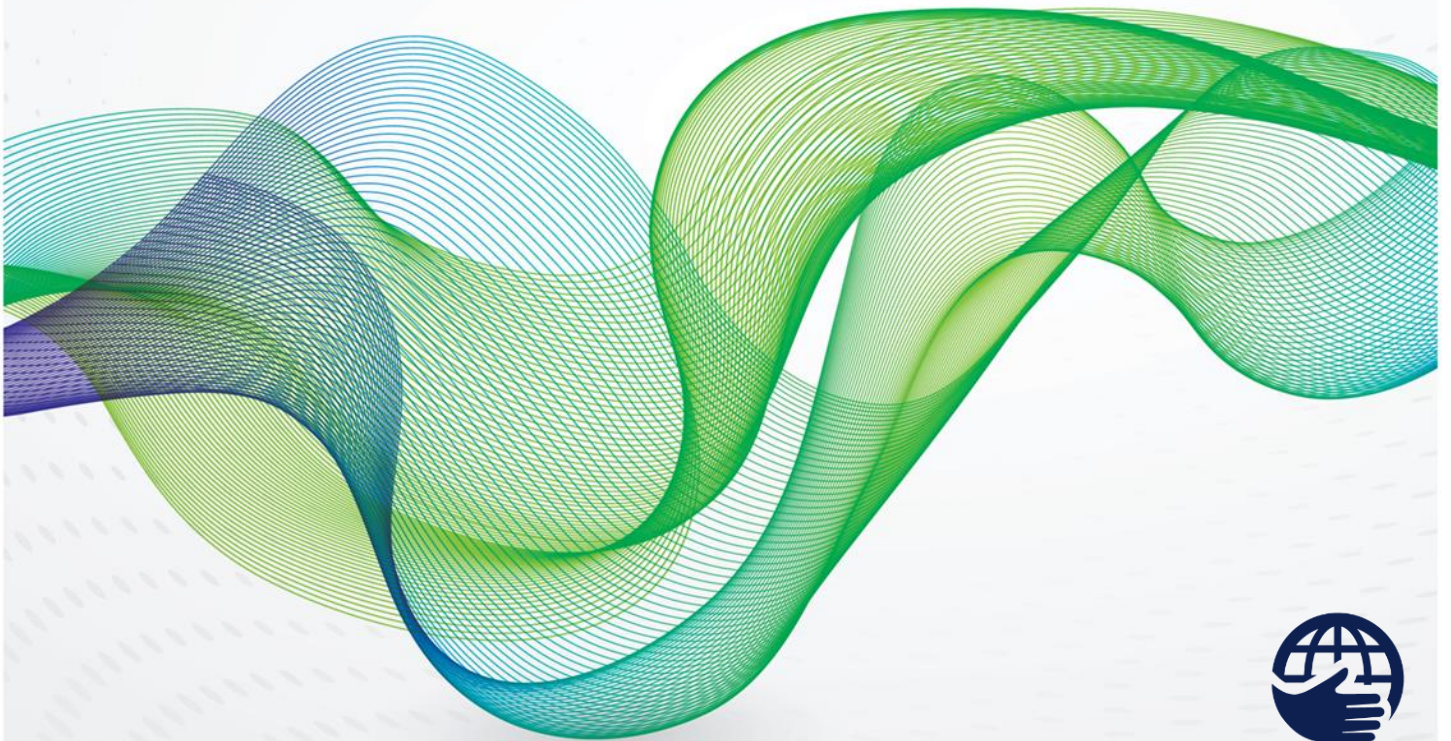
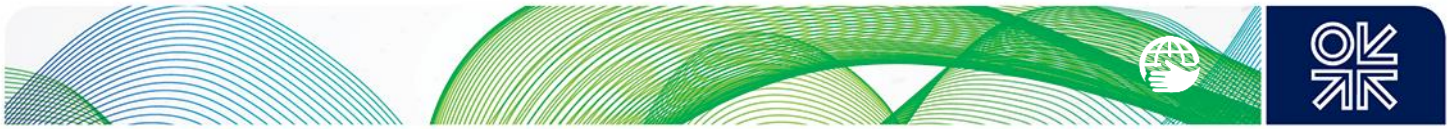


June 2022

Achieving net zero plus reliable energy supply in Germany by 2045: the essential role of CO₂ sequestration



Energy
Transition



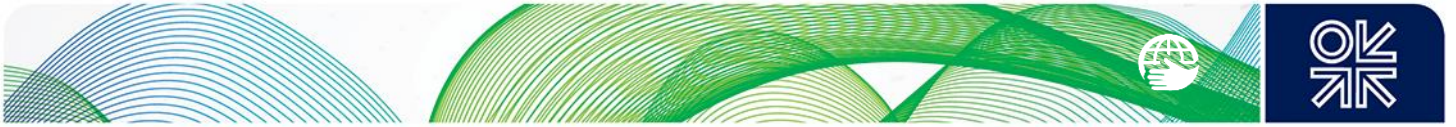
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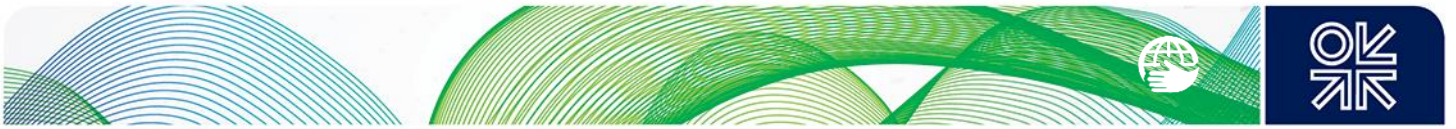
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Ralf Dickel, June 2022



Executive Summary

Germany is an interesting case for decarbonization policy in view of its ambitious objective of net zero by 2045 and its pioneering role in and focus on developing renewables and energy efficiency as predominant instruments. While other countries differ regarding their energy supply potential and their climate, geography and economy, Germany's decarbonisation policy can certainly serve as a point of reference, especially for countries with a similar seasonality of energy demand and renewables supply.

This paper shows why for Germany an all-renewables, predominantly electric approach to achieving net zero by 2045 will not work, nor will it maintain reliable energy supply. The inclusion of CCS from power plants and blue hydrogen from ATRs (Autothermal reforming) is essential for achieving Germany's decarbonization goals, it will open a challenging but feasible way to reach net zero by 2045 and keep the high reliability of energy supply. In view of the limited carbon budget and the short time left until 2045 it is urgent to develop a concept of capture, transport and sequestration of CO₂ and foster its implementation. In view of political but also geological restrictions for CO₂ sequestration in Germany cooperation with Norway to use its large potential for sequestration on the Norwegian shelf looks like an obvious and promising approach.

The use of natural gas in Germany (especially Russian gas) is questioned now as a result of the war in Ukraine. However, carbon capture and sequestration for decarbonisation is not limited to gas: post-combustion CO₂ capture from lignite power plants works just as well and is more advanced than for gas-fired power and is based on a national resource, while blue hydrogen also can be produced with ATRs from oil. It should be noted however that both lignite and oil produce larger CO₂ streams that need to be handled than natural gas.

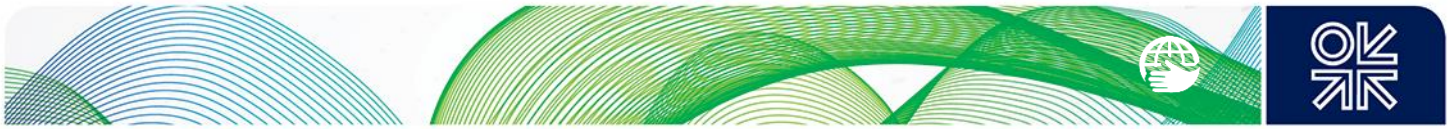
With the short time left to 2045 and the new uncertainties, caused by the pandemic and the present Russian-Ukrainian war, feasibility is of the essence, accounting for natural, technical but also political givens.

Chapter 1 (introduction and context) addresses the landmark Ruling on the Climate Protection Act of 2019 (CPA) by the German Constitutional Court of 29 April 2021. The Ruling argued that Germany with its 1% share of the world's population could not claim more of the tight remaining global CO₂ budget than such share of the ca. 500 Gt CO₂ outlined in the IPCC report on global warming of 1.5°C). Spending too much of this budget by 2030 by the present adult generation would unfairly curtail the freedom of the younger generation. As a result, an Amendment to the Climate Protection Act of June 2021 pushed up the 2030 GHG emissions reduction target from 55% to 65% compared to 1990 levels and introduced a binding net zero target for 2045. This added a second major rule for energy to the existing reliable energy supply requirement of the 2005 Energy Industry Act (EnWG Art. 1).

In its Coalition Agreement (CA), the new German Government¹ sworn in on 8 December 2021 stipulated concrete targets for the rollout of renewables by 2030. It claimed a transitional role for gas in stabilising energy supply, as well as technology openness, but was silent on CO₂ sequestration (and conspicuously on the CO₂ budget) and on how to combine decarbonisation and reliability.

With the start of the war in Ukraine by Russia on 24 February 2022, the issue of dependence on Russian gas (and oil, coal and nuclear fuel) has come into focus again. Major changes in energy policy are under discussion: to become more independent of Russian gas supply at least in the medium term, without renegeing on climate targets. However, the difficulties of transforming intermittent renewable power production into reliable dispatchable power or energy-rich molecules are often ignored or underestimated in that discussion.

¹ The new Government is based on a coalition of the Social Democratic Party (SPD), the Green Party (Bündnis 90 / Die Grünen) and the Liberal Party (Freie Demokratische Partei – FDP).



A challenge for Germany in that context is the seasonality of sunshine and weather. The country also faces a north-south divide: strong offshore and onshore wind, *de facto* all salt caverns for H₂ storage and the potential to export CO₂ are in the north, while the south is dominated by large PV capacities.

Chapter 2 raises the question of how to provide reliable energy on demand while reaching Germany's climate targets for 2030 and 2045. Renewable energy is predominantly intermittent power from PV and wind, which do not provide reliable dispatchable electricity nor energy-rich molecules. The conversion of renewable power into hydrogen by electrolysis is in the very early stages of deployment globally, and the development of hydrogen storage in Germany needed to provide hydrogen on demand is not even at a phase of conceptual discussion. The rollout speed of renewable energy foreseen in the CA is highly ambitious judged by past performance and by the obstacles and restrictions which can be expected. But even at that speed and with very optimistic assumptions on reducing final energy demand – just on a volume basis (i.e., disregarding structure), the 2045 target for net zero will be missed by some decades if it is based on renewables only.

Chapter 3 looks at the essential role of carbon capture and sequestration (CCS) for reaching Germany's net zero and energy reliability targets. CCS for lignite-fired power and for blue hydrogen from gas or liquid hydrocarbons needs to be added as another key component of Germany's energy strategy. While this would require substantial efforts in addition to the ongoing efforts for the further development of renewables, the combination of both approaches should allow Germany to reach net zero by 2045 while maintaining reliable and competitive supply. Including CCS would create the diversification of technologies and parallel paths to simultaneous early decarbonisation saving on the CO₂ budget.

The technologies for CCS are available and tested on an industrial scale, but they will be deployed only when the price of CO₂ emissions reaches the level sufficient to cover the costs of the CCS chain, which for large volumes is estimated at around 100 €/t CO₂. The discontinued development of technologies to retrofit lignite power plants with industrial-scale post-combustion decarbonisation would need to be resumed as soon as possible for lignite to be used as a national resource in line with the net zero target for 2045.

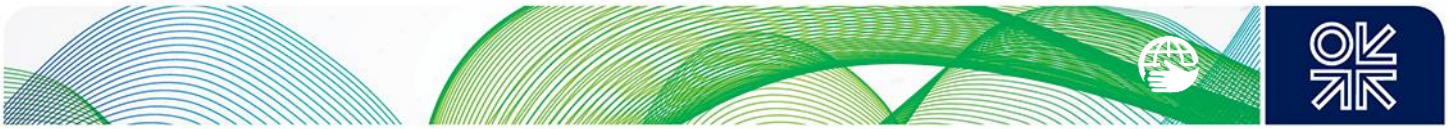
While Germany is not ready for CO₂ sequestration on its own territory, CO₂ transportation by pipeline in Germany for shipment to Norway is possible: Norway is developing its large CO₂ sequestration potential beyond its own limited needs for use by its international partners, and Germany could certainly be such a partner.

Chapter 4 looks at the need and requirements for a German infrastructure to export CO₂ to Norway.

In view of the prospect of more than 200 mln t CO₂/a from Germany to be sequestered under the North Sea, a large CO₂ collection system with several trunk lines will be needed by 2045. Transportation of CO₂ in the superfluid phase is a proven technology applied in the US (e.g., the 800 km, 186 bar, 30-inch Cortez pipeline with a 20 mln t CO₂/a capacity). It requires a steady CO₂ flow, as does sequestration in saline aquifers. While Germany could start with a system designed to carry large volumes with high load factors, as in the US, over time more streams from scattered sources with lower volumes / load factors would have to be integrated, e.g., from load-following power plants.

This raises issues of moving CO₂ into and out of storage,² possibly salt caverns, needed to steady the CO₂ flow. It is high time to develop concepts for CO₂ collection systems in Germany, fill in the missing rules for CO₂ transportation and come to arrangements with North Sea littoral states like Norway to allow the export of CO₂ under the 2009 Amendment to the London Protocol. Such measures would not be particularly expensive, but addressing them now would save precious time in view of the limited carbon budget.

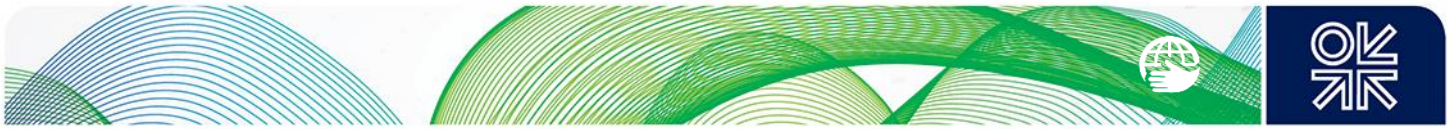
² In this paper, the term "sequestration" is used for the permanent disposal of CO₂ and "storage" – for CO₂ disposal for later withdrawal.



Chapter 5 looks at how to mobilise the investment for reaching net zero by 2045 while maintaining reliable energy supply. With 23 years left until the set target date, new investment and new infrastructure should be minimised when existing investment or infrastructure can continue to be used, in view of the stress on the work force and capital and the complexity coming with a completely new energy infrastructure.

A penalty for CO₂ emissions appears to be a good instrument for stimulating investment into decarbonisation. However, without the possibility for industry to abate CO₂ emissions by its own action, mainly by CCS, the CO₂ price would become just an additional unavoidable tax – if the industry chooses to stay in Germany. While it would be used to pay for decarbonisation via renewables according to Government planning, this would not have the desired effect on cutting carbon emissions in the industry sector. With the CO₂ price reaching the level where CCS becomes commercially reasonable, the German Government should take action to remove the obstacles to CCS and foster taking up stalled development of technology to retrofit fossil fuel-fired power plants with decarbonisation and equip ATRs with CO₂ capture.

Finally, *conclusions* are drawn for a decarbonisation approach. It is essential that *Germany revise its rejection of CCS as an instrument of decarbonisation and of maintaining reliable energy supply*. The immediate steps should include fostering cooperation with Norway on large-scale CO₂ collection in Germany with corresponding sequestration under the Norwegian Shelf. This would require Germany to ratify the Amendment to Art. 6 of the London Protocol and agree with Norway on its provisional application. In Germany, a concept for large-scale CO₂ capture and collection should be developed as soon as possible. This could be based on existing TRL 9 technologies. Projects to retrofit lignite power plants with post-combustion decarbonisation, unfortunately cancelled ten years ago, should be revitalised. This would also contribute to reducing import dependence in the light of the Russia-Ukraine war, as well as to decarbonising dispatchable power. With assurance of a high enough CO₂ price covering the costs of the CCS chain, filling the gaps in the rules for permitting CO₂ pipelines and for the recognition of CO₂ sequestration abroad, the industry should be able to develop business models for all of the CCS chain.



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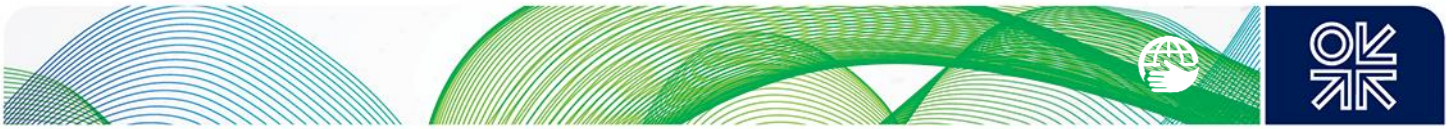
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1. Introduction

1.1 Legislative development

1.1.1 Reliability of energy supply as a legally binding target

So far, the reliability and competitiveness of energy supply have been the main criteria for the German energy sector stipulated in Art. 1 of the Energy Industry Act (*Energie Wirtschaftsgesetz – EnWG*)³. The EnWG goes back to 1935 and was worked over in 2005. Adequacy of resources and reliability of supply were in focus. It is the binding standard for the construction of new energy infrastructure.

High reliability was achieved in Germany notwithstanding phasing out nuclear and an impressive build-up of renewable power. The German SAIDI (system average interruption duration index), both for gas and electricity, continues to be amongst the lowest in Europe.

1.1.2 Decarbonisation, climate targets

In 2001, Art. 20a GG (GG = *Grundgesetz*, the German Constitution) was added to the Constitution, raising the protection of the environment for future generations to constitutional rank, with an obligation for governmental institutions to act accordingly.⁴

The *Energiewende* of 2010⁵ was a framework declaration by Parliament with generic and legally non-binding climate targets, such as achieving an 80% to 95% GHG reduction by 2050 compared to 1990 levels. This declaration was supported by a bundle of specific legislation and regulatory actions to foster decarbonisation, such as the rules for planning gas and electricity grids. Unlike in countries such as the UK, decarbonisation was not enshrined into binding legislation.

As Germany became part of the 2015 Paris Agreement and with Art. 20a GG, decarbonisation was translated into binding law by the Climate Protection Act⁶ of 15 November 2019. It made the decarbonisation target (-55% vs the 1990 level) binding for 2030, putting it on a par with the legally binding reliability target for the energy sector. The targets beyond 2030 remained non-binding ambitions.

The CPA affects all energy sectors, however it does not impose actions or restrictions on the energy industry, but an obligation on the Government to take necessary actions to deliver the detailed targets of the Act. Its decarbonisation targets became challengeable in the Constitutional Court, and they were challenged as not stringent enough for present younger generations.⁷

1.1.3 The Ruling of the Constitutional Court

By its Ruling of 29 April 2021,⁸ the Constitutional Court declared parts of the Climate Protection Act to be unconstitutional. The reasoning was remarkable in several aspects:

³ (Energy Industry Act, 2005), Art. 1(1): "(1) Zweck des Gesetzes ist eine möglichst sichere, preisgünstige, verbraucherfreundliche, effiziente und umweltverträgliche leitungsgebundene Versorgung der Allgemeinheit mit Elektrizität, Gas und Wasserstoff, die zunehmend auf erneuerbaren Energien beruht".

⁴ (German Constitution), Art. 20a: „Der Staat schützt auch in Verantwortung für die künftigen Generationen die natürlichen Lebensgrundlagen und die Tiere im Rahmen der verfassungsmäßigen Ordnung durch die Gesetzgebung und nach Maßgabe von Gesetz und Recht durch die vollziehende Gewalt und die Rechtsprechung“.

⁵ (Bundestag, 2010). On 30 June and 1 July 2011, this concept was translated into a package of legal acts, which *inter alia* banned nuclear power in Germany after 31 December 2022: (Bundestag, 2011).

⁶ (CPA, 2019).

⁷ One complaint was raised in 2018 by the solar industry, BUND (an NGO) and several individuals from Germany. It was followed by three more complaints in 2020 by younger individuals (one was 11 years old), including from Bangladesh and Nepal, supported by several NGOs, such as DUH (Deutsche Umwelthilfe). All complaints were dealt with by the ruling.

⁸ (The Federal Constitutional Court, 2021).



- The Court derived its yardstick from the IPCC report on 1.5°C,⁹ with its assessment of the remaining CO₂ budget. The Court concluded that a reasonably conservative CO₂ budget should be the starting point for the Climate Protection Act.
- It pointed out that Germany could not hide behind other countries not doing enough and that Germany could only claim a share of the carbon budget in 2015 in proportion to its share in global population in 2015, i.e., roughly 1%.
- In the Court's view, given the tight remaining CO₂ budget, the Climate Protection Act of 2019 implied more stringent restrictions becoming necessary after 2030 to the detriment of the freedom of present younger generations: the law was not sufficiently ambitious for before 2030 and not concrete enough for after 2030.

The legislator was given until the end of 2022 to remedy these shortcomings.

Already on 12 May 2021, the Government presented a draft amendment to the Climate Protection Act.¹⁰ This amendment passed both chambers of Parliament¹¹ just before the summer break and subsequent federal elections. As a result, the CPA includes now (i) a more ambitious binding decarbonisation target of -65% for 2030, (ii) binding – instead of previously only intended – targets for the time after 2030, mainly an 88% CO₂ reduction (vs 1990 levels) by 2040, and (iii) a net zero target for 2045. The targets are broken down by sector and year. It is the responsibility of the respective ministry to adopt adequate measures if development is off track.

In parallel, the Government approved a support package of EUR 8 bln on 23 June 2021 to implement the new targets.¹²

1.2 The Coalition Agreement of the new Government

The new German Government elected on 8 December 2021 is supported by the Social Democrats, the Green Party and the Liberal Party. These parties signed a Coalition Agreement¹³ on 7 December 2021, which put at its core climate protection in a social-ecological market economy.¹⁴ The CA confirmed the climate goal of 1.5°C while claiming a position for Germany as a strong industrial economy.¹⁵ It took a holistic approach to climate protection, dealing with aspects of the economy, environment and nature protection, agriculture and food, and mobility before addressing the specific climate-related issues of transformation of the energy sector. The new Government aims at shaping a reliable and cost-efficient path to climate neutrality by 2045 in a technology-open way.¹⁶ Any reference to the CO₂ budget, the guideline for the Ruling of the Constitutional Court, is conspicuously absent, ignoring the scientific yardstick to guide climate policy to stay within 1.5°C. The CA is also silent on how much the single measures spelled out in it should contribute to reaching the targets of the amended Climate Protection Act.

1.2.1 Aiming at minus 65% of GHG by 2030

Partly due to a shrinking economy linked to Covid-19, partly due to closing some of the oldest lignite power plants, in 2020 Germany reached its decarbonisation targets of -40% GHG emissions compared to 1990. Reducing the emissions by another 25%, or 291 mln t CO₂ eq per year, would translate into 438 mln t CO₂ eq per year in 2030, as shown in Figure 1.

⁹ (IPCC, 2018).

¹⁰ (Draft Law on the First Act to Amend the Federal Climate Protection Act, 2021).

¹¹ (The Federal Government, 2021). The amendment passed the Bundestag on 24 June 2021 and the Bundesrat on 25 June 2021.

¹² (The Federal Ministry of Finance, 2021).

¹³ (CA, 2021).

¹⁴ *Ibid.*, pp. 24-64.

¹⁵ *Ibid.*, p. 24.

¹⁶ *Ibid.*, p. 55: „Dabei sichern wir die Freiheit kommender Generationen im Sinne der Entscheidung des Bundesverfassungsgerichtes, indem wir einen verlässlichen und kosteneffizienten Weg zur Klimaneutralität spätestens 2045 technologieoffen gestalten.“

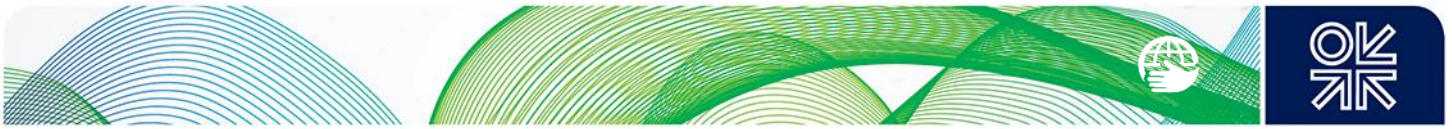
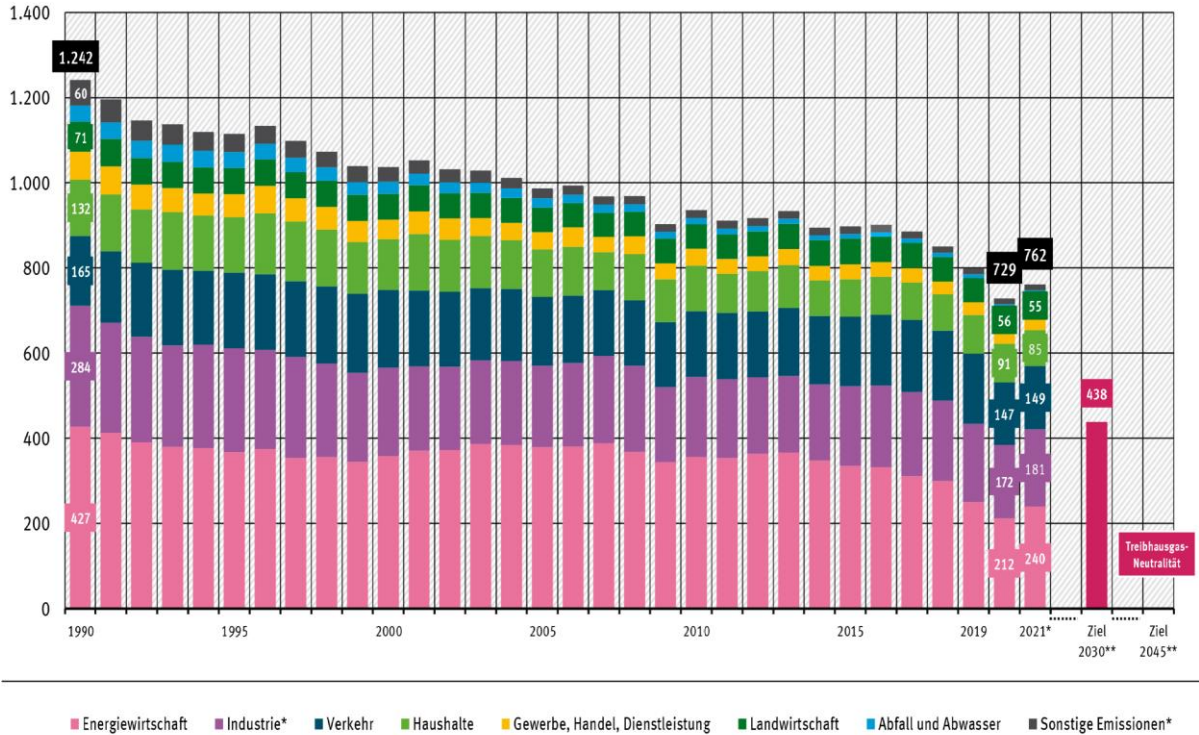


Figure 1: Greenhouse gas emissions covered by the UNFCCC, mln t CO₂ eq



Emissionen nach Kategorien der UN-Berichterstattung ohne Landnutzung, Landnutzungsänderung und Forstwirtschaft
 * Industrie: Energie- und prozessbedingte Emissionen der Industrie (1.A.2 & 2);
 Sonstige Emissionen: Sonstige Feuerungen (CRF 1.A.4 Restposten, 1.A.5 Militär) & Diffuse Emissionen aus Brennstoffen (1.B)
 ** Ziele 2030 und 2045: entsprechend der Novelle des Bundes-Klimaschutzgesetzes vom 12.05.2021

Quelle: Umweltbundesamt, Nationale Treibhausgas-Inventare 1990 bis 2020 (Stand 01/2022), für 2021 vorläufige Daten (Stand 15.03.2022)

energy sector, industry, road transport, households, commercial, agriculture, waste and water, other emissions

Source: (The Federal Environment Agency, 2022)

To allow for net zero by 2045, a major step is reaching the 2030 target of -65% of GHG emissions (compared to 1990 levels). The CA aims at (“ideally”) phasing out lignite and hard coal power production by 2030, eight years earlier than the phase-out of coal-fired capacity under the existing Coal Phase-out Act. The CA provides concrete detailed targets for creating new renewable peak capacity to replace coal-fired power, while envisaging extra power demand from sector coupling (BEVs and heat pumps) and maintaining reliability by gas-fired power.

For 2030, gross electricity production is to grow to 680-750 TWh¹⁷ – an increase of 20%-32.2% compared to the 2020 figure of 567 TWh,¹⁸ e.g., due to assuming 15 mln BEVs.

Renewables should contribute 80%, resulting in 544-600 TWh (an increase of 105%-135% vs 2020 levels, with 254.7 TWh renewables)

For PV, the 2030 target is 200 GW (vs 58.4 GW in 2020) resulting (at 800 h/a) in 160 TWh

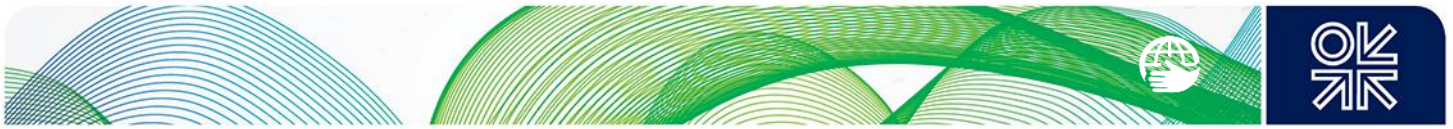
For offshore wind, the target is 30 GW (vs 7.8 GW in 2020) resulting (at 3500 h/a) in 105 TWh

Assuming biomass and hydro as in 2020: 70 TWh

That leaves for onshore wind: 209-265 TWh

¹⁷ (CA, 2021, pp. 56-57), for projections for renewables.

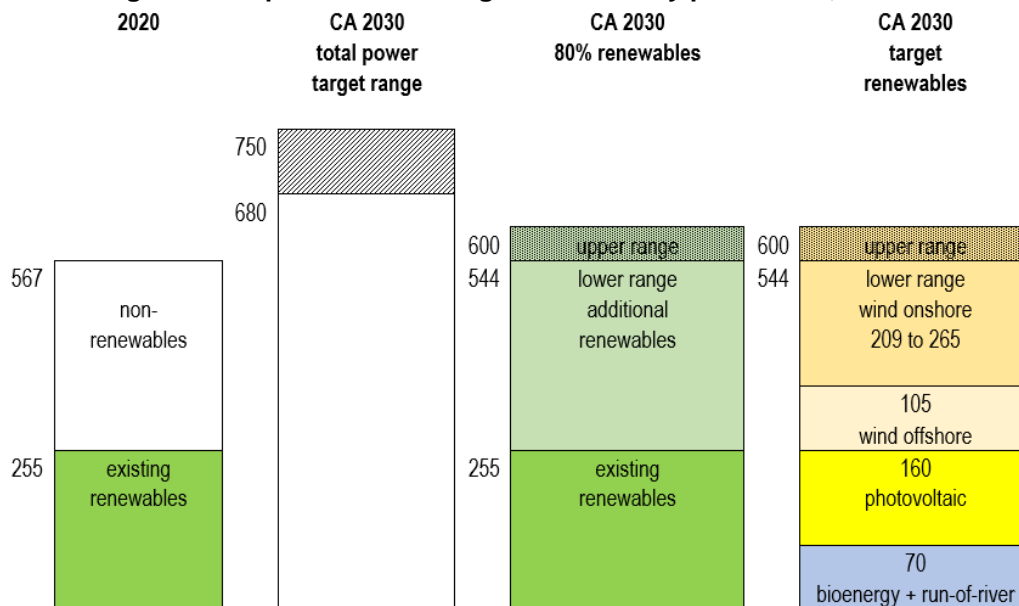
¹⁸ (Destatis Statistisches Bundesamt, n.d.).



Compared to power generation of 104 TWh from onshore wind in 2020, this would require an increase of 90 TWh to 146 TWh. At 1,800 h/a, this would translate into a capacity of 116 GW to 147 GW, an addition of 59.4 GW to 90.4 GW, respectively.

No concrete target is mentioned in the CA for onshore wind capacity, but 2% of the area of Germany is stipulated to become available for onshore wind; however, no timeframe is mentioned. A study by the UBA (*Umweltbundesamt* – Federal Office for the Environment)¹⁹ estimates a need of 0.9% of the German area for a total of 80 GW of onshore wind by 2030; 1.7% – corresponding to a total of 130 GW by 2040; and 1.9% – to achieve 155 GW by 2050. Twenty percent of gross electricity production, i.e., 136-150 TWh, would be fossil fuel-based by that point, compared to 181.6 TWh fossil fuel-based generation in 2020, as demonstrated in Figure 2.

Figure 2: Envisaged development of annual gross electricity production, TWh/a



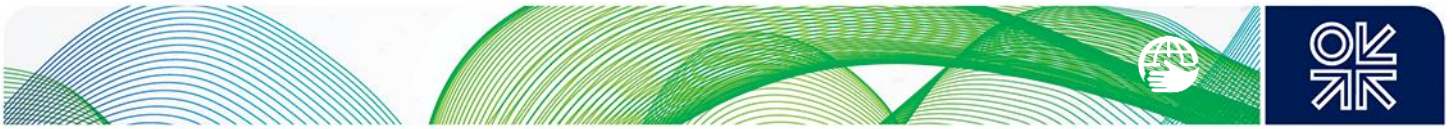
While these detailed targets for renewables deployment are very ambitious and in need of more discussion, reaching them would contribute substantially to phasing out unabated coal and thus to reaching the overall -65% decarbonisation target by 2030.

In 2020, power production from lignite and hard coal stood at 134.5 TWh – way below 171.5 TWh in 2019 and then 162.6 TWh in 2021. This suggests that a substantial part of the 2020 decrease was due to the effects of Covid-19 on the economy. At the same time, CO₂ emissions from lignite and hard coal-based power production reached 126 mln t CO₂ in 2020 (compared to ca 160 mln t CO₂ in 2019).²⁰ An increase in renewable production from 289 TWh to 345 TWh should be able to replace today's total power production from lignite and coal (assuming there is enough dispatchable power left), thereby reducing today's CO₂ emissions by up to 150 mln t CO₂ (not CO₂ eq).

The targets for renewable capacity additions by 2030 are concrete and lend themselves to detailed discussions on how to achieve them and on their implications for reliability and reaching net zero by 2045. The CA is vaguer on other major elements (not surprising for a compromise between three political parties with different priorities).

¹⁹ (Federal Ministry for Economic Affairs and Climate Action, 2021, p. 47).

²⁰ (The Federal Environment Agency, 2022).



1.2.2 Hydrogen and reliable power supply

The 2020 Hydrogen Strategy will be developed further, with priority given to domestic production based on renewable energy. By 2030, the capacity of electrolysis is planned to reach 10 GW.²¹

For reliability of power supply, the CA suggest building new gas-fired power capacity with the caveat of it being hydrogen-ready.²² “Natural gas is indispensable for the transition period.”²³ This suggests the availability of green hydrogen to take over the role of primary energy supply for flexible gas / hydrogen power plants. The CA is silent on how much hydrogen transportation and storage and how much hydrogen-fired capacity is needed for that vision.

1.2.3 Net zero by 2045

While the targets for 2030 are detailed by the CA, addressing net zero by 2045 remains abstract, except for the further deployment of offshore wind to reach 70 GW by 2045. Keeping within the limited CO₂ budget, a core argument of the Ruling of the Constitutional Court, is not mentioned.

The CA claims technology openness in its introductory remarks.²⁴ However, by 2045, infrastructure should not be used any longer for fossil fuels.²⁵ CO₂ sequestration is only mentioned implicitly with a vague reference to “technical negative emissions” and with a weak commitment to look into that concept.²⁶

This strongly suggests an underlying model of an all-renewables world by 2045, where the necessary input of energy-rich molecules comes from green hydrogen from renewable electricity via electrolysis. This concept of an all-renewable energy supply implied by the CA depends on uncertain technology developments followed by large-scale deployment, which are not addressed in any substantive way.

1.3 Fallout of the war in Ukraine started by Russia on 24 February 2022

Tension about the deployment of Nord Stream 2 already existed following US sanctions starting with CAATSA²⁷ in 2017 and the more recent delay of the start of operation in view of EU regulations. The present Russia-Ukraine war added new concerns about Russian gas supplies, which were put under further scrutiny. Stopping gas deliveries has become part of the rhetoric of both sides and the question of payments has become contentious.

A high share of German energy imports is from Russia, not only for gas, but also for coal, oil and nuclear fuel. This triggered discussions and activities to reduce dependence on Russian gas imports by pipeline, as well as on imports of oil and coal. Nuclear fuel is not an issue any more, as Germany’s remaining three nuclear plants will close by 31 December 2022 and prolonging their operation would run into legal and, above all, practical obstacles.

The intention of the German Government is to foster the construction of two land-based LNG terminals: one in Wilhelmshaven, the other in Stade or Brunsbüttel. As they will only be available in the medium term, probably not before 2025, the plan is to charter several FSRUs²⁸ to be moored near

²¹ (CA, 2021, pp. 59-60).

²² *Ibid.*, p. 59: „Wir beschleunigen den massiven Ausbau der Erneuerbaren Energien und die Errichtung moderner Gaskraftwerke, um den im Lauf der nächsten Jahre steigenden Strom- und Energiebedarf zu wettbewerbsfähigen Preisen zu decken. Die bis zur Versorgungssicherheit durch Erneuerbare Energien notwendigen Gaskraftwerke müssen so gebaut werden, dass sie auf klimaneutrale Gase (H₂-ready) umgestellt werden können.“

²³ *Ibid.*, p. 59: “Erdgas ist für eine Übergangszeit unverzichtbar.“

²⁴ *Ibid.*, p. 55: „Dabei sichern wir die Freiheit kommender Generationen im Sinne der Entscheidung der Bundesverfassungsgerichts, indem wir einen verlässlichen und kosteneffizienten Weg zur Klimaneutralität spätestens 2045 technologieoffen ausgestalten.“

²⁵ *Ibid.*, p. 65.

²⁶ *Ibid.*, p. 65: “Wir bekennen uns zur Notwendigkeit auch von technischen Negativemissionen und werden eine Langfriststrategie zum Umgang mit den etwa 5% unvermeidlichen Restemissionen erarbeiten.“

²⁷ (US Department of the Treasury).

²⁸ (News Text Area, 2022).



Wilhelmshaven and Brunsbüttel and to launch an emergency procedure to construct a pipeline to link the Wilhelmshaven FRSU to the national gas grid, using existing plans from an earlier LNG project at Wilhelmshaven. Also, the German Government took initiatives to acquire extra LNG cargoes from Qatar and the UAE to fill German storages to levels achieved in previous years.²⁹ In addition, the first warning stage of the emergency plan for gas has been announced.³⁰

Further considerations include replacing gas in power production by more lignite as a national resource, and in the medium run, further expanding and accelerating the rollout of renewables and energy saving. For the time being, issues of climate protection were moved further down the priorities list in favour of energy security and military issues.

1.4 German geography

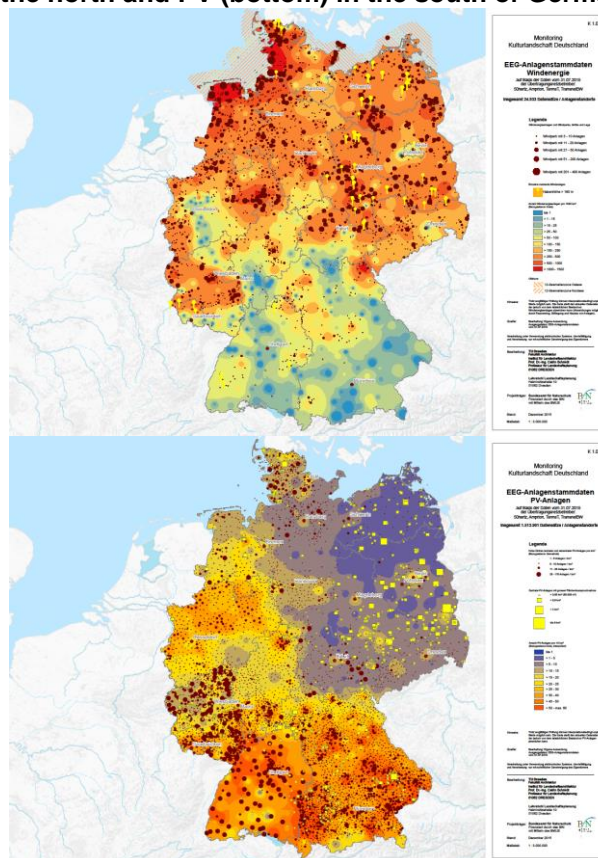
Germany has reliable power and gas systems; while electricity grids cover all of the country, gas covers all densely populated areas.

The energy geography of Germany has several north-south dichotomies.

1.4.1 For electricity

Winds are much stronger in the north (onshore and even more so offshore), while the sun is stronger in the south. This is reflected in the distribution of the respective wind/PV capacity, the winter/summer divide and in the summer day/night divide of renewable power production.

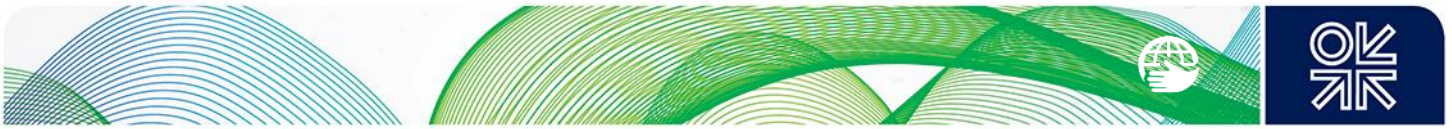
Figure 3: Wind (top) in the north and PV (bottom) in the south of Germany



Source: (Technische Universität Dresden, 2015)

²⁹ (Kurmayer, 2022) and (Deutsche Welle, 2022).

³⁰ (Deutsche Welle, 2022).



This adds to the historical north-south bottleneck in the electricity grid.

1.4.2 For natural gas

After the closing in of Groningen and the changes in the use of Russian gas import routes, Germany predominantly imports gas in the north via Emden/Dornum, Greifswald and at bidirectional transfer points in Frankfurt/Oder. Bidirectional import points in the south (Waidhaus, Oberkappel) and the west (from the Netherlands) lost their earlier importance.

Storage capacity differs as well: the south has less send-out capacity and volume and has only porous storages (mainly exhausted gas fields); higher storage volumes are in the north, as are all salt caverns (except for some in Sachsen Anhalt).

1.5 Germany's link to neighbouring countries / the EU

Due to its central position in the EU, both the power grid and the gas grid are interlinked with neighbouring countries and are part of the EU market. In 2021, Germany exported 65 TWh_{el} with a net export of 21.2 TWh_{el} compared to net public³¹ power generation of 491.5 TWh_{el}.

The (non-) availability of renewables is similar in neighbouring countries (simultaneous wind in the north and sunshine in the south). The EU market allows for mitigating renewables unreliability with hydropower in neighbouring countries, mainly in the Alps. There are underwater cables³² connecting the UCTE system of which Germany is a part with the hydro plants of the NORDEL system in Sweden and Norway. These opportunities are limited and are shared with other EU countries.

Germany plays an important role in the transit of gas: of the overall supply of 1,724 TWh in 2020- most of it being imports - about 910 TWh,³³ were consumed in Germany, the rest was transported to neighbouring countries. There are several large transit systems for Russian, Norwegian and Dutch gas: north-south (Eugal, OPAL, TENP) and east-west (NETRA, MEGAL, MIDAL, NEL, etc.).

As for hydrogen, there is a concept for an EU-wide grid (H₂ Backbone) based on expected hydrogen imports from North Africa and a concept for using the (rather low-diameter) pipelines in Spain and France for hydrogen transportation to northwestern Europe. It remains to be seen what volumes can be realised and by when within these concepts.³⁴

CO₂ exports from the EU northwest coastline are part of the Norwegian Longship / Northern Lights pilot project to transport CO₂ to Norway and sequester it in saline aquifers under the Norwegian part of the North Sea.

³¹ Public electricity supply does not cover industrial supply, which is dealt with in a different category, i.e., power generation predominantly for industrial purposes, not feeding into the public grid.

³² The recently started Nordlink has a capacity of 1 400 MW.

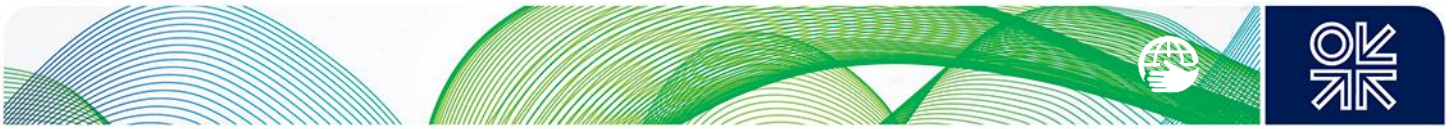
³³ (Bundesnetzagentur, 2022, p. 334).

³⁴ (Gas for Climate, 2021).

Figure 4: Germany's natural gas network in 2021



Source: (ENTSOG, 2021)



2. Net zero and reliable energy supply: renewables alone will not deliver by 2045

For Germany, there are three basic instruments to minimise CO₂ emissions: (i) reducing demand through energy efficiency and saving, (ii) harvesting energy from renewables – solar, wind and biomass (subject to LULUCF),³⁵ and (iii) fossil fuels, which have to be decarbonised by CCS. Nuclear is not an option, as the last three nuclear plants will be phased out by law by the end of December 2022 (more details *below*), and tidal and geothermal energy are marginal at best.

Due to the mistaken identification of carbon capture with the disposal of highly radioactive waste (see Section 3.7.2), CO₂ sequestration in Germany is *de facto* impossible under the CCS Act of 2012, which will be difficult to change quickly. However, Norway offers a large potential for offshore CO₂ sequestration, which could be used by Germany. There is no reason to discard this opportunity. Nevertheless, the green vision reflected in the CA is an attempt to achieve net zero by 2045 with the help of energy efficiency and renewables alone, i.e., without using hydrocarbons (including gas) beyond 2045 and without addressing CCS. This has been reinforced by the wish to become independent from Russian gas and from gas more generally in view of the present Russia-Ukraine war.

Unfortunately, the public discussion erroneously suggests that more intermittent renewables could directly replace dispatchable on demand oil and gas and that peak wind or PV capacity would be comparable with the dispatchable capacity of hydro or thermal plants. In this Chapter, we will look at the implications of this misperception and the reasons why net zero by 2045 and maintaining reliability can be achieved only by including gas or other fossil fuels with CCS in Germany's energy strategy. This would be necessary until an all-renewables energy sector providing energy on demand becomes achievable, possibly in the second half of this century.

In view of the short time horizon, trial and error is not an option, nor is betting on technology breakthroughs. If we do not want to play poker with the climate, then feasibility must be the yardstick and the use of the limited CO₂ budget must be kept in mind: early savings on CO₂ emissions give more flexibility at the end of the set timeline. While costs matter, it would be unrealistic not to go for a robust solution because it might require spending of a small share of GDP more compared to imagined solutions, which may be cheaper – on paper.

In Chapter 2, we look first at the implications of renewables' intermittence for the reliability of supply and if this has a chance to be managed by 2045. Assuming this would be possible, we then look into whether the highly ambitious rollout speed for renewables suggested by the CA would achieve the net zero target by 2045 on a volume basis. In Chapter 3, we move to the CO₂ capture and sequestration required to decarbonise the existing reliable power supply by lignite or gas and to convert gas or oil into blue hydrogen. The implications for a new CO₂ infrastructure are discussed in Chapter 4.

2.1 Compensating the fluctuations of renewables

Germany has been a pioneer of renewable power production over the last two decades (at a price). It has installed a remarkable capacity of renewable electricity by the end of 2021: 58.4 GW of PV, 56.3 GW of onshore wind and 7.8 GW offshore wind, reaching a share of 50.3%³⁶ of net public electricity supply in 2020. In 2021, that share went down to 45.8% due to low wind and a post-Covid rebound of power demand.

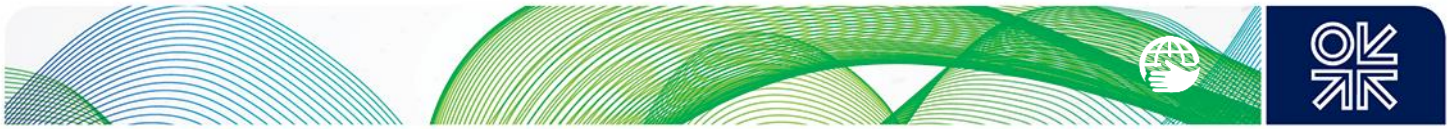
2.1.1 Short-term variations of renewable power feed-in

So far, the variations of power supply from renewables could be compensated, while maintaining a very high reliability (low SAIDI)³⁷ by a large domestic thermal power capacity and an extensive cross-border

³⁵ The LULUCF (land use, land use change and forestry) sector is used to report the CO₂ flows between different terrestrial reservoirs (biomass, soils, etc.) and the atmosphere.

³⁶ (Energy-Charts, Fraunhofer ISE).

³⁷ (Bundesnetzagentur, 2021).

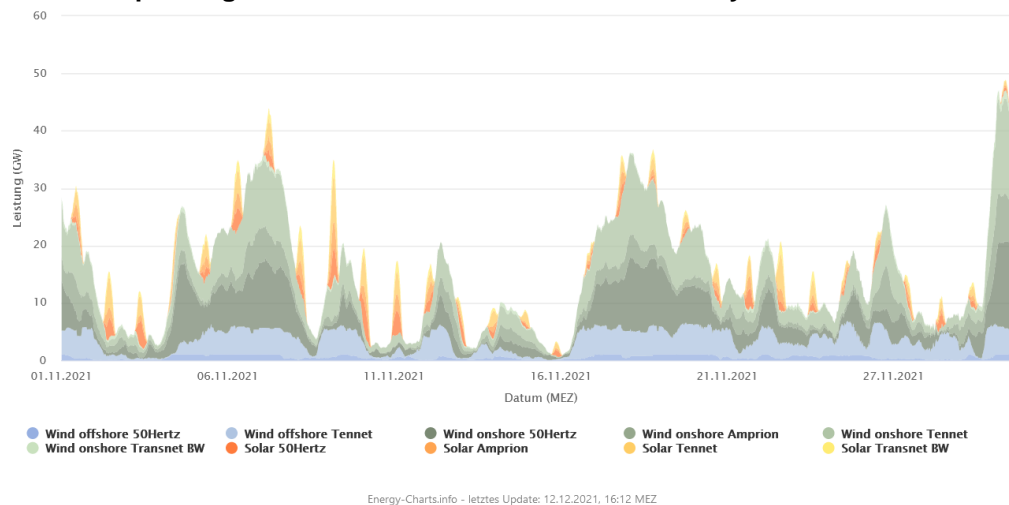


exchange of power. Integrating renewables has its specific characteristics in winter (dominated by wind, mostly in the north) and in summer (dominated by PV, mostly in the south).

Winter

In winter, the PV feed-in is minor; feed-in of onshore wind in the north and offshore dominates, but it is unreliable. Variations depend on the randomness of wind, which has no particular correlation with consumption patterns. Figure 5 uses the example of November 2021 to illustrate the requirements stemming from typical variations of wind in winter, which may be softened or reinforced by opposite or parallel movements of the load demand curve.³⁸

Figure 5: Public power generation from PV and wind in Germany in November 2021



Source: (Energy-Charts, Fraunhofer ISE)

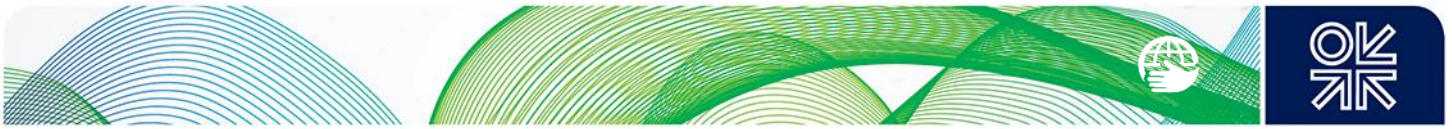
Renewable power increased from 29 November 2021 at 20:30 with 11.9 GW renewable feed-in (almost exclusively wind) to 46.7 GW at 6:45 on 30 November – by 34.8 GW within 10 hours. That was a gradient of 3.5 GW per hour, equivalent to taking the capacity of five large CCGTs or four large coal blocks off the grid per hour, for 10 hours.

As an example of the opposite: renewables had a peak of 43.9 GW on 7 November at around midday, coming down to 4.0 GW at about 0:00 on 9 November, i.e., an overall decrease of 39.9 GW within 36 hours. This corresponds to 1.1 GW extra thermal capacity coming on stream every hour for 36 hours.

Wind patterns can be predicted reasonably for more than 24 hours in advance, longer than the cold start time of coal or even lignite power plants. Capacity gradients of coal-fired power plants from minimum to maximum load are about 3% of peak capacity per minute, so they can increase their feed-in from 50% capacity to 100% capacity within 20 minutes. As long as there is enough operational thermal capacity, the ups and downs of wind production should be manageable, at the cost of keeping such large backup operational. The CO₂ footprint for such reliability might be acceptable and can be minimised by post-combustion decarbonisation, while the alternative – blackouts of indefinite duration – is not.

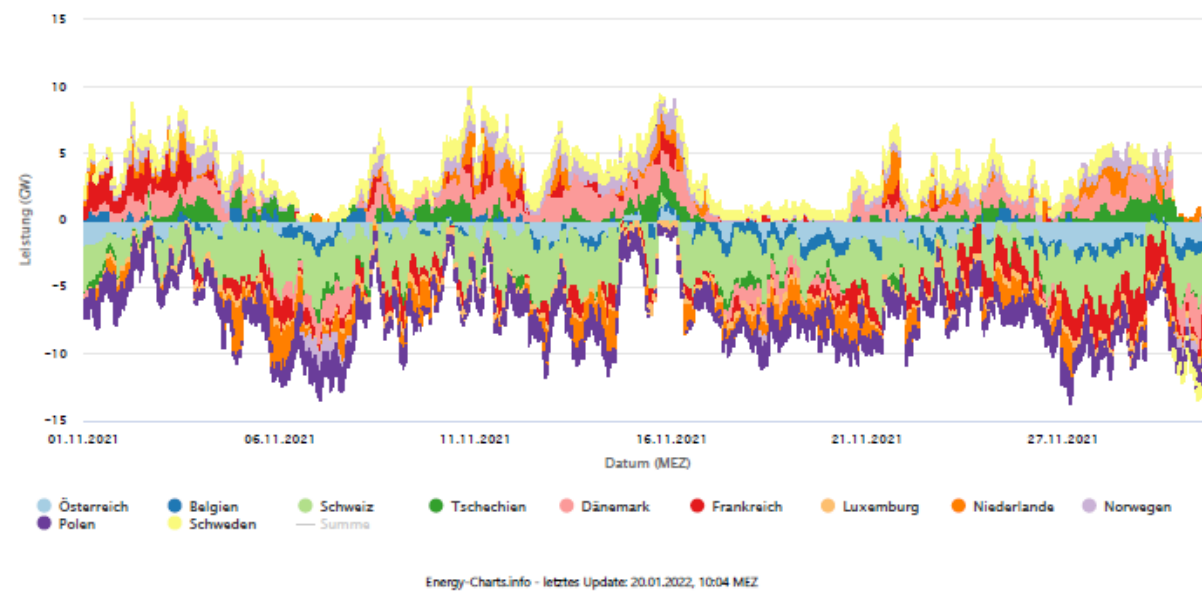
The fluctuations in November 2021 were also managed through imports and exports (see Figure 6), each up to 10 GW, while gas and coal-fired power each contributed similar amounts. However, in future, Germany will not be able to count on resolving its supply intermittence by turning to neighbouring countries as they too install more renewables capacity, increasing the need for dispatchable power. Wind and PV tend to have a compensatory effect across the EU on a monthly basis, and there may be some compensation by wind from neighbouring countries. However, during cold winters, low wind

³⁸ (Energy-Charts, Fraunhofer ISE, 2021).



situations often combined with low sunshine tend to spread from east to west; betting on neighbours does not work in critical situations.

Figure 1: Germany's power import and export in November 2021



Source: (Energy-Charts, Fraunhofer ISE)

Box 1. Dunkelflaute 16-26 January 2017

“*Dunkelflaute*” is a situation with low wind and little sunshine – often occurring in winter with cold weather. The *Dunkelflaute* on 16-26 January 2017 is often used as a reference case, with renewables (including run-of-river and from biomass) staying below 20 GW (at 10 GW on average) and with demand between 60 and 80 GW.

During this *Dunkelflaute*, a dispatchable capacity of up to 70 GW was needed for reliable supply, in addition to ca 10 GW coming from biomass and run-of-river generation. On average, 60 GW non-renewable capacity was used, i.e., a total electricity generation of 60 GW for 10 days x 24 hours = 14.4 TWh was provided from non-renewable dispatchable power and imports.

Even if each of the almost 50 mln passenger vehicles in Germany in 2022 had a 100 kWh battery, this would offer a total electricity storage of merely 5 TWh, just bridging 4 days of *Dunkelflaute*.

In an all-renewables system, during *Dunkelflaute* the only final energy available would be renewables independent of sun and wind, i.e., run-of-river, hydro storage, biomass for power and other biomass. The remainder of electric and non-electric demand would HAVE TO BE provided out of storage as e-fuel or biofuel and hydrogen storage.*

In addition, *Dunkelflaute* is usually a cold period, as low-wind situations tend to coincide with cold weather from the east – a factor, which should be kept in mind in an all-renewables world, where heating also would depend on power.

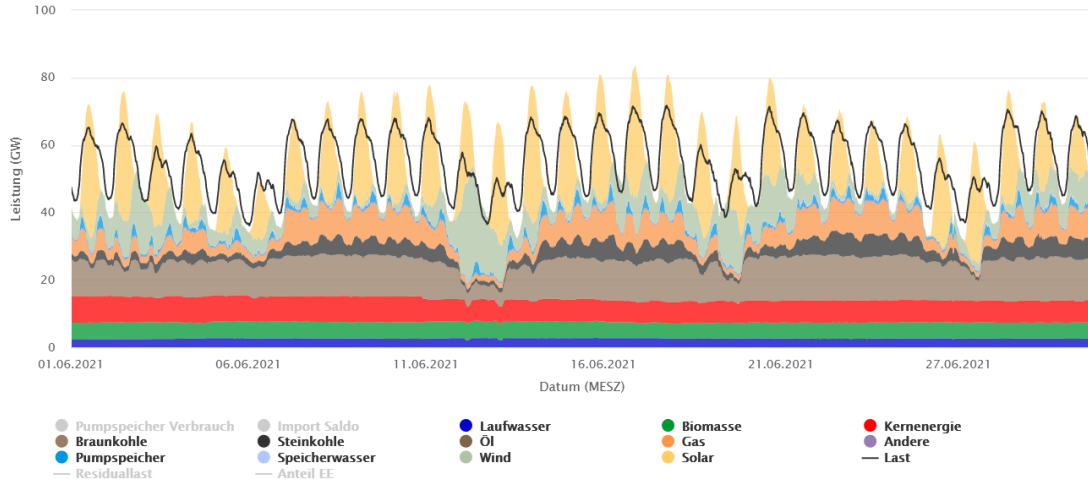
* In 2020, 10 days of average final energy consumption amounted to 65 TWh (not accounting for seasonal variation). See <https://www.bdew.de/energie/energieverbrauch-deutschland-2018/>.



Summer

In summer, PV from the south dominates the picture with a very peaky profile but with a more regular pattern than in winter (and largely similar to the daily load curve) (see Figure 7).

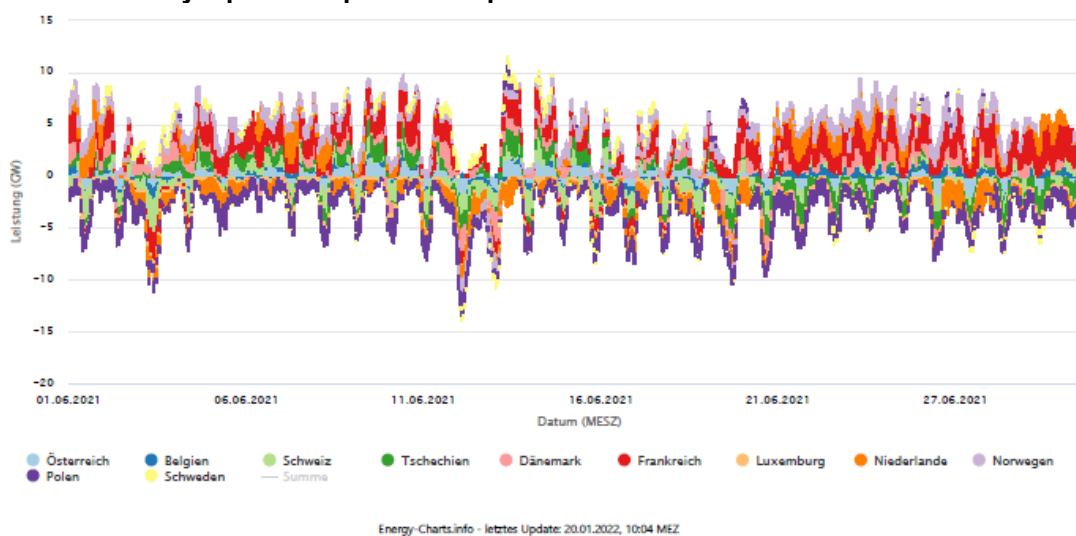
Figure 7: Net public power generation in Germany in June 2021



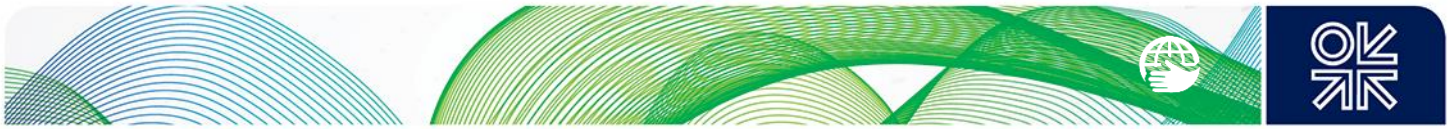
Source: (Energy-Charts, Fraunhofer ISE)

The situation in June 2021 was managed with gas and hard coal power during the night and for the ramp-up and ramp-down during daylight, and lignite ramp-down and up over weekends. Midday peaks (exceeding demand by up to 20 GW) were exported to neighbouring countries (see Figure 8), using the flexibility of hydro plants in the Alps. With more PV capacity coming on stream – not only in Germany – this possibility will reach its limits, so more PV at noon must be regulated down. These midday peaks are beginning to be evened out by individual wall-mounted batteries or BEVs. However, even if replacing power from the grid by self-generated electricity provides for noticeable savings, many private PV owners are hesitating to install batteries to store midday peak load for private consumption at another time, waiting for battery prices to come down.

Figure 8: Germany's power import and export in June 2021



Source: (Energy-Charts, Fraunhofer ISE)



Annual import-export balance

The daily and weekly patterns resulted in the following (physical) import and export balance in 2021: Germany's net exports stood at 17.4 TWh, with 57.0 TWh of exports and 39.6 TWh of imports.³⁹

2.1.2 Longer-term variations of renewables production

Substantial variations of overall renewable power production⁴⁰ occur from year to year, while demand may also vary.

Table 1: Power supply and demand, 1st half of 2021 vs 2020

	1 st half 2020, TWh	%	1 st half 2021, TWh	%	Change, 1 st half 2021/2020, TWh
Total grid feed-in	248.9	100	258.9	100	+10.0
Conventional	119.8	48	144.9	56	+25.1
Renewables	129.1	52	114	44	-15.1
of which wind	72.3	29	57.1	22	-15.2

Source: (Destatis Statistisches Bundesamt, 2021)

In the first half of 2021, power from renewables (wind) was 15.1 TWh lower compared to the first half of 2020.⁴¹ Fossil-fuelled plants covered that gap and also the increase of power demand following the first recovery from the Covid-19 crisis with a rather exceptional increase in GDP. Fossil power had to provide an extra 25 TWh out of 258 TWh total power production in the first half of 2021, around 10%. These variations will be difficult to cover by demand-side response; they exceed the total annual consumption of the aluminium industry, which was 8.1 TWh in 2017.⁴²

Share of dispatchable power needed

The Coalition Agreement recognises the need for the construction of new gas-fired power plants on the condition that they be H₂-ready until security of supply by renewables is established.⁴³

A share of dispatchable power *volumes* of at least 20% seems to be common wisdom for Germany and the EU, although there is no stringent derivation for it. The NEP 2035 (*Netzentwicklungsplan – grid development plan*) assumes a share of intermittent renewables of under 80% by 2050.⁴⁴ This is also the result of model calculations of an all-renewables energy sector.⁴⁵

The point about volumes should not be confused with the need to provide enough dispatchable *capacity*. Except for a total of less than 10 GW of run-of-river and biomass capacity, the entire peak load must be covered by dispatchable power or power imports. A probabilistic concept of reliable power supply looks risky in a society depending on power for almost everything. Neighbouring countries will not be able to help Germany when increasing their renewables capacity in a similar way, especially as low wind in winter often occurs across several countries in northwest Europe.

³⁹ (Bundesnetzagentur, 2022).

⁴⁰ (Destatis Statistisches Bundesamt, 2021).

⁴¹ (Federal Ministry for Economic Affairs and Climate Action, 2019, p. 1), for comparison: the total power consumption of the food industry was 16.11 TWh in 2016.

⁴² *Ibid.*, 4.

⁴³ (CA, 2021, p. 59).

⁴⁴ (50Hertz Transmission GmbH; Amprion GmbH; TenneT TSO GmbH; TransnetBW GmbH, 2021, p. 8).

⁴⁵ (Ruhnau & Qvist, 2021).



2.2 All-renewable energy supply bottlenecks, need for dispatchable power and reliable H₂

Reaching net zero inevitably requires deploying as much renewable electricity as possible to replace as much unabated fossil fuel-fired power as possible. It also requires expanding the use of electricity to other final energy uses, as much as possible, mainly by BEVs and heat pumps. And all of that in view of the CO₂ budget – as quickly as possible. In the first phase, 1 kWh renewable will replace 1 kWh of unabated fossil fuel-fired power as long as it is backed by enough thermal power generation.

The remaining ca 20% of power generation must come from on demand dispatchable power. One way to bridge that gap is an all-renewable energy supply, which would have to come from temporary surplus or rather purpose-built extra renewable capacity converted by electrolysis into hydrogen and transported and stored to be available on demand for power generation. This needs an infrastructure to transport the hydrogen to storage and to power plants, a large storage capacity to mitigate between the intermittent renewable power production and the load-following capacity requirements, as well as backup for *Dunkelflaute* and annual variations. For every kWh of dispatchable power, 3.0-3.7 kWh of renewables have to be produced to compensate for the 25% losses in electrolysis, some 10% for transportation and storage, then for at least 50% losses in a hydrogen-fired CCGT as soon as it becomes available or 60% in a H₂-fired boiler plant.

While the availability of the primary energy needed to bridge a *Dunkelflaute* at any time is no major challenge for fossil fuels, the replenishment of hydrogen storages is an open issue: low wind and sun periods may last longer and repeat themselves at short intervals, so there is always a remaining risk of shortage. Annual variations in the order of 15 TWh at the present level of wind capacity installed would require an enormous hydrogen storage volume of 50 bcm, which is about twice the present maximum gas storage volume in Germany. This could only be used once in several years and would be difficult to refill quickly after use. These variations are likely to increase as more wind capacity is installed.

Primary energy for the non-electric half of final energy consumption has to be supplied by energy-rich molecules – hydrogen or ammonia. The losses related to their production from renewables, transportation and storage will have to be compensated by a higher renewables feed-in. For each kWh_{th} about 1.48 kWh_{el} renewable have to be generated to compensate for conversion losses and losses in hydrogen transportation and storage.

2.3 Technology development, technical readiness for broad rollout

The target of 2045 requires focusing on feasibility; there is no time for trial and error. That means applying all available technologies (TRL 9) to reduce CO₂ emissions to keep within the CO₂ budget, and the sooner the better.

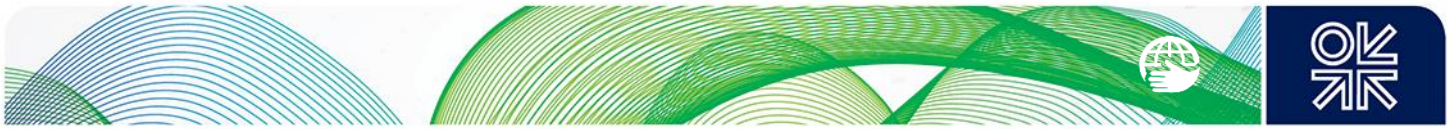
Feasibility today depends on technologies ready for rollout (TRL 9), which may not yet be receiving the necessary price signals for CO₂ avoidance and abatement. At the time of writing, the ETS price has reached a level of 80 €/t CO₂ and above, coming close to a level of 100 €/t CO₂, at which the CCS chain becomes economically feasible.⁴⁶ Rollout speed may be restricted further by production capacities, by geographic, meteorological and geological givens and political acceptance.

Most existing TRL 9 technologies could be improved in order to reduce costs and increase performance, but they are already sufficient for reaching net zero and staying within the carbon budget.⁴⁷ The only technologies necessitating rapid development are DAC technologies⁴⁸ needed to compensate for the last ca 5% of GHG emissions (at today's level). BECCS, which also can be used to compensate for the

⁴⁶ (Dickel, 2020, p. 29) and Section 5.1.2 below.

⁴⁷ Cost optimising models for reaching net zero by 2050 have to make assumptions on technological progress, often as learning curves. TRL 9 technologies tend to have proven learning curves – like the impressive learning curve for PV. At the same time, technologies with TRL < 9, such as electrolysis, batteries, fuel cells or pyrolysis, are based more on theoretical considerations than on past evidence. A cost optimisation model using learning curves risks showing results only reflecting the theoretical assumptions of that model for not yet ready technologies.

⁴⁸ An assessment of the present status of DAC, its future potential and further research and development needed is given in: (Viebahn, 2019)



remaining CO₂ emissions, is well developed on the bioenergy side, but entails extra production of bioenergy under the LULUCF restrictions. Both require CO₂ sequestration for achieving a negative CO₂ result.

The following Section focuses on the gaps in the development and deployment of the chain to transform intermittent renewable power into hydrogen or power available on demand, namely (i) the early stage of electrolysers development, (ii) the challenges to build a nationwide H₂ transportation system, and (iii) the open issue of H₂ storage which must be in salt caverns.

2.3.1 Electrolysers

While well known in principle, the presently installed electrolyser capacity is small worldwide: according to the IEA less than 300 MW were installed in 2020, with the largest unit having a capacity of 20 MW.⁴⁹ At the end of 2021, an electrolyser with a capacity of 150 MW started operation in China.⁵⁰ There are many projects in the 100 MW class, but their progress is not always clear. This compares to 120 GW of renewable peak capacity installed in Germany already at the end of 2021 and the total capacity of ca 350 GW planned for 2030 in Germany, of which a substantial share would not be absorbed by the power market but would need to be transformed into H₂ by electrolysis.

Table 2: Electrolyser technology deployed or in development⁵¹

Type	Energy consumption, kWh/Nm ³ H ₂ ⁵²		
	Today	2030 (10MW)	2050 (100MW)
alkaline electrolysis (TRL 8-9) AEL	4.6	4.5	4.3
membrane-/PEM electrolysis (TRL 7-8) PEMEL	4.8	4.8	4.3
high-temperature electrolysis (TRL 4-6) HTEL*	3.8	3.6	3.6

* The figures for HTEL do not include the required steam

Source: (Energy-Charts, Fraunhofer ISE), own calculations

The H₂ production rates shown for AEL and PEMEL translate into the following energy efficiencies – for GCV: at 3.54 kWh H₂/Nm³ an energy efficiency today of 74% to 77%; for LCV: at 3.0 kWh/Nm³ an energy efficiency of 63% to 65%.⁵³ Efficiency is expected to improve slightly over time and with the increasing size of electrolysers. As these figures do not necessarily include all system energy use (e.g., water treatment), an efficiency of 75% related to the GCV appears to be ambitious. (GCV assumes that the evaporation heat of the water from the combustion of hydrogen will be fully recouped).

2.3.2 Hydrogen transportation

H₂ transportation pipelines already exist in the northwest of the EU and close to Leipzig, with a total of ca 2 000 km, partly in operation for 90 years. These pipelines were built for the use of H₂ as raw material in the chemical industry. They do not necessarily compare with the transportation needs of an all-renewables hydrogen system.

For the same pipeline parameters, the energy transportation capacity of H₂ is at 80%-90% of a CH₄ pipeline. Hydrogen is very compression-sensitive, it needs 3.0 to 3.5 times the compression required for methane (energy and drive capacity),⁵⁴ as well as piston compression. It has an inverse Joule-

⁴⁹ (International Energy Agency, 2021).

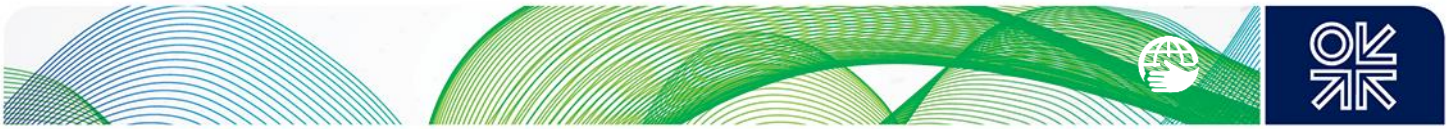
⁵⁰ (Collins, 2022).

⁵¹ (Dickschas & Smolinka, 2019, p. 7).

⁵² Nm³ = 1.055 Sm³.

⁵³ (The Linde Group, 2013).

⁵⁴ (Adam, Heunemann, von dem Bussche, Engelshove, & Thiemann, 2020, p. 17).



Thomson effect and has a different classification than methane, requiring new technical standards and new permitting procedures.

Whether the conversion from power or natural gas to hydrogen should be at a central upstream point with a corresponding hydrogen transmission grid or rather close to the consumption points using existing power and natural gas infrastructure is an open question which requires more investigation.

2.3.3 Hydrogen storage

Currently, there are very few examples of H₂ storages (beyond spherical tanks), and all are in salt structures: three in Texas, each with ca 600 000 m³ geometric volume, and one site in the UK with a total of ca 200 000 m³ geometric volume.⁵⁵

Storing H₂ is considered realistic in salt caverns, but so far not in porous rock formations.⁵⁶ With a target of 2045, the focus should be on salt caverns, but several technical issues must be sorted out, amongst them – the impact of the negative Joule-Thomson effect of H₂ on surface installations. The energy content of hydrogen is only about 1/3 that of methane, requiring a corresponding higher geometric volume for the same energy content. Apart from several open technical issues, a major obstacle for the deployment of hydrogen caverns is the leaching rates for new caverns, which are limited to protect fauna against excessively high salt concentrations.

During a period of *Dunkelflaute*, an H₂ outlet capacity corresponding to 70-80 GW_{el} is needed to cover at least the present winter peak power demand – probably more with increased power demand. If used in a CCGT, this means an hourly H₂ output of 140-160 GWh(H₂)/h = 47-53 mln m³ (H₂)/h, corresponding to an energy withdrawal rate of 14-16 mln m³/h as CH₄.

Meeting peak H₂ demand is likely to be of a similar order. At a load factor of 4000 h/a, total non-electric energy supply of 720 TWh would translate into a peak of 180 GW_{th} (H₂) = 60 mln m³ H₂/h. This compares to the present total volumetric outlet capacity of 22 mln m³ (CH₄)/h of all the salt caverns in Germany.

To what extent H₂ caverns can achieve the same energy outlet rates as CH₄ caverns is yet unclear, e.g., because H₂ warms up with expansion (negative Joule-Thomson effect), while CH₄ cools down, with strong implications for aboveground equipment and its technical parameters.

Surplus renewable power conversion by electrolyser to hydrogen, its transportation and storage in salt caverns, transportation and distribution to final customers and for power generation with subsequent use in turbines (not in boilers) means breaking new ground.

NH₃ could be a way to store and transport green hydrogen indirectly, as such technologies are well known and applied. However, the development of pure NH₃-fired boilers is at a very early stage.⁵⁷

These elements – electrolysers, H₂ transportation and H₂ storage –will hardly all be resolved in time for an all-renewables system by 2045, even if they face no obstacles in the longer run. So far, there is not even a serious conceptual discussion about the coordinated development of these elements, nor on the volumes and capacities needed.

Even assuming that these issues could be solved in time, the question remains whether the rollout of renewable power generation can go fast enough to achieve net zero by 2045 while maintaining reliable supply of final energy. This is discussed *below*.

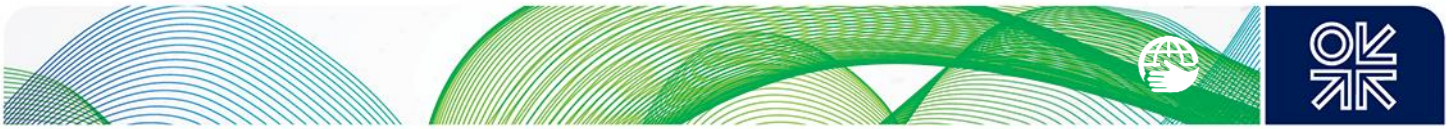
2.4 Targets

Replacing unabated coal-fired power production by renewable power production comes with corresponding substantial reductions of CO₂ emissions. However, it is necessary to back up the lack of

⁵⁵ (Warnecke & Röhling, 2021); e.g., table with comparison of existing hydrogen storages on p. 12.

⁵⁶ *Ibid.*, p. 15 gives a comparison of the development status of salt caverns, depleted gas fields and aquifers.

⁵⁷ (Mitsubishi Power, 2021).



renewable power due to low wind and/or low sun by abated or unabated fossil-fuelled power capacity in order to achieve reliability, with costs for keeping that capacity operational. Unabated capacity will not harm the 2030 decarbonisation goal only if it is used for a short duration. Phasing out coal power generation by 2030 to the extent possible is not the same as closing the coal-fired capacity as defined in the *Kohleausstiegsengesetz* (Coal Phase-out Act) of 2020, under which the last lignite plants have to be closed by 2038.

Backing the intermittence of renewables by thermal power will become more difficult with the increasing renewable capacity involved: as the load-following capacity becomes larger, the load-change gradients grow higher and the load factor – lower. However, long before the (sizeable) potential of replacing unabated lignite, coal or gas power generation on an intermittent basis with renewables is exhausted, combining decarbonisation with reliability of supply must be addressed to open the way to net zero and reliable supply by 2045.

This suggests three stages:

- until 2030 – quickly reduce annual GHG emissions by applying well-known renewable technology on an intermittent basis to replace unabated fossil-fuelled generation on an *ad hoc* basis, while keeping enough dispatchable fossil power generation capacity for load following.
- from 2030 and until 2045 – decarbonise dispatchable power capacity (lignite or gas-fired) and the supply of energy-rich molecules based on known TRL 9 decarbonisation technologies (ATRs with CCS); develop DAC and BECCS to compensate for hard-to-abate processes, to reach net zero by 2045.
- beyond 2045 – aim at sustainable GHG-free energy supply reliant on renewable supply as soon as it becomes technically possible and competitive.

2.5 Capacity rollout speed

In view of the limited CO₂ budget, a fast rollout of renewables with the highest CO₂ reduction capability (offshore wind and onshore wind) is necessary. While a fast coal to gas switch could also contribute to early CO₂ savings, this is not on the agenda in the reassessment of the role of gas in light of the war in Ukraine.

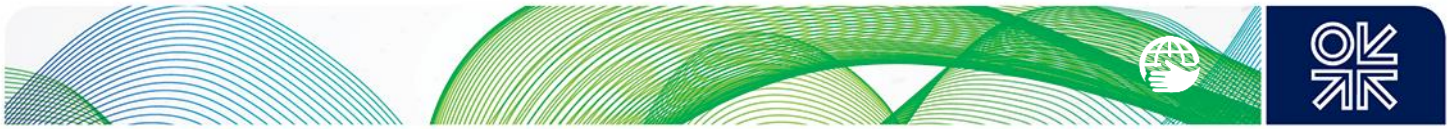
Sector coupling can reduce fossil fuel consumption and related CO₂ emissions through the increased (renewable) electricity use by BEVs and heat pumps; this would require expanding the existing power generation, transmission and distribution system.

Converting renewable power produced beyond demand – which would be curtailed otherwise – into hydrogen via electrolysis will play a limited and highly unreliable role in the production of green hydrogen.⁵⁸ Extra installed renewable power capacity should be used mostly to replace fossil-fuelled power generation, as argued by this author in “Blue hydrogen as an enabler of green hydrogen: the case of Germany” (Dickel, 2020). However, renewable capacity beyond peak load, which might contribute to meeting demand when the yield of renewables is below its maximum, risks being curtailed more often than the capacity within the peak load, raising questions about its economic viability.

The following arguments are developed *below*:

- Section 2.5.1 looks at whether the assumptions of the Coalition Agreement on the rollout of PV, offshore and onshore wind are realistic, taking into account past experience and foreseeable obstacles
- Section 2.5.2 gives a condensed overview of the different components of final energy demand to be provided by renewable energy

⁵⁸ (Dickel, 2020, p. 7).



- Section 2.5.3 works out the rollout speed of annual volumes of renewable energy implied in the Coalition Agreement
- Section 2.5.4 calculates the rollout times necessary to achieve net zero if based on renewables only and its dependence on the final energy consumption reduction rate
- Finally, Section 2.5.5 raises the question whether green hydrogen imports could make a substantial contribution to Germany's efforts to achieve net zero by 2045 to compensate for the shortfall of domestic renewables.

2.5.1 Renewables capacity addition under the CA

The contribution of renewables to replacing fossil fuel-fired power *generation (not capacity)* depends on the rollout speed for wind and PV, as these technologies are well developed. While cost reductions are possible for PV and to a lesser extent for wind, technical maturity is not an issue.

The targeted capacity increases of renewables under the CA by 2030, which should cover 80% of the electricity demand substantially increased by sector coupling (BEV and HP), appear possible but might be a stretch, judging by past performance, as shown in Table 3. This would be even more difficult if the renewable capacity additions were also intended to replace gas supply volumes (which would hardly work given the intermittent character of renewables).

Table 3: Past renewable capacity additions vs the Coalition Agreement

	Max addition		Additions (GW) in 2021	Status (GW)		Addition (GW/10 yrs) 2011-2020	Status (GW) end 2021	CA addition (GW/10 yrs) 2021-2030
	Year	GW/a		2011	2020			
PV	2011	7.9	4.4	25.4	54.0	28.6	58.4	141.6
onshore wind	2017	4.9	1.6	28.6	54.7	26.1	56.3	59-90
offshore wind	2015	2.3	0	0.5*	7.8	7.3*	7.8	22.2

*start in 2014

Source: BMWi⁵⁹ columns 1, 2, see Table 18; columns 3, 4, 5, see Table 17; CA additions: CA, p. 55 ff; calculation of onshore capacity see Section 1.2.1

For each category of renewables, the rollout from 2021 to 2030 under the CA (last column) is a multiple of the rollout of installed capacity during 2011-2020: five times for PV, two to three and a half times for onshore wind, and two times for offshore wind (accounting for the start of offshore wind in 2014). The average envisaged annual rollout rate over ten years (last column divided by ten) would compare with the peak rollout rate of the best year (first column) as follows: for PV – 14.2 GW vs 7.9 GW, i.e., by a factor of almost two; for onshore wind – 5.6 GW to 9.1 GW vs 4.9 GW, a factor of one to almost two; and for offshore wind – 2.2 GW vs 2.3 GW, a factor of one. All this looks very challenging but feasible with the right policy support.

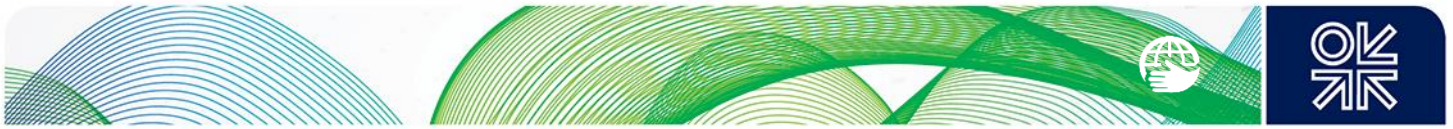
The rollout of onshore wind in the past ran into various obstacles in different German states assessed by a joint report between the authorities at the federal and state levels.⁶⁰ The report listed public resistance, low speed of permitting, incoherent and changing standards for assessing environmental impacts, and minimum distance requirements defined at state level, especially in the south.

The CA envisages allocating 2% of the area of Germany for wind power without specifying a timeframe.⁶¹ It offers only an indirect indication for onshore wind capacity additions. The range of

⁵⁹ (Federal Ministry for Economic Affairs and Climate Action, 2022).

⁶⁰ (Federal Ministry for Economic Affairs and Climate Action, 2021).

⁶¹ See Section 1.2.1 above.



additional 56 GW to 91 GW (resulting in 116 GW to 147 GW, respectively) has been derived from the overall renewables target volume range by deducting the contribution of PV, offshore wind, hydro and biomass and assuming a load factor of 1,800 h/a for onshore wind, which is in between the load factor of 2021 and 2020. The capacity of 150 GW foreseen for 1.9% of Germany's territory for 2050 coincides with the upper part of the derived capacity range of 116 GW to 147 GW; therefore, the figure of 147 GW for onshore wind is used for further analysis.

Regarding offshore wind, the targets of the CA exceed the most optimistic projections of the wind industry.⁶² Their target of 20 GW by 2030 was subject to an agreement of 11 May 2020 between the Federal Ministry of Economy, the local littoral states of the North and Baltic Seas and the TSOs concerned.⁶³

Table 4: Wind capacity in the German EEZ: wind industry projections vs the CA, in GW

	2020	2025	2030	2035	2040	2045	max
Wind industry:	7.8	10.8*	20**	-	40	-	60
Coalition Agreement:	-	-	30	40	-	70	n.a.

* Status as of end 2020: 7.8 GW, no additions in 2021. Capacity awarded for construction by 2025: 3.1 GW, see footnote ⁶⁴

** Expected tenders by 2025 for construction by 2030: 9.7 GW⁶⁵

2.5.2 Development and composition of final energy supply by 2045

With the maximum replacement of one kWh of dispatchable power by one kWh of intermittent renewable power and the wide rollout of BEVs and HPs (and CO₂ capture from the cement, ammonia and steel industry), the less demanding part of decarbonisation which can be delivered by existing technology is done. The reliability of energy supply (electric and non-electric) can be maintained to the extent that enough reliable power supply and enough reliable supply of hydrocarbons can be ensured. However, for further progress in decarbonisation – while maintaining the reliability of final energy supply – tasks that are more difficult have to be addressed:

- providing about 20% of load following for decarbonised power generation,
- providing non-electric final energy demand beyond present renewables (wood, biowaste) as CO₂-free energy.

Once the potential to replace thermal electricity on an *ad hoc* basis by intermittent renewable electricity is exhausted, further decarbonisation by renewables would also have to compensate for the losses related to hydrogen production, storage, transportation⁶⁶ and use.⁶⁷

Figure 9 is an update of the illustration in “Blue hydrogen as an enabler of green hydrogen: the case of Germany” (Dickel, 2020, p. 16). The base year is updated from 2018 to 2020 and the target year is updated from 2050 to the new net zero-year 2045. The left-hand side shows the shares of electric and non-electric final energy demand and the respective share of renewables in 2020. In 2020, energy consumption shrank, largely due to the effect of Covid-19 on the economy, bouncing back in 2021 by

⁶² (CA, 2021, p. 57).

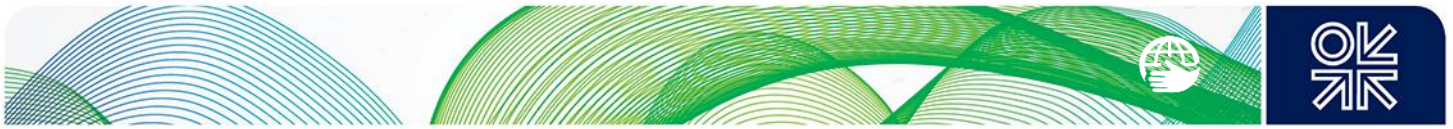
⁶³ (Federal Ministry for Economic Affairs and Climate Action, 2020).

⁶⁴ (Deutsche Windguard, 2020, p. 3).

⁶⁵ *Ibid.*, p. 6.

⁶⁶ (IET Institute for Energy Technology, 2014), compression depends on volume throughput, but in view of the lower energy content of H₂ compared to CH₄, the specific compression losses when storing hydrogen when compressed to 250 bar are 9.1%, compared to 2.5% for methane.

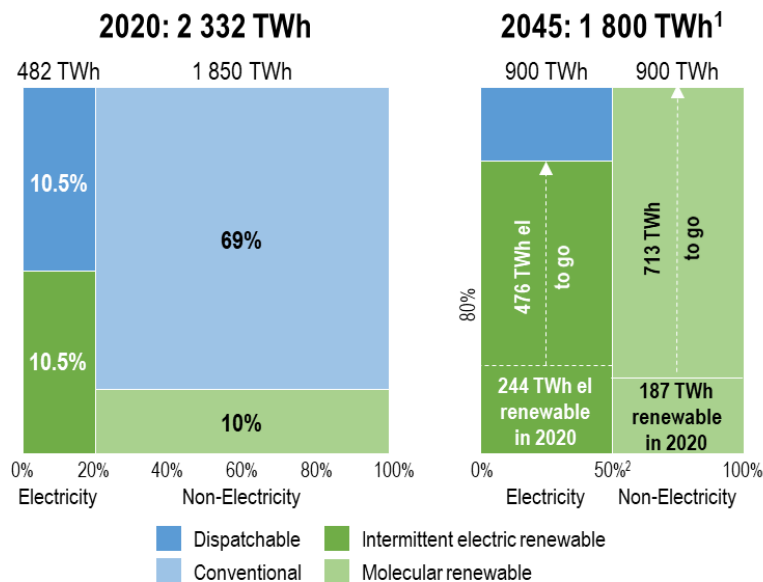
⁶⁷ See Section 2.2 above.



ca 2.5%. The share of renewables in electricity production was slightly above 50%⁶⁸ in 2020, but lower in 2021. Here, 50% is assumed.

The section on the right-hand side reflects the new target year 2045 for net zero. A reduction of 1% per year of final energy consumption after 2020 is assumed, resulting in a total final energy consumption of 1,813 TWh rounded to 1,800 TWh. It is assumed for 2045 that 50% of final energy consumption will be electric, resulting in an electric final energy consumption of 900 TWh – an increase of 418 TWh over 2020, mainly due to sector coupling. 20% is assumed to be dispatchable power (see Section 2.1.2). That results in a final energy consumption of 180 TWh as dispatchable power, and an additional 476 TWh, which could be fed in as intermittent renewables. In addition, from the 900 TWh of non-electric final energy, 187 TWh would be covered by renewables as is the case today (mainly wood and biowaste), so that 713 TWh have to be covered by renewables, i.e., renewable electricity converted into green hydrogen or ammonia.

Figure 9: Share of renewables in final energy consumption (electric/non-electric): 2020 and vision for 2045



¹ Energy saving 1% p.a. for 25 years – total reduction for 1994-2019 (pre-Covid): 1.5%; or for 1995-2020 (Covid effects): 10.5%

² Increase of electricity share to 50%

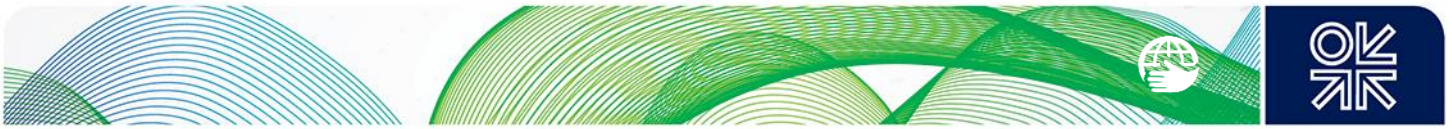
Source: for the original graph, see (Dickel, 2020, p. 16); (Federal Office for the Environment, 2021)

2.5.3 The rollout speed of total renewables under the CA

Such a reduction of final energy demand and sector coupling resulting in a 50-50 split between electric and non-electric final energy consumption requires us to take a look at the speed of renewables rollout given by the CA with the aim of reaching the net zero target by 2045.

The CA rollout speed of renewable power generation is based on the 2030 target of gross electricity production growth to 680-750 TWh_{el}/a, of which 80% should be renewable electricity, i.e., a range of 544-600 TWh_{el}/a. As shown above, this is very optimistic for each of the renewables components (PV, onshore and offshore wind) judging by past performance, as well as by the technical and social restrictions on future rollout for onshore and offshore wind. The optimistic upper end of the range, 600 TWh_{el}/a, implies the following annual rates of increase:

⁶⁸ (Energy-Charts, Fraunhofer ISE).



- an average of 34.5 TWh/a/a when compared to year 2020 (with 255 TWh/a renewables, an addition of 345 TWh/a spread over 10 years), or
- an average of 41.6 TWh/a/a when compared to year 2021 (with 225 TWh/a renewables, an addition of 375 TWh/a, spread over 9 years).

We take the more optimistic 41.6 TWh/a/a as reference because the Coalition Agreement was written at the end of 2021.

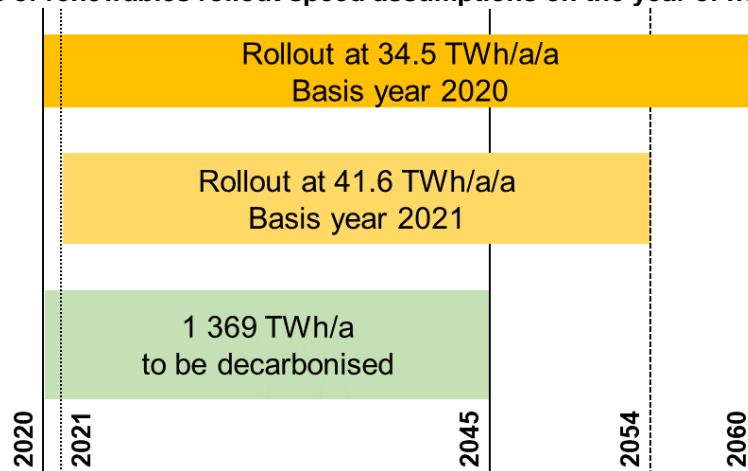
2.5.4 Resulting renewables rollout time

It is an open question whether the ambitious rollout speed of the CA can be maintained beyond 2030, as the most suitable locations for renewables will increasingly have been used up. Table 3 implies that the deployment of renewables reduced in the last few years. From the onshore wind volume of 1,320 MW auctioned off on 1 May 2022, there were only offers for 931 MW.⁶⁹

But even if the rollout speed can be achieved and kept up and even if the issues of conversion into hydrogen, its transportation and storage are resolved in time, the rollout speed of renewables under the CA is still not sufficient to achieve net zero by 2045 and cannot be compensated by imports of low-CO₂ hydrogen, as shown in Section 2.5.5.

Calculated on a pure kWh basis (without any conversion losses) and using 2021 as the reference year, at this rollout speed, the replacement of an additional 1,369 TWh/a (180 of dispatchable power + 476 electric + 713 non-electric renewables) by renewables would take 32.9 years from 2021, bringing us to 2054 (2020 as the reference year would bring us all the way to 2060).⁷⁰

Figure 10: Effects of renewables rollout speed assumptions on the year of net zero



It is not possible to maintain a 1:1 ratio when replacing fossil-fired power with electric renewables on an intermittent basis. For 180 TWh/a of dispatchable electricity, 533 TWh/a (i.e., an additional 353 TWh/a) have to be produced as renewable electricity to compensate for all the related losses.⁷¹ Adding 353 TWh/a at the assumed annual rate of 41.6 TWh/a would take 8.5 years more. For non-electric energy of 720 TWh/a, 398 TWh/a has to be compensated;⁷² at the assumed annual rate of 41.6 TWh/a, that would add another 9.3 years to net zero target date. Even assuming the availability of the necessary technology and its adequate rollout, accounting for conversion losses would defer the net zero year into the early 2070s (see Figure 11).

⁶⁹ (Federal Network Agency, 2022).

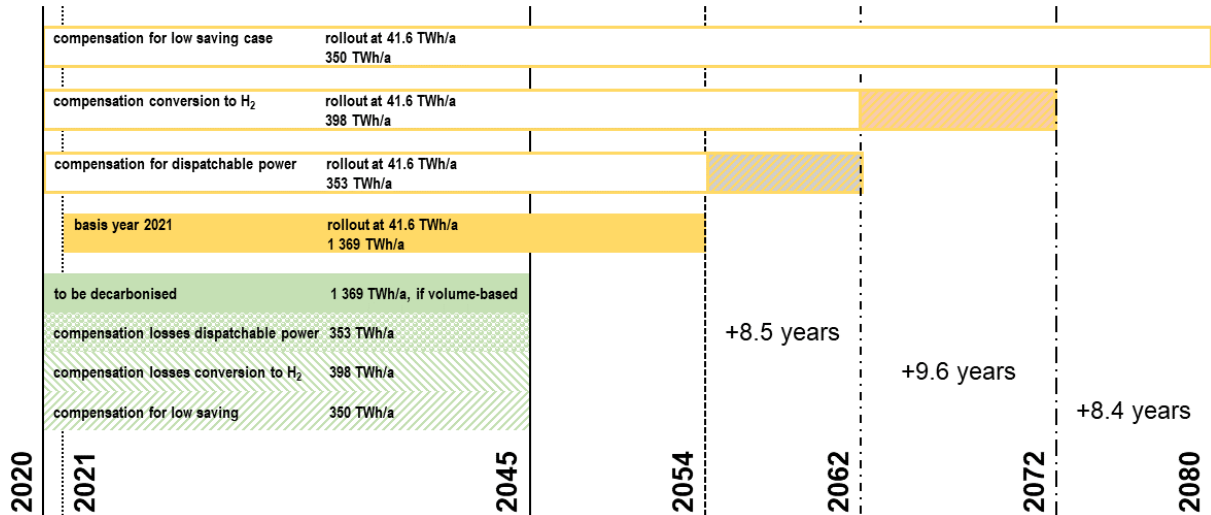
⁷⁰ Calculated as follows: $1\,369\text{ TWh/a} / 34.5\text{ TWh/a/a} = 39.7\text{ yrs} + 2020 = 2059.7$.
And $1\,369\text{ TWh/a} / 41.6\text{ TWh/a} = 32.9\text{ yrs} + 2021 = 2053.9$.

⁷¹ See Section 2.2 above.

⁷² *Ibid.*



Figure 11: Effects of extra renewable power needed for conversion losses of ATRs and dispatchable power, and of a low saving case



These roll out times are based on an annual 1% reduction of final energy consumption. In reality, final energy consumption in Germany developed over the past 25 years as follows:⁷³

- From 9,322 PJ in 1995 to 8,341 PJ in 2020 (Covid-19) = -10.5%, and
- From 9,110 PJ in 1994 to 8,975 PJ in 2019 = -1.5%

Applying a 10.5% final energy consumption reduction rate over 25 years instead of the 25% assumed would result in an additional 350 TWh/a to be produced by renewable power if counted on a 1:1 kWh basis. This would add yet another 8.4 years to the timeline (350 TWh/a / 41.6 TWh/a), pushing net zero even further to 2080, as illustrated by the upper bar in Figure 11.

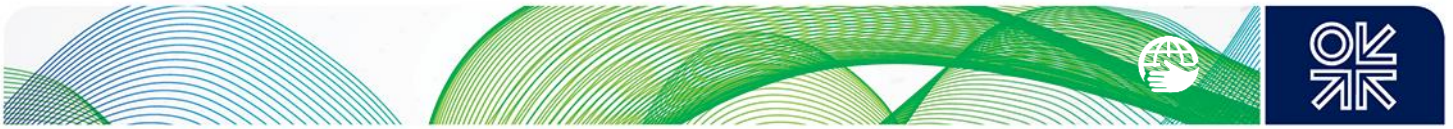
An all-renewables German economy will neither deliver net zero by 2045, nor stay within the CO₂ budget, nor provide reliable energy to the final customer. Even the ambitious rollout of renewables announced in the CA will not create enough CO₂-free energy to decarbonise the economy until much later than 2045. Bridging the irregularities of renewable power requires H₂ storage volumes not achievable by 2045. With regard to the reliable supply of both H₂ and power, the required send-out capacity from H₂ storages does not look feasible by 2045 (see Section 2.3.3).

2.5.5 Import of hydrogen

Hydrogen imports may be envisaged to compensate for the shortfalls in Germany's own H₂ production. However, this presupposes that exporting countries would have enough renewable electricity to produce H₂ exports on top of the renewables replacing their own fossil fuel-fired power. Most countries considering green hydrogen or ammonia exports would need renewable power to replace fossil fuel-fired power in their own mix as a matter of priority, where it would contribute the most to global decarbonisation, particularly since exports come with substantial conversion losses at the export and import points. Very few cases of isolated renewable enclaves exist. Exploiting them would hardly fill the gap in the German renewable energy balance, but would be easily associated with past exploitation for fossil resources.

It should also be noted that, with the exception of China, the countries considered for hydrogen export do not have electrolyzers anywhere near the scale required, nor any hydrogen storage for the handling of intermittence. Another point is that the transportation of hydrogen as LH₂ or by LOHCs is untested.

⁷³ (AG Energiebilanzen e.V., 2021), see Table 2.2.



The transportation of hydrogen in the form of NH_3 is technically proven however, though the use of pure NH_3 for power generation other than for co-firing in power plants is still a long shot.⁷⁴ In any case, Germany would become dependent on other countries and their deployment of not yet fully developed technologies, just to avoid addressing CCS, even offshore on the Norwegian Shelf.

The status of technology development and the required rollout time for large volumes demonstrate that the combination of the reduction of final energy consumption and the availability of renewable power alone will not be sufficient for achieving net zero by 2045, nor for maintaining the reliability of final energy supply. The contribution of hydrogen imports looks remote and should not be built on. **An all-renewables policy is clearly unrealistic to deliver the goals of the Paris Agreement.**

3. Net zero and reliable energy supply: adding CO_2 sequestration is essential to achieve net zero in 2045

Chapter 2 demonstrates that relying on renewables and energy efficiency alone for reaching net zero and reliable energy supply by 2045 leaves a substantial gap as well as considerable risks of not meeting the targets. As energy from present solar radiation (Biomass, solar PV and HP, Wind and hydro) is not enough to meet the 2045 targets and energy not stemming from solar radiation (geothermic, wave energy and nuclear energy) is not enough to make a substantial contribution – definitely for Germany – the energy available to fill the gap is (i) solar radiation from earlier times transformed by photosynthesis millions of years ago into fossil fuels. (ii) To stay within the CO_2 budget however, the CO_2 created by the use (combustion) of such fossil fuels cannot be discharged into the atmosphere but must be withheld and safely sequestered. Without (i) energy demand would not be met and without (ii) the CO_2 budget would be overrun. Therefore, adding CO_2 sequestration to Germany's decarbonisation strategy is an essential element in order to achieve net zero by 2045 and guarantee reliable supply of power and energy-rich molecules without CO_2 emissions. But it is not only essential in the sense of physically necessary. With the political support required, which may well be comparable with that given to renewables, adding CO_2 sequestration to the renewable and energy efficiency policies offers a good chance of achieving net zero by 2045 while maintaining reliability of energy supply.

3.1 CO_2 handling

In order to reach net zero by 2045, it will be necessary to introduce CCS in parallel to other measures to bridge the substantial remaining decarbonisation gap. This can be done independently of the progress of renewables and offers the diversification of technology development and rollout. Its deployment is mainly an investment issue (and not a technology development issue) and it can provide decarbonised energy on demand (hydrogen and dispatchable electricity), which in turn can be used to regularise intermittent electricity and green hydrogen.

With the potential for 1:1 replacement of power by intermittent renewables fully used up, it would be reasonable to direct the remaining renewables (of the rollout of 41.6 TWh/a x 24 years) for green hydrogen production, subject to the successful rollout of electrolysis. The remaining part of H_2 demand would be covered by blue hydrogen produced by ATRs (based on gas or liquid hydrocarbons) with CO_2 transported for sequestration under the Norwegian Shelf.

Most of the dispatchable low- CO_2 power would be produced from lignite power plants with CCS⁷⁵ for the high-load factor part of load following. The load following with a low load factor could come from plants run on decarbonised H_2 (for local units like CHPs) or from peak load plants run on decarbonised liquid fuel, with a maximum use of cables to hydropower plants in Scandinavia used for load balancing.

⁷⁴ (Mitsubishi Heavy Industries, 2022).

⁷⁵ While post-combustion capture of CO_2 can be improved further, there will always be a remainder of some percentage points, which will have to be compensated by DAC or BECCS.

Box 2: CO₂ injection compared to renewable power production

CO₂ sequestration holds a highly concentrated potential for providing low-CO₂ energy:

1 mln t CO₂ capacity per injection well (like in Sleipner) corresponds to the combustion of 0.55 bcm of CH₄ ($1 \text{ mln t CO}_2 * (16/44) \text{ mln t CH}_4 * (3/2) \text{ bcm CH}_4 / \text{ t CH}_4 = 0.55 \text{ bcm CH}_4$).

At an efficiency of 0.9 of an ATR based on natural gas, this corresponds to ca 5 TWh_{th} of decarbonised energy as H₂, which would need 7.5 TWh_{el} as renewable input in view of the losses of 35% for conversion, storage and transportation.

For gas-fuelled power generation with an efficiency of 45% (instead of 50% to compensate for the losses of post-combustion decarbonisation), this corresponds to 2.2 TWh_{el} of dispatchable power. Alternatively, an H₂-fired CCGT plant would require 6.8 TWh_{el} of renewable power to be fed in via electrolyzers.

For a lignite plant, the power output per mln t CO₂ sequestered would be 1.1 TWh_{el}. Alternatively, it would require 3.4 TWh_{el} of renewable power via electrolyser and a H₂-fired CCGT power plant.

While the deployment speed of new renewable power is limited (see Section 2.5), the capacity for the energy input into CCS exists already and the deployment of CCS technology is independent of the limits of renewables deployment.

Figure 12: CO₂ sequestration to achieve net zero by 2045

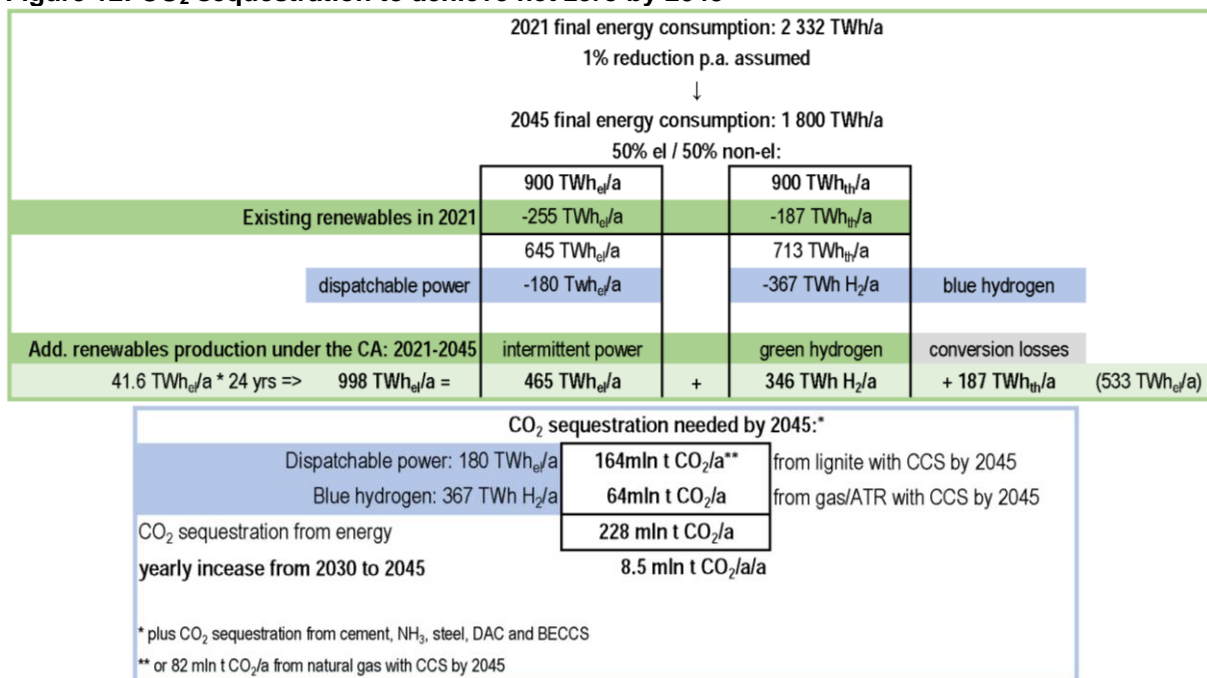
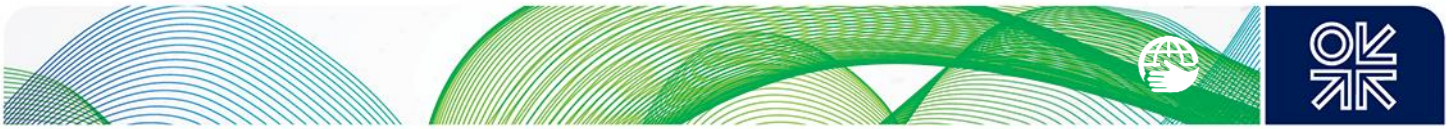


Figure 12 assumes that today's electric and non-electric renewables production is maintained to 2045. The overall addition of intermittent renewable electricity production of 998 TWh/a from an annual increase of 41.6 TWh/a in line with the increase foreseen in the CA is first used to replace 465 TWh/a of non-dispatchable electricity, and the rest is used to produce 346 TWh/a of green hydrogen, after conversion losses. The remaining 367 TWh/a of non-electric final energy is assumed to be produced as blue hydrogen from ATRs based on gas, requiring the injection of 64 mln t CO₂/a by 2045. 180 TWh/a of dispatchable power would need the sequestration of 164 mln t CO₂/a by 2045 if produced



from lignite (or 82 mln t CO₂/a if natural gas is used instead). The sequestration of a total of 228 mln t CO₂/a by 2045 would require drilling 8.5 CO₂ wells per year (at the capacity of the Sleipner injection well of 1 mln t CO₂/a) between 2030 and 2045, which is not a technical challenge.

3.2 Sequestration capacity needed

In addition, disposal of CO₂ from cement, ammonia and steel production processes could amount to ca 55 mln t CO₂/a,⁷⁶ and DAC would compensate for such unavoidable carbon dioxide emissions as leakage from CO₂ capture from ATRs – 32 mln t CO₂/a (calculated as 5% of CO₂ emissions in 2020).

This would bring the need for CO₂ sequestration by 2045 to about 210-290 mln t CO₂/a – certainly an immense challenge, but comparable to similar industrial developments in the 1980s and 1990s (e.g., the development of the Norwegian / EU gas infrastructure or the rollout of desulphurisation in Germany under the GFAVO – the German predecessor of the EU Large Combustion Plant Directive).⁷⁷

With a CO₂ price of about 100 €/t CO₂, ATRs with CO₂ capture, transportation and sequestration appear to be feasible (Dickel, 2020, p. 29). For fossil-fired power plants with CCS, some more pilot plants of industrial size would need to be tested before a Germany-wide rollout (*see further below*).

The load factor of load following to back intermittent renewables is probably between 1,000 and 1,500 h/a, which can be matched as a combination of some relatively high load factor and some very low load factor. Some lignite plants retrofitted with CO₂ capture should be adequate for the high load factor, but the investment required for post-combustion decarbonisation would probably be too high for the low-load factor part (below 1,000 h/a or even 500 h/a). The low load factor part might be served better by CO₂-neutral e-fuels or biofuels, which can be stored easily, or unabated gas with compensation by DAC, as soon as it becomes available. Both those options avoid capacity-bound decarbonisation with a low utilisation rate. Gas turbines run on hydrogen may have low specific investment, but a low load factor would burden the capacity of all upstream hydrogen production and transportation infrastructure. In any case they may be useful in smaller CHPs.

CO₂ is likely to be sequestered in geological structures away from populated areas because of the risks of CO₂ handling perceived in Germany. Sequestration under the North Sea bed not only makes sense for public acceptability, but also for the pressure handling of the geological structures: if necessary, in the case of Norway other nearby structures can be used or salty water (brine) from the storage can be pumped into the sea to release pressure without negative environmental effects. Norway offers a large potential for such CO₂ sequestration for use by other countries. This is discussed in Chapter 4.

Drilling offshore wells is certainly no bottleneck: during the 20 years from 2002 to 2021, about 4,000 wells were drilled on the Norwegian shelf alone.⁷⁸ ATRs with 1 bcm/a of gas input produce ca 1.87 mln t CO₂/a for sequestration and they are state of the art. So is transportation of CO₂ in large-diameter CO₂ pipelines onshore and offshore, so there are no technological bottlenecks in this respect either.

3.3 CCS to compensate for the shortfalls in reducing final energy consumption or rollout of renewables

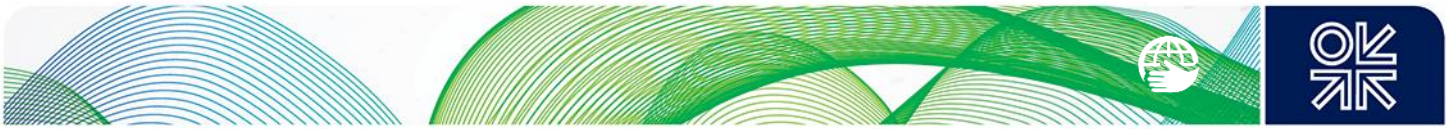
CO₂ sequestration offers a feasible way to compensate for the possible shortfalls in reducing final energy consumption or in the rollout of renewables:

- Germany's final energy consumption development over the last 25 years indicates the possibility that further reduction could fall short of the set goals by 290 TWh/a (assuming a reduction of 10.5% over 25 years, as between 1995 and 2020), which would correspond to

⁷⁶ Assumed to be 90% of 20 + 6.4 + 6 + 32 mln t CO₂ eq (from cement, lime, ammonia and steel, see Section 4.5.1, converted to CO₂ by a factor of 0.9).

⁷⁷ (GFAVO, 2021).

⁷⁸ (Norwegian Petroleum Directorate Factpages), used for own calculations.



adding about 3.5 CO₂ wells per year for the 15 years between 2030 and 2045 with a total capacity of 55 mln t CO₂/a.

- A 25% shortfall in the rollout of renewables corresponding to 10.4 TWh/a/a could be compensated by an additional two CO₂ wells per year for the 15 years between 2030 and 2045, with a total of 30 mln t CO₂/a.

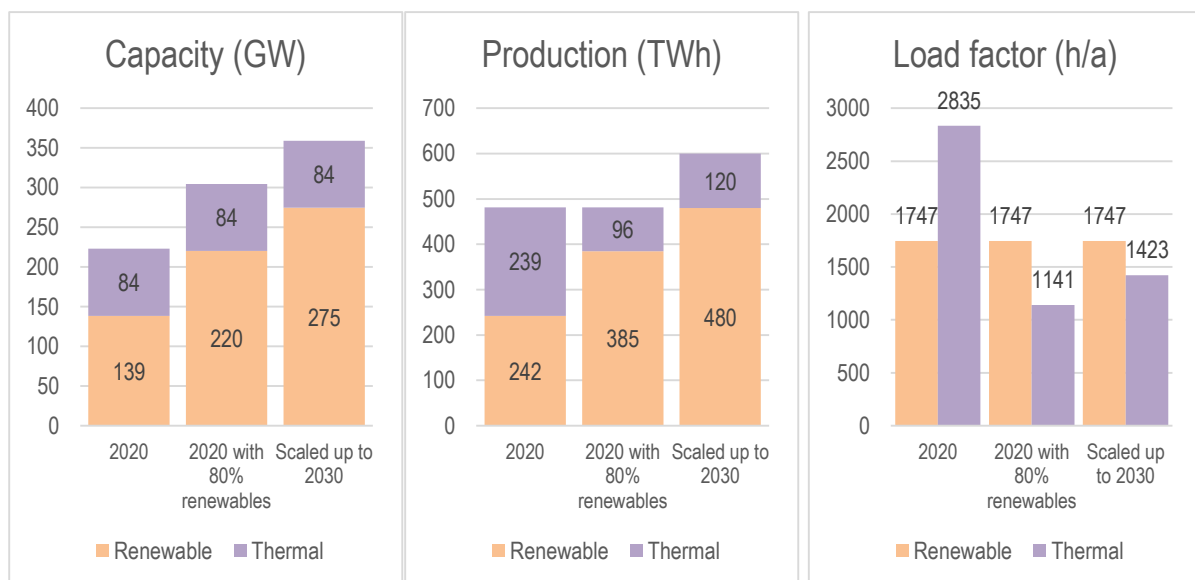
3.4 ATR with CO₂ transportation and sequestration offer reliable energy-rich molecules on demand

Gas or liquid hydrocarbons can be decarbonised by converting them into hydrogen by ATR with CO₂ capture with subsequent CO₂ transportation to the place of sequestration offshore under the floor of the North Sea. This option offers a reliable supply of low-CO₂ hydrogen with proven technology, as well as the basis for integrating intermittent green hydrogen. It would also provide H₂ supply for smaller hydrogen power units, typically for CHPs, for which post-combustion decarbonisation might not be feasible.

3.5 Load factor of dispatchable power

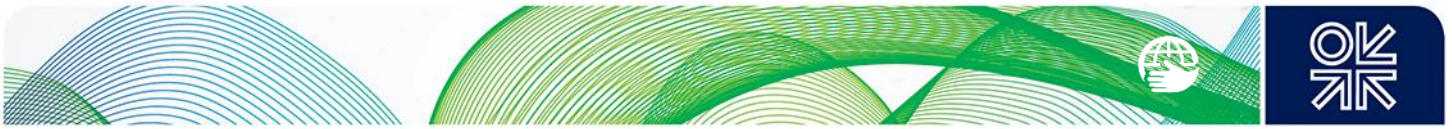
To guarantee reliable power supply in Germany, the peak load of about 80 GW⁷⁹ must be covered by reliable power generation capacity. With a planned increase of power consumption of between 20% and 32.2% by 2030, peak load is likely to grow by at least the same percentage, i.e., to between 96 GW and 105 GW. The contribution by run-of-river and biomass has never exceeded 10 GW in the past years, while the input of PV and wind can be below 5 GW, even below 1 GW. This leaves up to 90 GW to be covered by imports and dispatchable power capacity. Relying on imports is risky, as the wind will often not blow in neighbouring countries giving them the same problem. Covering such a deficit from batteries in BEVs is an untested vision so far, it would also imply severe restrictions on BEV use in times of *Dunkelflaute*.⁸⁰ This suggests that thermal capacity similar to that of today – increased in line with the intended expansion of the power system – must be ready, especially for backup during high-demand low-wind and low-sun periods.

Figure 13: Illustration of thermal backup power load



⁷⁹ On 11 January 2021, peak load demand in Germany reached 78.8 GW.

⁸⁰ Such a solution would not provide enough volume: even if all of today's 50 mln passenger vehicles were BEVs each with a 100 kWh battery, this would only add up to max 5 TWh of battery volume, compared to about 14 TWh of deficit due to *Dunkelflaute*, as discussed in Section 2.1.1 above.



The CA forecasts an increase in power consumption by 2030 which, however, may not affect peak demand, as most of the increase would come from BEVs. Assuming that present fossil-fuelled plants will be sufficient in that situation, their overall load factor would be halved from 2,835 h/a to 1,423 h/a. This could translate into 3,000 h/a for lignite and 1,000 h/a for coal and gas combined, illustrating the decreasing utilisation rates of the backup power needed. Pump storage in Germany is small due to its geography (60 GWh, including contracts with Austria, Switzerland and Luxemburg). Biomass and run-of-river can serve as valuable base load with 8.25 GW and 3.87 GW max capacity respectively (2020 figures),⁸¹ but they offer little increase potential and no flexibility.

3.5.1 Potential future CO₂-free and reliable thermal power

Power production by nuclear fission is to end in Germany by 31 December 2022, with the last three nuclear plants⁸² set to go offline following the 13th Amendment to the Nuclear Act.⁸³ Continuing their operation beyond 31 December 2022 would require new legislation and new operating permits. Even with sufficient political will to overcome these hurdles in view of the war in Ukraine, practically it would not be possible just to prolong their operation: the decommissioning measures are well advanced, implying a lack of nuclear fuel/rods, which have to be tailored to specific plants, and a lack of qualified staff after 31 December 2022.⁸⁴

For any new nuclear project, new legislation would be required, and this is not likely. At the same time, the lead-time between the FID and first power to the grid is likely to be 15 years and more, as in Finland or France. After the withdrawal of Siemens from the nuclear business in 2011 there are no more construction companies familiar with German nuclear standards, adding to the lead-time needed for new reactors. Any new nuclear plant would come too late to contribute to net zero by 2045.

Another option to consider is stand-alone power for short-term use (independent of a gas or H₂ grid), fuelled by e-fuels or biofuels. A standard tank of 20,000 t of fuel oil has an energy content of ca 240 GWh_{th} to produce ca 100 GWh_{el} by a gas or steam turbine with 40% electric efficiency – almost twice the total potential from pump storages in or under contract with Germany. Covering a *Dunkelflaute* of present level of 14 TWh by e-fuels or biofuels would require 140 oil tanks of 20,000 m³ or 6 caverns in Etzel with a volumetric storage volume of 500,000 m³ each.

New or retrofitted lignite or coal-fired power plants with relatively high load factors (ca 3,000 h/a) with post-combustion decarbonisation and equipped for CO₂ sequestration should also be considered. While lignite-fired plants are bound to lignite mines, coal-fired power plants are more spread out through Germany. Retrofits of existing power plants with post-combustion decarbonisation are possible, making use of existing investment in the power plant at a given place.

3.6 Post- vs pre-combustion decarbonisation

The main choice is between pre- and post-combustion decarbonisation of power generation from fossil energies, that is, between a chain from CH₄ (or liquid hydrocarbons) to H₂ by ATR and subsequent transportation to H₂-burning power plants on the one hand; and burning fossil fuel⁸⁵ in a power plant with post-combustion CO₂ capture, on the other.

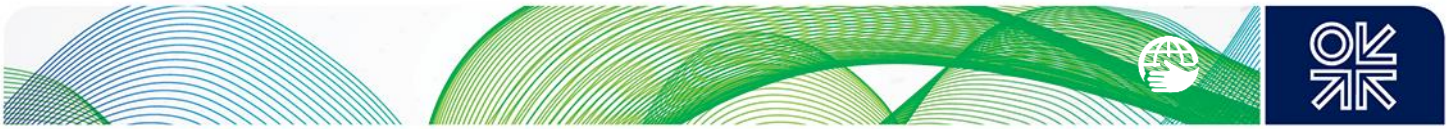
⁸¹ (Statista, 2021).

⁸² Isar 2, Emsland und Neckarwestheim 2.

⁸³ (Thirteenth Act amending the Atomic Energy Act, 2011).

⁸⁴ (Dow Jones News, 2022) and (Kuntschner, 2022).

⁸⁵ Fossil fuels other than natural gas can be decarbonised in principle, but – compared to natural gas – with more environmental impacts and, due to their chemical composition, with larger streams of CO₂, and larger injection and sequestration volumes needed, which would become a bottleneck in the longer run.



3.6.1 Pre-combustion

An advantage of pre-combustion decarbonisation is that it produces CO₂-free H₂ molecules, which can be used in smaller units, from CHPs down to households, for which individual post-combustion decarbonisation would make no economic sense.

H₂ could be used in turbines (and CCGTs), but its high combustion temperature (2,000° C) would cause problems with the inlet temperature for CH₄ turbines and with NO_x formation. 100% H₂ use in GTs does not seem to be technically possible yet, but manufacturers are developing turbines to take in an increasing H₂ share with the eventual target of 100%. Equinor is working with Vattenfall on an H₂-fired gas turbine in Vattenfall's power plant in Eemshaven.

Using H₂ in boilers for steam generation appears to be possible – hydrogen combusting burners in boilers are on the market for smaller applications (Bosch) and tested (Toyota).⁸⁶ H₂-burning boilers could be used in smaller CHP units to supply CO₂-free district heating. Where H₂ is available, existing boilers may be retrofitted with new H₂ burners⁸⁷ with new stoichiometry.

3.6.2 Post-combustion

For post-combustion decarbonisation, two approaches are well advanced: (i) Oxyfuel, where the combustion process is fired with pure oxygen (from air splitting), so that the exhaust stream is predominantly CO₂ (plus water vapour in the case of gas-fired power plants), which is relatively easy to capture, or (ii) amine scrubbing of the exhaust streams from combustion of fossil fuels using ambient air, however, with a low concentration of CO₂.

Both approaches have been tested by retrofitting parts of the exhaust stream of lignite or coal-fired power plants. The substantial capacity of post-combustion decarbonisation will result in the diversification of technology of CO₂ abatement in addition to ATRs. The potential parallel rollout of post- and pre-combustion installations would accelerate decarbonisation. Also, the diversification of post-combustion technology development (Oxyfuel and amine scrubbing) would make the decarbonisation of power plants more robust.

3.6.3 Retrofitting existing fossil fuel-fired power plants with post-combustion decarbonisation⁸⁸

Worldwide, there are two industrial-scale pilot projects:⁸⁹

- In Saskatchewan: the retrofit of the coal-fired Boundary Dam Unit 3 with 115 MW_{el} and ca 90% CO₂ capture,⁹⁰ which started operation in 2014 and has since doubled the capture rate of CO₂ to 2,400 t CO₂/day and availability to 90%.⁹¹
- In Texas: the Petra Nova post-combustion decarbonisation corresponding to 240 MW_{el} and capture of 1.4 mln t CO₂/a.⁹²

Both are coal-fired power plants relying on amine scrubbing. The captured carbon dioxide is then used for enhanced oil recovery (EOR).

In Germany, there were two smaller retrofitted pilot power plant projects by Vattenfall and RWE about 10 years ago, using parts of the exhaust stream of existing lignite power plants:

- Vattenfall's Oxyfuel project in Schwarze Pumpe⁹³ with 30 MW_{th} opened in 2008, closed in 2012,

⁸⁶ (Toyota, 2018); (Bosch, 2020).

⁸⁷ Already offered by the industry, e.g., (Saacke) and (Toyota, 2018).

⁸⁸ (International Energy Agency, 2012), the possibility of retrofit.

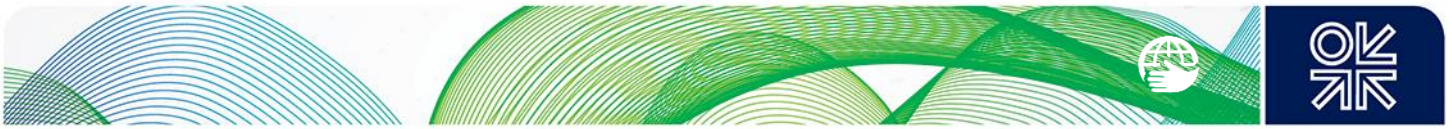
⁸⁹ (Madejski, Chmiel, Subramanian, & Tomasz, 2022), a global overview and (International Energy Agency, 2021), on projects.

⁹⁰ (SaskPower).

⁹¹ (Giannaris, et al., 2021), a detailed discussion of the learning process.

⁹² (Kennedy, 2020), final report and (US DOE Office of Fossil Energy and Carbon Management).

⁹³ (van Laak, 2008).



- RWE's test facilities at the BoA power plant in Niederaussem^{94,95} with amine scrubbing and CO₂ utilisation.⁹⁶ The first test phase started in July 2009 with 7.2 t CO₂ /d or 300 kg CO₂/h captured from a flue gas slipstream downstream of the desulphurization plant. In several additional phases different treatment processes and capture technologies are still being tested.⁹⁷

These pilot projects for CO₂ capture by retrofit to lignite power plants were not followed up by industrial-scale projects, which were ready to go, because of the negative political attitude towards CO₂ sequestration at that time. Vattenfall's pilot project in Schwarze Pumpe was stopped in 2012 due to the unsatisfactory prospects of CO₂ sequestration in Germany.⁹⁸ RWE's project, which planned to transport CO₂ for sequestration in Schleswig-Holstein in northern Germany, was opposed by the local parliament.

Using existing investment in thermal power plants not only may save costs but also would avert investment bottlenecks. With a view to gaining technology leadership, Germany could develop pilot plants for both Oxyfuel and amine scrubbing building on its experience from the smaller pilot projects and by returning to former industrial-scale projects, which were ready to go but unfortunately were cancelled.

3.7 The debate on CO₂ sequestration in Germany

Germany is one of the few countries with very strong opposition to CO₂ sequestration, which is even reflected in its legislation. This Section offers some thoughts on the origins of this attitude and the further development of the debate.

3.7.1 Similarities and differences between the disposal of radioactive waste and CO₂, perceived and real

A widespread association of CO₂ disposal with the disposal of highly radioactive waste developed in Germany around 2010. This led to strong public resistance to CO₂ sequestration.

Gorleben, a site for the disposal of highly radioactive waste chosen on political grounds

Germany's 1959 Nuclear Law requires the safe disposal of radioactive waste from nuclear power generation. Due to the development of heat in nuclear waste, the site search focussed on salt structures, which were able to dissipate the heat from radioactive decay. Geologists from the Federal Office for Raw Materials and Geoscience came up with several sites classified by their suitability.⁹⁹

Gorleben, the site announced on 22 February 1977, while not considered unsuitable, was not the first choice. In view of its proximity to the border between East and West Germany, it was considered a politically motivated tit-for-tat answer by the Government of Lower Saxony to East Germany's earlier choice of Morsleben – also close to the border - as the deposit site for its radioactive waste.

The announcement of the choice of Gorleben¹⁰⁰ triggered public resistance lasting for 40 years, with demonstrations of up to 100,000 people in this very remote part of West Germany. The first Red-Green Government¹⁰¹ negotiated a nuclear phase-out with the power industry in 2000 and issued a moratorium of 10 years for Gorleben, to give time to reconsider the disposal of nuclear waste. While the resistance calmed down initially, it flared up again once the moratorium elapsed in 2010, and was fuelled by the

⁹⁴ (Aachener Zeitung, 2007).

⁹⁵ (The University of Edinburgh, 2014).

⁹⁶ (Align CCUS, 2019).

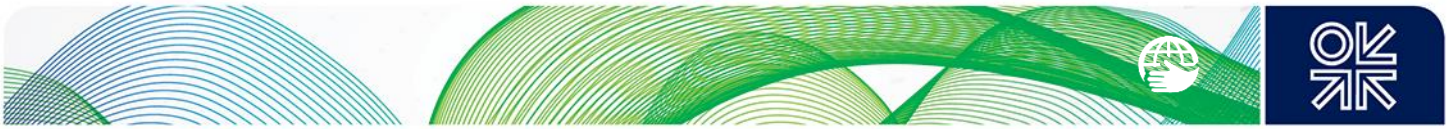
⁹⁷ (RWE Power, 2009, pp. 10-11).

⁹⁸ (Kluger, 2009). Jänschwalde: retrofit 250 MW_e Oxyfuel, see Chart 18.

⁹⁹ (BGR Federal Institute for Geosciences and Natural Resources).

¹⁰⁰ (NDR, 2021).

¹⁰¹ In October 1998, the Social Democrats (SPD) and the Greens (Bündnis 90 / die Grünen) formed a Coalition Government. Both parties had ending the use of nuclear power as a major point in their election campaigns.



prolongation of the lifetime of nuclear reactors (by 8 or 14 years for old or new reactors, respectively) by the new Conservative Liberal Government, on which the power industry had speculated when signing the initial agreement in 2000.

Finally, an act (*Standortauswahlgesetz*) passed the parliament in 2013 and was amended in 2017,¹⁰² defining a new open-ended procedure to find a site for nuclear waste by 2031. The 2020 interim report did not list Gorleben as the potential site, and the closure of the Gorleben operation was announced on 17 September 2021.¹⁰³

Most people protesting against Gorleben – grudgingly – accepted the need for the disposal of radioactive waste as a consequence of a past decision to use nuclear power, but argued that Gorleben was the wrong choice based on geology, with the risk of water encroachment and the resulting contact of radioactive material with surface and ground water.¹⁰⁴

Two failed, one successful CO₂ sequestration project

Two industrial-size CO₂ sequestration projects from lignite power plants in Germany were promoted by RWE and Vattenfall at the same time. The projects lacked credibility due to the companies' inconsistent stand on the agreed nuclear phase-out:

- RWE's project focused on CO₂ sequestration from its power plant in Hürth (near Cologne) transported to Schleswig Holstein via a 500 km pipeline. RWE ended the project after its rejection by the local parliament of Schleswig-Holstein in June 2010.
- Vattenfall planned a pilot project at a lignite plant in Jänschwalde for CO₂ sequestration in Beeskow in Brandenburg. The company stopped this project¹⁰⁵ in view of the political resistance to the planned CCS Act by several (northern) states. The resulting 2012 CCS Act was a diminished version of the original draft, allowing only research projects. Most of the northern states opted out of even that version.

By contrast, the comprehensive *research* project on CO₂ sequestration in Ketzin (ca. 40 km west of Berlin) initiated in 2004 and finalised on schedule in 2017, did not meet any significant public resistance. One of the reasons for that was targeted information (visitor centre, events for the public, e.g., schools, meetings with the project scientists, up-to-date information, etc.).¹⁰⁶ Other explanations include the fact that:

- Ketzin was a research project run by public scientific institutions and not by commercial companies with vested interests and strong pro-nuclear lobbying tarnishing their credibility,
- Ketzin was a project limited in size (the CO₂ was transported by trucks to the project site, a total of 67,000 t CO₂ was injected) and duration compared to the other two projects, which were for large volumes and for an indefinite duration,
- At that time, high volumes of renewable capacity were added, especially PV, creating overoptimistic hopes for a strong role for renewables.

Unlike the need for the disposal of nuclear waste, the necessity of CO₂ sequestration was not very clear. The narrowly limited CO₂ budget entered the public discussion only after 2010; prominent examples were the IEA WEO 2012 and the Fifth Assessment Report of the IPCC of 2014. "Since it was brought to prominence by the Fifth Assessment Report of the IPCC, the carbon budget has changed how climate change is enacted as an issue of public concern, from determining the optimal rate of future emissions to establishing a fixed limit for how much emissions should be allowed before they must be

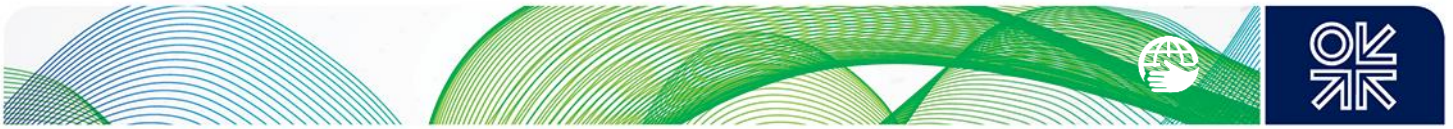
¹⁰² (Act on the search for and selection of a site for a repository for high-level radioactive waste, 2017).

¹⁰³ (Federal Office for the Safety of Nuclear Waste Management, 2021).

¹⁰⁴ (Deutschlandfunk, 2008).

¹⁰⁵ (Chemie Technik, 2011).

¹⁰⁶ (Scientific Services of the German Bundestag, 2018, p. 36).



stopped altogether.”¹⁰⁷ While the necessity of safely storing nuclear waste is clear and attributable, the need for CO₂ sequestration is part of the efforts to keep within the global CO₂ budget (attributed to Germany proportionately to its population by the Constitutional Court), but still subject to the mix of energy efficiency, renewables and CO₂ sequestration, creating the illusion that it could be avoided or ignored.

3.7.2 Comparisons made between the disposal of radioactive waste and CO₂ sequestration

Apparently, the common denominator is the concern about the connection between the place of disposal and surface or ground water and resulting leakage via some geological faults. There is indeed a risk of leakage via existing wells or through cracks in the ceiling of a geological structure created by over-pressurising in the process of CO₂ injection.

“When CO₂-bearing fluids or supercritical CO₂ are injected at depth into geologic formations, the sequestration of CO₂ in the subsurface porosity relies on the impermeability of the caprock of the reservoir. Suitable reservoirs are saline aquifers, depleted oil and gas reservoirs (may or may not be associated with enhanced oil recovery, i.e., CO₂ EOR) [...].

Ideal properties of saline formations for CO₂ storage include high permeability to enable high rates of CO₂ injection without large pressure build-up, thick formations with many interbedded low permeability barriers to use the pore space efficiently (Wen and Benson, 2019), and having salinity in excess of 10,000 ppm of total dissolved solids to comply with groundwater protection regulations. It is important to limit pore pressure build-up in order to avoid fracturing the caprock and inducing seismic events (National Academies of Sciences Engineering Medicine, 2019).”¹⁰⁸

The problem with the disposal of radioactive waste differs from the sequestration of CO₂ for the following reasons:

- Radioactive waste produces heat from radioactive decay infinitely, salt takes up and transfers such heat from CO₂,
- The problem for radioactive waste is rather water encroachment creating a potential contamination link to the ground surface; not an issue for gas leaks, including CO₂,
- Radioactive material might be a danger to people if it reaches the surface, and that danger can hardly be mitigated. Handling radioactive contamination is difficult and almost impossible once radioactive elements have entered the food chain. Excessive CO₂ concentration is of a temporary and manageable nature.

For CO₂ – especially if offshore or under deserts – there should be no immediate danger for people, but leakage would diminish the benefits of sequestration, so it must be avoided or minimised. Even if a certain percentage of some sequestered volumes were to resurface due to leakage, there would still be a positive effect, especially for keeping within the CO₂ budget. Additionally, longer-term mitigation should be possible with DAC.

An outstanding element of the Ketzin project was the many *in situ* measurements of the movement of CO₂ and its impacts on the reservoir rock; even small amounts of CO₂ could be measured and traced. Their evaluation concluded that the movement of CO₂ was accurately modelled, measured and surveyed.

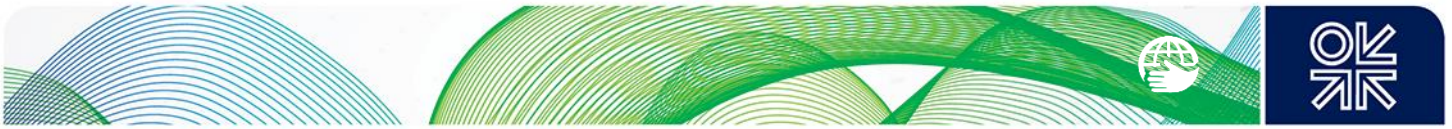
3.7.3 Outlook

The time has come for a new discussion on the necessity for CCS.¹⁰⁹ The German Academy of Science and Engineering has called for assessing the need and the options for a broad application of CCS

¹⁰⁷ (Lahn, 2020).

¹⁰⁸ (Kelemen, Benson, Pilorgé, Psarras, & Wilcox, 2019).

¹⁰⁹ (Scientific Services of the German Bundestag, 2018, pp. 7-8).



technologies and discussing them with all actors in society. This initiative was also supported by the WWF Germany and Germanwatch.¹¹⁰

Under the CCS Act of 2012, CO₂ sequestration in Germany is *de facto* impossible, but capture and transportation to sequestration sites, including those abroad, is explicitly possible. There is even the possibility to expropriate for the right of way for the building of pipelines for CO₂ export.

“The Sleipner Saline Aquifer Storage Project is the first commercial-scale CO₂ storage project. It commenced in 1996 and has injected CO₂ into an offshore saline aquifer formation, comprised of permeable sandstone beneath a low-permeability shale caprock for permanent disposal and climate change mitigation (Baklid *et al.*, 1996). This project shows that CO₂ storage in subsurface sedimentary reservoirs at a rate of 1 mln t/a is possible and safe.”¹¹¹

Location and geology also support sequestration offshore on the Norwegian Shelf. Offshore vs onshore is not only an issue of risks for the population but a difference for pressure management in the respective geological structure: you can dispose of the salty brine of an aquifer offshore, but only with difficulty onshore. In addition, the potential sites for CO₂ disposal in Germany are relatively small, limiting the pressurising of these geological structures. However, they may be used for the disposal of smaller CO₂ volumes from local industry, once the legal situation changes.

For these reasons, CO₂ exports to Norway appear to be the obvious solution, in view of the legal situation in Germany.

A concept for the combination of decarbonised load-following power and related infrastructure is missing in Germany and should be developed as soon as possible. For the implications for CO₂ collection pipelines and infrastructure, see Chapter 4.

4. The role of infrastructure: the need for a CO₂ collection system

Chapters 2 and 3 looked at the availability of primary energy and power at all times and concluded that a system based solely on renewables input would not be able to provide net zero by 2045, nor the reliability of energy supply. The conclusion was that large-scale CO₂ capture and collection for sequestration is necessary to achieve these goals and should be addressed as soon as possible.

The present Chapter will focus on the spatial aspects of the infrastructure needed to handle CO₂.

A completely new large-scale CO₂ transmission infrastructure would be needed to collect and dispose of CO₂ volumes at the level of ca 200 to 280 mln t CO₂/a.

4.1 Infrastructure for CO₂

While *de facto* CO₂ sequestration in Germany is not possible under the CCS Act of 2012, CO₂ transportation and export are possible but have not been addressed so far. This conceptual blank has to be filled in if Germany is to reach net zero by 2045.

4.1.1 Experience with onshore/offshore CO₂ pipelines

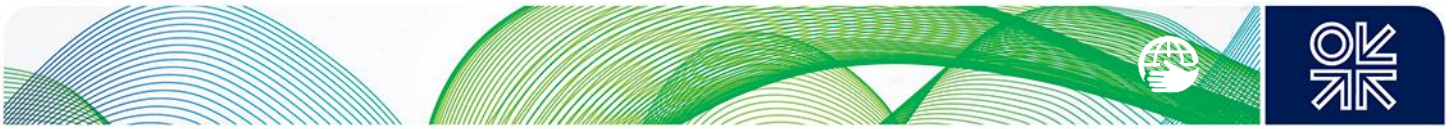
The US has 50 years of experience of CO₂ transportation by onshore pipelines.¹¹² The largest is the Kinder Morgan Cortez Pipeline, which has 19.3 mln t CO₂/a capacity, 803 km length, 30-inch diameter and operates at a pressure of 186 bar.¹¹³ Overall, 66 mln t CO₂/a are handled by CO₂ pipelines in the US.

¹¹⁰ *Ibid.*

¹¹¹ (Kelemen, Benson, Pilorgé, Psarras, & Wilcox, 2019).

¹¹² (National Petroleum Council, 2019), a concise overview of the US CO₂ pipeline system and the experience from it is given in Chapter 6 of the report.

¹¹³ (Serpa, Morbee, & Tzimas, 2011, p. 3).



“CO₂ has been safely and reliably transported in the United States via large-scale commercial pipelines since 1972, when the Canyon Reef Carriers Pipeline was constructed in West Texas. During the last 50 years, there have been no fatalities associated with the transportation of CO₂ via pipeline.” And “although CO₂ is not considered a hazardous material by the US Department of Transportation, CO₂ pipelines are regulated because of the operating pressures of these pipelines.”¹¹⁴

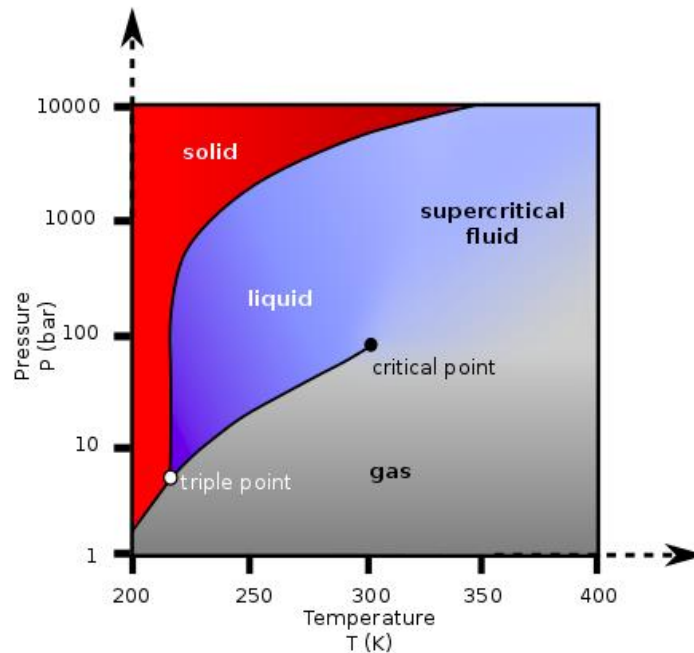
The US certainly could serve as a point of reference when designing German/EU standards for the pipeline transportation of CO₂. An offshore pipeline is already installed for offshore CO₂ injection at the Snoehvit project (153 km).¹¹⁵

4.1.2 Transportation by pipeline: pressure regime, capacity, repurposing, quality

Pressure regime

CO₂ pipelines are usually run at a pressure where CO₂ is in its superfluid state, see Figure 14. It then behaves as a fluid that can be pumped – instead of compressed, as when in a gaseous state. Pumps are cheaper than compressors.

Figure 14: Design overview: high-pressure dense-phase CO₂ pipeline transportation in flow mode



Source: (Patchigolla & Oakey, 2013)

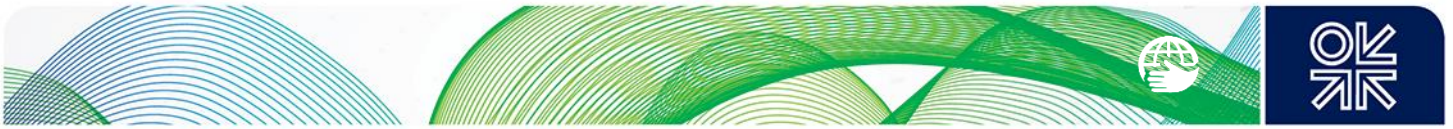
Capacity

The formula for gas transportation by pipeline (including for CO₂)¹¹⁶ suggests that pipeline capacity is proportionate to the power of 2.5 of the diameter – it doubles when the pipeline diameter is increased by 32%, e.g., from 30 to 40 inches, everything else being equal. As pipeline investment is roughly proportionate to pipeline diameter, this results in very substantial economies of scale, which could be fostered by some upfront tax stimulus for large-diameter pipelines.

¹¹⁴ *Ibid.*, pp. 6-8.

¹¹⁵ *Ibid.*, p. 3.

¹¹⁶ (Correia Serpa Dos Santos, Morbee, & Tzimas, 2011, p. 18), for the gaseous state, and (Peletiri, Rahmanian, & Mujtaba, 2018, p. 14), for the fluid state.



Repurposing of gas pipelines (onshore)

Repurposing onshore methane gas pipelines for CO₂ transport in Germany does not make much sense due to the differences in the pressure regime. Onshore gas pipelines in Germany have a design pressure of max 100 bar. By contrast, CO₂ pipelines in the US are designed for the pressure of 151.7 bar (2200 psig).¹¹⁷ Running CO₂ pipelines at pressures below 100 bar would result in substantial reduction of capacity.

What may be used is the route of existing gas pipelines, which have already been optimised for distances to settlements, avoiding naturally protected areas, crossing of other infrastructure, etc. Eventually using the existing rights of way might accelerate the planning process.

Impurities of the transported CO₂

CO₂ impurities can play an important role in the design and operation of CO₂ pipelines.¹¹⁸ In the US, the concentration of CO₂ in pipelines is generally above 95%. CO₂ for EOR largely comes from natural CO₂ resources with a high degree of purity.

4.2 German context for pipeline transportation and export of CO₂

While *de facto* CO₂ sequestration is not possible in Germany under the 2012 CCS Act, CO₂ transportation is possible.

Paragraph 4 Section 5 of the CCS Act provides for eminent domain (expropriation) also for CO₂ pipelines serving final sequestration of CO₂ outside Germany if the CO₂ emissions in Germany are permanently reduced. Under Paragraph 4, Section 6, the Ministry of Economy is authorised to issue an ordinance stipulating the details of the permitting procedure and the standards for CO₂ pipelines. This has not happened yet.

The main hindrance for CO₂ export is Art. 6 of the London Protocol, which bars the export of CO₂ for sequestration.¹¹⁹ This has been addressed by the 2009 Amendment to Art. 6, which Germany has not ratified yet. Recital 13 of Resolution LP.5(14) adopted on 11 October 2019 on provisional application reads: "Recalling that the national acceptance process of the 2009 amendment has shown to be time consuming and that, despite great efforts only a few acceptances have been made[...]."¹²⁰ The purpose of that Resolution is to allow members who have ratified the Amendment to Art. 6 to agree on provisional application following specific standards; the first such case was between Norway and the Netherlands.¹²¹

4.2.1 Germany needs to export large volumes of CO₂

Germany is barred from using its own CO₂ sequestration potential by an unfortunate perception of a linkage of CO₂ sequestration with the disposal of nuclear waste at the time when the legislation on CO₂ sequestration was finalised in 2012.

Various industrial processes inevitably produce CO₂ (cement, ammonia, steel), but most CO₂ comes from the use of fossil fuels in power generation and from the production of blue hydrogen. As shown *above*, these cannot be replaced by renewables or green hydrogen within the short remaining timeframe left.

In the decades to come, Germany will have to dispose of large volumes of CO₂ - 200 mln t CO₂/a and more - depending on how much power and blue hydrogen production will be based on natural gas,

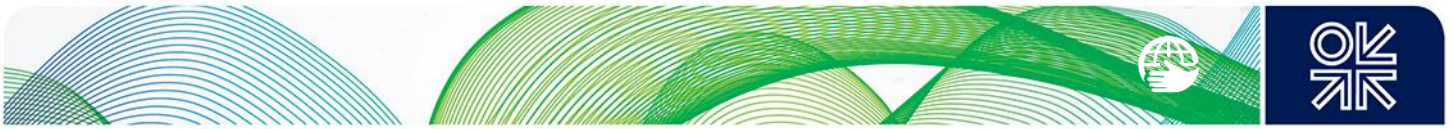
¹¹⁷ (National Petroleum Council, 2019), See Chapter 6, updated 12 March 2021.

¹¹⁸ *Ibid.*, pp. 6-10 ff.

¹¹⁹ (UCL Carbon Capture Legal Programme).

¹²⁰ (IEAGHG, 2021, p. 10).

¹²¹ *Ibid.*, overview.



lignite and liquid hydrocarbons. In any case, the volumes will be large enough to justify several CO₂ collection pipelines with the maximum possible diameter to make use of economies of scale.¹²²

4.2.2 Norway

Norway is probably the leading country with experience and ambitions to sequester CO₂ in view of:

- The large potential to sequester CO₂ under the Norwegian Shelf, especially the potential of ca 40 Gt CO₂ in the aquifer of the Utsira formation, as part of ca 70 Gt CO₂ in the Norwegian part of the North Sea,
- The country's long experience with capture and injection of CO₂ streams from gas production (Sleipner and Snoehvit) and the ongoing test projects - Northern Lights (CO₂ injection) and Longship (for the collection of CO₂ by ship),
- The legislation and rules for CO₂ transportation and sequestration on the Norwegian Shelf already in place (Regulation of 5 December 2014 nr. 1517),¹²³
- The fact that the geology of the Norwegian Shelf is well understood; in the last 20 years, some 4,000 wells have been drilled in the North Sea part of the Norwegian Shelf alone,
- The country's long-standing experience in building and running a large-scale offshore pipeline grid.

Norway has an interest in continuing to valorise its natural resource base and maintaining the geological and offshore industry and the related skill basis by developing CO₂ sequestration on a large scale. Developing a large-scale CO₂ import and injection infrastructure is certainly within the competence of the Norwegian offshore industry given its past performance in developing large-scale gas production and the related gas pipeline infrastructure in the 1980s and 1990s (Statpipe, Zeepipe, Europipe 1 and 2 and Franpipe).

CO₂ will require a predominantly new infrastructure, as repurposing the existing gas export pipelines would be complicated, and only the Norpipe system might fall idle soon and potentially become available for repurposing. Developing CO₂ sequestration in Norway is not only about using the existing hard infrastructure, but rather the soft infrastructure such as the knowledge of geology, offshore technologies and related management skills.

Also, in view of the longstanding successful cooperation in building the infrastructure to market its gas in Germany, Norway is an obvious partner for the sequestration of Germany's CO₂. However, other potential useful cross-border projects with the Netherlands or Denmark should not be overlooked.

Given the short remaining timeframe, Norway and Germany should conceive a bold large-scale scheme to follow up on the experience of the Norwegian Longship/Northern Lights projects, but adapt it to large offshore CO₂ pipelines and the corresponding CO₂ pipeline collection system in Germany.

4.3 To-dos for Germany

Germany needs to address the following issues as soon as possible.

4.3.1 Vis-a-vis Norway

Germany should ratify the Amendment to Art. 6 of the London Protocol, and Germany and Norway should swiftly enter into an agreement on the Protocol's provisional application. In parallel, the technicalities of CO₂ transfer should be addressed by including the interested industry parties in the concept development process (potential locations, such details on CO₂ streams as metering, quality,

¹²² (Serpa, Morbee, & Tzimas, 2011, p. 18).

¹²³ (Regulations relating to utilisation of subsea reservoirs on the continental shelf for storage of CO₂ and transport of CO₂ on the continental shelf; Chapter 9: Special rules on compensation to Norwegian fishermen, 2014).



certification procedures and the concept of crossing the Wadden Sea, as was done previously for Europipe).

4.3.2 Inside Germany

Germany's Ministry of Economy should fill in the details of Paragraph 4, Section 6 of the 2012 CCS Act regarding CO₂ pipelines (permitting procedures and technical standards). For technical standards of CO₂ handling, the impeccable safety performance of the US may serve as guidance. The German energy industry jointly with BNetzA should develop a technical, economic and regulatory concept for a CO₂ collection infrastructure.

The German government together with the EU should ensure an adequate reliable price level for CO₂ abatement covering all costs along the CCS chain, including a risk-commensurable profit.

CO₂ storage (injection and withdrawal) is not covered by the 2012 CCS Act¹²⁴ but should be addressed to allow for intermediate storage e.g. in salt caverns in the north.

4.3.3 Location of the CO₂ transfer points

Transfer point(s) for CO₂ transportation by pipeline to the Norwegian Shelf would need to be at the German North Sea coast, as onshore transit through the Netherlands or Denmark would unnecessarily complicate things.

A challenge is crossing the Wadden Sea National Park, stretching from the German-Dutch to the German-Danish border, except for the shipping areas; the park is under special protection which does not allow pipe laying. As a start, a landing point near Dornum (between Emden and Wilhelmshaven) looks reasonable, using the same approach as for Europipe 1 and 2, which were laid into a tunnel under the relevant part of the Wadden Sea¹²⁵ and taken up outside the Wadden Sea area. The proximity to the large salt domes/salt caverns in this area might be useful for the temporary storage of CO₂ to even out the gas flow before final transfer.¹²⁶

4.4 Need for a concept for CO₂ handling in Germany

A concept for CO₂ collection pipeline systems in Germany must be developed based on the transfer point(s) at the German North Sea coast. The concept should address the pipeline dimension and pressure regime, fluctuation handling, routing, timing/sequencing of CO₂ input, and economic rules. This is already a request by the German cement industry,¹²⁷ which has no alternative to CO₂ sequestration for decarbonisation due to the nature of the cement production process.

Box 3: Proposal for a CO₂ collection system in the US

For reference, the US National Petroleum Council in its concept for decarbonising the US industry suggested using a CO₂ collection system organised at the national (federal) level:

“Regardless of the rationale for building and expanding existing networks, it appears that rather than constructing a multitude of new point-to-point pipelines, a more considered and strategic approach consisting of key trunk lines and connector pipelines would be economically advantageous for scaling CCUS deployment. Large-scale deployment of CCUS will require a marked increase in commitment by both government and industry to plan and build a CCUS system, of which a functioning transportation infrastructure is a critically important part. Although developing infrastructure will be done by industry in most cases, government commitment and leadership is particularly important in this regard.”*

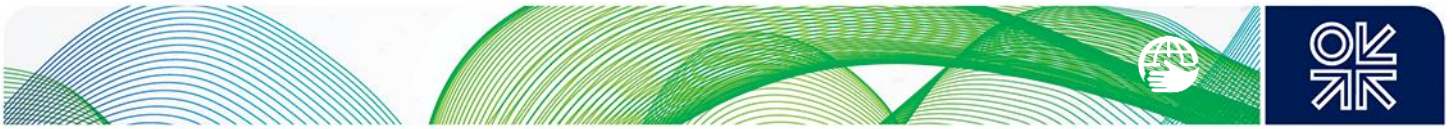
* Meeting the Dual Challenge, Chapter 6, updated 12 March 2021, pp. 6-14 f.

¹²⁴ (CCS Act, 2012), §3 definitions, sec 7: „Kohlendioxidspeicher zum Zwecke der *dauerhaften* [emphasis RD] Speicherung...“ *dauerhaft* = permanent hint at sequestration, not storage.

¹²⁵ (DAUB German Tunnelling Committee).

¹²⁶ (Minkley, Brandt, Dostál, Stepanek, & Lehman, 2021).

¹²⁷ (VCI German Chemical Industry Association, 2021).



4.5 Considerations for a CO₂ collection system in Germany, CO₂ transportation and storage

4.5.1 The first project and further sequencing

As Germany does not yet have much experience with handling CO₂ by pipeline, it should start with large industrial CO₂ emitters with a high load factor, which are not dependent on further technological development. These include the cement industry, the ammonia industry and ATRs for hydrogen production for the steel industry and other large high-load CO₂ volumes. Such a system would largely correspond to the existing US systems with high load factors.

A trunk line from the Rhine-Ruhr area to a transfer point, e.g., near Dornum, would be a good start because of the demand for CO₂ sequestration in that area and the relatively short distance of ca 300 km. Such a pipeline should be built with the largest technically reasonable diameter to profit from the economies of scale for later use.

The starting volumes¹²⁸ should be from:

- cement clinker – 20 mln t CO₂ eq
- building lime – 6.4 mln t CO₂ eq
- chemical industry – 16.4 mln t CO₂ eq
- *of which ammonia and H₂ production – ca 6 mln t CO₂ eq*
- steel industry – 32 mln t CO₂ eq.

These volumes are of CO₂ eq, Pure CO₂ emissions are smaller by a factor 0.9 to 0.8.

The second phase should address CO₂ transportation with a low load factor but high volumes from load-following power and from blue hydrogen production for smaller low-load factor applications, such as the residential and commercial sectors, mainly for heating.

4.5.2 Load factor

The starting question concerns the operational requirements for a steady flow needed for CO₂ injection into aquifers and for the stable operation of pipelines transporting CO₂ in the fluid phase. This is followed by addressing the load factor as the major influence on costs along the chain.

The pipeline load factor can be improved by storage. Salt caverns close to the transfer point appear to be a straightforward choice for equalising streams for the offshore part of the system; existing converted or newly leached caverns near Dornum could be used for this purpose. Upstream salt caverns exist only in Sachsen Anhalt. Technically, CO₂ storage in salt caverns does not pose a problem; the retrieved CO₂ might even be used for power generation.¹²⁹

The Ketzin project¹³⁰ suggests that CO₂ storage (injection and withdrawal) also might be possible in porous storages; this could open possibilities for their use in upstream CO₂ stream equalisation, subject to further large-scale testing.

4.5.3 Economies, regional aspects

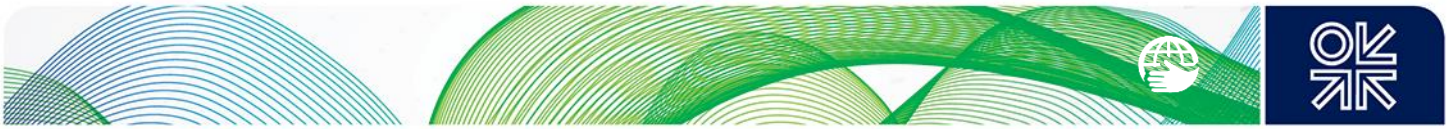
CO₂ and CH₄ pipelines have similar economies of scale (with increasing diameters): a 24-inch pipeline is shown¹³¹ to have a mass flow rate of 15 Mt CO₂/a with the onshore investment estimated at 0.83 mln €/km; while a 40-inch pipeline has a mass flow rate of 50 Mt CO₂ with an investment of 1.49 mln €/km.

¹²⁸ (German Emissions Trading Authority, 2021).

¹²⁹ (Minkley, Brandt, Dostál, Stepanek, & Lehman, 2021).

¹³⁰ (Schmidt-Hattenberger, Cornelia & Ketzin-Team, 2019), see chart 11.

¹³¹ (Serpa, Morbee, & Tzimas, 2011, p. 36).



For 800 km (about the distance from Munich to Emden), the investment for a 50 mln t CO₂/a pipeline can be derived as 1.49 x 800 = EUR 1.2 bln (2010). 50 mln t CO₂/a corresponds to the combustion of 27.5 bcm of CH₄. Given the decades-long experience in the US and the relatively low costs, the location of CO₂ capture from power plants or ATRs should not be an obstacle, especially for base load, even for the distance from the south of Germany to the North Sea coast.

All of these considerations suggest that CO₂ pipeline construction should start in regions with large CO₂ producing industry (cement, steel, ammonia) close to the North Sea coast – Ruhr (ca 300 km) and Leipzig (450 km).

The location of the centres of CO₂ production from load-following power generation is linked to the choice of input fuel. Lignite plants with decarbonisation are tied to the large lignite production sites between Cologne and Aachen in the west and the Lausitz region in the east. Both locations are close to other large-scale industry needing CO₂ transportation for sequestration, so CO₂ from power generation could be integrated later into the CO₂ transportation system. However, gas and coal-fired power plants are more spread out through Germany. It is possible to retrofit power plants with CO₂ sequestration, making use of the existing investment, while new capacity for gas or coal could be built close to the coastline, minimising the need for CO₂ transportation.

There is a trade-off: on the one hand, there is the domestic lignite resource, which results in higher CO₂ streams with a given CO₂ transportation distance, with a more advanced capture technology. On the other hand there is natural gas as imported primary energy with lower CO₂ streams, which allow for some optimisation of the CO₂ transportation distance but with less global and German experience with CO₂ capture technologies.

Given the need to make up for the delays in scaling up CO₂ sequestration in power plants, the integration of CO₂ streams from the decarbonisation of fossil-fuelled power plants requires scaled up pilot projects in the 300 MW range, followed by a rollout on the scale needed. This will take several years.

ATRs for the industrial use of H₂ will have high load factors; their CO₂ streams would be steady and would not particularly entail levelling out variations. By contrast, any production of blue hydrogen for heating purposes would come with low load factors, which would be reduced further by better building insulation.

5. Implications for the German economy

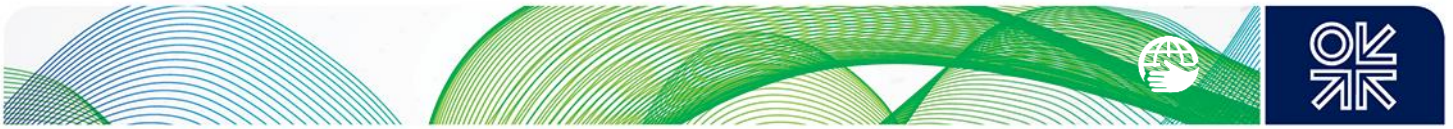
The previous three Chapters raise two major points of concern for the German economy.

i. The exclusion of CCS jeopardises the German economy

A concept which excludes CCS as an additional decarbonisation instrument, would lead to the targets for net zero by 2045 and for maintaining reliability being missed. It would also result in energy customers paying a penalty without the possibility of improving CO₂ emissions and jeopardise living standards and industry competitiveness without delivering on decarbonisation.

While the present ETS price is closely approaching a level where CCS becomes economic,¹³² a policy, which *de facto* excludes CCS, would prolong the penalty of the ETS price while blocking a major economically viable avenue of decarbonisation. Energy consumers would pay for years for emission trading rights instead of paying for decarbonisation via CCS.

¹³² (Dickel, 2020) and Section 5.1.2 *below*. With a level of 80 €/t CO₂, the price is approaching the level, where the costs of the chain from CO₂ capture plus transportation and sequestration might be covered; indeed, in some special cases like ammonia, this level might already be sufficient, if economies of scale can be realised.



The energy consuming industry in Germany would be exposed to competition from more pragmatic countries like the UK and US. This policy risks that industry – if staying in Germany – will not decarbonise but will be burdened by paying the ETS price and lose its competitiveness.

Last but not least, decarbonising power from lignite, the only national fossil-fuel resource, would contribute to a policy of reducing energy import dependence in the wake of the Russia-Ukraine war.

- ii. Reliable power supply will become a critical issue with more renewable power

Given its importance both for industry and for everyday living, reliable dispatchable power should be addressed beyond a political declaration in order to compensate for the intermittence of expanding renewable power. A detailed concept needs to be developed for low-CO₂ load following by power plants retrofitted with CCS, complemented by power in smaller units from CO₂-free H₂, ammonia and bio- and e-fuel.

5.1 Essential elements of a CCS policy

In order not to jeopardise the German industry's competitiveness and to foster its decarbonisation success, the concept of CCS must be included in German climate policy as soon as possible and on a scale to live up to the net zero ambition by 2045. Apart from the political support for a high enough price for CO₂ abatement, the Government should focus on a coordinating and enabling role. Such a concept must address the factors discussed below.

5.1.1 CCS as an essential avenue for decarbonisation

While it remains true that in the long run only renewable energy is sustainable,¹³³ policy makers must acknowledge that the Paris Agreement is about staying with the 1.5°C target and the corresponding CO₂ budget as detailed by the IPCC, which is a different task with a much shorter target date. Otherwise, policy would be orienting at long-term targets but forgetting the immediate relevant target.

5.1.2 A sufficiently high ETS price to ensure economic viability of the CCS chain, defining rules for onshore CO₂ transportation

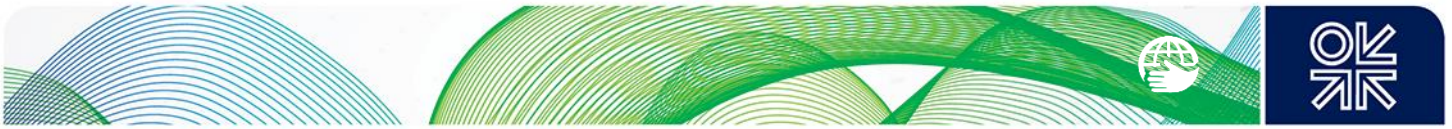
The level of the ETS price plus other CO₂-related levies, such as national taxes, should be credibly maintained at a level covering the costs of the chain (supported by policy commitments, including CfDs). That way the industry (mainly the energy infrastructure industry, but also large energy consumers like steel and chemistry) should be able to build the infrastructure needed to collect CO₂ in Germany. The CO₂ then can be handled at a transfer point at the North Sea coast (including intermediate storage) and moved for sequestration in the geological structures under the North Sea in Norway. Costs for CCS from the ammonia and cement industries and ATRs for the steel industry should be covered at a minimum ETS price level of ca 100 €/t CO₂.¹³⁴

Early depreciation might help mitigate some longer-term and utilisation risks, as would investing from the start in economies of scale of large-diameter CO₂ collection systems. Germany should look into:

- Establishing the rules to credit CO₂ sequestration in Norway against the ETS price. Obviously, rules are needed to trace the CO₂ from the source to the point of sequestration and to certify long-term reliable sequestration (in line with the German CCS Act of 2012, but also the Amendment to Art. 6 of the London Protocol),
- Defining the rules for CO₂ transportation by pipeline and the permitting procedure for CO₂ pipelines as entrusted to the Minister of Economic Affairs by Art. 4(6) of the CCS Act of 2012.

¹³³ This truism is included as footnote 1 in Germany's national hydrogen strategy: "The Federal Government considers only hydrogen that has been produced using renewable energy (green hydrogen) to be sustainable in the long term."

¹³⁴ (National Petroleum Council, 2019), see Chapter 3, updated 12 March 2021, pp. 3-18. A level of 90-110 \$/t CO₂ is also envisaged by the US NPC as the next step to expand CCS in the US.



The necessary infrastructure can be arranged by the industry as long as the ETS price covers the costs of the entire chain. The industry could also sort out the distribution of costs and revenue, as well as the interfaces along the CO₂ value chain.

Regulation (beyond the necessary HSE regulation) could use the model of the initial construction of the gas infrastructure in Germany (and CO₂ pipelines in the US),¹³⁵ of light-handed regulation based on competition law, or alternatively, rTPA with a grace period to allow for large negotiated projects in the beginning.

Total Energies and others recently announced a feasibility study of a CO₂ pipeline from Sachsen Anhalt to the North Sea.¹³⁶ The study, which should also evaluate the potential for repurposing gas pipelines, is planned to be finalised in 2023. Given the targets and the volumes of CO₂ that Germany will have to sequester, as well as the practical knowledge of CO₂ pipelines in the US, this can only be a first step forward. However, it is difficult to see how the savings from using parts of the existing infrastructure can compete with the economies of scale of a large new CO₂ pipeline.

A more ambitious and comprehensive project was announced in April 2022 by OGE together with Tree Energy Solutions from Belgium (TES): a grid would collect CO₂ from industry across Germany for transportation to Wilhelmshaven and Brunsbüttel from 2028. The CO₂ could be reduced by imported green hydrogen to methane or be shipped off to a site for sequestration.¹³⁷

5.2 The actors

It is not necessary for the state itself to become involved directly. The industry concerned should be able to take the initiative, provided this is commercially attractive. Actors could include the oil and gas companies operating downstream (offshore) on CO₂ sequestration and energy supply and infrastructure companies, as well as large chemical, steel and cement companies upstream (onshore) on CO₂ collection. Interfaces could be horizontal and vertical, whatever works fast. This is also suggested by the past experience with the building up of the downstream oil and gas infrastructure.

A reference may be the build-up of offshore and onshore gas infrastructure in Norway and on the Continent following the conclusion of the Troll deal in 1986. In the period to the year 2000, Norway built four large-diameter export pipelines to the Continent and increased its gas production capacity by more than 50 bcm/a. The gas companies on the Continent built the corresponding additional gas transmission infrastructure and developed the additional gas market.

At the same time, governments have to address points within their scope of responsibility as soon as possible.¹³⁸

As mentioned, CO₂ transportation in Germany is covered in principle by the CCS Act of 2012¹³⁹ with the following elements:

- Fostering the setting of HSE standards,¹⁴⁰ Paragraph 4, Section 6, 2nd sentence (in general, it is considered that the HSE standards of natural gas pipelines can be applied),
- Establishing details of permitting procedures under the 1st sentence,
- The possibility to expropriate (eminent domain) is covered in Paragraph 4, Section 5 and is linked to a permanent reduction of CO₂ emissions in Germany,

¹³⁵ (Caldwell & Kidner, 2021), for a discussion on the regulatory steps for the US to triple its CO₂ transportation.

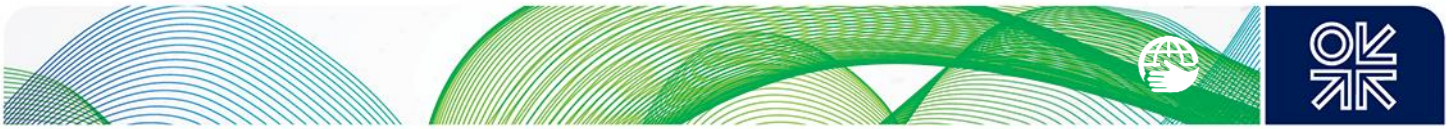
¹³⁶ (ener|gate messenger, 2022).

¹³⁷ (OGE).

¹³⁸ (National Petroleum Council, 2019), the discussion in the US on fostering a CO₂ collection infrastructure.

¹³⁹ (CCS Act, 2012).

¹⁴⁰ *Ibid.*



- The Act appears to refer to a point-to-point pipeline between a source and a CO₂ storage; this has to be modified to cover the transportation to a collection point for further eventual transportation to a variety of CO₂ storage schemes.

Filling in the unresolved parts of the 2012 CCS Act, particularly the standards for CO₂ transportation and rules for permitting procedures for CO₂ pipelines, would allow the industry to act.

Germany should not delay ratifying the Amendment to Art. 6 of the London Protocol any further.

As Norway signals its preparedness to follow up on the Northern Lights/Longship projects, it would certainly be helpful if Germany/the EU would come with a political commitment to use the large Norwegian sequestration potential. Agreeing on the provisional application of the Amendment to Art. 6 of the London Protocol with Norway and others would be a good signal.

5.3 Reliable decarbonised power

The concept of reliable power under the Coalition Agreement looks vague, it must be detailed with figures. The acid test being *Dunkelflaute* (days with low renewables contribution) and low-wind years. As a first step, how/by what thermal generation capacity to bridge *Dunkelflaute* until 2030 must be clarified; and in a second step – how such backup thermal capacity can be decarbonised. The concept should include efforts to take up the unfortunately stalled development of retrofitting lignite power plants with post-combustion decarbonisation on an industrial scale. This would open an avenue to reliable low-CO₂ dispatchable power generation based on the national lignite resource.

In parallel, the use of pre-combustion decarbonisation based on hydrogen or ammonia should be fostered in view of their potential for smaller-size applications needed in CHPs, district heating and industry applications.

5.4 Technology development

While all of these measures require substantial investment, in combination with the ambitious renewable roll out and efficiency measures they are sufficient to meet the targets derived from the Paris Agreement and as set out in Germany's amended CPA. So far, much of the CO₂-handling technologies, like ATRs, post- and pre-combustion decarbonisation in power plants, CO₂ transportation and (injection and withdrawal) storage, have not been developed with large-scale decarbonisation in mind. According to the IPCC, as well as the IEA, reaching the targets of the Paris Agreement is impossible without CCS. That should open a substantial future global potential for CCS technology.

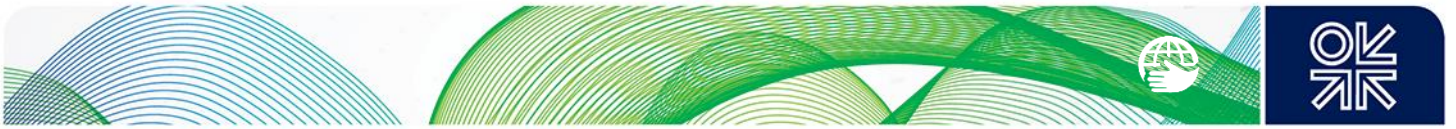
Conclusions

The Ruling of the German Constitutional Court of 29 April 2021 has emphasised the sense of urgency to tackle GHG reduction in view of the small remaining CO₂ budget. This was subsequently addressed by the amendments to the Climate Protection Act at the end of June 2021, stipulating net zero by 2045. The Coalition Agreement of the new Government sworn in on 8 December 2021 developed this approach further but based its very ambitious targets exclusively on energy efficiency and the deployment of renewables. The war in Ukraine started by Russia on 24 February 2022 has turned dependence on fossil fuel imports, especially on Russian gas, into an additional element of the political discussion. The result is an aspiration to accelerate energy saving and the rollout of renewables even beyond the targets of the CA.

Early large-scale CCS is key

Dependence on Russian gas, oil and coal can be mitigated – at least in the medium term – by recourse to global markets; the decarbonisation of dispatchable power generation needed for reliable power supply could be based on domestic lignite with CCS.

This paper shows that a decarbonisation concept without including CCS, i.e., a renewables-only concept, will not deliver net zero by 2045, nor reliable energy supply. Vice versa, including CO₂ capture



in Germany with sequestration in the large aquifers on the Norwegian Shelf would be able to close the gap and to provide backup for falling short of the renewables and energy efficiency targets. Energy consumers will pay extra ETS prices and other penalties on CO₂ emissions without being able to avoid them if CCS is not fostered or is even blocked. German industry will be disadvantaged compared to industry from countries with a more pragmatic approach to CCS, like the UK and US. Germany is overdue to revise its rejection of CCS as an instrument of decarbonisation. In a first step, CO₂ capture, transportation and export to Norway should be addressed. This would not need any change of existing legislation. In Norway, which has only a limited demand for CO₂ sequestration of its own, the well-explored formations in the North Sea offer a sequestration potential estimated at 70 Gt CO₂. Therefore, Norway is the obvious partner for large-scale cooperation on CCS with Germany.

Decarbonisation technologies for fossil fuels, such as ATR for the production of blue hydrogen and post-combustion decarbonisation of coal and lignite-fired power plants, as well as CO₂ transportation and sequestration, are TRL 9 (ready for market rollout). However, so far, they have been deployed only in exceptional cases, as the price for avoiding CO₂ emissions was too low. With recent increases in the ETS price to a level of 80€/t CO₂, the economic viability for large CCS volumes comes within reach. Germany and the EU should commit to policies giving confidence to investors that the CO₂ price will underpin the necessary investment in the whole CCS chain. A conceptual discussion of CO₂ collection schemes in Germany should be initiated as soon as possible.

Beyond that, Germany should promote the creation of a CO₂ collection infrastructure of large pipelines to transfer points at the North Sea coast. This must be coordinated with a mirrored infrastructure on the Norwegian side.

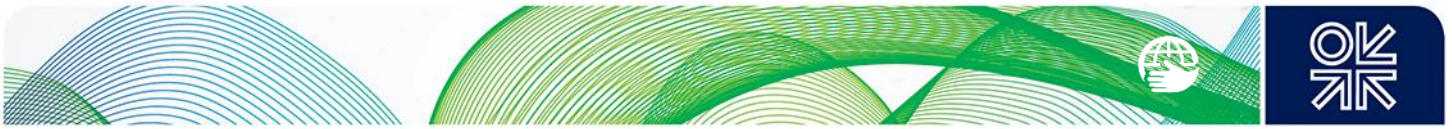
Within the timeframe to 2045, it is feasible and necessary first to produce blue hydrogen at the local and regional level for non-electric final energy demand, and then to phase in green hydrogen if and when available to achieve the reliability of low-CO₂ hydrogen supply. Blue hydrogen offers a way to start decarbonising the non-electric sector in parallel with the power sector, creating early savings on the CO₂ budget. While ATRs are successfully operated in large numbers and have been for many decades, globally there are only two cases of post-combustion decarbonisation in a power plant on an industrial scale (Boundary Dam in Canada and Petra Nova in Texas). Germany should revitalise its own projects to retrofit lignite power plants with Oxyfuel or amine-scrubbing decarbonisation, unfortunately stalled a decade ago.

Compensating for the last ca 5% GHG emissions inclusive of some unavoidable CO₂ leakage in the CCS process will require DAC and BECCS. While DAC needs substantial technology progress, which must be pushed for net zero by 2045, BECCS is restricted by LULUCF and needs the development of additional biomass, which may be difficult in Germany. Both approaches require CO₂ sequestration.

The industry should be able to develop adequate business models for the CO₂ value chain across borders, based on sufficiently high ETS prices and some coordination by governments on the rules for building the infrastructure, the recognition of standards and licensing regimes for CO₂ sequestration.

The inclusion of CCS with a CO₂ collection system is a must. CCS would provide an additional instrument of decarbonisation, speed it up, and would diversify technological approaches. It would have important implications for the design and sequencing of decarbonisation measures. The pipeline infrastructure for CO₂ sequestration in Norway is determined by transfer points at the North Sea coast (near Dornum), and on the other side – the location of the cement, chemical and steel industry as given sites of CO₂ feed-in. An initial CO₂ collection infrastructure should be built right away with the maximum pipeline diameter to use economies of scale, probably between the Rhine-Ruhr area and Dornum. The conversion of CH₄ or liquid hydrocarbons to blue hydrogen is state of the art, as well as CO₂ transportation and sequestration.

Retrofitting existing power plants with post-combustion decarbonisation has proven feasible and appears to be less expensive than building new integrated power plants by making use of the existing power plant investment, suggesting CO₂ collection at existing power plants, mainly lignite plants. Lignite as a national resource is close to Germany's main industrial areas, so the CO₂ output from lignite-fuelled



plants can be integrated with that from industry. Retrofitting lignite power plants comes with advantages over gas-fired power: easier CO₂ extraction due to the composition of the exhaust stream, industrial experience in the US/Canada and on a pilot basis in Germany, as well as low and stable costs of lignite production. On the negative side, power from lignite produces twice the volume stream of CO₂ compared to gas. Beyond the technical and economic aspects, combining energy independence with decarbonisation supports pushing the industrial-scale retrofit of lignite pilot projects, such as the one at Jämschwalde, cancelled in 2012.

Timeframe, sequencing and location

It should be possible to coordinate a large-scale CO₂ transportation scheme between Germany and Norway in view of the past successful large-scale cooperation to market Norwegian gas on the Continent: after the conclusion of the Troll contract in 1986, Norway built four large pipelines to the Continent and developed a gas export capacity of more than 80 bcm/a by 2000. Over the same period, the gas industry on the Continent developed the market for these volumes and the additional infrastructure.

Looking in more detail at the time needed on the German part, as a point of reference, the EUGAL pipeline, a 480-km double 56-inch pipeline, was built within 2.5 years. It should therefore be possible that a substantial large CO₂ pipeline infrastructure could be laid and put into operation before 2030 if enough political momentum can be created. ATRs are an industry standard with a construction time of 3-4 years. Retrofitting thermal power plants with post-combustion decarbonisation might take longer, but it should be possible to bring 2-3 industrial pilot projects to commercial operation by 2030, then to be rolled out on a larger scale.¹⁴¹ While the first CO₂ collection system would likely start in the north (from the Rhine-Ruhr area to a transfer point near Dornum), the inclusion of the south of Germany should be tackled in parallel, so as not to strand industrial investment in the south.

Imports

A global H₂ market is not in sight anytime soon. Germany should do its own homework with a speedy rollout of renewables and a swift design of CO₂ collection and sequestration in cooperation with Norway. Outsourcing the challenges of producing CO₂-free hydrogen to other countries would in any case take achieving its decarbonisation targets out of Germany's hands.

On policy

Germany should ratify the Amendment to Art. 6 of the London Protocol and sign agreements with Norway, the Netherlands, Denmark and the UK on its provisional application. There is no reason not to take this necessary step as soon as possible.

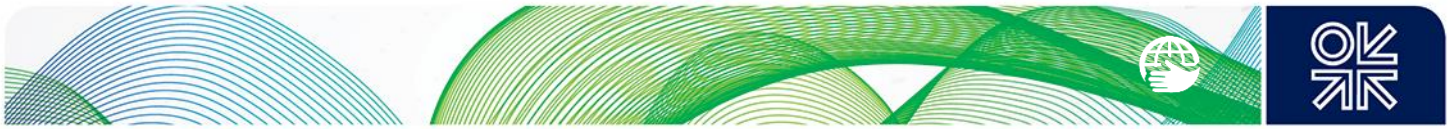
The grid planning process only targeting the power grid via three renewables scenarios appears to be obsolete if the net zero target by 2045 is to be achieved. It should be developed further, integrating all potential grids and the feed-in of reliable dispatchable low-CO₂ power and especially addressing a CO₂ collection system in Germany.

The German GHG policy is hampered by the confusion of the target – staying within the CO₂ budget for 1.5°C, and achieving net zero by 2045 – with the instrument, renewables. The situation created by the war in Ukraine started by Russia on 24 February 2022 risks reinforcing the illusory paradigm of renewables as the only perceived national energy resource to reach net zero by 2045, while ignoring national lignite resources, which could be decarbonised, and the persisting potential of global energy markets. A commitment to CCS would allow the industry to invest in reducing CO₂ emissions instead of just paying penalties and losing competitiveness.

¹⁴¹ (Kennedy, 2020, p. 9), the development time certainly could be reduced to deliver the basis for rollout by the end of the 2020s.

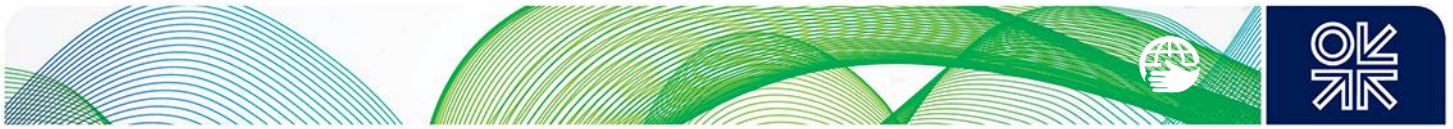


Developing the necessary concept for CCS and filling in the missing pieces of legislation now does not entail significant costs, but makes use of the short time and the small CO₂ budget left, not to delay unnecessarily the needed deployment of CCS.

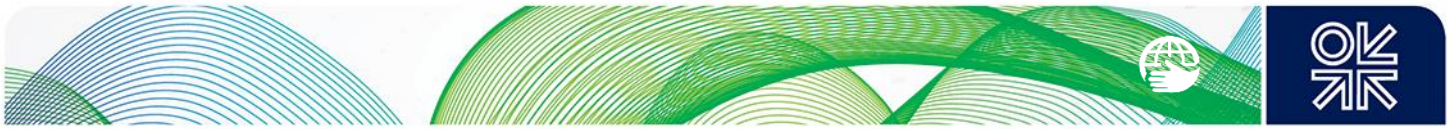


List of abbreviations and acronyms

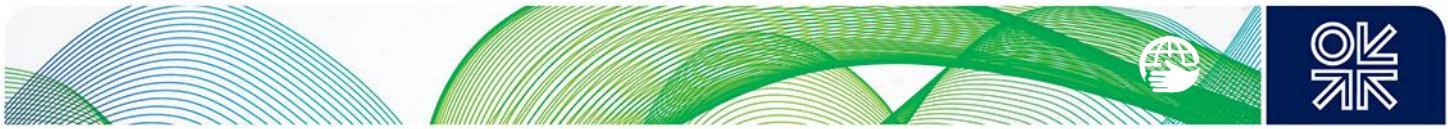
€	euro
€/t	euros per ton
AC	alternating current
AEL	alkaline electrolysis
ATR	autothermal reforming
bcm	billion cubic metres
bcm/a	billion cubic metres per year
BECCS	bioenergy with carbon capture and storage
BEV	battery electric vehicles
BGR	Germany's Federal Institute for Geosciences and Natural Resources
bln	billion
BMWi	Germany's Federal Ministry for Economic Affairs and Climate Action
BNetzA	Germany's Federal Network Agency (<i>Bundesnetzagentur</i>)
ca	<i>circa</i>
CA	Coalition Agreement
CAATSA	US Countering America's Adversaries through Sanctions Act
CCGT	combined-cycle gas turbine
CCS	carbon capture and storage/sequestration
CCUS	carbon capture, utilisation and storage
CfD	contract for differences
CH ₄	methane
CHP	combined heat and power
CO ₂	carbon dioxide
CO ₂ /a	carbon dioxide per year
Covid-19	coronavirus disease 2019
CPA	Germany's Climate Protection Act of 2019, amended in 2021
DAC	direct air capture
DENA	German Energy Agency (<i>Deutsche Energie-Agentur</i>)
EEA	European Economic Area
EEZ	exclusive economic zone
ENTSO-E	European Network of Transmission System Operators for Electricity
EnWG	Germany's Energy Industry Act (<i>Energie Wirtschaftsgesetz</i>)
EOR	enhanced oil recovery



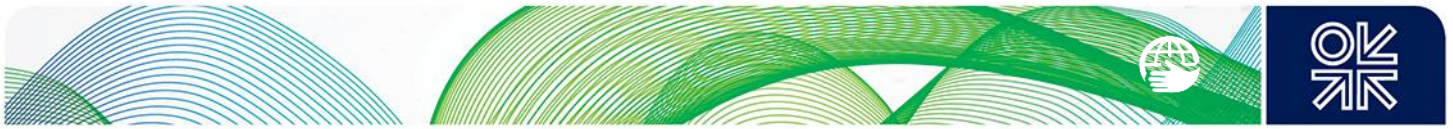
ETS	emissions trading system
EU	European Union
EUR	euro
FDP	Germany's Liberal Party (<i>Freie Demokratische Partei</i>)
FID	final investment decision
FSRU	floating storage and regasification unit
FSU	former Soviet Union
GCV	gross calorific value
GDP	gross domestic product
GFAVO	Germany's Large Combustion Plants Directive (<i>Großfeuerungsanlagenverordnung</i>)
GG	Germany's Constitution (<i>Grundgesetz</i>)
GHG	greenhouse gas
GT	gas turbine
Gt	gigatonne
GW	gigawatt
GWh	gigawatt-hour
GWh(H ₂)/h	gigawatt-hour (hydrogen) per hour
GWh _{el}	gigawatt-hour electric
GWh _{th}	gigawatt-hour thermal
h/a	hours per year
H ₂	hydrogen
HP	heat pump
HSE	health, safety and environment
HTEL	high-temperature electrolysis
HVDC	high-voltage direct current
IEA	International Energy Agency
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
km	kilometre
kWh	kilowatt-hour
kWh/Nm ³ H ₂	kilowatt-hour per normal cubic meter of hydrogen
kWh _{el}	kilowatt-hour electric
kWh _{th}	kilowatt-hour thermal



LCV	low calorific value
LH ₂	liquid hydrogen
LNG	liquefied natural gas
LOHC	liquid organic hydrogen carrier
LULUCF	land use, land-use change and forestry
m ³	cubic metre
m ³ /h	cubic metres per hour
mln	million
Mt	million tons
Mtpa	million tons per year
MW	megawatt
MWh	megawatt-hour
NCV	net calorific value
NEP	Germany's grid development plan (<i>Netzentwicklungsplan</i>)
NH ₃	ammonia
NIMBY	not in my back yard
Nm ³	normal cubic metre
NORDEL	Organisation of Nordic Transmission System Operators (now part of ENTSO-E, however the NORDEL system is asynchronous with the continental part of the ENTSO-E system)
NO _x	nitrogen oxides
NPC	National Petroleum Council
OIES NG	Oxford Institute for Energy Studies natural gas programme
OIES	Oxford Institute for Energy Studies
p.	page
p.a.	<i>per annum</i>
PA	Paris Agreement
PEMEL	proton exchange membrane electrolysis
PJ	petajoule
pp.	pages
psig	pounds per square inch gauge
PV	photovoltaic
PVC	polyvinylchloride
R/P	reserves to production ratio
rTPA	regulated third-party access



SAIDI	system average interruption duration index
Sm ³	standard cubic metre
SPD	Germany's Social Democratic Party
t	ton
TRL	technological readiness level
TSO	transmission system operator
TWh	terawatt-hour
TWh/a	terawatt-hour per year
TWh/a/a	an annual increase of annual energy production or consumption
TWh _{el}	terawatt-hour electric
TWh _{th}	terawatt-hour thermal
UBA	Germany's Federal Office for the Environment (<i>Umweltbundesamt</i>)
UCTE	Union for the Coordination of the Transmission of Electricity
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
WEO	World Energy Outlook
yrs	years



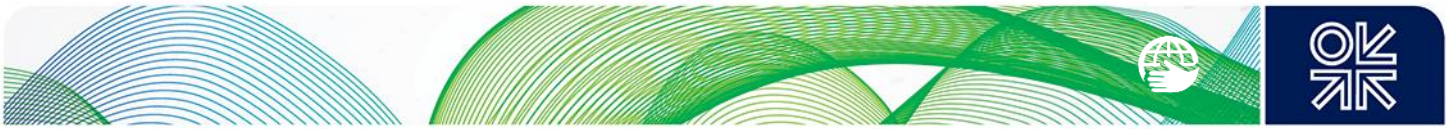
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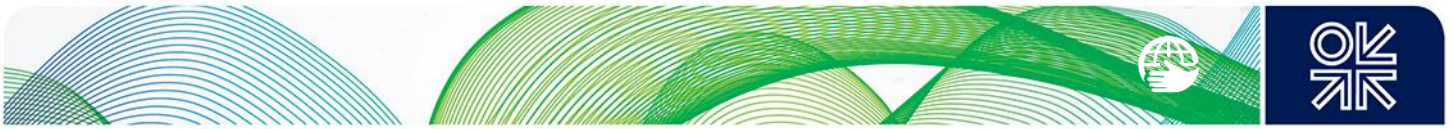
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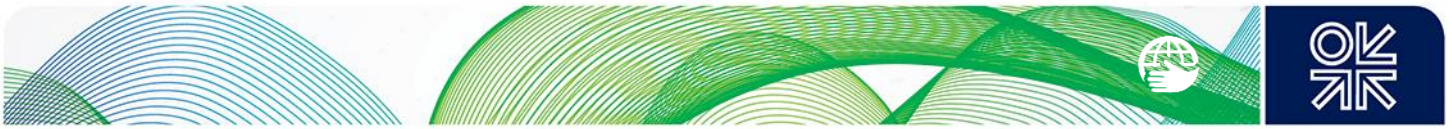
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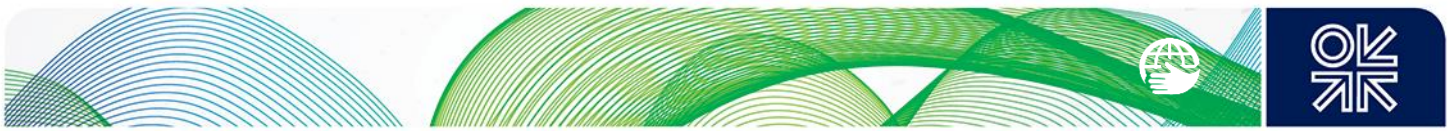
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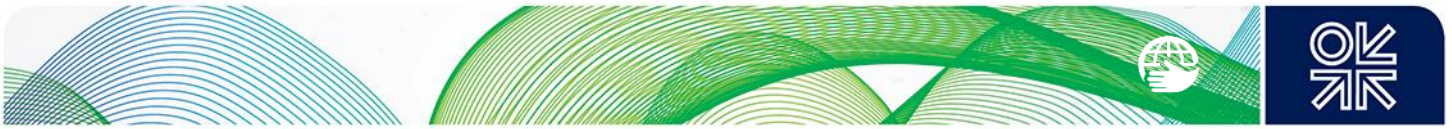
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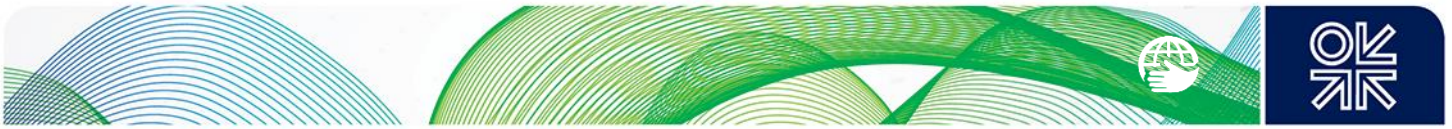
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