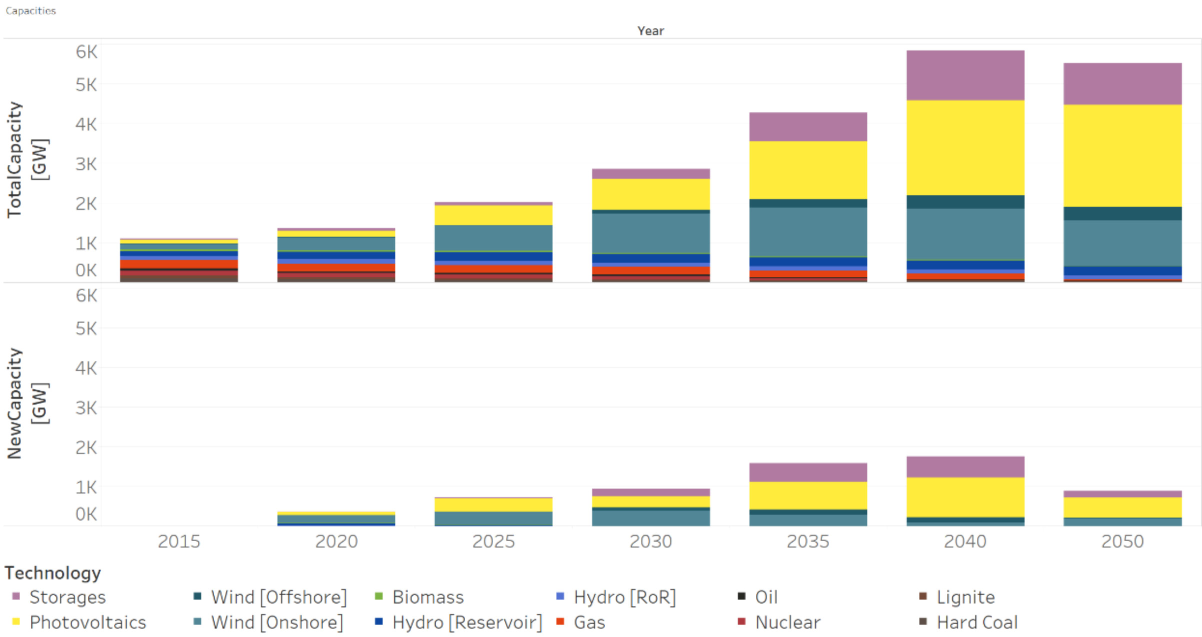

Figure 20: Electricity generation capacities Europe in the Paris-scenario until 2050.

Source: Hainsch et al. (2020, 11); absolute values (above), and period-on-period changes (below).

5.3.3 Another potential stranded asset

Under tight carbon constraints, investments into fossil gas-power plants do not pay off anymore. While existing capacities can still be used, investments into new capacity are not forthcoming. Countries developing incentives to switch from coal to gas should seriously reconsider these subsidies, because the danger of generating stranded assets is high.

Table 3 provides a scheme for analyzing potential stranded assets in the fossil gas sector, and summarizes the three case studies, i.e. on Nord Stream 2, LNG-import terminals, and fossil natural gas fueled power plants. For each case study, we summarize the basic arguments in favor of the investment, which are rooted in the narrative of the “bridge fuel”. These arguments are then opposed in the new setting we suggest, i.e. stringent carbon constraints and “natural gas exit”. In all three cases, likely outcomes are investments into fossil gas infrastructure that end up being stranded assets. Clearly whereas every project has its own specifics and dynamics, the risk of stranding significant assets (and of generating significant additional amounts of greenhouse gas emissions) is very high.

Project, type of infrastructure	Investor(s), further involved (capital) stakeholders	Pro: Traditional business model ("bridge fuel"), and supporting evidence	Against: Counterfactual ("natural gas exit"), and supporting evidence	Likely outcome: Stranded assets
1) Trans-continental fossil gas pipeline from Russia to Germany and the EU ("Nord Stream 2")	~ Gazprom (in combination with five Western energy firms as strategic investors) ~ Network operators in Germany (Ontras, etc.) and EU	~ Gaining market share in Europe ~ Profitable network investment & operation (Russia, EU, GER, etc.) ~ Evidence of a "natural gas gap" (Prognos 2017; ewi ER&S and EUCERS 2016)	~ No natural gas gap, there is no need for additional fossil gas imports from Russia ~ Investment analysis: Sberbank (2018) ~ Regional market modeling: Aune and Finn (2017) ~ European market analysis and regulation: Neumann, et al. (2018)	~ Geopolitical context very sensitive (Russia – EU – US) ~ Additional uncertainty about regulatory framework, access rules, etc. ~ Purely economic analysis clear: Nord Stream 2 not necessary ➔ Stranded asset
2) LNG import terminals on the North Sea coast: Wilhelmshaven (close to Bremen), Stade and Brunsbuettel (close to Hamburg, Elbe-estuary)	~ Fossile infrastructure groups, energy-intensive industries ~ no firm investment analysis yet possible	~ Infrastructure service provider ~ Support for additional infrastructure (regulated, and thus consumer paid, and/or subsidized) ~ Strong political support (federal, state, and local)	~ Lack of demand for LNG and for liquefaction services (Holz and Kemfert 2020) ~ Substituting fossil LNG by hydrogen (H_2) or other gases no option ~ Absence of business model for "tolling", in general: no evidence for existing business models thus far	~ Lack of viability shown in previous studies ~ Now political support, yet absence of business cases ➔ If built, will lead to stranded assets
3) New fossil gas-fueled power plants (CCGT, OC, CHP, etc.)	~ Traditional utilities ~ Independent power producers (IPPs, if possible)	~ Short-term market, perhaps helped by some carbon pricing (against coal) ~ reserve market ~ in some countries: capacity market ~ other "coal-to-gas" policy support (e.g. Germany)	~ Natural gas not required ~ Fossil gas not competitive (vis-à-vis renewables + storage, under carbon price) ~ Results for Paris-scenario (Hainsch et al. 2020) ~ dynELMOD paper on "stranded assets" (Gerbaulet et al. 2019)	~ Almost no new fossil gas plants in the last decade ~ capacity payments for (dirty) fossil gas plants unlikely (at EU-level, perhaps exception in few member states (van der Burg, Markus Trilling, and Ipek Gençsü 2019) ➔ Very likely to become stranded assets

Table 3: Scheme for identifying fossil gas stranded assets, and three case studies.

Source: Own compilation.

6 Changing the narrative: From "methane can decarbonize" to "fossil natural gas exit"

"Often the best alternative for expressing what one knows about the world is not an equation, but a narrative - a story with real characters facing some kind of dilemma." Thomas McCraw.[47]

Economic, energy, and climate policies are full of narratives, and these play a bigger role in policy and decision-making than generally acknowledged (Shiller 2019). This final section translates the findings of our research into a concrete proposal: If one takes climate constraints at the European level serious, a new narrative of fossil natural gas emerges. We discussed in detail the development of the current narratives to save the natural gas industry in times of decarbonization. These new narratives, which were summarized by the industry expert Jonathan Stern (Stern 2017a, 2017b, 2019) are based on the principle of decarbonizing the fossil fuel itself instead of decarbonizing the energy system. They appear to be part of the solution to the climate problem, but on closer inspection they turn out to be a rescue strategy for the existing, capital-intensive infrastructure and business models of the natural gas industry and the fossil energy system. Stern's "decarbonizing" narratives aim at perpetuating a relatively important share of natural gas, and to save the industry at least for a transition time which can, however, be quite long (several decades). A change of narrative is needed, from "methane can decarbonize" to the rapid end of fossil natural gas. In this section we discuss different aspects that are implied by the change of the narrative. As has been practiced throughout the paper, the main reference narrative, "methane can decarbonize", refers to the triade of papers by Stern.

6.1 A four-step procedure

We develop the new narrative of a natural gas exit in four steps:

i/ The paper starts out with an assessment of the energy transformation in Europe. In that section, we simply posit to take the objectives of the European Union in terms of climate policy, i.e. decarbonization and respect of the Paris Agreement, at face value. A climate neutral Europe requires full decarbonization, and the Paris Agreement limits the available greenhouse gas emission budget to a smaller two-digit Gigatonnes figure. In that context, natural gas is no longer part of the solution, but has migrated to become part of the problem.

ii/ In a second step, we test the mainstream hypothesis that "methane can decarbonize", i.e. that there is a way to convert the existing, "dirty" infrastructure into an alternative, but still gaseous, "clean" one. First we observe that the global warming potential (GWP) of fossil natural gas (methane, CH_4) has been largely underestimated: Current natural science research suggests a GWP of about 100 instead of the 25 used in the IPCC and other studies. We establish an overview of energy gases and find no way to "decarbonize methane": Hydrogen is not a full alternative, because most of it is produced using fossil fuels. Biogas has some potential, but limited capacities, and synthetic methane is, after all, no cleaner

[47] Cited after Wimmer, Nancy. 2012. Green Energy for a Billion Poor: How Grameen Shakti Created a Winning Model for Social Business. Vaterstetten: MCRE-Verl, p. 5.

than “natural” methane. We suggest to refrain from the taxonomy of “colors of gases”, and rather to rely on a technical description of the origin and the processes of the gas in questions.

iii/ We then report results form a modeling exercise in which we take the two pillars of the European climate policy, decarbonization and the Paris Agreement, serious, i.e. we impose tight carbon constraints. The lack of an economic perspective for nuclear power and the absence of a plausible deployment of large-scale carbon-dioxide removal technologies (CDR) imply that natural gas has no “sweet spot” any longer in the decarbonization process. Several recent studies, including our own show that renewables with some storage are cleaner and cheaper than fossil fuels for the decarbonization (Hainsch et al. 2020; Solar Power Europe and LUT University 2020; CAN Europe and EEB 2020). Over the last years, the phasing out of natural gas in Europe has already started, and will continue to do so until its complete phase-out, most likely towards 2040, i.e. only two decades from now.

iv/ Finally, we look at three case studies of possible investments into fossil natural gas infrastructure and find that, under tight carbon constraints, these are likely to produce stranded assets. The € 10 bn. investment into the North Stream 2 pipeline is not necessary to assure European supply security, let alone to make a return on investment. Projects of new LNG terminals on the shore of the German North Sea (Brunsbuettel, Stade, Wilhelmshaven) lack a business model. New natural gas power plants are likely to be unprofitable.

6.2 Discussion

Our analysis has implications, both for concrete business and policy decisions, but also at the more general level of the new narrative. Fossil gas, still often referred to as “natural gas”, is a very CO_2-intensive fossil fuel, the climate and other adverse effect of which have been hidden so far, by the focus of the climate debate on the phasing out of coal, and the narrative of “clean” fossil gas as an important “bridge” of the low-carbon energy transformation. However, taking into account the entire production chain, from production, long-distance transportation, and (often incomplete) burning in motors and turbines, the greenhouse gas impact of methane in many cases resembles that of coal, and in some cases even exceeds it (by unit of energy produced).

The hope of the industry that “methane can decarbonize” (Stern 2017b, 24), at least to a large extent, through carbon capture, transport, and storage (CCTS), was promoted for a long time by the fossil industry, to argue for a “low-carbon” and against a “no-carbon” transformation of the energy sector. This idea was wrong from the outset, yet today, over two decades of attempts to generate “clean” fossil fuels, the illusion of large-scale, technically and economically available CCTS should not be upheld.

Some energy gases may remain in the future, also in a 100% renewable system. Hydrogen, locally produced from 100% renewables may be needed for seasonal storage of excess electricity and locally reconversion on cold days with little wind and sun. In addition, hydrogen may be needed for specific industrial applications that cannot be converted to electricity (e.g. steel production or chemical industry). As a very valuable niche product, some electricity-based fuels (e-fuels) may remain for aviation or transport services which cannot be decarbonized. The quantities and applications must be discussed, but the long-term approach to infrastructure development must guarantee that the measures will not strengthen the lock-in effect in the fossil system.

The objective of reform is not to save “gas” as a gaseous state, to use existing infrastructure, but to use (or: develop) infrastructures to serve full decarbonization. The pro-industry narrative is one of “energy gases”, driven by the wish to keep the existing LNG, transmission and distribution infrastructure alive, and well-remunerated for its capital investors, without much of a risk. However, as we have shown above, other energy gases will not necessarily substitute fossil gas; this might as well be done by electricity and firm and/or liquid bio-energies. The rhetoric of many “shades of gas”, including “green”, “blue”, “grey”, “synthetic” but renewable, and yet other names and games, mainly targets the infrastructure issue, to create a sense of justification to maintain the fossil-induced infrastructure. This is neither technically nor economically justified. The failed history of global LNG markets (Jensen 2004; Neumann 2009) suggests not to bet on “globalization” of other gases, such as synthetic fuels or hydrogen. The hypothesis of global gas markets has not worked for LNG, which can be standardized quite easily, and it is much less likely to work for other types of gases, in particular hydrogen. Even though some quantities are currently being traded internationally, e.g. between Australia and Japan to fuel the 2021 Olympics, it is unlikely that large-scale hydrogen from renewables takes a significant share in the decarbonization agenda. If some energy gases remain in the energy mix (which is possible but not necessary), they should be locally sourced, and locally consumed.

Fossil fuels are still heavily subsidized from EU member countries, which is in direct contrast to a serious decarbonization strategy and phasing out of fossil fuels. Further, a new study from Friends of the Earth Netherlands, Climate Action Network Europe and the Overseas Development Institute (2019) found that none of the 28 member states developed sound plans for the phasing out of fossil fuel subsidies, while EU Governments agreed at the 2009 G20-summit on ceasing all subsidies latest by the year 2025.[48] Based on these agreements and predicted declines in natural gas consumption we argue, that investing in new natural gas infrastructure is not necessary anymore and is most likely to lead to „stranded assets“. As a (very) long-lived asset, and a system good with heavy interlinkages to upstream, downstream, and sidestream activities, fossil gas exit will not happen overnight, but rather on a time span of about two decades. Thus, private and public decisions need to be taken to address natural gas exit in the short term, e.g. through finally imposing an adequate price on carbon, but also in the long term, e.g. by prohibiting new fossil gas-fueled new heating (such as in the Netherlands from 2025 onwards).

7 Conclusions

In this paper, we challenge the mainstream conventional wisdom that natural gas, perhaps in combination with other gases, should play an important role in the energy transformation in Europe. The corresponding narrative of fossil natural gas as a bridge fuel towards other, decarbonized gases, offers a perspective for the incumbent fossil natural gas industry to transform gradually, and to convert most of its assets in the future energy system, where methane somewhat magically decarbonizes, and everything else, including profits, remain the same. Rather than putting industry interests first, trying to maintain the largest possible paths of the industry and treat climate effects as a secondary constraint,

[48] The Member States must show in their National Energy and Climate Plans (NECPs) how they intend to reduce these subsidies by the end of 2019.

we suggest to invert the priorities, i.e. place climate objectives first, and industry structure second, at the risk of not saving much of that structure, mainly sunk costs.

For some time, the fossil natural gas industry has embraced a climate protection rhetoric, to present itself as “more climate friendly as coal and oil” (Fitzgerald, Braunger, and Brauers 2019, 14). With a strict decarbonization agenda, and having to fulfil the Paris-Agreement agenda, this narrative is out of date. If, as we have shown, methane cannot decarbonize, fossil natural gas exit is the logical consequence of an ambitious climate policy. Therefore, the paper proposes to replace the dominant narrative (“natural gas in decarbonizing European energy markets“) with what we consider a more coherent narrative in the context of decarbonization: Fossil natural gas exit.

References

Alvarez, Ramón A., Daniel Zavala-Araiza, David R. Lyon, David T. Allen, Zachary R. Barkley, Adam R. Brandt, Kenneth J. Davis, et al. 2018. “Assessment of Methane Emissions from the U.S. Oil and Gas Supply Chain.” *Science* 361 (6398): 186–188.

Aoun, Sylvie Marie-Claire, and Sylvie Cornot-Gandolphe. 2015. *The European Gas Market Looking for Its Golden Age?* Paris, France: Les Etudes IFRI.

Auer, Hans, Pedro Crespo del Granado, Daniel Huppmann, Pao-Yu Oei, Karlo Hainsch, Konstantin Löffler, and Thorsten Burandt. 2020. “Quantitative Scenarios for Low Carbon Futures of the Pan-European Energy System.” Deliverable 3.1. Open_ENTRANCE. TU Wien, NTNU, IIASA, TU Berlin.

BCG, and Prognos AG. 2018. “Klimapfade für Deutschland.” Im Auftrag des Bundesverbandes der Deutschen Industrie (BDI) e.V. Berlin, Deutschland.

BMWi, and BMUB. 2010. “Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung.” Berlin, Germany: Federal Ministry of Economic Affairs and Energy (BMWi); Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).

Brauers, Hanna, Isabell Braunger, Franziska Holz, and Anne Neumann. 2019. “Infrastructure Lock-in: Lng Infrastructure Expansion Plans in Germany.” *Extended Abstract*.

Braunger, Isabell, and Christian Hauenstein. 2020. “How Incumbent Cultural and Cognitive Path Dependencies Constrain the ‘Scenario Cone’: Reliance on Carbon Dioxide Removal Due to Techno-Bias.” *Economics of Energy & Environmental Policy* 9 (1).

Brown, Stephen P.A., Alan J. Krupnick, and Margaret A. Walls. 2009. “Natural Gas: A Bridge to a Low-Carbon Future?” Resources for the Future: Washington D.C.

Brynolf, Selma, Maria Taljegard, Maria Grahn, and Julia Hansson. 2018. “Electrofuels for the Transport Sector: A Review of Production Costs.” *Renewable and Sustainable Energy Reviews* 81 (January): 1887–1905.

Burandt, Thorsten, Konstantin Löffler, and Karlo Hainsch. 2018. “GENeSYS-MOD v2.0 - Enhancing the Global Energy System Model.” *DIW Data Documentation* 94 (July).

CAN Europe, and EEB. 2020. “Building a Paris Agreement Compatible (PAC) Energy Scenario.” Brussels, Belgium: CAN Europe and EEB.

Capros, Pantelis, L. Mantzos, D. Kolokotsas, N. Ioannou, T. Georgakopoulos, A. Filippopoulitis, and Y. Antoniou. 1998. “The PRIMES Energy System Model–Reference Manual.” *National Technical University of Athens, Greece*.

Cremonese, Lorenzo, and Alexander Gusev. 2016. “The Uncertain Climate Cost of Natural Gas: Assessment of Methane Leakage Discrepancies in Europe, Russia and the US, and Implications for Sustainability.” *IASS Working Papers (December)*.

Creutzig, Felix, Christian Breyer, Jérôme Hilaire, Jan Minx, Glen P. Peters, and Robert Socolow. 2019. “The Mutual Dependence of Negative Emission Technologies and Energy Systems.” *Energy & Environmental Science*, no. 6.

Cumming, Lydia, Neeraj Gupta, Kenneth Miller, Christopher Lombardi, David Goldberg, Uri ten Brink, Daniel Schrag, David Andreasen, and Kristin Carter. 2017. “Mid-Atlantic U.S. Offshore Carbon Storage Resource Assessment.” *Energy Procedia* 114 (July): 4629–4636.

Davis, Lucas W. 2012. “Prospects for Nuclear Power.” *Journal of Economic Perspectives* 26 (1): 49–66.

dena. 2018. "dena-Leitstudie Integrierte Energiewende: Impulse für die Gestaltung des Energiesystems bis 2050 (Ergebnisbericht und Handlungsempfehlungen)." Berlin, Deutschland: Deutsche Energie-Agentur GmbH.

E3MLab. 2018. "PRIMES Model Version 2018 - Detailed Model Description." Athens, Greece: E3Mlab, National Technocal University of Athens.

EC. 2013. "EU Energy, Transport and GHG Emissions Trends to 2050: Reference Scenario 2013." Brussels, Belgium: European Commission.

———. 2016. "EU Reference Scenario 2016: Energy, Transport and GHG Emissions – Trends to 2050." Brussels, Belgium: European Commission.

Ecologic Institute. 2019. "Planning for Net Zero - Assessing the Energy and Climate Plans." Berlin, Germany.

EEA. 2018. "Trends and Projections in Europe 2018 Tracking Progress towards Europe's Climate and Energy Targets." Brussels (Belgium): EEA.

Egging, Ruud, Pedro Crespo del Granado, Franziska Holz, Péter Kotek, and Borbála Toth. 2019. "The Role of Natural Gas in an Electrifying Europe." SET-Nav Issue Paper. Brussels, Belgium.

Egging, Ruud, Franziska Holz, and Victoria Czempinski. 2020. "Freedom Gas to Europe? Scenario Analyses with the Global Gas Model." *DIW Berlin Discussion Paper*, no. in print.

Egging, Ruud, and Asgeir Tomasgard. 2018. "Norway's Role in the European Energy Transition." *Energy Strategy Reviews* 20.

ENTSO-G. 2013. "Ten-Year Network Development Plan (TYNDP) 2013–2022." Brussels, Belgium.

———. 2019. "TYNDP 2020 Scenario Methodology Report." Brussels, Belgium.

ENTSOG, and ENTSO-E. 2019. "TYNDP 2020 Scenario Report," October, 56.

EU TEG. 2020. "Taxonomy: Final Report of the Technical Expert Group on Sustainable Finance." Report. Brussels, Belgium: EU Technical Expert Group on Sustainable Financing.

European Commission. 2011. "A Roadmap for Moving to a Competitive Low Carbon Economy in 2050."

———. 2018. "Clean Planet for All - A European Strategic Long-Term Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy." Communication from the Commission COM(2018) 773. Brussels: European Commission.

European Court of Auditors. 2015. *Improving the Security of Energy Supply by Developing the Internal Energy Market: More Efforts Needed : (Pursuant to Article 287(4), Second Subparagraph, TFEU)*.

———. 2018. "Demonstrating Carbon Capture and Storage and Innovative Renewables at Commercial Scale in the EU: Intended Progress Not Achieved in the Past Decade." *Article 287(4), Second Subparagraph, TFEU*, 76.

Eurostat. 2019. "Energy Balances - Eurostat." Eurostat Your Key to European Statistics. 2019.

ewi ER&S, and EUCERS. 2016. "Options for Gas Supply Diversification for the EU and Germany in the next Two Decades." Final Report to the German Federal Foreign Office. Cologne, Germany; London, UK.

Fitzgerald, Louise Michelle, Isabell Braunger, and Hanna Brauers. 2019. "Destabilisation of Sustainable Energy Transformations: Analysing Natural Gas Lock-in in the Case of Germany." *STEPS Working Paper* 106.

Fletcher, Sara E. Mikaloff, and Hinrich Schaefer. 2019. "Rising Methane: A New Climate Challenge." *Science* 364 (6444): 932.

Fuss, Sabine, Christian Flachsland, Nicolas Koch, Ulrike Kornek, Brigitte Knopf, and Ottmar Edenhofer. 2018. "A Framework for Assessing the Performance of Cap-and-Trade Systems: Insights from the European Union Emissions Trading System." *Review of Environmental Economics and Policy* 12 (2): 220–241.

GCCSI. 2018. "The Global Status of CCS: 2018." Melbourne, Australia: Global CCS Institute.

Geden, Oliver, Glen P. Peters, and Vivian Scott. 2019. "Targeting Carbon Dioxide Removal in the European Union." *Climate Policy* 19 (4): 487–494.

Gerbaulet, Clemens, Christian von Hirschhausen, Claudia Kemfert, Casimir Lorenz, and Pao-Yu Oei. 2019. "European Electricity Sector Decarbonization under Different Levels of Foresight." *Renewable Energy* 10.1016/j.renene.2019.02.099.

Gibbins, Jon, and Hannah Chalmers. 2008. "Carbon Capture and Storage." *Energy Policy*, Foresight Sustainable Energy Management and the Built Environment Project, 36 (12): 4317–4322.

Goeppert, Alain, Miklos Czaun, G. K. Surya Prakash, and George A. Olah. 2012. “Air as the Renewable Carbon Source of the Future: An Overview of CO2 Capture from the Atmosphere.” *Energy & Environmental Science* 5 (7): 7833.

Götz, Manuel, Jonathan Lefebvre, Friedemann Mörs, Amy McDaniel Koch, Frank Graf, Siegfried Bajohr, Rainer Reimert, and Thomas Kolb. 2016. “Renewable Power-to-Gas: A Technological and Economic Review.” *Renewable Energy* 85 (January): 1371–1390.

Hainsch, Karlo, Hanna Brauers, Thorsten Burandt, Leonard Goeke, Christian von Hirschhausen, Claudia Kemfert, Mario Kendziorski, et al. 2020. “Make the European Green Deal Real – Combining Climate Neutrality and Economic Recovery.” No. 153. Politikberatung Kompakt. Berlin: German Institute for Economic Research (DIW Berlin).

Hainsch, Karlo, Thorsten Burandt, Claudia Kemfert, Konstantin Löffler, Pao-Yu Oei, and Christian von Hirschhausen. 2018. “Emission Pathways Towards a Low-Carbon Energy System for Europe - A Model-Based Analysis of Decarbonization Scenarios.” *DIW Berlin Discussion Paper*, no. 1745.

Haszeldine, R. Stuart, Stephanie Flude, Gareth Johnson, and Vivian Scott. 2018. “Negative Emissions Technologies and Carbon Capture and Storage to Achieve the Paris Agreement Commitments.” *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 376 (2119): 20160447.

Holz, Franziska, Hanna Brauers, Philipp M. Richter, and Thorsten Roobeek. 2017. “Shaking Dutch Grounds Won’t Shatter the European Gas Market.” *Energy Economics* 64: 520–529.

Holz, Franziska, and Claudia Kemfert. 2020. “Neue Gaspipelines und Flüssiggas-Terminals sind in Europa überflüssig (New gas pipelines and liquid gas terminals are superfluous in Europe).” *DIW aktuell*, no. 50.

Holz, Franziska, Tim Scherwath, Ivo-Valentin Kafemann, Christian Skar, Hector Maranon-Ledesma, Pedro Crespo del Granado, Andres Ramos, et al. 2018. “Case Study Report on The Role for Carbon Capture, Transport and Storage in Electricity and Industry in the Future: Which Role for Infrastructure?” SET-Nav Project. Navigating the Roadmap for Clean, Secure and Efficient Energy Information. Wien: TU Wien.

Howarth, Robert W. 2014. “A Bridge to Nowhere: Methane Emissions and the Greenhouse Gas Footprint of Natural Gas.” *Energy Science&Engineering* 2 (2): 47–60.

———. 2015. “Methane Emissions and Climatic Warming Risk from Hydraulic Fracturing and Shale Gas Development: Implications for Policy.” *Energy and Emission Control Technologies*, October, 45.

———. 2019. “Ideas and Perspectives: Is Shale Gas a Major Driver of Recent Increase in Global Atmospheric Methane?” *Biogeosciences* 16 (15): 3033–3046.

Howells, Mark, Holger Rogner, Neil Strachan, Charles Heaps, Hillard Huntington, Socrates Kypreos, Alison Hughes, et al. 2011. “OSeMOSYS: The Open Source Energy Modeling System: An Introduction to Its Ethos, Structure and Development.” *Energy Policy*, Sustainability of Biofuels, 39 (10): 5850–5870.

Hughes. 2011. “Life Cycle Greenhouse Gas Emissions from Shale Gas Compared to Coal: An Analysis of Two Conflicting Studies.” Resilience. June 30, 2011.

IEA. 2011. “Are We Entering a Golden Age of Gas? World Energy Outlook 2011 – Special Report.” Paris, France: OECD.

IPCC. 2018. “Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty.” New York, NY, USA: IPCC.

Jensen, Jim. 2004. “The Development of a GLobal LNG Market - Is It Likely? If so When?” Oxford Institute for Energy Studies (OIES) Paper NG 5. Oxford, UK: Oxford Institute for Energy Studies (OIES).

Joskow, Paul L. 2013. “Natural Gas: From Shortages to Abundance in the United States.” *American Economic Review* 103 (3): 338–343.

Keating, Dave. 2019. “‘We Need This Dinosaur’: EU Lifts Veil on Gas Decarbonisation Strategy.” *Euractiv.Com* (blog). September 18, 2019.

Kemfert, Claudia, Thorsten Burandt, Karlo Hainsch, Konstantin Löffler, Pao-Yu Oei, and Christian von Hirschhausen. 2017. “Nuclear Power Unnecessary for Climate Protection—There Are More Cost-Efficient Alternatives.” *DIW Economic Bulletin* 7 (48): 498–506.

Kemfert, Claudia, Christian von Hirschhausen, and Casimir Lorenz. 2014. “European Energy and Climate Policy Requires Ambitious Targets for 2030.” DIW Economic Bulletin. Berlin, Germany.

Kim, Hyewon, Yong Hoon Kim, Seong-Gil Kang, and Young-Gyu Park. 2016. “Development of Environmental Impact Monitoring Protocol for Offshore Carbon Capture and Storage (CCS): A Biological Perspective.” *Environmental Impact Assessment Review* 57 (February): 139–150.

Laurie van der Burg, Markus Trilling, and Ipek Gençsü. 2019. “Fossil Fuel Subsidies in Draft EU National Energy and Climate Plans.”

Leveque, Francois. 2006. “Antitrust Enforcement in the Electricity and Gas Industries: Problems and Solutions for the EU.” *The Electricity Journal* 19 (5): 27–34.

Lévêque, Francois, Jean-Michel Glachant, Julian Barquin, Christian Von Hirschhausen, and Franziska Holz. 2010. *Security of Energy Supply in Europe: Natural Gas, Nuclear and Hydrogen*. Cheltenham, Glos, UK ; Northampton, MA: Edward Elgar Publishing Ltd.

Löffler, Konstantin, Karlo Hainsch, Thorsten Burandt, Pao-Yu Oei, Claudia Kemfert, and Christian Von Hirschhausen. 2017. “Designing a Model for the Global Energy System—GENeSYS-MOD: An Application of the Open-Source Energy Modeling System (OSeMOSYS).” *Energies* 10 (10): 1468.

Mendelevitch, Roman, Christian Hauenstein, and Franziska Holz. 2019. “The Death Spiral of Coal in the U.S.: Will Changes in U.S. Policy Turn the Tide?” *Climate Policy*, July, 1–15.

Mendelevitch, Roman, Claudia Kemfert, Pao-Yu Oei, and Christian von Hirschhausen. 2018. “The Electricity Mix in the European Low-Carbon Transformation: Coal, Nuclear, and Renewables.” In *Energiewende “Made in Germany”: Low Carbon Electricity Sector Reform in the European Context*, edited by Christian von Hirschhausen, Clemens Gerbaulet, Claudia Kemfert, Casimir Lorenz, and Pao-Yu Oei. Cham, Switzerland: Springer Nature Switzerland AG.

Mendelevitch, Roman, and Pao-Yu Oei. 2018. “The Impact of Policy Measures on Future Power Generation Portfolio and Infrastructure: A Combined Electricity and CCTS Investment and Dispatch Model (ELCO).” *Energy Systems* 9 (4): 1025–1054.

MIT. 2003. “The Future of Nuclear Power.” Cambridge, MA: Massachusetts Institute of Technology.

Muttitt, Greg, Hannah McKinnon, Lorne Stockman, Stephen Kretzmann, Adam Scott, and David Turnball. 2016. “The Sky’s Limit.” Washington DC, USA: Oil Change International.

Myhre, Gunnar, Drew Shindell, François-Marie Bréon, William Collins, Jan Fuglestvedt, Jianping Huang, Dorothy Koch, et al. 2013. “Anthropogenic and Natural Radiative Forcing.” Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. United Kingdom and New York.

Neumann, Anne. 2009. “Linking Natural Gas Markets - Is LNG Doing Its Job?” *The Energy Journal* 31 (3): 87–200.

Neumann, Anne, Leonard Göke, Franziska Holz, Claudia Kemfert, and Christian von Hirschhausen. 2018. “Natural Gas Supply: Another Baltic Sea Pipeline Is Not Necessary,” DIW Berlin Weekly Report, , no. 27–2018: 241–248.

Neumann, Anne, and Christian von Hirschhausen. 2015. “Natural Gas: An Overview of a Lower-Carbon Transformation Fuel.” *Review of Environmental Economics and Policy* 9 (1): 64–84.

Newbery, David M., David M. Reiner, and Robert A. Ritz. 2019. “The Political Economy of a Carbon Price Floor for Power Generation.” *The Energy Journal* 40 (1).

Nisbet, E. G., M. R. Manning, E. J. Dlugokencky, R. E. Fisher, D. Lowry, S. E. Michel, C. Lund Myhre, et al. 2019. “Very Strong Atmospheric Methane Growth in the 4 Years 2014–2017: Implications for the Paris Agreement.” *Global Biogeochemical Cycles* 33 (3): 318–342.

Oei, Pao-Yu, Karlo Hainsch, Konstantin Löffler, Christian von Hirschhausen, Franziska Holz, and Claudia Kemfert. 2019. “A New Climate for Europe: 2030 Climate Targets Must Be More Ambitious.” *DIW Weekly Report*, no. 40.

Podesta, John D, and Timothy E Wirth. 2009. “A Bridge Fuel for the 21st Century.” *Center for American Progres*, 11.

Prognos. 2017. “Szenariorahmen für den Netzentwicklungsplan Gas 2018-2028 der Fernleitungsnetzbetreiber.” Berlin.

Rahmstorf, Stefan. 2019. “Klimaschutz: Wie viel Kohlendioxid bleibt Deutschland noch?” www.spektrum.de. 2019.

Roar Aune, Finn, Rolf Golombek, Arild Moe, Knut Einar Rosendahl, and Hilde Hallre Le Tissier. 2017. “The Future of Russian Gas Exports.” *Economics of Energy & Environmental Policy* 6 (2).

Rogelj, J., D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, et al. 2018. “Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development.” In *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, edited by V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, et al.

Rogelj, Joeri, Piers M. Forster, Elmar Kriegler, Christopher J. Smith, and Roland Séférian. 2019. “Estimating and Tracking the Remaining Carbon Budget for Stringent Climate Targets.” *Nature* 571 (7765): 335–342.

Sberbank Investment Research. 2018. “Russian Oil and Gas - Tickling Giants.” Moscow, Russia.

Schellnhuber, Hans Joachim, Stefan Rahmstorf, and Ricarda Winkelmann. 2016. “Why the Right Climate Target Was Agreed in Paris.” *Nature Climate Change* 6 (7): 649–653.

Shiller, Robert J. 2019. *Narrative Economics: How Stories Go Viral and Drive Major Economic Events*. Princeton: Princeton University Press.

Shindell, D., J. C. I. Kuylenstierna, E. Vignati, R. van Dingenen, M. Amann, Z. Klimont, S. C. Anenberg, et al. 2012. “Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security.” *Science* 335 (6065): 183–189.

Shindell, D. T., G. Faluvegi, D. M. Koch, G. A. Schmidt, N. Unger, and S. E. Bauer. 2009. “Improved Attribution of Climate Forcing to Emissions.” *Science* 326 (5953): 716–718.

Shindell, Drew T. 2015. “The Social Cost of Atmospheric Release.” *Climatic Change* 130 (2): 313–326.

Simon, Frédéric. 2019. “EU Clarifies Funding Scope for CO2 Capture Technology.” *Www.Euractiv.Com* (blog). July 10, 2019.

Solar Power Europe, and LUT University. 2020. “100% Renewable Europe - How to Make Europe’s Energy System Climate-Neutral Before 2050.” Brussels, Belgium.

Stern, Jonathan. 1997. “The British Gas Market 10 Years after Privatisation: A Model or a Warning for the Rest of Europe?” *Energy Policy* 25 (4): 387–392.

———. 2017a. “Challenges to the Future of Gas: Unburnable and Unaffordable.” Oxford Institute for Energy Studies (OIES) Paper NG 125. Oxford, UK: Oxford Institute for Energy Studies (OIES).

———. 2017b. “The Future of Gas in Decarbonising European Energy Markets: The Need for a New Approach.” Oxford Institute for Energy Studies (OIES) Paper NG 116. Oxford, UK: Oxford Institute for Energy Studies (OIES).

———. 2019. “Narratives for Natural Gas in Decarbonising European Energy Markets.” Oxford Institute for Energy Studies (OIES) Paper NG 141. Oxford, UK: Oxford Institute for Energy Studies (OIES).

Sterner, M, M Thema, F Eckert, T Lenck, and P Götz. 2015. “Bedeutung und Notwendigkeit von Windgas für die Energiewende in Deutschland.” Studie im Auftrag von Greenpeace Energy. Regensburg/Hamburg/Berlin: Forschungsstelle Energienetze und Energiespeicher (FENES) OTH Regensburg, Energy Brainpool.

Stockman, Lorne, Greg Muttitt, Alex Doukas, and Collin Rees. 2018. “Debunked: The G20 Clean Gas Myth.” Washington DC, USA: Oil Change International.

Strogies, Michael, and Patrick Gniffke. 2019. “Submission under the United Nations Framework Convention on Climate Change and the Kyoto Protocol 2019,” 945.

Teske, Sven. 2018. *Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-Energy GHG Pathways for +1.5c and +2c*. New York, NY: Springer Berlin Heidelberg.

Traber, Thure, and Hans-Josef Fell. 2019. “Erdgas leistet keinen Beitrag zum Klimaschutz.” Erdgasstudie 2019. Berlin: Energy Watch Group.

UNFCCC. 2015. “Paris Agreement.” Paris: United Nations Framework Convention on Climate Change.

van den Berg, Nicole J., Heleen L. van Soest, Andries F. Hof, Michel G. J. den Elzen, Detlef P. van Vuuren, Wenying Chen, Laurent Drouet, et al. 2019. “Implications of Various Effort-Sharing Approaches for National Carbon Budgets and Emission Pathways.” *Climatic Change*, February.

van der Burg, Laurie, Markus Trilling, and Ipek Gençsü. 2019. “Fossil Fuel Subsidies in Draft EU National Energy and Climate Plans Shortcomings and Final Call for Action.” ODI Reports. London.

von Hirschhausen, Christian. 2006. “Infrastructure Investments and Resource Adequacy in the Restructured US Natural Gas Market - Is Supply Security at Risk?” *MIT CEEPR Working Paper 06-018*.

von Hirschhausen, Christian, Johannes Herold, and Pao-Yu Oei. 2012. “How a ‘Low Carbon’ Innovation Can Fail--Tales from a ‘Lost Decade’ for Carbon Capture, Transport, and Sequestration (CCTS).” *Economics of Energy & Environmental Policy* 1 (2).

von Hirschhausen, Christian, Berit Meinhart, and Ferdinand Pavel. 2005. “Transporting Russian Gas to Western Europe — A Simulation Analysis.” *The Energy Journal* 26 (2).

von Hirschhausen, Christian von, Claudia Kemfert, Friedrich Kunz, and Roman Mendelevitch. 2013. “European Electricity Generation Post-2020: Renewable Energy Not to Be Underestimated.” *DIW Economic Bulletin* 3 (9): 16–28.

Wealer, Ben, Simon Bauer, Leonard Goeke, Christian von Hirschhausen, and Claudia Kemfert. 2020. “Economics of Nuclear Power Plant Investment: Monte Carlo Simulations of Generation III/III+ Investment Projects.” *DIW Berlin Discussion Paper*, no. 1833.

Wealer, Ben, Simon Bauer, Leonard Göke, Christian von Hirschhausen, and Claudia Kemfert. 2019. “High-Priced and Dangerous: Nuclear Power Is Not an Option for the Climate-Friendly Energy Mix.” *DIW Weekly Report* 30/2019: 235–243.