DIW BERLIN

Coal transition in Germany

Learning from past transitions to build phase-out pathways

2018

Authors
Hanna Brauers
Philipp Herpich
Christian von Hirschhausen
Ingmar Jürgens
Karsten Neuhoff
Pao-Yu Oei
Jörn Richstein

Climate Strategies

IDDRI

COAL TRANSITIONS
www.coaltransitions.org

Coal transition in Germany

Learning from past transitions to build phase-out pathways

A project funded by the KR Foundation

Authors

Hanna Brauers *(DIW Berlin, TU Berlin),* ***Philipp Herpich*** *(DIW Berlin),* ***Christian von Hirschhausen*** *(DIW Berlin, TU Berlin),* ***Ingmar Jürgens*** *(DIW Berlin),* ***Karsten Neuhoff*** *(DIW Berlin),* ***Pao-Yu Oei*** *(DIW Berlin, TU Berlin),* ***Jörn Richstein*** *(DIW Berlin, Corresponding author: jrichstein@diw.de)*

Cite this report as

Brauers, H., Herpich, P., von Hirschhausen, C., Jürgens, I., Neuhoff, K., Oei, P.-Y., Richstein, J. (2018). Coal transition in Germany - Learning from past transitions to build phase-out pathways. IDDRI and Climate Strategies.

Acknowledgments

The project team is grateful to the KR Foundation for its financial support.
We would like to thank Michael Kohlhaas and Oliver Sartor for helpful comments and support in preparation of this report; Julia Repenning (Öko-Institut) for providing additional modelling data; Martina Kraus and Carla Hornberg for data collection and preparation and Jonas Mugge for proof-reading the text.

Contact information

Oliver Sartor, IDDRI, oliver.sartor@iddri.org
Andrzej Błachowicz, Climate Strategies, andrzej.blachowicz@climatestrategies.org
Jörn Richstein, JRichstein@diw.de
Pao-Yu Oei, pyo@wip.tu-berlin.de
Karsten Neuhoff, kneuhoff@diw.de

Publishers: IDDRI and Climate Strategies
Editors: Pierre Barthélemy, Andrzej Błachowicz, Oliver Sartor
Graphic design: Alain Chevallier, Ivan Pharabod

Coal transition in Germany

Learning from past transitions to build phase-out pathways

Executive Summary

Historically, Germany has seen a large reduction of coal production and consumption, with significant socio-economic implications and corresponding policy action. Looking forward, this reports looks at pathways of phasing out coal and corresponding policy instruments to achieve the phase-out and accompany it.

Domestic hard coal production has been uncompetitive compared to imported coal since 1964, but coal subsidies kept levels of production close to consumption until 1990. Since 1990 Germany started to reduce subsidies, which led to a gradual hard coal production phase-out to be completed in 2018. Hard coal consumption has also gradually declined since 1960, first being replaced by consumption of oil and gas imports, and later by an increase in renewable energy and further gas utilization. Hard coal is mainly used in electricity generation and to a smaller degree for industrial production (mainly steel) and the reduction in consumption has had less impact on employment than the reduction in production.

The history of lignite production differs in the east and west of Germany. While the development of western lignite production has been relatively flat over the last decades, in eastern Germany it nearly doubled between the 1950s and reunification (in 1990). Due to the sector's low productivity in the east compared to the west, production sharply declined by more than half following reunification, with an even sharper decline in employment. The consumption of lignite mirrors that of production as its transport over longer distances is uneconomic due to the low energy density.

While posing a big challenge for the mining regions, Germany implemented a variety of successful policies to alleviate social impacts of the hard coal phase-out through e.g. early retirement schemes, retraining programs and support for economic development. Due to the abruptness and scale of the reduction in lignite production and the coincidence with an overall economic downturn in former Eastern Germany, the affected (mostly rural), regions in Eastern Germany still suffer from the structural break and initiatives to develop sufficient alternative industries have not yet succeeded.

More recently, reductions in coal consumption in Germany have stalled and coal-related emissions have even temporarily increased. However, to comply with the 2°C target, Germany would need to phase out both hard coal and lignite consumption in the energy sector well before 2050, with various studies suggesting a shut-down of large shares of the generation capacities in the 2020s and a complete phase-out achieved earliest by 2025 and at the latest by 2040. Besides for reasons of climate policy, structural developments in the electricity sector, such as the shift to renewable energy indicate that coal will not be economically viable in the future.

The uncertainty of a successful deep decarbonization, shifting from the currently insufficient level of ambition (represented by existing nationally determined contributions (NDC) to global emission reductions) an NDC to a 2° world (i.e. limiting global warming to a maximum of 2°C compared to the baseline), seem to largely depend on the availability and commercial deployment of technologies which require a supportive policy environment to succeed. Whereas competitive technologies exist in the electricity sector with renewable energy sources, the picture is more challenging in the industry sector, e.g. in steel production. Here competing technological innovations as well as public acceptance will decide whether coal remains viable with CCS or will be substituted by other energy carriers and reactants. NDC and 2° scenarios differ primarily in two ways: earlier reductions and more ambitious emission reductions in transport and industry are needed for achieving Germany's contribution to the 2° world.

Several studies suggest that Germany is able to phase out coal from an economical and technical perspective. Structural support and other policy instruments are needed to help affected regions on their path towards a just transition. Several concrete policy measures exist, which can lead to a successful phase-out and corresponding emission reductions. The basis for a coal-phase-out both in the NDC and 2°C scenarios is a strong carbon price. Several additional policy instruments are discussed which can lead to a phasing out of the ageing coal fleet, and a reduction of the full-load hours of newer plants. Accompanying structural policies can learn from the existing experience of previous phase-outs. Structural support should here be directed not towards coal companies but towards the most affected regions to create new opportunities for sustainable long-term employment and economic development.

1. Introduction

Through the 2015 Paris climate agreement, 195 states committed to keeping the global temperature rise below 2° and to aiming at 1.5°C above pre-industrial average temperatures in order to limit the impact of climate change. The UNEP Gap report, however, highlights that current nationally determined contributions (NDCs) would deliver no more than one third of the emission reductions required to reach even the 2°C target (UNEP 2017). In stepping up their efforts, countries like Germany will need to tackle the challenge of accelerating the phase-out of hard coal and lignite-consumption in power plants and industry.

Germany, in the past, often seen as a global frontrunner in the combat against climate change, will most likely miss its domestic emission reduction targets for 2020, in particular due to persistently high emissions from coal. However, the last five years seem to have created a momentum in Germany to phase out coal. While hard coal will no longer be mined by the end of 2018, the future of lignite mining and the consumption of lignite and hard in coal-fired power plants and industry is still uncertain. The German government has installed a commission in 2018 to agree on a phase-out date for its remaining coal-fired power plants. Among others, the commission, will need to tackle the question of how much support the federal German government is willing to provide for assisting the transition of the remaining lignite mining regions.

Yet, Germany has already effectively managed a strong decline in coal mining in the past, providing relevant learning and experience for similar transitions in and outside Germany. Furthermore, there is a growing consensus in civil society as well as in industry that an 80% reduction of greenhouse gas emissions by 2050 is feasible without large cost increases to society, and that up to a 95% reduction of greenhouse gas emissions in Germany is technically feasible by 2050, albeit with some uncertainties in terms of technology and costs.

Building on a sound understanding of the history, the rather different roles of lignite and hard coal, as well as the political and market drivers shaping these roles, this report gives a concise overview of the most relevant 80% and 95% reduction pathways for the German economy. A particular focus is on the pathways' implications for hard coal and lignite mining and consumption, and what can be learned from the German experience about how to organize a just transition away from coal today.

The structure of this report is as follows. The introduction is followed by a description of the status quo of coal in Germany. Different scenarios in line with its NDC and with the 2°C target are shown in Section 3, and policy instruments to achieve the respective pathways are discussed. The international policy implications of Germany as a frontrunner and test case for policies regarding the integration of renewables and development of climate-friendly technologies are also explored. Section 4 elaborates on Germany's past experiences with the decline of coal mining over the last decades, focusing on lessons learned. The final section concludes.

2. Coal in the national context of Germany

2.1. Role of coal in the national energy system

2.1.1. Demand, production and trade

Coal plays an important role in Germany's energy mix compared to other EU member states. In 2015 coal represented 25% of primary energy consumption. Due to the inefficiencies in transformation to secondary energy carriers, such as electricity, its share in final energy use is somewhat lower than its share in primary energy consumption indicates.

Coal is predominantly used for power generation (78%), where its varying shares have been affected by the availability of oil and gas imports (particularly up to 1990), the increase in renewable energy, varying carbon prices and the nuclear phase-out. Another 10% goes to coke production and 8% to final energy uses in industry (93%), households (5%) and the tertiary sector (2%). While other coal products (mainly coke, briquettes, other lignite products) play a minor role in energy generation (<1% compared to coal), their role in final energy use is more relevant (194 PJ compared to 272 PJ for coal). The latter includes 264 PJ of coke in metal production and processing of which 166PJ are converted to gases and used as further energy input. Taking a closer look at final energy use of coal and coal products (including coke), 65% of the 466 PJ (incl. 111 PJ of coke) is consumed in the metal production (mainly blast furnaces) and processing sector (200 PJ hard coal and 98 PJ of coke); 12% in processing of stones and soils (incl. 41PJ of other lignite products and 12 PJ of hard coal); and 7% in the manufacture of chemical products (incl. 27PJ hard coal). The 6% (or 28.6PJ) consumed by households is dominated by lignite briquettes (14 PJ), hard coal (9PJ) and hard coal briquettes (4.8PJ).

German hard coal production amounted to just around 10% of total supply (domestic supply plus exports), while the majority of lignite (97%) was produced in Germany. With similar supply and consumption levels for hard coal and lignite, the share of total coal production in total supply was 53%.

Domestic hard coal production provided more than 90% of primary consumption in 1990 and fell to just above 10% in 2015. Absolute production levels decreased by 90% in the case of hard coal and by almost 50% for lignite.

Table 1 . Primary energy consumption in Germany in 2015

Energy Carrier	[PJ]	[%] of total
Mineral Oil	4,491	34%
Coal (Hard coal + lignite)	3,294	25%
Hard coal	*1,729*	*13%*
Lignite	*1,565*	*12%*
Natural Gas	2,781	21%
Renewable Energy	1,644	12%
Nuclear Energy	1,001	8%
Other	224	2%
Electricity Exchange Balance	-174	-1%
Total	13,262	100%

Source : AG Energiebilanzen e.V. (2017).

Table 2. Coal consumption [PJ] (excluding coke consumption)

	Total coal	Total hard coal	Total lignite	Share coal	Share hard coal	Share lignite
Electricity generation	2565	1095	1470	76%	66%	92%
Coke production	337	332	6	10%	20%	0,35%
Briquet production	136	0	136	4%	0%	9%
Non-energy use	14,1	1	13	0,42%	0,04%	0,84%
Final energy use	355	271	84	11%	16%	5,2%
Statistical differences	-44	- -44	-1	-1%	-3%	0,0%
Total	3363	1655	1596	100%	100%	100%

Source : ibid.

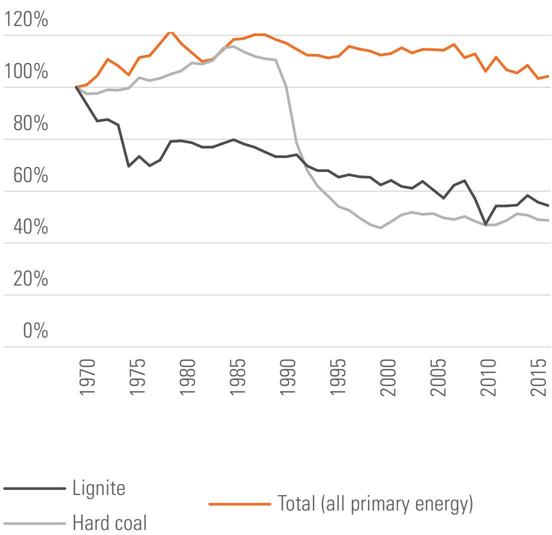
While total primary energy consumption fell by 11% since 1990, the share of coal fell from 37 to 25%, representing a fall of the share of hard coal from 15 to 13% and of lignite from 21 to 12%. In 1988, the GDR (German Democratic Republic) had lignite-fired power capacity of 15 GW, representing 2/3 of its entire power plant fleet (Kahlert 1988, 13). After the reunification (in 1990) lignite consumption declined steeply throughout the post-reunification decade, as lignite was phased out as household fuel and unproductive lignite power plants in East Germany were shut down (see Section 2.2). Increasing environmental concerns (and corresponding regulation on air quality, which became applicable to East Germany after the reunification) reinforced this trend. Since 1999, lignite consumption (and production) have been more or less stable and even slightly increasing. The increase in the renewable energy generation has not yet led to a decrease of fossil fuel-fired generation but compensated for reduced nuclear power production and contributed to an increase of electricity exports.. Also, lignite, as the most carbon intensive fuel, has benefited most from the extremely low carbon prices in the EU-ETS.

Figure 1 displays the change in the total energy consumption as well as the changes in the energy consumption supplied by coal. Whereas, the total energy consumption in Germany (after an increase until the 90s) now is close to the 1970 level, the amount of coal in the system is, for both lignite and hard coal, at around 50% compared to 1970. Before the reunification, hard coal was mainly replaced by imported mineral oil[1] and natural gas, while after 1990 the continued reduction of hard coal consumption went hand in hand with an increase in power generation from renewable energy (and a further increase in natural gas, the latter however dampened by the collapse in carbon prices in 2008[2]). However and against the backdrop of low carbon prices, coal consumption has increased in more recent years and never reached its all-time low of 2009 (see **Figure 2** 1970-2015 [right], Oko-Institut, 2017).

These differences between lignite and hard coal have important implications for the nature of the transition required for lignite versus hard coal. In the case of hard coal, it is mainly about reducing consumption by organising a well-managed and politically acceptable phase-out of coal-fired power plants. For lignite, the challenge is also on the production side, with strong implications for affected workers and regions.

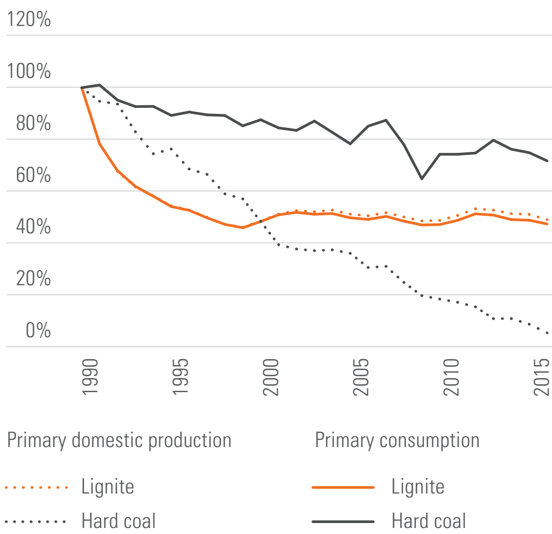
1 In 1950, mineral oil represented only 5% of primary energy consumption, increasing to 41% in 1990.
2 Between mid-2008 and mid-2013, the price of emission rights in the EU's trading scheme declined from almost 30€/t CO_2 to less than 5€/t CO_2.

Figure 1. Change of coal and total primary energy consumption in Germany from 1970 – 2015



Source : based on Öko-Institut (2017).

Figure 2. Primary energy production and consumption from lignite and hard coal in Germany 1990-2015



Source : based on AG Energiebilanzen e.V. (2017).

2.1.2. CO_2-Emissions from Coal

According to the German GHG emission inventory, primary consumption of coal causes 45% of all German energy related CO_2-emissions (down from 58% in 1990), with similar shares for hard coal (21.3%) and lignite (23.7%). For Germany to achieve its GHG emission targets coal consumption will need to be reduced (see **Table 3** and **Figure 3**), particularly in the light of the increase in the (share of) CO_2 emissions from coal in total energy related CO_2 emissions between 2009 and 2012 (for lignite) and 2013 (for hard coal)[3].

3 Since 2014 emissions have been declining again, but remain at a higher level compared to their all-time low in 2009.

2.2. Role of coal in the national/sub-national economy

Lignite as well as steam coal have been important pillars of the German economy for the last decades. Germany is the largest lignite producing country in the world with around 17% of global production (Statistisches Bundesamt 2017). In 2018, lignite is still being produced in three different regions, namely the Rhineland, Lusatia and Central Germany. In all regions, lignite is produced in open cast mines. The Rhineland is the largest lignite area, with 9,700 direct employees in mining and lignite-fired power plants and a production of 90 million t, followed by the Lusatian Region with 8,800 employees and 62 million t, while in Central Germany 2,400 coal

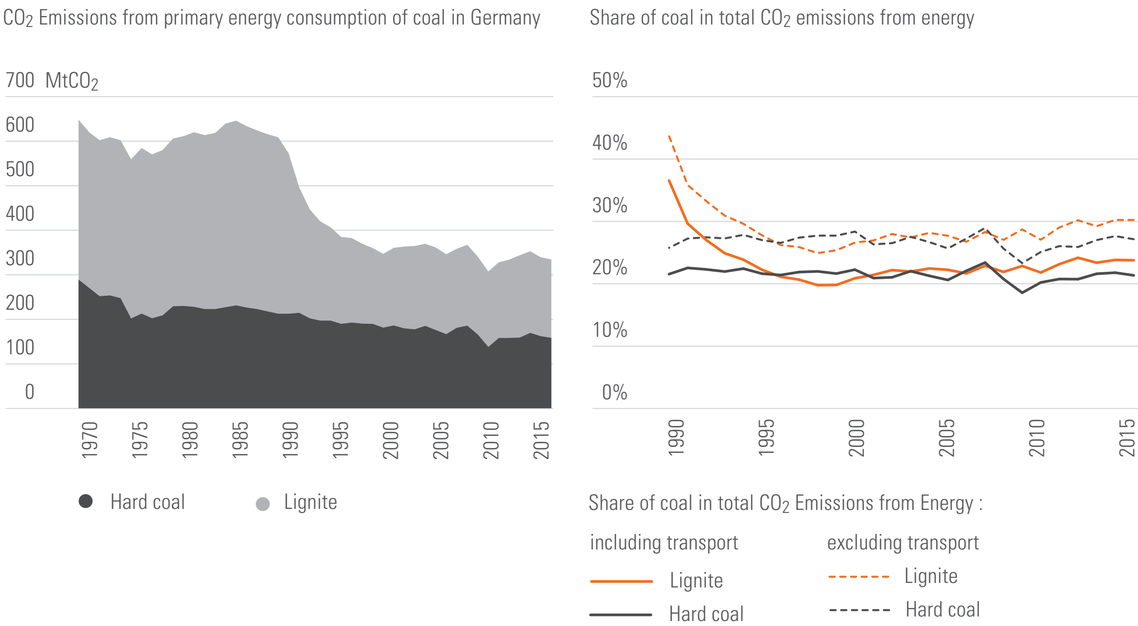
Table 3. CO_2-Emissions [Mt CO_2]

	1990	2000	2005	2010	2015
Hard coal	212,7	186,4	166,8	158,1	158,5
Lignite	361,0	174,8	180,0	170,5	176,5
Hard coal/total energy CO_2*	21,5%	22,2%	20,6%	20,2%	21,3%
Lignite/total energy CO_2	36,5%	20,8%	22,2%	21,7%	23,7%

** i.e. the share of CO_2 from hard coal in total energy related CO_2 emissions*

Notes: Emissions data for lignite and hard coal calculated based on primary energy consumption data from Öko-Institut (2017) and using emission factors 92,235 [t CO_2/TJ] for hard coal and 112,76 for lignite; Emissions data for total emissions from UBA (2017).

Figure 3. CO_2 emissions from primary energy consumption of coal in absolute and relative terms



Notes: Emissions data for lignite and hard coal calculated based on primary energy consumption data from Öko-Institut (2017) and using emission factors 92,235 [t CO_2/TJ] for hard coal and 112,76 for lignite; Emissions data for total emissions and total w/o transport from UBA (2017).

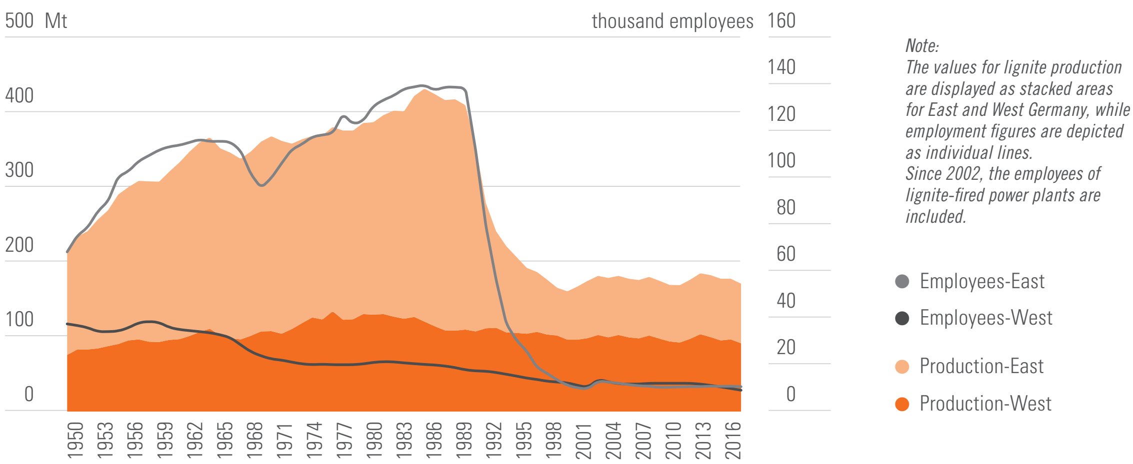
Source : based on AG Energiebilanzen (2017).

workers produce 18 million t of lignite (data for 2016, Statistik der Kohlenwirtschaft e.V. (2017c)). The majority of these employees, however, will retire in the next two decades. Already in 2020, around 30% of those workers will have exceeded the age of 60. By 2030, 2 out of 3 currently employed workers will have reached an age above 60 years (Sachverständigenrat für Umweltfragen 2017). A possible coal phase-out would then only affect a small share of the current workforce.

The majority of the transition is already completed in Germany - at the time of reunification, the East German lignite sector already went through a significant reduction in both employment and production (compare **Figure 4 and 5**). The major cuts were necessary as production was highly inefficient and costly (East German productivity was less than half of West Germany's productivity). After the reunification, companies were privatized and the infrastructure modernized. The efficiency in all German mining regions is now approximately at the same level.

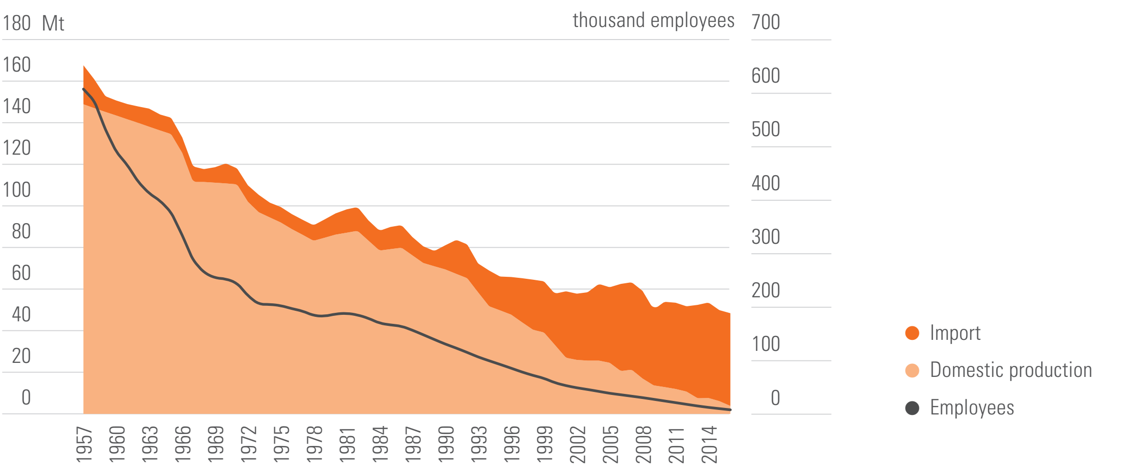
Due to its low energy density, transporting lignite is economically inefficient. There are, hence, no imports and exports of lignite and power plants within close distance to the mining sites. Lignite production is estimated to have had a value of around €800 million in 2015 while the total lignite sector created a value

Figure 4. Lignite production and employment



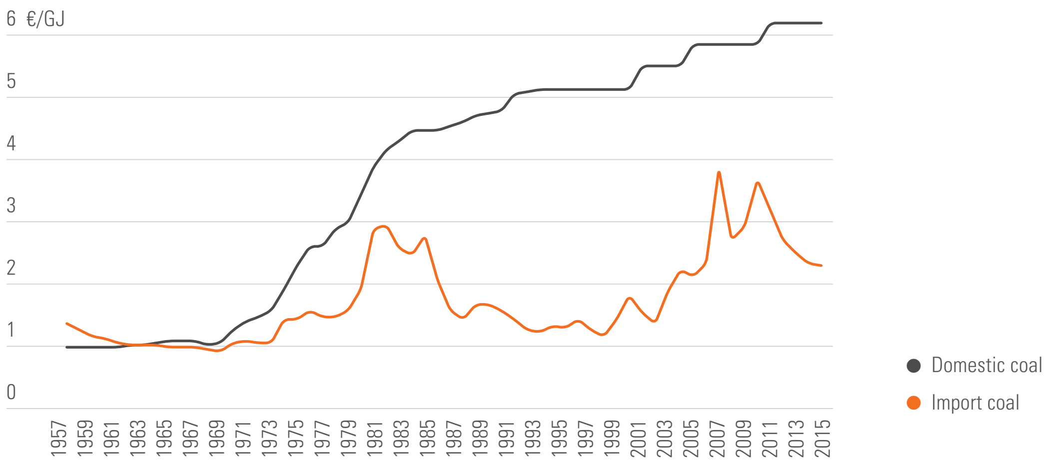
Source: based on Statistik der Kohlenwirtschaft e.V. (2017d).

Figure 5. Hard coal production, imports and employment in mining



Source : Own calculations based on Statistik der Kohlenwirtschaft (2017b, 2017c) and Verein der Kohleimporteure (2017).

Figure 6. Prices for domestic and import coal



Source : based on Verein der Kohleimporteure e.V. (2017), 111.

of around €6 billion (DEBRIV, 2015). In 2017, a total of 21 GW capacity of lignite-fired power plants was installed in Germany. The average age of the power plant fleet is more than 30 years; with the oldest being installed in 1936 and the newest in 2012 (Bundesnetzagentur, 2017).

Hard coal is produced in the deep mines of the Ruhr area. In 2017, around 5,700 employees produced around 3.7 million tonnes (Statistik der Kohlenwirtschaft e.V., 2017a). As **Figure 5** displays, domestic hard coal production is declining ever since the coal crisis in 1957, caused first by comparably cheap import oil and imported hard coal. **Figure 6** shows the price differences between domestic and imported coal. Since 1964, the price for domestic coal exceeds the one for import coal substantially. In order to protect domestic production, the hard coal industry received subsidies for more than 50 years to level-out the price difference. However, the subsidies were not able to prevent the decline of uncompetitive domestic hard coal mining, so that by 2001, the imported amount has exceeded domestic production. In 2016, 45 million tonnes were imported, mainly from Russia, North and South America (Statistik der Kohlenwirtschaft e.V., 2017a).

In 2018, when mining subsidies end due to EU competition laws, domestic hard coal production will cease entirely. The main consumer of German hard coal are power plants for electricity and heat generation with a capacity of 25 GW (Statistik der Kohlenwirtschaft e.V., 2017a). Due to imports, the phase-out of domestic production has no immediate effect on electricity generation. The average age of the hard coal power plant fleet is around 30 years, with the oldest being installed in 1923 and the latest in 2015 (Bundesnetzagentur, 2017). In 2018, one power plant, Datteln 4, with a capacity of 1.1 GW is planned to come online (however, it was first supposed to come online in 2011). Another 1 GW hard coal and 1.1 GW lignite are in the planning phase for several years already (BDEW, 2017). Whether they will ever supply electricity to the grid is at least doubtable. Recent projects like unit D of power plant Westfalen have shown technical problems with construction and conflicts with environmental regulations. The announcement of the closure of power plant Lünen in 2019 (500MW) illustrates the accelerating trend of hard coal power plant closures in recent years, which were no longer economical due to fallen whole-sale electricity prices.

A large share of the transition away from hard coal and lignite consumption and production has already been managed. Employment numbers and production output have been drastically reduced (see **Figure 4** AN and **Figure 5**) and the construction of new coal-fired power plants is no longer economically feasible. The challenge is now to learn from past transition experiences, using successful policy approaches and preventing past mistakes.

2.3. Recent coal policy context

Parts of civil society have demanded a coal phase-out in Germany for decades, but with only little success against vested interests (ranging from the coal industry, unions, regional politicians and others). While policies were introduced at the EU and German level to lower CO_2 emissions and increase renewables, these were not effective in significantly reducing coal consumption in recent years (due to a low carbon price since 2008). Several drivers, however, have created momentum which is most likely to result in an official coal phase-out plan by the German government by 2019:

- Rising global pressure on climate related issues, especially due to the Paris agreement
- The German "climate protection plan 2050" ("Klimaschutzplan 2050") implying a phase-out of coal
- The realization that Germany is likely to miss its 2020 climate targets
- An increased pressure from civil society to foster/concentrate on a coal phase-out on a national level (mobilizing people & capacities formerly engaged with the now decided nuclear phase-out) and international level (also including people & capacities from the climate justice movement).
- A weakening economic situation for coal power plants due to rising renewable shares and lower wholesale electricity prices.

This momentum was supported by alternative technical innovations to enable a coal phase-out as well as intensified research on climate mitigation and adaptation aspects.

The German Ministry for Economic Affairs and Energy (BMWi) already attempted to implement a "climate contribution" for power plants in 2015 to achieve a reduction of 22 $MtCO_2$, in addition to the reduction foreseen in the business-as-usual or BAU scenario. The "climate contribution" would have been an additional financial levy paid by power plant operators to the German state, addressing primarily old and CO_2-intensive coal power plants. A level of 18 €/tCO_2, in combination with a free allocation of 3-7 $MtCO_2$/GW of plant capacity (depending on the age of the plant) was deemed appropriate to assure a 22 $MtCO_2$-reduction by 2020. The levy included the option for power operators to emit beyond their free allocation levels when decommissioning additional EU-ETS CO_2-certificates (Oei, Gerbaulet, Kemfert, Kunz, Reitz, *et al.,* 2015). The introduction of the climate contribution, similarly to most of the other discussed additional measures, would have mainly affected older and CO_2-intensive lignite power plants in the state of North-Rhine-Westphalia (NRW) and Lusatia.

Local politicians, power plant companies and unions raised their concerns that this would result in the rapid closure of many power plants combined with job losses. A premature closure of most power plants was, however, unlikely (Oei, Gerbaulet, Kemfert, Kunz, Reitz, *et al.,* 2015). As the measure would have only resulted in a reduction of full load hours, it would have hardly affected employment in the power plants. In addition, many of the older plants are scheduled to go offline in the 2020s, and their workforce reductions would not have been related to the climate contribution..

The coalition of (local) politicians (esp. from NRW and the party of social democrats), union members (esp. from IG BCE) and power plant operators (esp. from RWE operating most coal fired power plants in NRW) urged national policy makers to shelve the idea of the "climate contribution". The alternatively proposed so-called "coal reserve" aimed at reducing CO_2 emissions by around 10 Mt by 2020. The reserve consists of eight relatively old lignite units with an overall capacity of 2.7 GW (see **Table 4**) (Oei *et al.,* 2016). The operators agreed that all units would be shut down entirely after the agreed reserve period of four years. Yet the technical requirements for this "coal reserve" such as an early notification period of 11 days prior to plant activation as well as the existing overcapacities in the German and European electricity market, make it unlikely that this reserve will ever be activated. In addition, the majority of units would have been closed anyways in the following years. These reserve payments of in total €1.6 bn therefore could be seen as an unnecessary scrappage bonus. Nevertheless, agreeing on a consensus between operators and the government had the advantage of not causing additional insecurity due to legal claims.[4]

To negotiate the details of a German coal phase-out, a non-partisan, structured dialog process with key stakeholders has been suggested (Agora Energiewende, 2016). The eleven concrete aspects to achieve a coal phase-out at the latest by 2040 include:

- The establishment of a 'Round Table on a National Consensus on Coal' with key stakeholders, similar to the approach taken with nuclear power.
- A set end date for coal as well as a phase-out trajectory enshrined in law.

4 Several operators in German are currently suing the state for having had to close down their nuclear power plants earlier than originally planned (see http://www.faz.net/aktuell/wirtschaft/energiepolitik/atomausstieg-staat-muss-energiekonzerne-entschaedigen-14561282.html).

Table 4. Newly introduced "Coal Reserve" in Germany in 2016

Owner	Unit	Power [MW]	Age in 2020	Reserve start (shut down after 4 years)	Particularities
Mibrag / EPH	Buschhaus	352	35	10 / 2016	Was moved into reserve in 09/2016 as the mining site was fully exploited. Next site is 150km away, resulting in higher variable costs.
RWE	Frimmersdorf P	284	54	10 / 2017	Last 2 (out of 8) units; facing economic problems for several years.
	Frimmersdorf Q	278	50	10 / 2017	
	Niederaußem E	295	50	10 / 2018	Were already listed in the official list of expected closures with the closing date 2019.
	Niederaußem F	299	49	10 / 2018	
	Neurath C	292	47	10 / 2019	Similar efficiency factors as other 300 MW units and near its technical lifetime.
LEAG / EPH (Vattenfall)	Jänschwalde E	465	33	10 / 2018	Most recent units at the site Jänschwalde (start of operation of the 6 units 1981-1989); it is sometimes easier to start shutting down the last units first.
	Jänschwalde F	465	31	10 / 2019	

Source : Oei et al. (2016); The plant in Jänschwalde was bought by LEAG in 09/2016 from Vattenfall.

- No new construction of power plants, no additional lignite mines and no more related relocations.
- A cost-efficient decommissioning plan with flexibility options between lignite mining regions and operators to avoid domino effects (between mines and power plants).
- The creation of a foundation for the follow-up costs of lignite mining, payed for by the operators.
- The implementation of a 'Structural Change Fund' over €250 million, payed for by the federal budget, to support affected regions.
- Safeguarding security of supply, as well as the economic competitiveness of the German economy and in particular the energy intensive industry.
- CO_2 certificates which are set free are retired immediately to strengthen the EU ETS.

The focus on phasing-out coal would need to be accompanied by an acceleration of renewable energy capacity expansion, as well as support for lignite regions, that need to cope with the coal exit. A fund for structural changes would need to provide both financial as well as capacity building support, to strengthen the economy, science and research, improve infrastructure and help civil society adapt to the changes (see Agora Energiewende, 2017) and Herpich *et al.* (Forthcoming).

In the 2017 general election campaign, Angela Merkel promised that Germany would meet its 2020 GHG emission reduction target of -40% compared to 1990 levels. To achieve these emission reductions, older and more inefficient coal-fired power plants would need to be closed by 2020. In the climate protection plan 2050, sectoral targets for 2030 have been set: The energy sector will need to reduce emissions to 175-183 million t CO_2-eq from 358 mt CO_2-eq in 2014 (Bundeskabinett 2016). Cutting the sector's emissions by half will require further coal-fired power plant closures (80% of electricity generation CO_2 emissions can be attributed to coal, see Umweltbundesamt (2017)).

Germany's coal sector is not only being challenged by domestic regulations but a strengthening global movement tackling climate change and coal. E.g., in 2017, during COP 23 in Bonn, the „Powering Past Coal" alliance has been announced. The United Kingdom and Canada, as well as more than 20 other states and regions pledged to end coal consumption. On a European level, the "Coal Regions in Transition Platform" addresses upcoming changes in former coal mining regions. Another aspect that could reduce economic viability for coal in Germany, is French President Macron's initiative for an EU-wide minimum CO_2-price.

Following these trends, the new German coalition government wants to set up a commission to structure the coal phase-out. The commission will need to achieve a consensus on an end date for coal as well as the pathway of declining coal consumption until then. Furthermore, this pathway will need to be in line with climate targets for 2020 and 2030. Part of the commission's work will be to also decide on new structural funds to support the coal regions. These funds are guaranteed €1.5 billion for the time period from 2018 to 2021 by the national government.

3. National coal transitions

3.1. Quantitative coal scenarios

In the following chapter, we lay out two scenarios for the decarbonization of Germany, with special focus on the role of coal during the transition. The presented scenarios are based on the results of the Climate Protection Scenario (Klimaschutzszenario) 2050 (Oko-Institut e.V and Fraunhofer ISI, 2015), as well as statistical data from AG Energiebilanzen e.V. (2017) for the starting year of 2010, and do not include any new simulations results.

3.1.1. Current "NDC-based" scenario and implications for coal

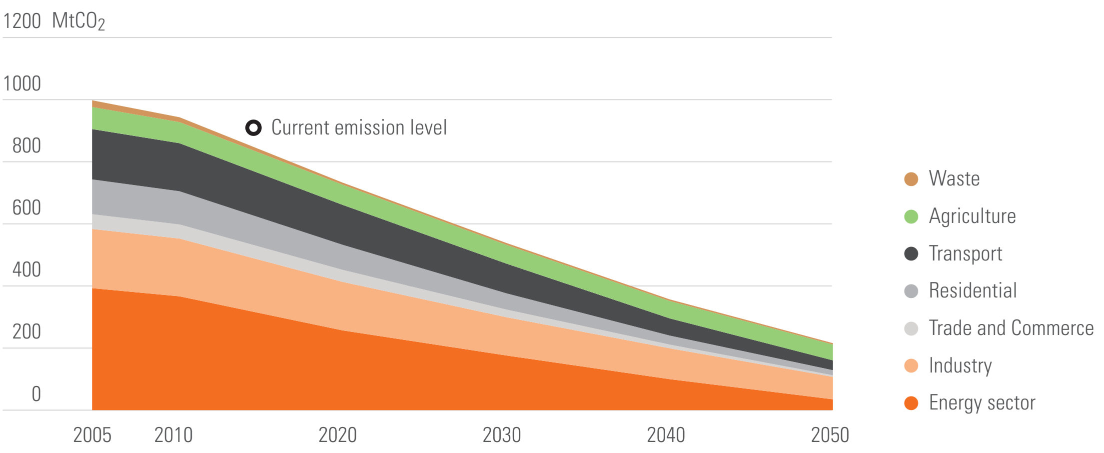
Current "NDC" scenario for Germany. Germany does not have an official NDC by itself, as the European Union submitted a joint NDC to the UNFCCC. The EU NDC (European Union, 2015) includes a binding 40% GHG reduction target by 2030, compared to 1990. This is in addition to the earlier target of 20% GHG reduction by 2020, and a reduction goal of 80-95% by 2050 (both compared to the baseline year of 1990).

Nonetheless, Germany submitted a national long-term strategy to the UNFCCC, in the form of the Climate Action Plan 2050 agreed by the German government (Bundeskabinett, 2016). In this plan, the German government set goals of a 55% GHG emissions reduction by 2030, as well as 80-95% reduction by 2050 (as compared to the basis year 1990) and defined sectoral goal ranges. The pathway of 55% GHG emissions reductions by 2030, and 80% by 2050 corresponds very closely to the KS80 (climate protection scenario 80%) in the Climate Protection Scenario 2050 (Oko-Institut e.V and Fraunhofer ISI, 2015), and is used as the "NDC" scenario for Germany in this report. In the recent coalition agreement (CDU, CSU, and SPD 2018) the governing parties agreed to make the 55% GHG emission reduction target by 2030 legally binding.

German "NDC" emissions pathway and sectoral emission reductions. In the overall emission pathway under the "NDC" scenario, GHG emissions are gradually reduced over time, with 57% emissions reductions until 2030, and 83% emissions reductions until 2050 (Emission reductions relative to 1990 and excluding international aviation and maritime traffic).

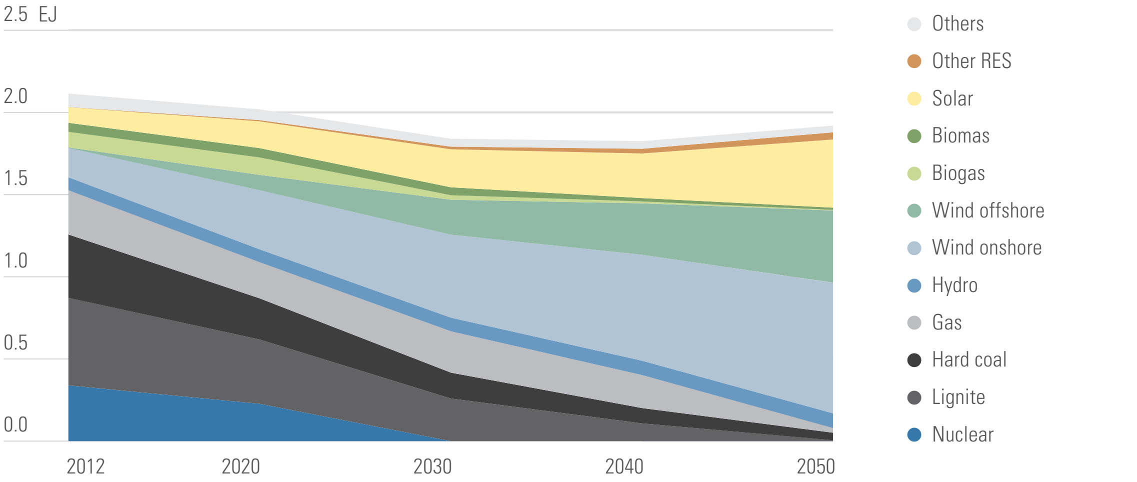
On a sectoral level, there are significant differences between mitigation efforts and timing (all numbers as compared to 2010 emissions levels). While the energy sector and residential sector reduce their emissions significantly already by 2030 (51.86% for the energy sector and 50.84% for the residential sector) and largely decarbonize by 2050 (90.5% and 84.8% respectively), most other sectors achieve the bulk of their emissions reduc-

Figure 7. German sectoral emissions under NDC scenario (excl. international aviation and maritime traffic)



Source : based on Öko-Institut e.V and Fraunhofer ISI (2015).

Figure 8. Energy mix in the power sector in the NDC scenario



Source : based on Öko-Institut e.V and Fraunhofer ISI (2015).

tions later (notably transport, with emissions reductions of 38.4% by 2030 and 79.7% by 2050). Some sectors do not achieve very high levels of further emissions reductions as compared to 2010, notably industry with 61.3% emissions reductions by 2050 and agriculture with only 25.3% emissions reductions by 2050.

In the electricity sector, emissions reductions are achieved by shifting to renewable energy (primarily onshore & off-shore wind, as well as photovoltaic), as can be seen in **Figure 8**. Nuclear energy is phased out in accordance with current government plants, and carbon capture, transport and storage (CCTS) is not applied in the electricity sector. In the industrial sector higher efficiency levels and a substitution of fossil fuels by biomass and electricity achieve the emissions reductions. It should be noted though that the relatively low levels of emissions reductions in the industrial sector are characteristic of many models as these often do not consider all potential mitigation options such as material substitution and new materials not included in traditional portfolios (IEA, 2017).

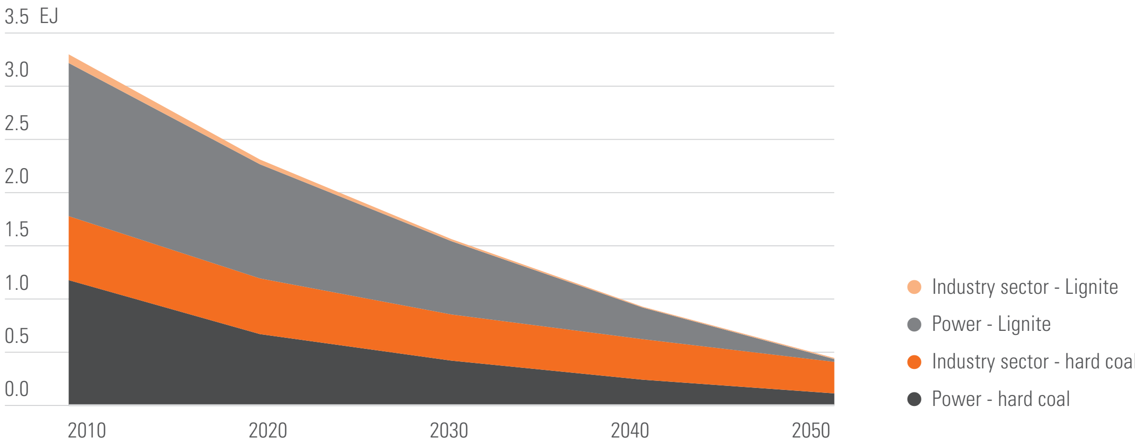
Impacts on coal consumption & discussion of drivers and uncertainties. The "NDC" scenario for Germany puts significant restrictions on coal consumption, reducing total coal consumption (hard coal and lignite) by 52.7% by 2030 and by 86.5% by 2050, as compared to the base year of 2010. Lignite is, at the beginning, phased out more slowly than hard coal due to lower electricity generation costs, given the assumed CO_2 prices; however, towards 2050 around 23% of the 2010 consumption of hard coal persists in the system, whereas lignite is nearly completely phased out (see **Figure 9**).

Reduction of coal consumption is mainly taking place in the power sector. As described previously, lignite consumption will end by 2050, and as lignite is almost exclusively used in the power sector, the reduction is achieved via the decommissioning of lignite power plants. Power production from hard coal diminishes significantly as well: It is down 64.4% by 2030 and 90.5% by 2050 as compared to the base year of 2010.

The difference between the two coal types is mainly driven by the continued consumption of hard coal in the industrial sector (consumption outside of the power and industrial sector is grouped together with consumption of the industrial sector, as the former comprises only a miniscule share of the overall total consumption). Here, as discussed in Section 2.1 a large share of consumption is determined by metal production, and more specifically the steel sector, which uses hard coal (via the transformation to coke) in the BF-BOF (blast furnace – blast oxygen furnace) production route (see **Figure 9**).

The reduction of hard coal consumption in the industrial sector is achieved via three mechanisms: Firstly, the shift from coal towards biomass in industrial furnaces, where high temperatures are needed; secondly, more efficient material use, as well as an increase in recycling; and thirdly, a relative shift from the BF-BOF route of steel production towards the electric arc furnace route (Oko-Institut e.V and Fraunhofer ISI, 2015) (Table 5-20, p. 149).

Figure 9. Coal consumption in Germany in NDC scenario



Source : based on Öko-Institut e.V and Fraunhofer ISI (2015).

An exception is the use of hard coal in blast furnaces for steel making; here, coal does not only serve the purpose of heat provision, but is also a reducing agent. While other primary steel making technologies exist, which use electricity or hydrogen as a reducing agents, these were not competitive under the assumptions of the technology scenario. The assumed CO_2 prices in the NDC scenario (increasing from 15 Euro/ton in 2010, to 50 Euro/ton in 2030 and 130 Euro/ton in 2050), were not sufficient to introduce CCTS in the industrial sector. Technology cost, CO_2 cost and hard coal price assumptions as well as the achievement of material efficiency targets and the success of substituting coal by biomass in industrial furnaces (and biomass availability) all determine what role hard coal plays in the NDC scenario.

3.1.2. Two degree-compatible coal scenario

Scenario choice. The climate protection scenario 95 (KS95) 2050 (Oko-Institut e.V and Fraunhofer ISI, 2015) serves as the two degree compatible scenario of Germany for this report, which foresees 94.4% emissions reductions by 2050 (as compared to 1990, and excluding international aviation and maritime transport) and which is very close in terms of sectoral targets to the climate protection plan 2050 of the German government.

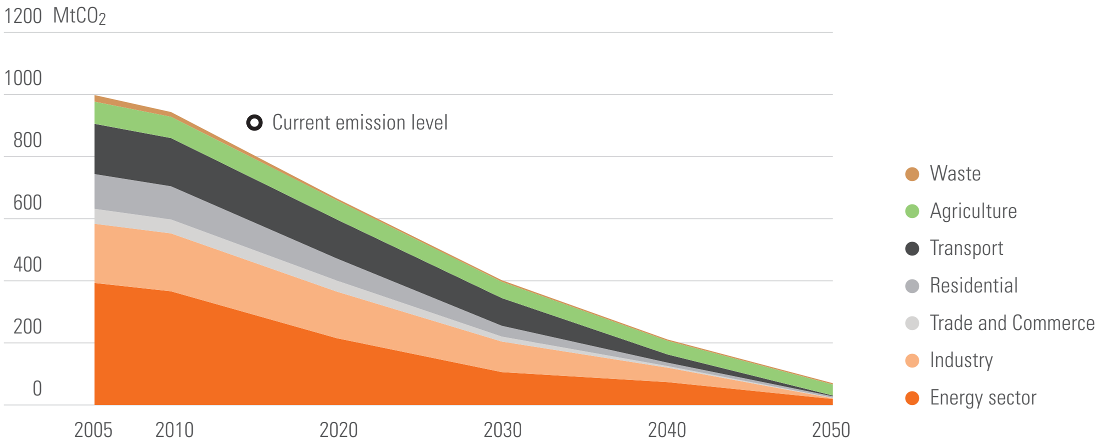
There is no universal approach to determine the fair share of contribution to emissions reductions, as it is a highly normative question and several principles exists to evaluate fairness in climate negotiations (Ringius, Torvanger, and Undertal, 2002). Among them being the polluter pays principle (including historic responsibility), egalitarian approaches (based on per capita emission allowances) and capability based approaches. Furthermore, the question of fairness is also influenced by the support (financial or technological) of richer countries to help poorer countries reduce their emissions.

Nevertheless, it is generally agreed by experts and policy makers, that, as a highly developed country with historically large emissions, Germany needs to set a highly ambitious emissions target to satisfy the condition of fairness. At present, based on current technological assumptions and the limited range of scenarios that have been developed, reducing emissions beyond 95% by 2050 is foreseen to potentially be highly costly. Further emission reductions could be reached by supporting other countries in their emission reduction ambition. However, in general, the question of how to achieve carbon neutrality is not as well-researched in Germany as the -80 to -95% scenarios.

Overall emissions pathway and sectoral emission reductions. Compared to the NDC scenario above, emissions reductions are achieved earlier in time, and go significantly deeper (see **Figure 10**). Emissions are reduced by 67.9% by 2030 and 94.4% by 2050 (as compared to 1990 and excluding international aviation and maritime transport).

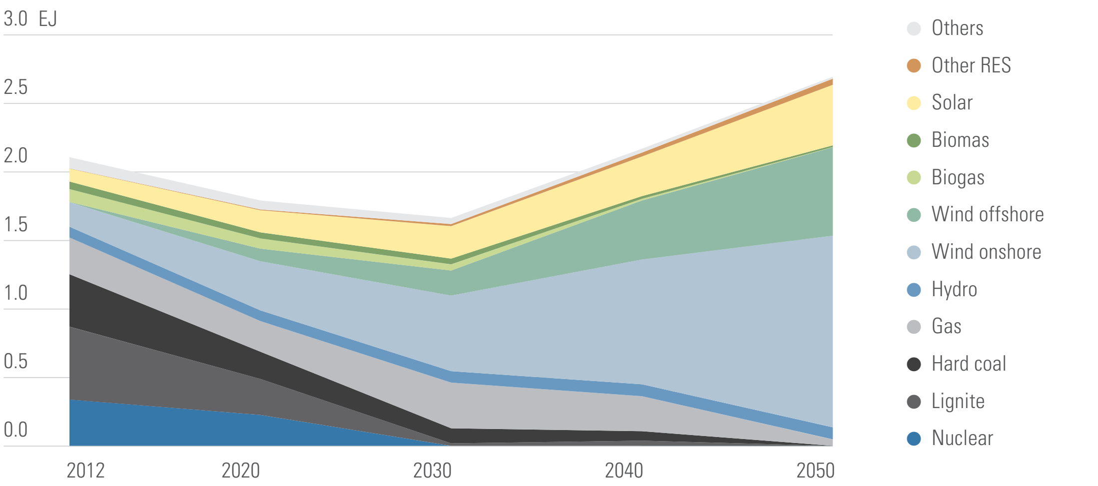
In contrast to the NDC scenario, in order to reach a 95% emission reduction levels, nearly all sectors excluding the agricultural (48.1% emissions reductions as compared to 2010) and waste sector (74.7% as compared to 2010) need to achieve emission reduction levels of 95% or high-

Figure 10. German sectoral emissions under 95% reduction scenario (excl. international aviation and maritime traffic)



Source : based on Öko-Institut e.V and Fraunhofer ISI (2015).

Figure 11. Energy mix in power sector in the 95% reduction scenario



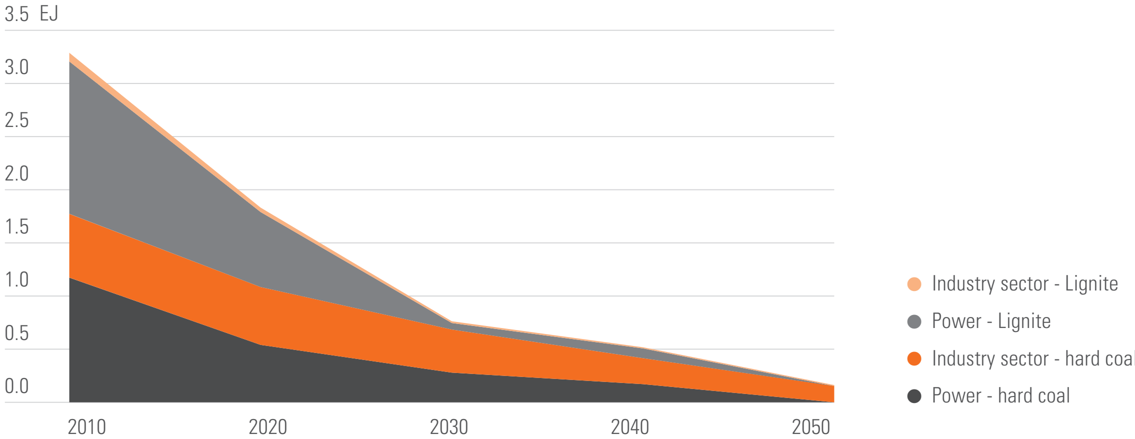
Source : based on Öko-Institut e.V and Fraunhofer ISI (2015).

er. This is in contrast to the higher remaining emissions in the transport and industry in the NDC scenario. These lower emissions are achieved by a higher rate of electrification, an increased use of biomass in industry (not only substituting hard coal, but also gas), the use of CCTS in the industrial (not the power) sector (which combined with biomass leads to negative emissions for some processes), an increased material efficiency leading to lower primary good demand, and a high level of energy efficiency (for example through the use of waste heat recovery *via* heat pumps).

In the power sector the most significant difference to the NDC scenario is the quicker phase out of coal (discussed in detail in the following subsection), and a long-term increase of power consumption, as other sectors electrify. As in the NDC scenario, conventional power generation is replaced by renewable energy sources, mainly wind and solar (visible in **Figure 11**). The additional electricity demand is mainly served by a significant increase in onshore and offshore wind power production, whereas solar power is only increased by a small percentage (as compared to the NDC scenario).

Impacts on coal consumption & discussion of drivers and uncertainties. In the two-degree scenario, impacts on coal consumption are coming significantly earlier

Figure 12. Coal consumption in Germany in in the 95% reduction scenario



Source : based on Öko-Institut e.V and Fraunhofer ISI (2015).

and are more far reaching than in NDC scenario. Coal consumption is reduced by 44.3% by 2020, 76.8% by 2030 and 95.1% by 2050 (see **Figure 12**).

As in the NDC scenario the largest emissions reductions are taking place in the power sector, with a quick reduction of power produced by lignite, which is reduced by 50.9% by 2020 and 95.6% by 2030 (a complete phase-out is only achieved by 2050). Power production from hard coal is also reduced significantly in the earlier years (53.8% by 2020), but then more gradually phased out by 2050.

By the year 2030, the largest share of coal remains the use of hard coal in the industrial sector. Until 2030, the consumption of coal in the industrial sector is reduced on a similar trajectory as in the NDC scenario, however, afterwards larger reductions of coal consumption are achieved (59.1% by 2040 and 74.5% by 2050). The difference to the NDC scenario is driven by the completion of the shift of coal to biomass in the industrial sector, so that coal is exclusively used for steel production. Within the steel sector there is a further increase of production of steel in electric arc furnaces, a higher material efficiency leading to lower steel demands, as well as higher energy efficiency.

Alternative pathways to the 2°C scenario. As in the NDC scenario several uncertainties exist which could affect the emissions trajectory as well as the consumption of coal. A high CO_2 price trajectory is assumed to incentivize emissions reductions (from 30 Euros/ton in 2020, via 87 Euros/ton in 2030 to 200 Euros/ton in 2050, however other studies see lower CO_2 price scenarios as feasible as well, for example (Philipp Gerbert *et al.,* 2018).

In the power sector, two of the characteristics relevant for this report vary between published studies on the future German energy transition: first, the speed and criteria by which coal is phased out, and second, by what it is replaced. With regard to the speed that a coal phase-out needs to happen at, two degree scenarios usually see a rather quick shutdown of coal capacity in the early twenties and a complete phase-out at the earliest by 2025 and at the latest by 2040 (New Climate Institute, 2016; WWF, 2017; Oei, Gerbaulet, Kemfert, Kunz, and Hirschhausen, 2015; Gerbert *et al.,* 2018; Öko-Institut e.V and Fraunhofer ISI, 2015). Often the age, structure, and in the case of lignite the clusters, of power plants and mines are taken into account for more detailed coal phase out plans (Oei *et al.,* 2014; Öko-Institut, 2017). In nearly all recent studies coal is replaced by renewable energy (and energy efficiency in the short run). These have all excluded the possibility of CCTS technology in the power sector, as there is limited storage potential, and opposition from civil society against a large-scale CCTS infrastructure (Von Hirschhausen, Herold, and Oei, 2012). In addition, and especially with the recent cost reductions in renewable technologies, CCTS in the power sector is economically unattractive. Different scenarios use varying combinations of RES technologies, energy efficiency and imports from other countries to replace coal. Simply replacing coal by natural gas is incompatible with long-term emission targets, although it may play a role in providing capacity to the market (Oko-Institut e.V and Fraunhofer ISI, 2014). Most studies focus on onshore wind and solar PV as providing most of the electricity, and depending on the availability, biomass is also used (Oko-Institut e.V and Fraunhofer ISI, 2014). The exact mix between solar, on- and offshore wind depends on the long-term cost assumptions regarding these technologies, as well as the costs and availability of storage and demand response as well as energy efficiency measures and has been extensively discussed in the literature (Schmid, Pahle, and Knopf, 2013).

A major impact on coal consumption is the availability and competiveness of the CCTS technology in the industrial sector, and specifically the steel sector. Whereas in the NDC scenario emissions reductions via efficiency improvements (material and energy) and a relative shift to electric arc furnace steel are sufficient to be compatible with an 80% emissions reduction goal in 2050, in the two degree scenario high emissions reductions also for the industrial sector are necessary, which imply a change of process. In this scenario, CCTS was applied to achieve these emissions reductions. If CCTS is not available (either due to technological or political reasons), or other technologies are more cost efficient, other production routes would be employed in the steel sector.

Technological alternatives in the steel sector for CCTS are for example hydrogen direct reduction, where hydrogen is used as a reducing agent, or iron ore electrolysis (Fischedick *et al.,* 2014). While CCTS technologies was seen to be closest to commercialization (European Commission, 2010), several CCTS pilots were cancelled and as a result the view of companies and policy makers has changed. Especially hydrogen direct reduction is seen as a main technological alternative, along with CCTS technologies in the future (Morfeldt, Nijs, and Silviera, 2015). Both hydrogen direct reduction and iron ore electrolysis do not use coal as an input and instead rely on electricity as the main energy source. This means most of the remaining hard coal use in the steel sector (and thus the industrial sector) may be substituted by electricity if CCTS technology is not used, and emissions reductions are to be achieved.

Next to lower-emission process choices, as well as emissions reductions via material efficiency, the substitution of carbon-intensive materials by more climate-friendly material choices may play an important role in two-degree scenarios as well; however, this option is often disregarded in many mitigation scenarios (IEA, 2017), as more attention in the policy discourse and research have so far been on new production technologies and processes, rather than materials substitution.

3.2. Coal-related policy dimensions for achieving NDCs and moving to 2°C scenarios for Germany

3.2.1. Implementing NDCs and coal

In the following we lay out the existing EU and German policy framework (and recent reforms), as these play a fundamental role in phasing out coal. Subsequently, we point out where additional policies may be needed. The German government and the European Commission use different instruments to decrease the effects of human-induced climate change at different levels (e.g., at the national and EU levels). At the EU level, the policies most relevant for the coal phase-out are the European Emissions Trading System (EU ETS) (European Union, 2009b), which covers around 45% of the EU's emissions, and the renewable energy directive (European Union, 2009a).

However, these policies alone have been ineffective in phasing out coal in Germany. A variety of different mechanisms to complement the EU's policies are therefore discussed in Germany and in parallel an ambitious structural reform of the EU-ETS was pursued (discussed in the following paragraph). The aim of this polycentric approach is not to establish mutually exclusive instruments or mechanisms, but to take action in several areas simultaneously. The German government cites three possible courses of action: greater commitment outside the framework of the EU-ETS such as further deployment of RES technologies and increased efficiency on the demand side, a focus on an ambitious structural reform of the EU-ETS and flanking measures within the context of the Energiewende (see also description below) (Bundeskabinett, 2016). Support for such an agreement has been expressed by different players of the energy sector. These companies would profit from higher load factors for their gas capacities and an accompanying rise in wholesale electricity prices. Energy-intensive industries, on the other hand, benefit from currently low wholesale prices and are therefore opposed to any measures that might lead to a price increase. The major argument from these branches of industry is a fear of deindustrialization (or "carbon leakage") as Germany might no longer be able to compete with lower production costs in foreign countries. Various studies, however, have shown that a moderate increase in electricity prices would have only limited effects on the competitiveness of German industry.[5] There are also some signs that industry opposition to deep emissions cuts is decreasing. A recent study commissioned by the German industry association BDI finds that an 80% reduction of greenhouse gas emissions by 2050 is feasible without large cost increases to society (and negative cost for industry, due to significant energy cost savings, which more than compensate investment costs for emissions reductions and energy efficiency), and that up to 95% reduction of greenhouse gas emissions in Germany are technically feasible by 2050, albeit with some technological and cost uncertainties (Philipp Gerbert *et al.,* 2018). The report however underlines the challenge of deep decarbonization (i.e. moving from "-80 to -95%") for industry and the development of a credible portfolio of (policy and financial) measures for supporting and incentivizing the significant innovation effort will be crucial for guiding the energy intensive industry sectors on the decarbonisation pathway (Neuhoff *et al.,* 2018).

But the EU-ETS has so far failed to induce significant investments in new technologies; and even the recent reforms proposed by the European Commission and currently discussed by the legislators, (European Union, 2018), while likely to raise prices, will not deliver price signals sufficient for phasing out coal completely (especially lignite).

The reform includes a regular stocktaking with regard to the Paris agreement and a strengthening of the linear reduction factor of the emissions cap from 1.74% to 2.2%. It also comprises a reform of the market stability reserve, leading to a quicker reduction of the banking surplus by a doubling of the intake rate and a cancellation of those allowances in the market stability reserve that exceed the previous year's emissions (from 2023). Finally, national governments may reduce the amount of allowance they auction if they implement additional national measures that lead to the closure of electricity generation capacity within their territory. Especially the last point would allow additional national measures taken with regard to coal generation capacities to be fully effective as an emission reducing policy also at the European level.

This carbon effectiveness of national measures is relevant, as in the medium term, prices from emissions trading may not provide sufficiently strong signals to drive a shift away from high-carbon energy sources, especially with regard to lignite generation capacities. The NDC scenario foresees a significant reduction in lignite generation before 2030. However, the marginal costs of lignite based energy production in Germany lie below those of combined cycle gas turbine (CCGT) power plants as long as CO_2 prices do not exceed 40-50 €/tCO_2. As this exceeds most current price estimates during the time period until 2030, a fuel switch seems unlikely. The CO_2-prices required to switch from older hard coal power plants to new gas power units are in the range of 20-40 €/tCO_2, which makes this scenario more probable. These prices depend primarily on fuel costs as well as power plant efficiency and can therefore vary for each unit (Oei *et al.,* 2014). Thus, while EU policy makers are taking action to increase the EU-ETS in the medium term, it has also become clear that it may be necessary to introduce additional national instruments that governments could introduce in parallel to emissions trading. Furthermore, the high uncertainty in timing and potential abruptness with which a price-induced phase-out might occur could create challenges in managing a just transition, which may make an orderly approach via additional measures more desirable. These are discussed in the following.

The introduction of the "coal reserve" in 2016 – although being less effective than the previously discussed climate contribution – marks only the first step in upcoming additional national measures to structure the German coal phase-out. Some countries in the EU and North America have taken similar initiatives by adopting complementary measures: the UK (CO_2 emissions performance standards, EPS, and a carbon price floor), the USA (EPS and an additional retirement plan for older plants), and Canada (EPS).

In **Table 5**, we summarize policies designed to reduce German power sector GHG emissions in general and to phase out coal in particular. Possible accompanying measures to reduce coal-based power generation in Germany include minimum fuel efficiency or greater flexibility re-

5 See Agora Energiewende (2014): Comparing Electricity Prices for Industry. Analysis. An Elusive Task - Illustrated by the German Case. Berlin; and Neuhoff *et al.,* (2014): Energie- und Klimapolitik: Europa ist nicht allein. (DIW Wochenbericht Nr. 6/2014) DIW Berlin. Neuhoff *et al.,* (2016): Energiekostenindex für die deutsche Industrie in den letzten Jahren deutlich gesunken. DIW Wochenbericht 41 / 2016.

Table 5. **Possible instruments for reducing coal-based power generation (in the German context)**

PROPOSED MEASURE	EXPECTED EFFECT	POSSIBLE ADVANTAGES	POSSIBLE SHORTCOMINGS
EU-ETS reform	Price signal through: introduction of market stability reserve (MSR) in 2019 instead of 2021; 900 mn EUA from backloading directly in MSR; increase of intake rate to 24% until 2023; invalidation of certificates in the reserve; possibility for voluntary reduction of auctioned certificates in case of national policy-induced power plant closures.	EU-wide instrument; thus, no cross-border leakage effects targets several sectors besides electricity	Structural reforms uncertain from today's perspective; the timing of the impact is unpredictable due to high surplus of certificates
CO_2 floor price	CO_2 certificates would become more expensive; stronger effect if the minimum price is valid in the entire EU or at least in several countries	Investment security for operators	Feasible prices probably too low to result in a switch from lignite to natural gas in the short term
Minimum efficiency	Closure of inefficient power plants	More efficient utilization of raw materials	Open cycle gas turbines (OCGT) could also be affected; complex and time-consuming test and measurement processes
Flexibility requirements	Closure or singling out of inflexible power plants	Better integration of fluctuating renewable energy sources	Combined cycle gas turbines (CCGT) could also be affected; complex and time-consuming test and measurement processes
Coal phase-out law	Maximum production [TWh] or emissions allowances [tCO_2] for plants	Fixed coal phase-out plan & schedule investment security	Outcome of auctioning of allowances would be difficult to predict
Emissions performance standard (per unit; for new plants and retrofits)	Restrictions for new plants and retrofits (without CO_2 capture) [< x g/MWh]	Prevention of CO2-intensive (future stranded) investments	Minor short-term reduction in emissions
Emissions performance standard (emissions cap for existing plants)	Reduce load factor for depreciated coal - fired power plants (e.g., >30y) [< x g/MW]	Preservation of generation capacities	Negative impact on economic efficiency of power plants might lead to closure of older blocks
Capacity mechanisms or reserve for coal plants	Incentive for construction of less CO_2-intensive power plants when including environmental criteria	Support for gas power plants or moving of coal power plants into a reserve to reduce their emissions and prevent supply bottlenecks	Difficult to establish criteria that are in line with EU state aid laws if payments should only be given to selected units
Climate contribution fee	Additional levy for old CO_2-intensive power plants	Limiting output of most CO_2-intensive generation facilities; preserving capacities; compatible with EU-ETS	Older units might become uneconomical if the fee is too high
Reduced transmission grid expansion	Increased congestion might prohibit lignite electricity generation in times of high renewable energy production	Redispatch of less CO_2-intensive capacities; lower investment costs for transmission lines	Transmission grids might be needed for renewables in the long run
Forbidding new lignite mines	Terminating current plans for new mining sites in East Germany	No displacements of villagers; no retrofits for lignite power plants; investment security for all affected people	No effect for regions with sufficient already granted mining rights
Closing existing lignite mines	Reducing mining volumes of active mines in North-Rhine Westphalia (NRW)	Concentration on one mine (instead of three) reduces fixed costs and less displacements; overall volumes insufficient for entire lignite fleet leading to some closures	Does not necessarily hit the oldest inefficient power plants first

Source : Own depiction based on Oei et al. (2014).

quirements, national minimum prices for CO_2 emissions allowances, capacity mechanisms, a residual emissions cap for coal-fired power plants, emissions performance standards, and policies regulating transmission grids. In Germany, these could be implemented in parallel to the desired EU-ETS reform.[6] An analysis of the policy options reveals that:

- The introduction of a national CO_2 emissions performance standard (EPS) for new and existing fossil-fired power plants could be contemplated as a specific means of reducing coal-based power generation, e.g., taking into account the plant age structure;
- a national CO_2 floor price would presumably not be sufficient to effect a switch from lignite to natural gas in the near future;
- minimum efficiency and flexibility requirements for power plants do not directly aim at a reduction of CO_2

6 This section is based on a study by Oei *et al.,* (2014) phasing out coal, in particular lignite.

emissions and, depending on specifics, would also affect gas power plants;

- a coal phase-out law with fixed production or emissions allowances for coal-fired power plants could prescribe a schedule for phasing out coal-based power generation in Germany and therefore provide investment security for all affected parties;
- older plants could be integrated into a capacity reserve to compensate the operators and at the same time prevent scarcity of generation capacity;
- the discussed "climate contribution" fee for old coal power plants, as proposed by the German Ministry for Economy and Energy in 2015, would be another cost-efficient instrument. It is also compatible with the EU-ETS, as certificates are taken from the market and no leakage effect occurs;
- future electricity transmission planners now have concrete CO_2 targets that need to be respected in their calculations and will influence the planning of new lines in a way that is more closely aligned with the goals of the Energiewende;
- a useful demand side instrument would be a ban on new lignite open strip mines (in the eastern part of Germany) or earlier closure of existing mines (in North-Rhine Westphalia).

In conclusion, plenty of suitable instruments to organize a coal phase-out exist. The effect of each instrument, however, depends on their specific configurations and their effectiveness in addressing existing exemptions or loop holes. Given a political will to foster a phase-out, deciding which instrument to choose is most important not in terms of effectiveness (CO_2 reduction), but much more as regards potentially significant distribution effects in terms of fuel-switches, operators, regions or individual power plants.

The decision to use one specific climate instrument might, however, not necessarily result in the expected phase-out and emission reductions if power plant operators manage to install additional exemption criteria. One option is therefore to push for a combination of different instruments targeting different characteristics of the intended coal phase-out and thus increasing the probability for success. This might include a control mechanism to phase-out older plants (e.g. through specific CO_2 emissions for plants older than 30 years), the reduction of emissions by younger plans (e.g. through absolute CO_2 emissions) as well as a moratorium on new mines and power plants.

Outside of the electricity sector, additional policies are needed as well:

In the industrial sector, additional policies might be needed to drive efficiency changes (Neuhoff *et al.,* 2018; BMWi, 2016) and a shift to biomass, if CO_2 prices do not reach levels of around 50 Euros/ton by 2030. As the carbon price currently is muted due to free allocation of allowances, the carbon price needs to be reestablished and become visible to intermediate firms and end consumers. This can either be done in concert with other major producers of materials and products, or via the inclusion of consumption policy, which reintroduces the carbon price via a carbon charge in sectors where free allocation is taking place (Neuhoff *et al.,* 2016). Innovation policies such as carbon contracts for differences or public procurement may also be considered and become necessary for the two-degree scenario. Some sectors, such as transport and the building stock are not covered by the EU ETS. However, as they do not use coal as a significant input factor, they are outside the focus of this report.

3.2.2. Moving from NDCs to 2°C compatible transitions for coal

Moving from NDCs to 2°C compatible transitions calls for enhanced and faster action in all sectors. Although the shift will have a big impact across all sectors, the electricity sector will see the most room for leverage, due to a variety of available low-carbon alternatives and existing policies such as the renewable policy regime.

The German government is currently aiming at a reduction of their CO_2 emissions in the electricity sector from 2014 until 2030 by at least 50%. Decreasing overall CO_2 emission in the German electricity sector to comply with the 2°C target would therefore imply closing the majority of coal capacities , at the latest in the early 2020s. 50% of all remaining lignite and hard coal capacities in Germany were constructed before 1990. A study for WWF (2017) consequently recommends the closure of these older plants already by 2020 and a complete coal phase-out by 2035.

Although politically and technically challenging, the phase-out is both technically and economically feasible. But in order for this to be achieved, a number of crucial conditions would need to be met to address the current barriers to a phase-out (Brauers, 2017):

- Regional support: Ease the fear of lignite regions/communities of being left behind

- Industry support: Ensure that climate policy framework supports low-carbon transition rather than carbon leakage.
- Workers: Ensure current coal workers a transition into new, decent jobs or social security payments
- Civil Society: Address fear of being left alone with follow-up costs
- New industries: Reducing uncertainty concerning coal's future and facilitating the settling of new companies in former coal-dominated regions

In order to make these conditions a reality, the following measures would need to be prioritised:

- Structural funds securing long-term payments financed by the national or the European budget to build up new capacities (for education, research, industry, civil society,...)
- Address potential price effects for low-income households.
- Guaranteed secured retirement payments for older workers and retraining for younger workers. Creation of new (job) opportunities for the next generations
- Secure sufficient funding from the operators to pay for renaturation and other follow-up costs
- Clear political signals (e.g. a phase-out corridor for coal)

Several barriers have prevented these changes until this day: the coal industry resisted a reduction in coal consumption as it threatened their core business. Electricity corporations frequently supported the coal industry as a large share of their electricity was produced in coal-fired power plants whilst unions wanted to prevent job losses. Civil society often feared rising electricity prices, reduced supply security and the regional economic dependence complicated the support for a reduction (Brauers, 2017). However, it is worth mentioning that a range of factors supporting a reduction in coal consumption have developed in the German context which could help provide the basis for a genuine coal phase-out going forward:

- NGOs and civil society are actively engaged in policy making in Germany. They are involved in the coal phase-out debate especially due to air pollution and health concerns as well as environmental protection and climate change.
- Prosumers and community owned renewable energy assets increase the acceptance for the energy transition.
- Unions have a strong influence on German politics. One of the two most important coal unions has shown an increased awareness of current trends, no longer asking to stop a further reduction in coal consumption, but instead demanding social security for affected workers (enervis, 2016). If unions can be convinced that other well paid jobs will be provided for coal workers, or their social security will otherwise be guaranteed, one of the most important stakeholders might support an earlier phase-out date.
- Mining regions are actively engaged in planning ahead for the transition away from coal (BMWi, 2018). Increased (financial) structural support for these regions can increase acceptance for a coal phase-out decision. The new German government included €1.5 billion for structural change, including structural policies in coal regions, for the time period from 2018 to 2021.

Unsuccessful coalition talks in late 2017 of Christian Democrats, Liberals and the Green party discussed the immediate closure of 7 GW of coal capacities already by 2020.[7] Deciding against an immediate beginning of the progressive closure of sufficient coal capacities would make it impossible to stay within a carbon budget compatible with a 2°C-scenario. The annual emissions of German coal-fired units would in this case exceed the remaining budget within the next decade, leaving no emissions for other sectors that are facing more difficulties and higher abatement costs. It is therefore of importance that emissions from coal, especially in the electricity sector, decrease at a very steep rate in the next decade. An important advantage of an early shut-down of the oldest capacities is that it consequentially allows for more feasible reduction pathways in the following years, smoothening the transition period for affected communities and regions (Sachverstandigenrat fur Umweltfragen, 2017).

Moving from the NDC to the 2°C scenario will be especially relevant for the industrial sector, and specifically the material producing industries like the steel sector, as the ambition of sector specific emissions reduction is significantly increased as compared to the NDC scenario. Having to replace coal earlier and to a greater extent with biomass and other substitution technologies, significant technology improvements and innovation are needed to

7 The Ministry of Economics and Energy announced to install a coal commission in the summer of 2018 to decide upon a planned coal phase-out.

realize the two-degree scenario, among them technological options that represent substantial changes to the production processes such as hydrogen technologies or CCTS. An important part of the policy mix are therefore innovation policies that bring new technologies closer to commercialization and bridge the valley of death between the pilot to full scale installations (Nemet, Kraus, and Zipperer, 2016). Policy options to achieve these goals include carbon contracts for differences (Richstein, 2017), the inclusion of consumption, as well as public procurement to create niches for new technologies (Neuhoff *et al.,* 2017)

3.2.3. International policy implications

As Germany is not a coal exporting country, nor does it qualify for financial support for NDC implementation (unlike developing countries), (future) international policy implications from the German coal phase-out relate to two other sets of challenges. Firstly, Germany (and Europe) provide lessons for designing a power system based increasingly on renewables; and secondly, for innovation and realization of deep industrial decarbonization (and industrial coal phase-out).

The already high and ever increasing share of (intermittent) renewable energy sources requires an evolution of electricity market design. Essential in this context is the role of system operation and of short-term markets in providing flexibility for (the differences between) renewable and conventional energy infrastructure. This flexibility in operation may for example be realized by "pooling resources over larger geographic areas through common auction platforms [and] realizing the full flexibility of different assets based on multi-part bids" (Neuhoff, Wolter, and Schwenen 2016). Another key element is the (re-)investment framework (ibid.) in the light of the significant differences between fossil and renewable energy's cost structure. To realize the further expansion of renewables in line with the phasing out of coal at the lowest final cost for consumers, the regulatory framework will have to be such that financing costs for capital investment in renewables are minimized (see e.g. May *et al.,* 2017). Revenue streams from renewable power generation will need to be predictable for longer time spans in order to draw in more risk-reverse investors (Neuhoff, Wolter, and Schwenen, 2016).

A different dimension of international policy implications from the example of German (or EU) coal phase out is less obvious as of yet and pertains to the options that will (need to) be developed for supporting and financing research and innovation support on deep decarbonization, including among others the substitution of coal in industry in general and steel in particular. While approaches to reducing the use of coal as industrial energy source are more obvious (fuel substitution, energy efficiency improvements), hard coal also serves as a so-called reducing agent in the blast-furnace route of steel making. While technology options to replace coal here do exist, these options, namely the switch to hydrogen or electricity as reducing agents, were not competitive under the assumptions of our technology scenario (and under assumptions of other studies, although hydrogren is listed as a potential game changer by (Philipp Gerbert *et al.,* 2018). The same holds for CCTS in industry under the assumed CO_2 prices of the NDC scenario.

Lacking competitive options and with the steel industry still representing sizeable shares of GHG emissions in major economies across the world, the incentives for and support and financing of respective research and innovation may represent a case in point for international policy coordination and cooperation.

4. National case study: Germany — Past experiences and strategies for the pending coal transition

The case study Germany illustrates that even in one country coal reduction pathways vary strongly and require different measures. **Table 6** lists some of the main differences between the reduction in hard coal and lignite production in Germany.

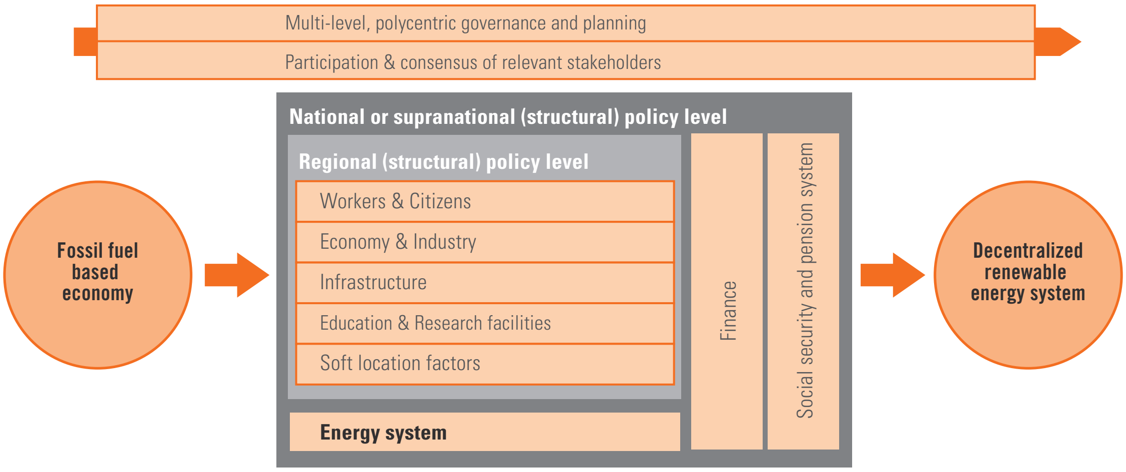
Even though the circumstances are different, the German historical experience, however, also shows that regardless of the specificity of each reduction, certain identical dimensions need to be addressed to enable a "just transition" (based on the concept by the International Labour Organization, in order to create social justice (ILO, 2015)). **Figure 13** illustrates important aspects following the concept of the "just transition", which need to be addressed when a region transitions from a fossil fuel-based economy to a low-carbon society in a just way. They can be divided into aspects that account mainly for the mining regions and others that have to be dealt with on a national or even supranational level. The figure lists important areas that should be addressed by policy makers in future transitions, while actually implement-

Table 6. Differences between the Ruhr and Lusatian mining regions.

	Ruhr area	Lusatian region
Main energy carrier	Hard coal	Lignite
Type of mining	Deep mines	Open cast mines
Follow-up costs	High costs over a long time period with an uncertain end date ("eternity costs"); mainly for water management in the former mines	Costs for renaturation and reuse of the vast areas of destroyed land (cost and time period easier to predict compared to hard coal)
Environment/Population	Most densely populated area in Germany, >5 million people	Rural/peripheral area ~1.1 million people
Phase-out consequences for energy system	Limited; coal demand covered with imports from overseas 1957-2018	No imports, mining and power plants are coupled; potential "domino-effects" Since 1989
Time period phase-out	Long, continuous process	Rapid reduction in only a few years with follow-up consequences
Employment in mining	1957: ~600,000 1967: ~290,000 1977: ~190,000 2016: ~6,000	1989: ~139,000 1999: ~11,000 2016: ~8,000
Civil society	Protests against coal reduction in the mining regions; Strong connection and identification with jobs in hard coal production	Very little ecological concerns before reunification; Reduction in coal dominated by reunification effects
Reasons for mining reduction	Comparably cheap imported oil and hard coal	Reunification, inefficient and costly production compared to West Germany
Labor productivity	Increased more than 4-fold since 1950	Almost constant from 1950s to 1990; then steep increase catching up with Western German standards
Replacement of jobs	Focus on education, the service industry and becoming a "knowledge society"; strong social security net, however, also a strong increase in unemployment	Replacement of coal jobs difficult due the economic and political breakdown also outside the lignite sector

Source: based on Agora Energiewende (2017), RAG-Stiftung (2015, 1), Sachverständigenrat für Umweltfragen (2017), Verein der Kohleimporteure e.V. (2017), Statistik der Kohlenwirtschaft (2017d, 2017c), Goch (2009, 12) and Matthes (2000, 238).

Figure 13. Dimensions for a just transition in coal regions



Note: The size of each area does not implicate any valuation in terms of financial volume or importance of the dimensions

ed measures will vary for each case study depending on regional specifics. In both the Ruhr area and Lusatia some of the aspects were addressed successfully while others were neglected. While important lessons can be identified through the two transition pathways, room for improvement is left and neither region has yet completed a just transition. In the following, important German experiences with structural policies on both the regional and national (supranational) level are highlighted. The whole process of the just transition away from fossil fuels should be guided by multi-level governance and planning, encouraging the different political levels to interact with each other in order to plan and implement effective strategies. Furthermore, planning and decision making should include a high degree of participation of all relevant stakeholders and deliver consent-based solutions to increase acceptance and to tap endogenous potentials.

4.1. Regional level

Workers & citizens

A just transition needs to guarantee social security of the mining workers and give them and the regions a perspective beyond coal mining: That means that lost jobs in the mining industry need to be replaced with new comparable jobs in other industries and sectors. In the Ruhr area, the strong influence of mining companies and the energy and steel sector resulted in high subsidies which slowed-down the decline in coal production. All employees entered either new employment or went into early retirement. Additional anticipative measures included retraining of the workers.

Regardless of the success of policies to ensure a more moderately-paced decline, the Ruhr area struggled for a long time to create new jobs, especially due to the coal and steel crises coinciding with the end of a period of strong economic growth. The inability to create new jobs was mainly caused by the resistance of the mining companies[8], problems for the domestic industries caused by increasing competition due to globalization and the misjudgment of the true nature of the coal and steel crises, which prevented action towards a transition. The Lusatian region faced and still faces the challenges of demographic changes and outward migration (to West Germany), which is a common problem for rural areas. The situation for Lusatia was aggravated as not only the employment in the mining sector broke down but the whole economic and political system. Moreover, the decline in Eastern German coal production was significantly more abrupt than had been the case for hard coal in the Ruhr area. Measures like early retirement were implemented to ease tension on the labor market in the entire East Germany. Consequently, Lusatia faces even stronger problems than the Ruhr area to attract new businesses providing local jobs.

Anticipative elements like retraining and an early communication of phase-out plans can ease the disruptive-

8 Mining and steel companies did not sell land (often unused) they owned to new enterprises from other sectors in the fear of losing qualified workers to the competition (in literature referred to as “ground lock”; German: Bodensperre).

ness of upcoming changes, by helping former coal miners to stay in the labor market and to prevent erroneous education and employment choices. A consideration of the age structure in the German lignite sector for example shows that over 50% of the employees are older than 50 in 2017. The job decrease in an up-coming phase-out could hence be organized along the age structure, without causing high numbers of unemployment (Sachverständigenrat für Umweltfragen, 2017). Furthermore, early retraining and different education choices can alleviate problems for phase-outs not only in Germany, but also other countries. The case study of the Ruhr area further shows that at the beginning of the coal crisis, the job losses could be covered by new jobs in the metal sector, which was in a comparatively good economic condition at the time. The close relation of these industries was an important factor for the success of this shift of workers. Germany now has the possibility to shift workers from the fossil-fuel sector to the related renewable sector, the development of energy storage technologies, construction of electric vehicles or the particularly labour intensive task of insulating the existing building stock. The energy transition thus poses not only a challenge for the mining regions but might also be an opportunity: In 2016, the German renewable energy industry employed around 334,000 people, compared to only around 160,000 in 2004 (Burger *et al.,* 2015; IRENA, 2017). Although not all former coal workers will simply be able to transition to the renewables sector, it can enable regions to continue to play an important role in the energy sector (Agora Energiewende, 2017).

Especially in Lusatia, people feel left behind and not taken seriously of (inter-)national policy (Morton and Müller, 2016). Therefore, a stronger participation of various stakeholders including civil society is necessary to achieve better policy outcomes and public acceptance.

Economy & industry

The just transition should transform an economy which strongly relied on mining and related industries (e.g. suppliers or steel production) into a sustainable economy that ensures a decent life for people by including elements of participation and consent-based decision making. In the Ruhr area, the economy shifted from the primary sector to the tertiary sector ("knowledge society"), although, the necessary developments were prolonged for a long time in the Ruhr area, especially due to the strong resistance of coal asset owners to any changes. In the beginning, mining and steel companies blocked developments by not selling their land to new enterprises. Additionally, a substantial financial amount of the structural policy packages was spent on the coal and steel industry, instead of focusing on new sectors.

Nevertheless, the economy in the Ruhr area is now more diversified thanks to a reorientation towards a more participative approach in structural policy making, the polycentric coordination of national, state and regional policy making, and the majority of policy focus and support dedicated to industries and sectors other than the coal and steel industries. In particular, the Ruhr area experimented with different structural policy instruments and governance structures, as previously only a limited amount of experience with structural change existed. The current approach focuses support on projects and companies within promising "lead markets". Within the Ruhr area, cities are now more independent and able to create their own development strategies. This change was necessary to reflect the individual needs of each city. For example, the city Dortmund has constructed a technology center, successfully specializing on microsystem technologies, using synergies of research and innovative companies. However, a closer look reveals that these individual and competitive strategies of the cities can result in redundant industries and projects in the Ruhr area, which prevents further growth and limits the exploitation of the regions' economic potential (Bogumil *et al.,* 2012). As a contrary example, the Ruhr area succeeds in coordinating different cities' efforts in the health sector with the joint initiative "MedEcon Ruhr" (Büter, 2012). The health sector in the Ruhr area employs more than 300,000 people and creates more than €5 billion in yearly revenues, focusing on applying new technologies and services. Future transitions should consider coordinating plans of cities at an early planning stage, to prevent or coordinate redundant or similar developments.

A struggle during the development of structural policy in the Ruhr area, was to identify the right system of governance to lead the transition. The first large projects initiated on a federal level were ineffective and faced regional and local resistance. Over time, decision making and planning shifted to a more regional level, to include the endogenous local potentials and to enhance approval of the transition by increasing participation of the stakeholders. The implementation of an institution (RAG foundation) representing the Ruhr area as an entity has helped to coordinate national funding but is still not fully capable of creating a coherent strategy for all cities in the Ruhr area, possibly leading to further exploitation of its (economic) potential.

The Lusatian economy still suffers from the structural break which occurred after the reunification, when many industries collapsed. The region additionally faces the challenges many rural areas have (demographic changes, a lack in infrastructure, emigration, etc.). Due to a failure to develop alternative industries, the local economy in some communities still heavily depends on lignite production. Investment support for new businesses often comes from outside the region. As a result, over the decades, projects have heavily relied on this financial and intellectual support, resulting in repeated closures of projects that cannot sustain themselves when the support ends.

The East German mining regions need additional measures besides job creation measures and investment support in order to create a sustainable economy beyond mining. Experience and knowledge with new projects and structural policy is needed to build up within the regions themselves. Additionally, the regions need modern infrastructures (transport, internet, etc.), as well as a network of education and research facilities. Attractive living conditions (cultural opportunities, leisure time possibilities, low air pollution levels, etc.) are essential not only keep its citizens but to attract new ones. In order to reverse current migration trends it is necessary to further local corporations that provide jobs fit for the future, but in a much more broad sense it is also vital that cities provide attractive places for younger people to live in. How to make local cities and villages more livable is a task that needs to be structured by local stakeholders, however, with the opportunity of (financial) support from other governance levels.

Infrastructure

In the Ruhr area, infrastructure investments were a crucial aspect of the first structural policy program "Development Program Ruhr", since the "new economy" beyond the mining industry relied on an enhanced mobility of the people. The area now plays a major role in the logistic sector due to its links to economic centers within Europe. However, on a regional level, there is still room for improvement in the public transportation systems, as each city still possesses its own transportation company, limiting regional effectiveness (Bogumil *et al.,* 2012). A major part in the programs of "Reconstruction East" after reunification consisted of infrastructure programs. Due to the condition of the existing infrastructure and the urgency to renew it, many projects were realized without a sufficient planning phase (demographic changes and economic development were not taken into account properly). This has resulted in a situation where many infrastructure projects are now not being used to their full potential. Besides the traffic infrastructure, the regions (especially Lusatia) need high-speed data connections in order to create an attractive environment for companies.

Education/Research institutions

Education and research institutions can play an important role in order to enable a shift from a mining area towards a more knowledge based society. In 1965 the Ruhr area was devoid of a single university; the opening of several new universities enhanced the attractiveness of the region for companies as well as for citizens, constituting an important location factor. In 2014, 22 universities existed with more than 250,000 students (Kriegesmann, Böttcher, and Lippmann, 2015). The deployment of the universities enabled a shift from the mining economy towards an economy which is based on high-value adding sectors (such as the lead markets in the Ruhr area) with increased demand for highly skilled workers and research-based innovation. The universities and research facilities need to be integrated into networks of companies and other institutions in order to create competitive and resilient structures which keep companies in the region and attract new ones. In Lusatia, only two universities exist, concentrating skills in these cities. However, due to a lack of related skilled jobs, migration after completing a degree remains a problem.

Soft location factors

Soft location factors like cultural and leisure time possibilities, but also environmental issues (air pollution levels, clean rivers, etc.) play an important role in the public perception of a region. They increase the quality of life in the region and can convince people to stay in or to move to a region. Migration is not only caused by better job options but also because of higher cultural potential of regions. In the Ruhr area, the aspect of soft location factors was neglected for a long time but with the "Action Program Ruhr" and the "IBA Emscher Park" these issues were addressed. Former industrial sites were transformed into landmarks and cultural sites in order to conserve the identification with the region but also to enable a shift towards a new, more future oriented perception. The entire migration effect is not likely to be due to soft location factors, but must be seen as a combination with job and study opportunities, trends coinciding with the new focus on living quality: Net migration turned after the "Action Program Ruhr" and the "IBA Emscher Park". Within 8 years (1987-95) 247,000 people migrated (net) to the Ruhr area, whilst net migration stabilized after a new downward trend after IBA Emscher Park. As a comparison, net migration from 1977 until 1986 was minus 158,000 (Regionalverband Ruhr, 2017). For Lusatia, the pending renaturation, hence, not only poses a challenge but also an opportunity to increase the attractiveness of the region.

4.2. National and supranational level

Energy system

In Germany, the decline in coal production affects electricity and heat generation. The reduction in hard coal production starting in the 1950s was replaced (and also caused) by comparatively cheap hard coal and oil imports. The decrease in the domestic production therefore had little immediate consequences for hard coal-fired power plants. However, the reduction of lignite mining in East Germany caused a decline in lignite based electricity generation of almost 40 TWh between 1989 and 1995 (which corresponds to a decline of approximately 40% of the East German gross electricity generation). In 2017, Germany generated more than 35% of its electricity with renewable energies and exported more than 50 TWh of electricity. To prevent lock-ins and resistance to a coal phase-out, timely investments in alternative electricity and heat generation are crucial, guaranteeing energy security, grid stability and affordable energy prices. The deep integration of local electricity markets into national and EU markets facilitates the transition where not every region needs to be energy self-sufficient. It can be attractive for former coal regions to use their expertise in the energy sector and to move towards renewable energies, energy storages or other innovative energy solutions.

Finance

A just transition requires financial resources and a fair distribution of the responsibilities for the costs. Germany therefore financed most of the subsidies for the Ruhr area with the national budget. As future coal-phase-outs are mostly a political decision due to global climate change concerns, costs should not be born only by the regions but by the whole country or even the supranational level.

The consideration of the finances includes, besides the structural policy and social policies, sufficient measures to guarantee the polluter-pays principle, also in line with the German mining law. In both the hard coal and lignite phase-out, the state is at risk to bear shares of the so called eternity costs, for example for water pumping and damages inflicted on bulidig stock from underground mines. For hard coal mining, a foundation to secure the provisions was implemented, however whether the funds will be sufficient remains to be seen. In East Germany, the state bore the full costs for the recultivation. After the reunification of German, the responsibilities for environmental damages were socialized whereas the lignite companies were privatized. In a future lignite phase-out, Germany (and other countries) need to implement measures which secure the polluters-pay principle. Possibilities include the introduction of a public fund (analog to the nuclear sector in Germany), a foundation (analog to hard coal sector in Germany) or laws to protect at least the provisions which mining companies have built up so far from insolvency. Securing sufficient funds needs to be ensured as fast as possible before the regular mining business ends (see also Oei *et al.,* 2017).

Lessons learned

As the hard coal and lignite reduction have shown, the situations differ from case to case and therefore policies guiding the transformation need to be adjusted to the respective circumstances. In East Germany the drastic reduction in lignite mining was accompanied (and caused) by the German reunification which resulted in a breakdown of the whole economic and political system. This should be taken into account when assessing the consequences of the lignite reduction and the effect of structural policies.

The case of the Ruhr area is characterised by a particularly long time period for a phase-out.

In the past, a strong identification and pride existed among workers (and entire regions) with the manly, tough and often dangerous mining job, thought to be essential for economic development. This, along with the influence of powerful unions, helped to prevent a faster and significantly less expensive transition away from coal. However, the perception of coal mining as an attractive and necessary profession is fading, which might facilitate the transition away from coal in other countries.

The structural policy of the Ruhr area showed that single, centrally decided large projects were not able to replace the mining (and steel) industry and instead faced resistance within the region. Former mining cities had individual needs that needed to be addressed independently. Therefore, the level of decision making shifted more and more from a centralized national level to a regional one. Today, there exists an institution which conceptualizes development strategies for the entire region, coordinating bottom-up strategies from within the various cities themselves. Such an institution might help to guide future phase-outs as well to limit the bureaucratic friction (especially in a federal state like Germany when mining areas cross borders) and improve the participation of relevant stakeholders. The endogenous potential of the region might be exploited better and the transformation as such becomes more consent based.

From an energy system´s point of view, the transformation has become easier and cheaper for other countries than it was for Germany in the past. The cost of renewable energy technologies has decreased significantly in the last decade, and is now just a fraction of the price compared to when Germany started deploying photovoltaics and onshore wind on a large scale. The ongoing development and installation of renewables in Germany threatens the economic and technical feasibility of its coal-fired power plants. The inflexibility of coal-fired power plants limits their application in energy systems mainly based on volatile renewables. Many studies have successfully modelled energy systems that are entirely based on 100% renewables not only for Germany but for the global energy system (Fraunhofer ISE, 2012; Jacobson *et al.,* 2017; Löffler *et al.,* 2017).

Germany's two examples of reducing coal mining provide valuable lessons learned but also illustrate the difficulties of structuring a phase-out without negative consequences for employees, companies and entire regions. An important lesson from Germany's past experience is that it is not only necessary to have policies addressing unemployment, the economy and the energy system, but also measures to improve former coal regions' infrastructure, universities and research facilities as well as soft location factors like culture and environmental health. The German example suggests that implementing a fair and realistic transition from a fossil fuel-based economy can be managed when city, regional, national and supranational governments work together on designing a phase-out and a multi-level polycentric structural policy mix. The historical case study further shows that the majority of coal's decline in Germany (but also in many other European countries) has already happened. The upcoming remaining transition can succeed when past experiences with structural policies and social security systems are considered, along with the incorporation of affordable alternative forms of energy generation and other promising innovative sectors providing new job opportunities for people in the affected regions.

Moving from the NDC to the 2°C pathway would imply much quicker changes for all German communities currently dependent on coal. Moving e.g. the phase-out date from 2040 to 2030 or deciding to close down around half of all existing coal-fired power plants by 2025 would e.g. imply the necessity for larger funds for retraining and unemployment payments, quicker investments in renewable electricity and heat generation, as well as more support to attract new businesses to the affected regions. Therefore, when deciding on a coal phase-out date and shut-down pathway, accompanying structural and social policies need to be decided on and implemented in parallel.

5. Conclusion

Historically, Germany has seen a large reduction of coal production and consumption, with significant socio-economic implications and corresponding policy action. Experiences with the hard coal mining phase-out has shown that holding on to old structures can only slow down change but cannot stop it. While posing a big challenge for the mining regions, Germany implemented a variety of successful policies to mitigate social impacts through e.g. early retirement schemes and retraining programs. Cohesion and industrial policies related to a coal phase-out need to be implemented jointly by municipal, regional, national and supranational governments to obtain the necessary financial volumes and capacities as well as local acceptance.

More recently, reductions in coal consumption in Germany have stalled and coal-related emissions have even temporarily increased. The share of coal in primary energy consumption has never decreased below its 1999 (for lignite) and 2009 (for hard coal) levels, while coal-related GHG emissions did not fall below 2010 levels). One reason are low carbon price signals from the EU emissions trading system. With a share of about 45% in total, energy-related GHG emissions, coal's contribution to Germany's carbon balance will need to be reduced significantly for Germany to reach its climate targets. Therefore, in 2018, Germany's government installed a commission to decide on a structured coal phase-out plan.

Besides the implications of climate policy for the coal sector, other developments indicate that coal will not be viable in the future. The large-scale deployment of renewable energy threatens the economic viability of coal-fired power plants, as renewables increase competition and lower whole-sale electricity prices. The existing (economic and political) situation in Germany will prevent the construction of new coal-fired power plants. Therefore, eventually, coal would be phased-out at the latest at the end of the power plants' lifetimes. To achieve a coal phase-out in line with climate protection commitments, climate policy measures need to be introduced to accelerate the decline of coal.

To comply with the 2°C target, Germany would need to phase-out both hard coal and lignite consumption in the energy sector well before 2050. Germany's NDC and 2° scenarios foresee emission reductions (relative to 1990 levels) of 83% and 95% respectively, by 2050. In terms of the timing, various scenarios imply a rather quick shutdown of coal capacity in the early twenties and a complete phase-out at the earliest by 2025 and at the latest by 2040. Substituting coal in the steel sector by 2050 will be challenging, as key technology options are not yet competitive due to low CO_2 prices and high technology costs and carbon capture with continued coal use is one of the technological options.

A set of concrete policy measures exists, which can lead to a successful phase-out and respective emission reductions with a low impact on employment and industry. A strong carbon price is the basis for emissions reductions in both scenarios. However, it will not be high enough to induce sufficient early reductions in coal consumption, especially of electricity generation from lignite. Several additional national policy instruments are therefore discussed for i) phasing out the aging coal fleet constructed before 1990 (accounting for around 50% of capacities) and ii) reducing the full load hours for newly constructed plants to preserve sufficient capacities and jobs but still reduce overall emissions. For the industrial sector, the inclusion of consumption in emissions trading via a carbon charge on materials could reintroduce the carbon price that is muted due to free allocation and set the right incentives for resource efficiency and materials substitution.

Success and uncertainty of deep decarbonization (i.e. the shift from an NDC to a 2° world) seem to hinge largely on the availability and commercial deployment of technologies which requires a supportive policy environment to succeed especially in the industry sector. As we see from the scenario analysis, policies will need to support innovation and market penetration of innovative solutions to bring down technology cost. Innovation could be supported by project-based carbon contracts for difference and public procurement. Regulators will also need to have the social cost of carbon reflected in the price of GHG emissions. Building on these, only a portfolio of measures is likely to solve the puzzle of a competitive and 2°C-compliant industrial sector in Germany (and beyond).

NDC and 2° scenario differ primarily in two ways: earlier reductions and more ambitious emission reductions in transport and industry are needed for Germany's contribution to the 2° world. Reducing total CO_2 emissions in order to comply with the 2°C target would, therefore, require increased efforts in the electricity sector. According to all analysed scenarios, the majority of the lignite-fired power plants need to phase-out before 2030, and should be replaced by an increasing production of electricity from renewables enables other sectors to reduce emissions as well via increased electrification. For industry, the extra effort is achieved via increased material and energy efficiency, substitution of materials with low-carbon alternatives, enhanced recycling, as well as new primary production processes based on hydorgen, biomass or combined with CCTs.

Germany is able to phase out coal from an economical and technical perspective. Nevertheless, it currently faces some key barriers which need to be addressed to achieve a transition towards deep decarbonization. Main barriers are that lignite regions fear to be left behind, the energy-intensive industry fears to lose their competitiveness to other countries due to higher wholesale energy prices, workers want a reliable future (new jobs/ social security), funds for renaturation are not yet secured and uncertainty about coal´s future and corresponding future aid and cohesion policies prevents new companies from settling in mining areas. To overcome these barriers the following measures were identified:

- Structural funds securing long-term payments financed by the national or the European budget to build up new capacities (for education, research, industry, civil society, ...)
- Policies to address distributional impacts of potential power price increases for poor households and to provide carbon leakage protection for energy intensive industries.
- Guaranteed secured retirement payments as well as retraining for workers. Creation of new (job) opportunities for the next generations
- Secure sufficient funding from the operators to pay for renaturation and other follow-up costs
- Clear political signals (e.g. a phase-out corridor for coal) and additional incentives (e.g. tax exemptions, loans) for new industries´ investments (new industries are e.g. renewables but also others)

These elements will have to be well coordinated through local or national bodies. Additional support through (local) stakeholder interaction hereby increases their efficiency but especially their acceptance. Enabling a just transition from coal towards more sustainable energy usage is important as it will encourage other regions to follow.

References

- AG Energiebilanzen e.V. 2017. "Bilanz 2015 - Bearbeitungsstand 10.08.2017." Bilanzen 1990 - 2015. August 10, 2017. https://ag-energiebilanzen.de/7-0-Bilanzen-1990-2015.html.
- Agora Energiewende. 2016. "Elf Eckpunkte für einen Kohlekonsens. Konzept zur schrittweisen Dekarbonisierung des deutschen Stromsektors (Langfassung)." Impulse. Berlin: Agora Energiewende.
- ———. 2017. "Eine Zukunft für die Lausitz: Elemente eines Strukturwandelkonzepts für das Lausitzer Braunkohlerevier." Impulse. Berlin: Agora Energiewende. https://www.agora-energiewende.de/fileadmin/Projekte/2017/Strukturwandel_Lausitz/Agora_Impulse_Strukturwandel-Lausitz_WEB.pdf.
- BDEW. 2017. "BDEW-Kraftwerksliste - In Bau oder Planung befindliche Anlagen." Berlin, Germany. https://www.bdew.de/media/documents/170424-bdew-kraftwerksliste.pdf.
- BMWi. 2016. "Grünbuch Energieeffizienz - Diskussionspapier des Bundesministerium für Wirtschaft und Energie." Berlin: Bundesministerium für Wirtschaft und Energie. https://www.bmwi.de/Redaktion/DE/Publikationen/Energie/gruenbuch-energieeffizienz-august-2016.html.
- ———. 2018. "Strukturwandel in den Braunkohleregionen." Themenseite - Regionalpolitik. April 4, 2018. https://www.bmwi.de/Redaktion/DE/Artikel/Wirtschaft/strukturwandel-in-den-braunkohleregionen.html.
- Bogumil, Jörg, Rolf G. Heinze, Franz Lehner, and Klaus Peter Strohmeier. 2012. *Viel erreicht - wenig gewonnen: ein realistischer Blick auf das Ruhrgebiet*. 1. Auflage. Essen: Klartext.
- Brauers, Hanna. 2017. "Diverging Coal Phase-out Strategies and Their Implications for EU Climate & Energy Policies." Master Thesis, Berlin: Berlin University of Technology (TU Berlin).
- Bundeskabinett, Beschluss. 2016. "Klimaschutzplan 2050-Klimaschutzpolitische Grundsätze Und Ziele Der Bundesregierung." Online] Verfügbar unter: www.bmub. bund. de/themen/klima-energie/klimaschutz/nationaleklimapolitik/klimaschutzplan-2050/[Zugriff am 15 12 2016].
- Bundesnetzagentur. 2017. "Kraftwerksliste." 2017. https://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/Versorgungssicherheit/Erzeugungskapazitaeten/Kraftwerksliste/kraftwerksliste-node.html.
- Burger, Andreas, Benjamin Lünenbürger, David Pfeiffer, and Benno Hain. 2015. "Klimabeitrag für Kohlekraftwerke - Wie wirkt er auf Stromerzeugung, Arbeitsplätze und Umwelt." Positionspapier. Dessau-Roßlau: Umweltbundesamt.
- Büter, Kai. 2012. "Clusterpolitik und Clusterinitiativen in Nordrhein-Westfalen: Eine prozessorientierte Garbage-Can-Analyse im politischadministrativen Mehrebenensystem." Dissertation, Bonn: Rheinische Friedrich-Wilhelms-Universität Bonn. http://hss.ulb.uni-bonn.de/2013/3425/3425.pdf.
- CDU, CSU, and SPD. 2018. *Ein Neuer Aufbruch Für Europa. Eine Neue Dynamik Für Deutschland. Ein Neuer Zusammenhalt Für Unser Land. Koalitionsvertrag Zwischen CDU, CSU Und SPD*.
- DEBRIV. 2015. "Braunkohle in Deutschland 2015 - Profil Eines Industriezweiges." Köln: Bundesverband Braunkohle. http://www.braunkohle.de/index.php?article_id=98&fileName=debriv_izb_2013.pdf.
- enervis. 2016. "Verdi: Gutachten Sozialverträglicher Kohlekonsens." Berlin: enervis Studie im Auftrag von Ver.di. https://ver-und-entsorgung.verdi.de/themen/energiewende/++co++98e6b066-7b06-11e6-918f-525400a933ef.
- European Commission. 2010. "Final Report of the SET-Plan Workshop on Technology Innovations for Energy Efficiency and Greenhouse Gas (GHG) Emissions Reduction in the Iron and Steel Industries in the EU27 up to 2030." Brussels, Belgium: European Commission.
- European Union. 2009a. *DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009 on the Promotion of the Use of Energy from Renewable Sources and Amending and Subsequently Repealing Directives 2001/77/EC and 2003/30/EC, Published in the Official Journal of the European Union on 5.6.2009*.
- ———. 2009b. *DIRECTIVE 2009/29/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009 Amending Directive 2003/87/EC so as to Improve and Extend the Greenhouse Gas Emission Allowance Trading Scheme of the Community*.
- ———. 2015. *Intended Nationally Determined Contribution of the EU and Its Member States*.
- ———. 2018. "DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL Amending Directive 2003/87/EC to Enhance Cost-Effective Emission Reductions and Low-Carbon Investments." COM(2015)0337 - C8-0190/2015 - 2015/0148(COD)).
- Fischedick, Manfred, Joachim Marzinkowski, Petra WInzer, and Max Weigel. 2014. "Techno-Economic Evaluation of Innovative Steel Production Technologies." In *The Journal of Cleaner Production, 563–80. Volume 84(1)*.
- Fraunhofer ISE. 2012. "100% Erneuerbare Energien Für Strom Und Wärme in Deutschland." Freiburg, Deutschland: Fraunhofer-Institut für Solare Energiesysteme ISE. https://www.ise.fraunhofer.de/de/veroeffentlichungen/veroeffentlichungen-pdf-dateien/studien-und-konzeptpapiere/studie-100-erneuerbare-energien-in-deutschland.pdf.
- Goch, Stefan. 2009. "Politik für Ruhrkohle und Ruhrrevier - von der Ruhrkohle AG zum neuen Ruhrgebiet." In *Kumpel und Kohle - Der Landtag NRW und die Ruhrkohle 1946 bis 2008, edited by Die Präsidentin des Landtages Nordrhein-Westfalen, 19:125–65. Schriften des Landtags Nordrhein-Westfalen. Düsseldorf, Germany*.
- Herpich, Philipp, Hanna Brauers, and Pao-Yu Oei. 2018, instead of Forthcoming "Coal Transition in Germany: An Historical Case Study." IDDRI and Climate Strategies.
- IEA. 2017. *Energy Technology Perspectives 2017: Catalysing Energy Technology Transformations*. Paris, France. http://dx.doi.org/10.1787/energy_tech-2017-en.
- ILO. 2015. "Guidelines for a Just Transition towards Environmentally Sustainable Economies and Societies for All." Geneva, Switzerland: International Labour Organization. http://www.ilo.org/global/topics/green-jobs/publications/WCMS_432859/lang--en/index.htm.

- IRENA. 2017. "Renewable Energy and Jobs - Annual Review 2017." Abu Dhabi: International Renewable Energy Agency. http://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/May/IRENA_RE_Jobs_Annual_Review_2017.pdf.
- Jacobson, Mark Z., Mark A. Delucchi, Zack A. F. Bauer, Savannah C. Goodman, William E. Chapman, Mary A. Cameron, Cedric Bozonnat, *et al.,* 2017. "100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World." *Joule 1 (1): 108–21. https://doi.org/10.1016/j.joule.2017.07.005.*
- Kahlert, Joachim. 1988. "Die Energiepolitik der DDR - Mängelverwaltung zwischen Kernkraft und Braunkohle." Bonn, Germany: Verlag Neue Gesellschaft GmbH.
- Karsten Neuhoff, Roland Ismer, William Acworth, Andrzej Ancygier, Carolyn Fischer, Manuel Haussner, Hanna-Liisa Kangas, *et al.,* 2016. "Inclusion of Consumption of Carbon Intensive Materials in Emissions Trading – An Option for Carbon Pricing Post-2020." Climate Strategies.
- Kriegesmann, Bernd, Matthias Böttcher, and Torben Lippmann. 2015. *Wissenschaftsregion Ruhr: (Langfassung): wirtschaftliche Bedeutung, Fachkräfteeffekte und Innovationsimpulse der Hochschulen und außeruniversitären Forschungseinrichtungen in der Metropole Ruhr. Essen: Regionalverband Ruhr.*
- Löffler, Konstantin, Karlo Hainsch, Thorsten Burandt, Pao-Yu Oei, Claudia Kemfert, and Christian von Hirschhausen. 2017. "Designing a Model for the Global Energy System—GENeSYS-MOD: An Application of the Open-Source Energy Modeling System (OSeMOSYS)." *Energies 10 (10): 1468. https://doi.org/10.3390/en10101468.*
- Matthes, Felix Christian. 2000. *Stromwirtschaft und deutsche Einheit: Eine Fallstudie zur Transformation der Elektrizitätswirtschaft in Ost-Deutschland.* Berlin, Germany: F.C. Matthes; Libri.
- Morfeldt, Johannes, Wouter Nijs, and Semida Silviera. 2015. "The Impact of Climate Targets on Future Steel Production – an Analysis Based on a Global Energy System Model." In *Journal of Cleaner Production*, 469–82. Volume 103.
- Morton, Tom, and Katja Müller. 2016. "Lusatia and the Coal Conundrum: The Lived Experience of the German Energiewende." *Energy Policy* 99: 277–287.
- Nemet, Gregory F., Martina Kraus, and Vera Zipperer. 2016. "The Valley of Death, the Technology Pork Barrel, and Public Support for Large Demonstration Projects." DIW Berlin Discussion Paper 1601. Berlin, Germany: DIW Berlin. https://www.diw.de/sixcms/detail.php?id=diw_01.c.540712.de.
- Neuhoff Karsten, Olga Chiappinelli, Chris Bataille, Manuel Haußner, Roland Ismer, Eugénie Joltreau, Ingmar Jürgens, Carlotta Piantieri, Jörn Richstein, Oliver Sartor, Puja Singhal, Jan Stede. 2018. "Filling Gaps in the Policy Package to Decarbonise Production and Use of Materials" London: Climate Strategies
- Neuhoff Karsten, Olga Chiappinelli, Richard Baron, John Barrett, Maciej Bukowski, Vicki Duscha, Tobias Fleiter, Manuel Haussner, Roland Ismer, Robert Kok, Gregory F. Nemet, Hector Pollitt, Jörn Richstein, Tatiana Vakhitova, Tomas Wyns and Lars Zetterberg. "Innovation and Use Policies Required to Realize Investment and Emission Reductions in the Materials Sector." Berlin, Germany: Climate Strategies, DIW Berlin.
- Neuhoff, Karsten, Sophia Wolter, and Sebastian Schwenen. 2016. "Power Markets with Renewables: New Perspectives for the European Target Model." *Energy Journal 37.*
- New Climate Institute. 2016. "Was Bedeutet Das Pariser Abkommen Für Den Klimaschutz in Deutschland?" Kurzstudie im Auftrag von Greenpeace Germany. Köln und Berlin, Deutschland: NewClimate - Institute for Climate Policy and Global Sustainability.
- Oei, Pao-Yu, Hanna Brauers, Claudia Kemfert, Christian von Hirschhausen, Dorothea Schäfer, and Sophie Schmalz. 2017. "Climate Protection and a New Operator: The Eastern German Lignite Industry Is Changing." 6+7. Economic Bulletin. Berlin, Germany: DIW Berlin, German Institute for Economic Research. http://www.diw.de/documents/publikationen/73/diw_01.c.552351.de/diw_econ_bull_2017-06-1.pdf.
- Oei, Pao-Yu, Clemens Gerbaulet, Claudia Kemfert, Friedrich Kunz, and Christian Hirschhausen. 2016. "'Kohlereserve' vs. CO_2-Grenzwerte in Der Stromwirtschaft - Ein Modellbasierter Vergleich." *Energiewirtschaftliche Tagesfragen 66 (1/2): 57–60.*
- Oei, Pao-Yu, Clemens Gerbaulet, Claudia Kemfert, Friedrich Kunz, and Christian von Hirschhausen. 2015. "Auswirkungen von CO_2-Grenzwerten Für Fossile Kraftwerke Auf Den Strommarkt Und Klimaschutz." DIW Berlin, Politikberatung kompakt 104. Berlin, Germany: DIW Berlin — Deutsches Institut für Wirtschaftsforschung e. V. https://www.diw.de/documents/publikationen/73/diw_01.c.521081.de/diwkompakt_2015-104.pdf.
- Oei, Pao-Yu, Clemens Gerbaulet, Claudia Kemfert, Friedrich Kunz, Felix Reitz, and Christian von Hirschhausen. 2015. "Effektive CO_2-Minderung Im Stromsektor: Klima-, Preis- Und Beschäftigungseffekte Des Klimabeitrags Und Alternativer Instrumente." DIW Berlin, Politikberatung kompakt 98. Berlin, Germany: DIW Berlin — Deutsches Institut für Wirtschaftsforschung e. V. https://www.diw.de/documents/publikationen/73/diw_01.c.509387.de/diwkompakt_2015-098.pdf.
- Oei, Pao-Yu, Claudia Kemfert, Felix Reitz, and Christian von Hirschhausen. 2014. "Braunkohleausstieg – Gestaltungsoptionen im Rahmen der Energiewende." DIW Berlin, Politikberatung kompakt 84. Berlin, Germany: DIW Berlin — Deutsches Institut für Wirtschaftsforschung e. V. https://www.diw.de/documents/publikationen/73/diw_01.c.471589.de/diwkompakt_2014-084.pdf.
- Öko-Institut. 2017. "Die deutsche Braunkohlenwirtschaft - Historische Entwicklungen, Ressourcen, Technik, wirtschaftliche Strukturen und Umweltauswirkungen." Studie im Auftrag von Agora Energiewende und der European Climate Foundation. Berlin. https://www.agora-energiewende.de/fileadmin/Projekte/2017/Deutsche_Braunkohlenwirtschaft/Agora_Die-deutsche-Braunkohlenwirtschaft_WEB.pdf.
- Öko-Institut e.V, and Fraunhofer ISI. 2014. "Klimaschutzszenario 2050 - 1. Modellierungsrunde."
- ———. 2015. "Klimaschutzszenario 2050 - 2. Endbericht."
- Philipp Gerbert, Patrick Herhold, Jens Burchardt, Stefan Schönberger, Florian Rechenmacher, Almut Kirchner, Andreas Kemmler, and Marco Wünsch. 2018. "Klimapfade Für Deutschland, Study Commissioned by BDI." BCG; prognos.
- RAG-Stiftung. 2015. "RAG-Stiftung: Geschäftsbericht 2015." Essen. http://www.rag-stiftung.de/ueber-uns/

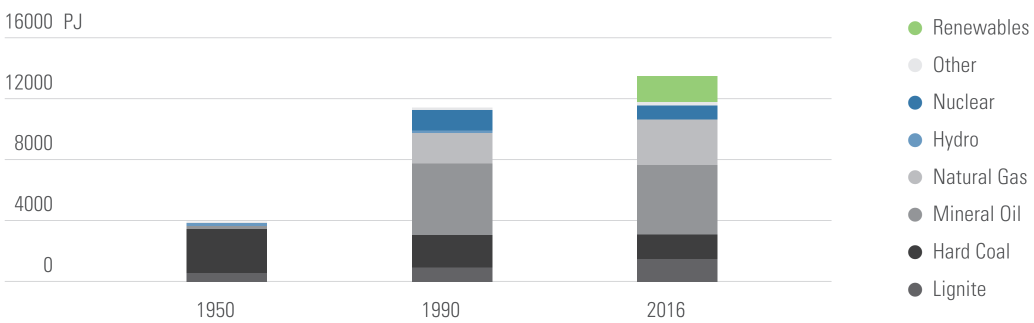
jahresabschluesse/.

- Regionalverband Ruhr. 2017. “Bevölkerungsbewegung in der Metropole Ruhr - Zeitreihe seit 1962.” 2017. www.metropoleruhr.de/fileadmin/user_upload/metropoleruhr.de/05_MR_Sonstige/Excel/Statistik/Bevoelkerung/Zeitreihe_Bevoelkerungsbewegung.xlsx.
- Richstein, Jörn. 2017. “Project-Based Carbon Contracts: A Way to Finance Innovative Low-Carbon Investments.” DIW Berlin Discussion Papers.
- Ringius, Lasse, Asbjørn Torvanger, and Arlid Undertal. 2002. “Burden Sharing and Fairness Principles in International Climate Policy.” In *International Environmental Agreements: Politics, Law and Economics*. Volume 2. https://doi.org/10.1023/A:1015041613785.
- Sachverständigenrat für Umweltfragen. 2017. “Kohleausstieg jetzt einleiten.” Stellungnahme. Berlin. https://www.umweltrat.de/SharedDocs/Downloads/DE/04_Stellungnahmen/2016_2020/2017_10_Stellungnahme_Kohleausstieg.pdf?__blob=publicationFile&v=16.
- Schmid, Eva, Michael Pahle, and Brigitte Knopf. 2013. “Renewable Electricity Generation in Germany: A Meta-Analysis of Mitigation Scenarios.” *Energy Policy 61 (October): 1151–63. https://doi.org/10.1016/j.enpol.2013.06.105.*
- Statistik der Kohlenwirtschaft e.V. 2017a. “Steinkohle.” Statistik der Kohlenwirtschaft. 2017. http://www.kohlenstatistik.de/18-0-Steinkohle.html.
- ———. 2017b. “Steinkohle - Belegschaft im Steinkohlebergbau.” Steinkohle. 2017. https://kohlenstatistik.de/18-0-Steinkohle.html.
- ———. 2017c. “Braunkohle.” Statistik der Kohlenwirtschaft. September 9, 2017. https://kohlenstatistik.de/19-0-Braunkohle.html.
- Statistisches Bundesamt. 2017. “Preise - Daten zur Energiepreisentwicklung - Lange Reihen von Januar 2000 bis November 2017 -.” https://www.destatis.de/DE/Publikationen/Thematisch/Preise/Energiepreise/EnergiepreisentwicklungPDF_5619001.pdf?__blob=publicationFile.
- UBA. 2017. “Nationale Trendtabellen für die deutsche Berichterstattung atmosphärischer Emissionen 1990 – 2015.” Dessau-Roßlau. https://www.umweltbundesamt.de/dokument/nationale-trendtabellen-fuer-die-deutsche-2.
- Umweltbundesamt. 2017. “Entwicklung der Kohlendioxid-Emissionen der fossilen Stromerzeugung nach eingesetzten Energieträgern.” https://www.umweltbundesamt.de/daten/energiebereitstellung-verbrauch/energiebedingte-emissionen#textpart-3.
- UNEP. 2017. “The Emissions Gap Report 2017.” Nairobi, Kenia: United Nations Environment Programme (UNEP). http://wedocs.unep.org/handle/20.500.11822/22070.
- Verein der Kohleimporteure e.V. 2017. “Jahresbericht 2017 - Fakten und Trends 16/17.” Hamburg, Germany. http://www.kohlenimporteure.de/publikationen/jahresbericht-2017.html.
- Von Hirschhausen, Christian, Johannes Herold, and Pao-Yu Oei. 2012. “How a ‘Low Carbon’ Innovation Can Fail - Tales from a ‘Lost Decade’ for Carbon Capture, Transport, and Sequestration (CCTS).” *Economics of Energy & Environmental Policy 1: 115–24.*
- WWF. 2017. “Zukunft Stromsystem Kohleausstieg 2035 - Vom Ziel her denken.” ISBN 978-3-946211-07-5. Öko-Institut e.V.; Prognos; WWF. https://www.oeko.de/fileadmin/oekodoc/Stromsystem-Kohleausstieg-2035.pdf.

Appendix

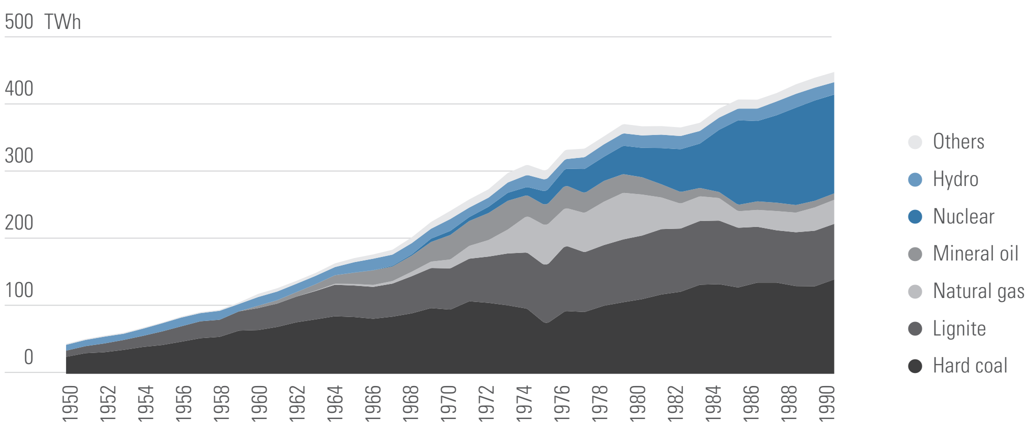
Historical coal statistics

Figure I.1. Primary energy consumption in West Germany in 1950 and 1990 and in Germany in 2016



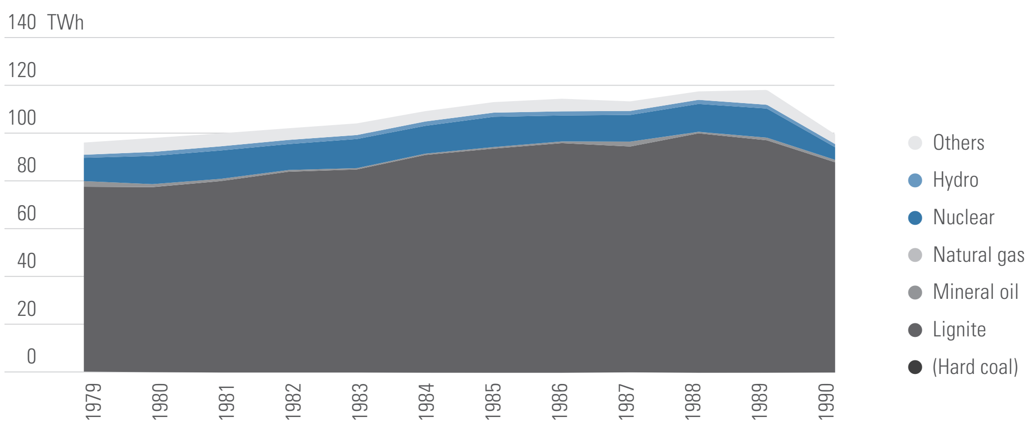
Source : based on AG Energiebilanzen e.V. (2017a, 2017b).

Figure I.2. Gross Electricity Generation in West Germany from 1950 until 1990



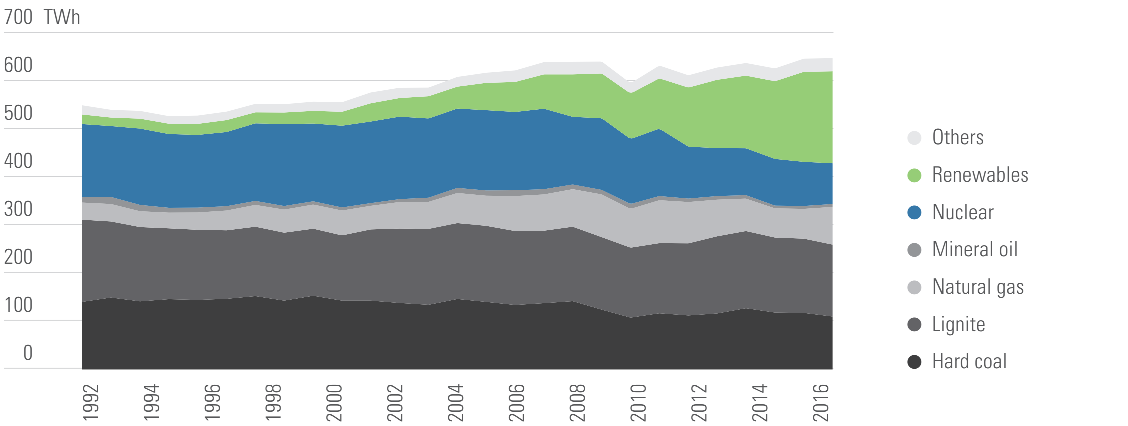
Source : based on Statistik der Kohlenwirtschaft e.V. (2017a).

Figure I.3. Gross electricity generation in East Germany



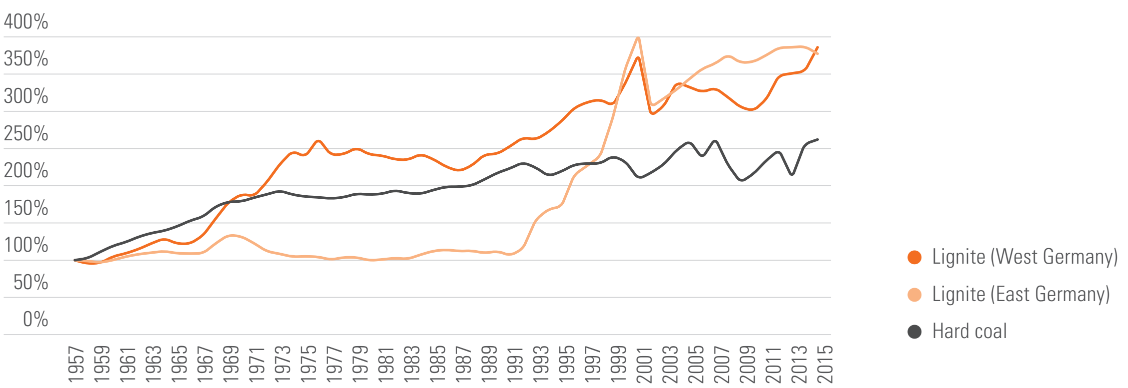
Source : based on Statistik der Kohlenwirtschaft e.V. (2017a).

Figure I.4. Gross electricity generation in Germany since 1990



Source: based on Statistik der Kohlenwirtschaft e.V. (2017a).

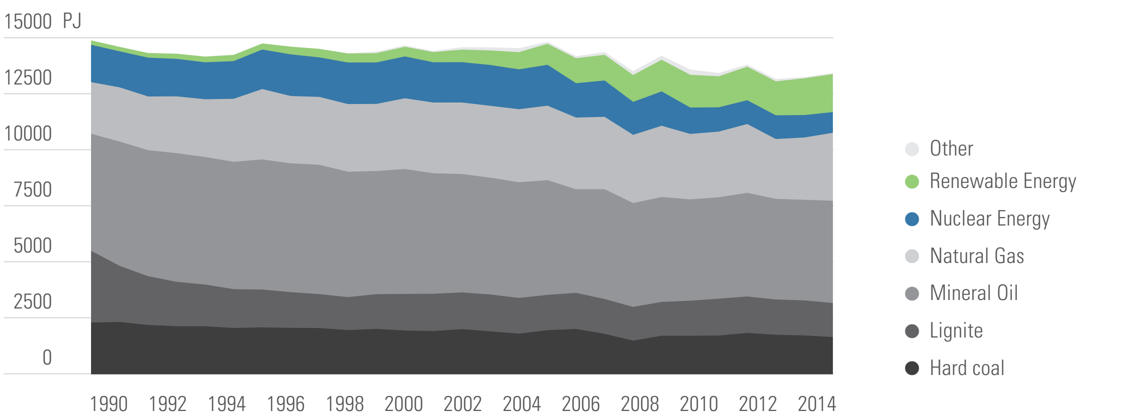
Figure I.5. Development of the standardized labor productivity in the German mining industry



Note: The drop in labor productivity for lignite in 2002 is due to a statistical change, as from 2002 onwards employees in lignite-fired power plants are included.

Source: Own calculation and depiction based on Statistik der Kohlenwirtschaft (2017b, 2017c, 2017d).

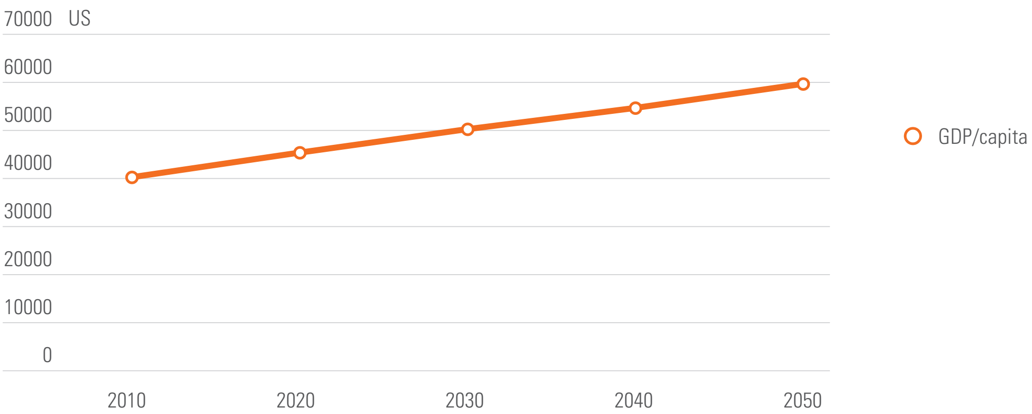
Figure I.6. German Energy Mix (Primay energy consumption)



Source: based on Ökoinstitut (2017).

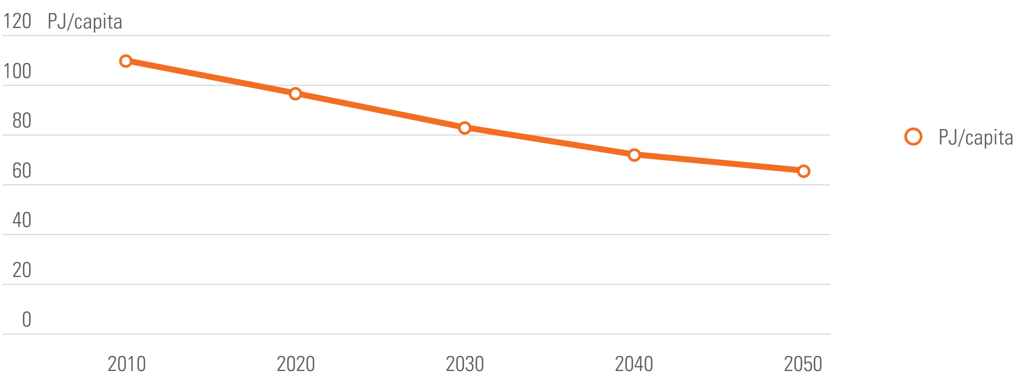
Both scenarios

Figure II.1. GDP per capita



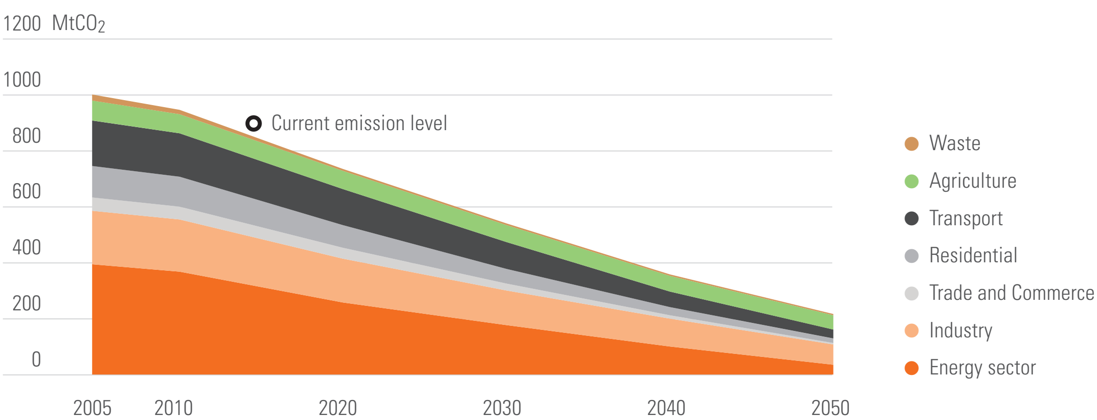
NDC scenarios

Figure III.1. Final energy consumption per capita in the NDC scenario



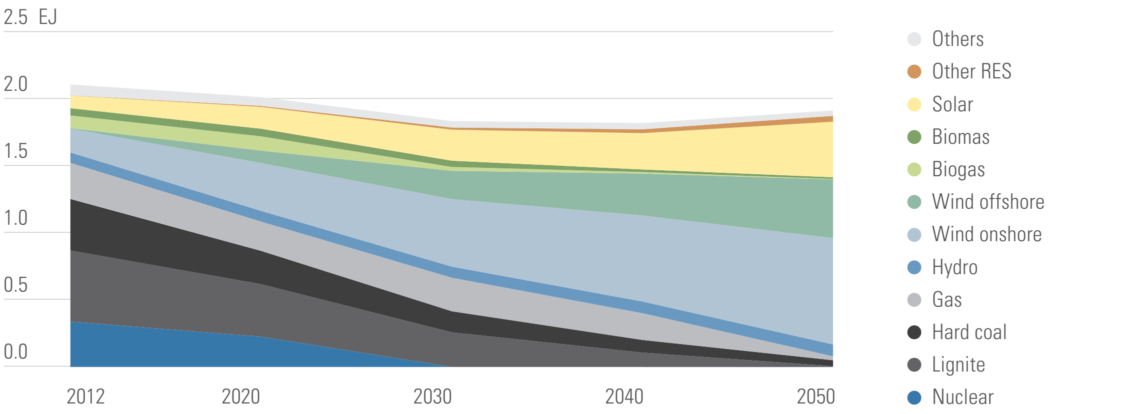
Source : based on Öko-Institut e.V and Fraunhofer ISI (2015).

Figure III.2. German sectoral emissions under NDC scenario (excl. international aviation and maritime traffic)



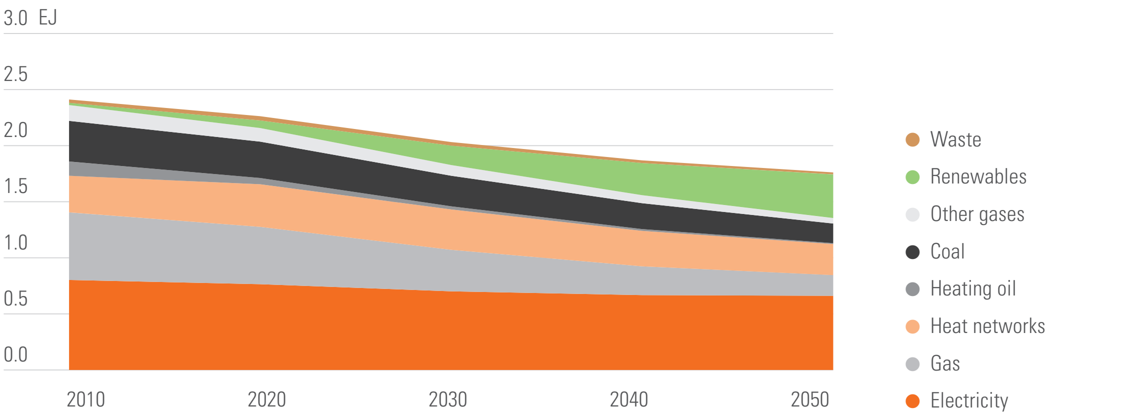
Source : based on Öko-Institut e.V and Fraunhofer ISI (2015).

Figure III.3. Energy mix in the power sector in the NDC scenario



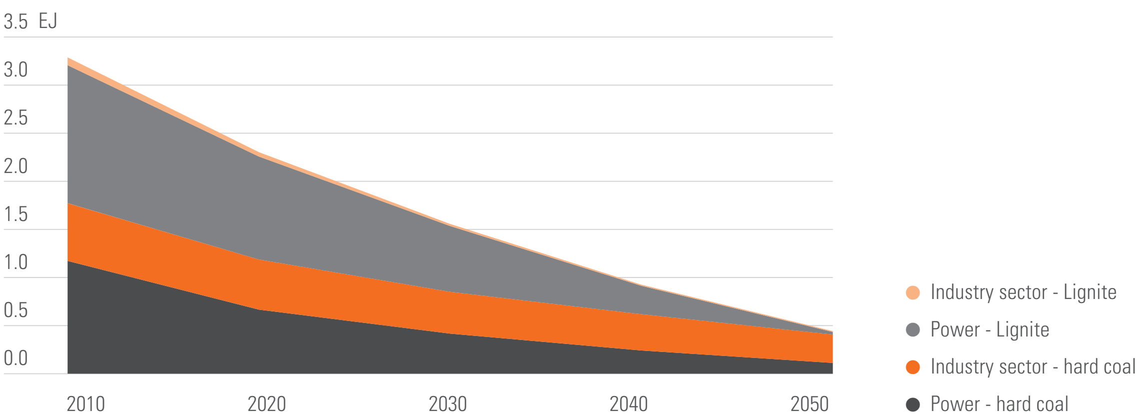
Source : based on Öko-Institut e.V and Fraunhofer ISI (2015).

Figure III.4. Energy mix in the industrial sector in the NDC scenario



Source : based on Öko-Institut e.V and Fraunhofer ISI (2015)

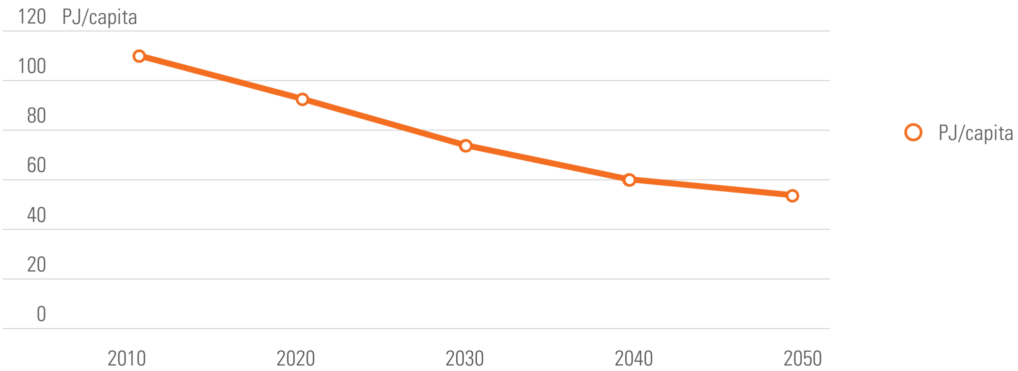
Figure III.5. Coal consumption in Germany in NDC scenario



Source : based on Öko-Institut e.V and Fraunhofer ISI (2015).

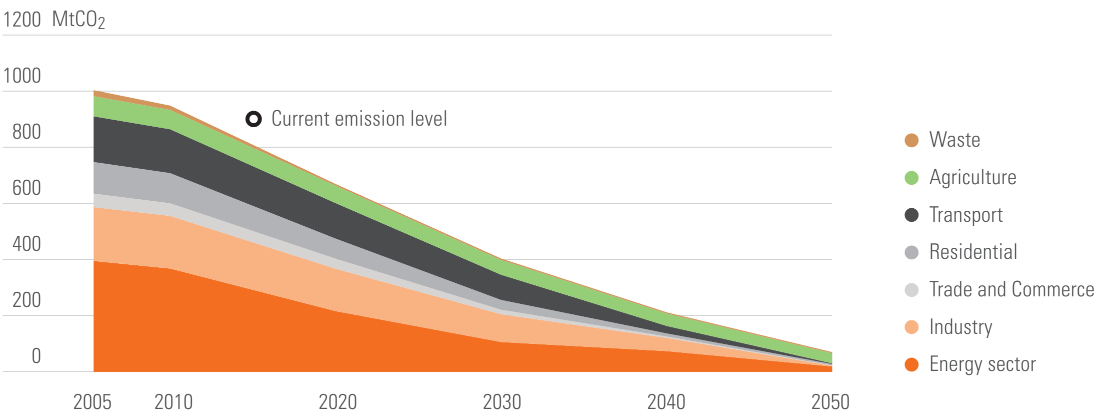
95% reduction scenario

Figure IV.1. Final energy consumption per capita in the 95% reduction scenario



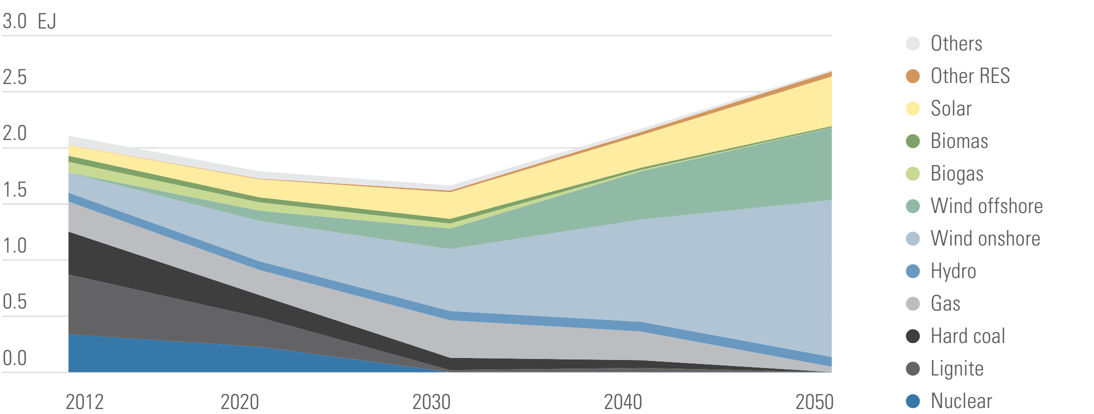
Source : based on Öko-Institut e.V and Fraunhofer ISI (2015)

Figure IV.2. German sectoral emissions under 95% reduction scenario (excl. international aviation and maritime traffic)



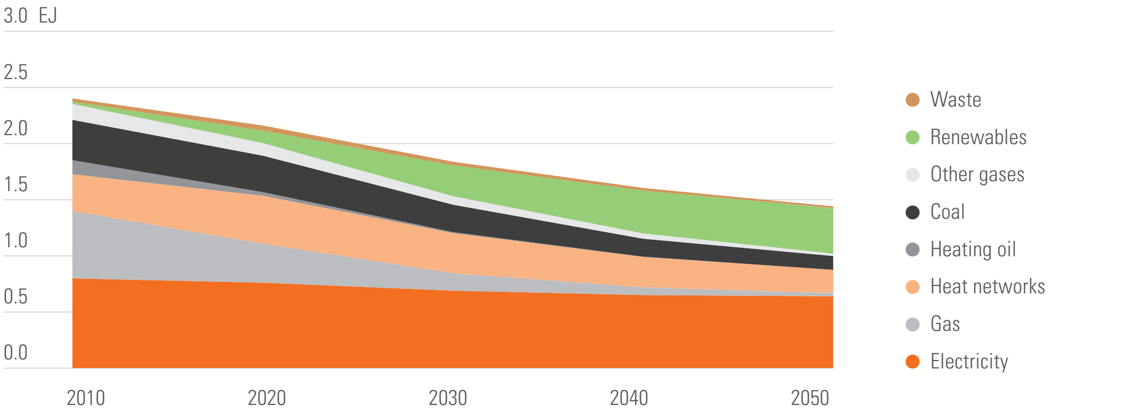
Source : based on Öko-Institut e.V and Fraunhofer ISI (2015).

Figure IV.3. Energy mix in power sector in the 95% reduction scenario



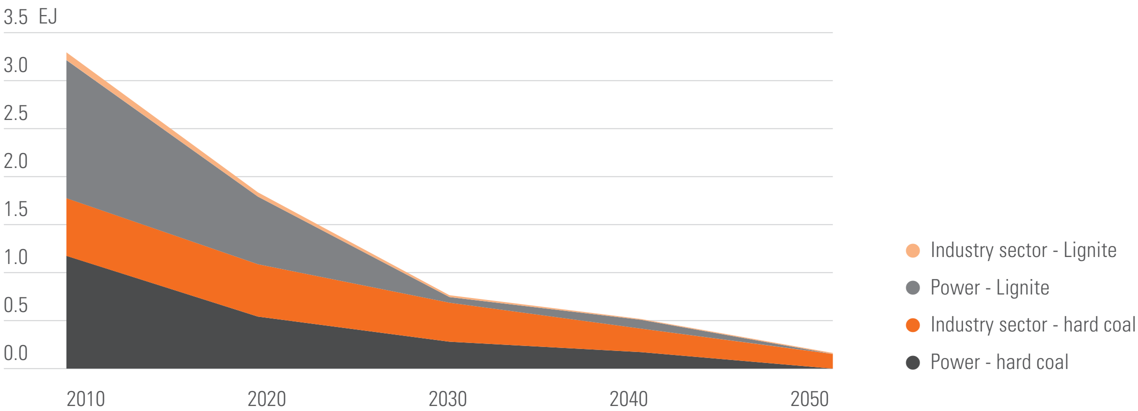
Source : based on Öko-Institut e.V and Fraunhofer ISI (2015).

Figure IV.4. Energy mix in the industrial sector in the 95% reduction scenario



Source : based on Öko-Institut e.V and Fraunhofer ISI (2015).

Figure IV.5. Coal consumption in Germany in in the 95% reduction scenario



Source : based on Öko-Institut e.V and Fraunhofer ISI (2015).

COAL TRANSITIONS:
RESEARCH AND DIALOGUE ON THE FUTURE OF COAL

COAL TRANSITIONS is a large-scale research project leaded by Climate Strategies and The Institute for Sustainable Development and International Relations (IDDRI) and funded by the KR Foundation.

The project's main objective is to conduct research and policy dialogue on the issue of managing the transition within the coal sector in major coal using economies, as is required if climate change is to be successfully limited to 2°C.

THIS PROJECT BRINGS TOGETHER RESEARCHERS FROM AROUND THE GLOBE, INCLUDING AUSTRALIA, SOUTH AFRICA, GERMANY, POLAND, INDIA AND CHINA.

www.coaltransitions.org

Climate Strategies

IDDRI