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Ways to a low-emission energy system - repercussions of a German coal phase-out

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Abstract
Under the influence of global climate change, Germany is undertaking considerable efforts to protect the climate with the implementation of the energy transition (Energiewende). In light of the Paris Agreement and limiting global warming to below 2°C, Germany is seriously considering phasing out power generation from hard coal and lignite. In its final report the Commission on "Growth, Structural Change and Employment" also pointed out a specific path towards phasing out the use of coal. For us, this raises the question of the repercussions of ambitious climate protection policies in the German transformation sector.
For the comparative assessment of climate policy and coal phase-out repercussions we conduct a scenario-based energy system analysis. The Pan-European TIMES Energy System Model (TIMES-PanEU) is an energy system model comprising 31 regions, which includes all EU28 countries as well as Switzerland and Norway. The modeling period extends from 2010 to 2050 with 5-year time step. As an energy system model, TIMES-PanEU represents all sectors, concerning energy supply and demand, such as the raw materials supply sector, public and industrial electricity and heat generation, industry, trade, services, households, and transport. The objective function of the model is the minimization of the total discounted system costs for the time horizon 2010 to 2050. This model enables us to determine the economically optimal energy supply structure with a specified useful energy or energy service requirement with simultaneous consideration of energy and environmental policy specifications.
Our reference case is represented by a scenario with the specifications of the climate protection plan of the German Federal Government. On this basis, a total emission reduction of 90% compared to 1990 will be achieved by 2050, through sector-specific greenhouse gas reduction targets. In comparison, we evaluate scenarios with a specific, measure-based implementation of climate protection in the transformation sector. The measures considered are the phase-out of coal in accordance with the Commission's guidelines and the setting of a country-specific minimum CO2 price. Optionally, we combine these scenarios with increased quotas for renewable energies as well as a certificate decommissioning in the ETS system to compensate for the emerging waterbed effect. We analyze the multiple repercussions in the energy system with regard to system cost changes, electricity prices, electricity import and export patterns, certificate prices in the EU-ETS system, greenhouse gas emissions of the transformation sector as well as the repercussions of the respective climate protection policy on the level and composition of the resulting final energy consumption by sector.

Introduction

Under the influence of global climate change, Germany is undertaking considerable efforts to protect the climate with the implementation of the energy transition (Energiewende). In light of the Paris Agreement and limiting global warming to below 2°C, Germany is seriously considering phasing out power generation from hard coal and lignite. In its final report the Commission on "Growth, Structural Change and Employment" also pointed out a specific path towards phasing out the use of coal.

In addition, there are currently growing numbers of supporters who are considering the introduction of CO2 pricing for Germany and are actively putting the issue up for discussion.

This raises the question of the repercussions of ambitious climate protection policies in the German transformation sector as well as their impacts on the final consumers as well as the interactions with the neighboring countries.

Model and Methods

For the comparative assessment of climate policy and coal phase-out repercussions we conduct a scenario-based energy system analysis. The Pan-European TIMES Energy System Model (1) (TIMES-PanEU) is an energy system model comprising 31 regions, which includes all EU28 countries as well as Switzerland and Norway. Germany as a model region is further subdivided into Baden-Württemberg as well as the remainder of Germany. The modeling period extends from 2010 to 2050 with 5-year time step and 12 time steps intraannual resolution (four seasons and three daily time segments). As an energy system model, TIMES-PanEU represents all sectors, concerning energy supply and demand, such as the raw materials supply sector, public and industrial electricity and heat generation, industry, trade, services, households, and transport. The objective function of the model is the minimization of the total discounted system costs for the time horizon 2010 to 2050. The system optimization is being performed under perfect foresight.

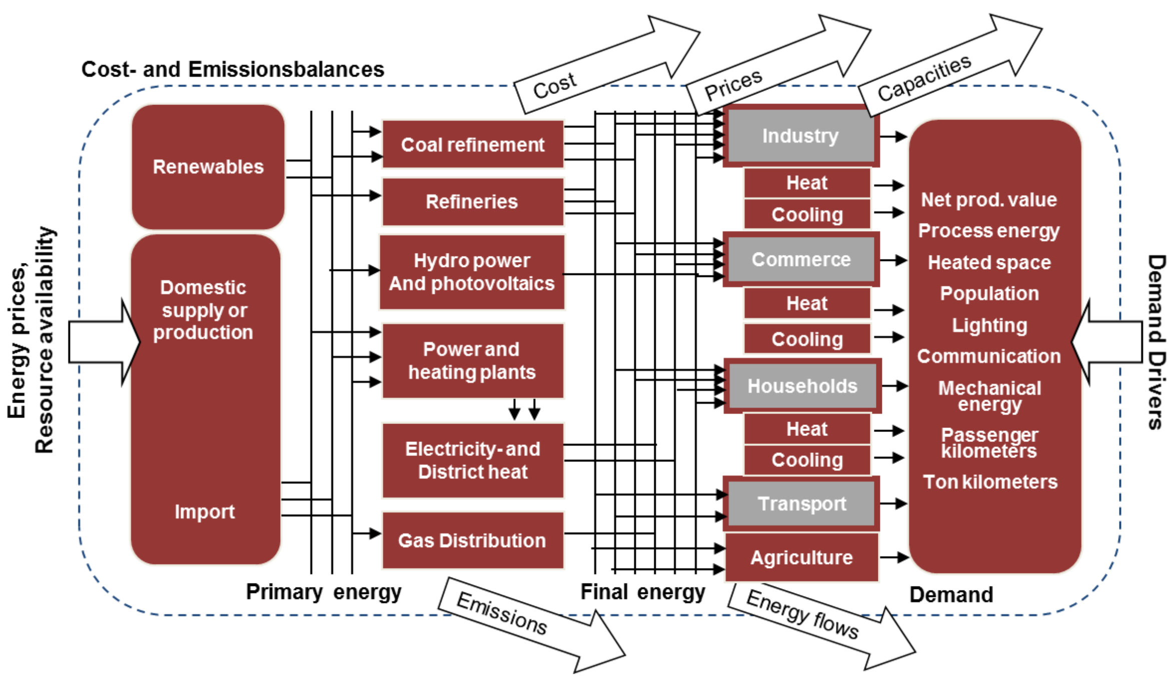

Figure 1 Simplified Reference Energy System (RES) of TIMES PanEU

This model enables us to determine the economically optimal energy supply structure with a specified useful energy or energy service requirement with simultaneous consideration of energy and environmental policy specifications.

Scenarios

I. Baseline and Reference	Germany		European Union		Scenario Identifier
	Energy	Other sectors	forerunners	others	
baseline	ETS	ETS	ETS	ETS	**ETS**
Reference case for Comparison	ETS	KSP90	COP	ETS	**REF**

II. Intermediate Steps	Germany		European Union		Scenario Identifier
	Energy	Other sectors	forerunners	others	
Quick **Ex**it from **c**oal	CEX-Q	KSP90	COP	ETS	**CEX-Q**
CO2 **p**ricing scenario	COP	KSP90	COP	ETS	**COP**

III. Policy Packages	Germany		European Union		Scenario Identifier
	Energy	Other sectors	forerunners	others	
With accompanying measures	CEX-Q +RES +CR	KSP90	COP	ETS	**CEX-Q+**
With accompanying measures	COP +RES +CR	KSP90	COP	ETS	**COP+**

Table 1 Scenario definitions for the energy system analysis

Our analysis is based on a scenario comparison. For this purpose, we define a scenario framework with regard to energy policy measures at the level of Germany and the European Union. Our scenario framework is subdivided into three groups. First are the comparison scenarios (I), which serve as a reference against which we will measure the effects of energy policy measures in the transformation sector. The scenarios "ETS" and "REF" are to be mentioned here - on the one hand exclusively with the specifications from the EU ETS for all countries and sectors, as well as the measures already decided today (e.g. nuclear energy phase-out and renewable energy law promotion), on the other hand as "REF" scenario which makes specifications for the final consumption sectors in Germany following the climate protection plan of the Federal Government (2). To this end, a fixed greenhouse gas reduction target is set for each of the sectors. Together with corresponding measures in the transformation sector, a 90% reduction in greenhouse gas emissions compared to 1990 could thus be achieved for Germany.

Sector / Year	Buildings	Transport	Industry	Agriculture
2030	-65%	-40%	-49%	-34%
2050	-94%	-90%	-81%	-89%

Table 2 Sector specific Greenhouse gas mitigation targets in Germany (KSP90)

Outside Germany, with the exception of the baseline scenario (ETS), the existence of a so-called forerunner alliance is assumed for all scenarios. These countries – namely Belgium, Denmark, France, Luxembourg, Netherlands and Sweden) set themselves a minimum CO2 price on all emissions, regardless of their origin. According to our assumption, this price will start in 2020 and then rise linearly from €30 in 2020 to €120 in 2050. In the COP and COP+ scenarios, Germany will also join this forerunner alliance.

Year / CO_2-Minimum Price	2020	2025	2030	2035	2040	2045	2050
[$€_{2015}$ / t CO_2-Equi.]	30	45	60	75	90	105	120

Table 3 Pathway for CO2-price of forerunner alliance from 2020 to 2050

A second group is defined as the scenarios CEX-Q and COP. Here, two policy paths for the energy industry in Germany are examined. On the one hand in the scenario Quick Exit from Coal (CEX-Q) the option of early decommissioning of lignite and hard coal-fired power plants in the sense of the Coal Commission (3) and on the other hand in the CO2 pricing scenario (COP) the effects of a general CO2 price according to the forerunner alliance.
Apart from the energy industry requirements described above, they fully correspond to the REF scenario.

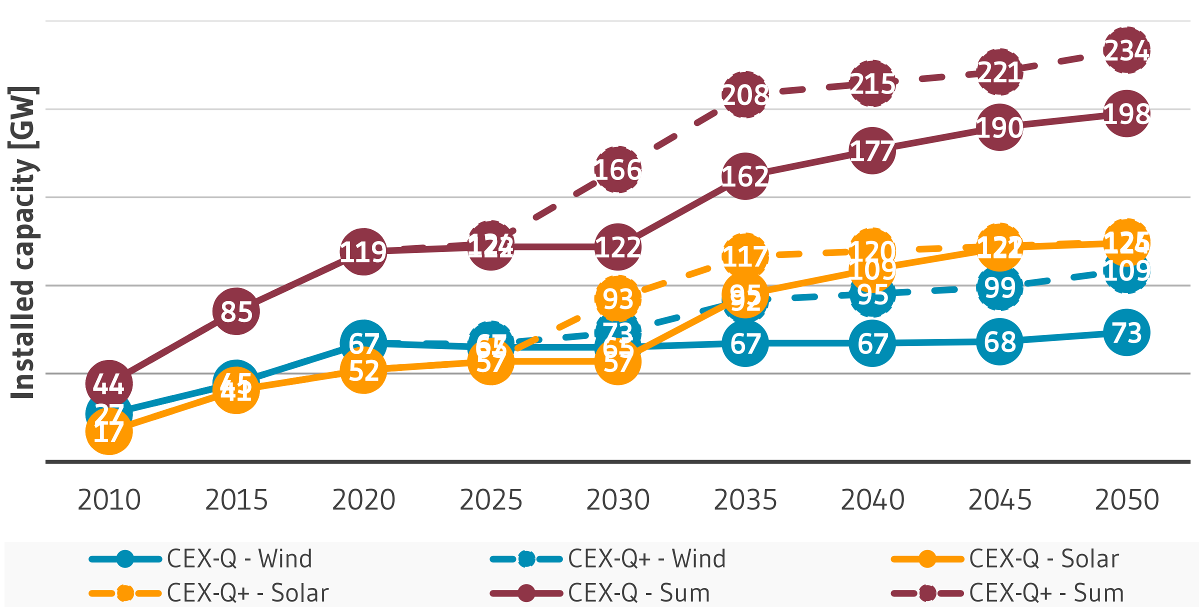

Figure 2 Additionally installed renewable capacities (Wind and Solar) for +RES-Scenarios

In addition to our basic scenarios, ultimately we consider two further scenarios with so called accompanying measures. One of the accompanying measures is the increased promotion of renewable energies (wind and solar), parallel to the closure of coal-fired power plant capacities. In total, this corresponds to an additional installed capacity of around 40 GW from 2030 onwards. The share of renewable energies in electricity generation is specified, but the division between wind power and photovoltaics is based on cost-optimal aspects, model endogenous.
The second accompanying measure is the implementation of a certificate decommissioning in the EU-ETS system to compensate for the waterbed effect described in the following. The certificate decommissioning quantity is calculated on the basis of the greenhouse gas reduction achieved within Germany in the scenarios CEX-Q and COP compared to the REF scenario.

Results

- **Greenhouse gas emissions of the conversion sector**

The development of greenhouse gas emissions (power plants, heating plants, refineries,) in the German transformation sector is to be regarded as the primary indicator of compliance with the targets. In order to achieve a reduction of 90% in 2050 compared to 1990 together with the given sector targets, the level of about 20 Mt. p.a. would have to be reached.
Starting with the ETS scenario, there is a relative standstill in emissions reduction between 2020 and 2030, partly due to the effects of Germany's phasing out of nuclear energy and the corresponding replacement of the electricity lost by fossil fuels with associated higher emissions. In comparison, in the REF scenario even higher emissions in the transformation sector are shown in a counterintuitive way. As will be shown subsequently, this can be explained by the fact that final energy consumption must be decarbonized massively by the CSP90 target in the final consumption sectors. This is done using electrification and district heating, as these energy sources are emission-free locally. Emissions are thus indirectly transferred to the transformation sector - for us, this in turn means that successful decarbonization of final energy consumption significantly increases the pressure to act in the energy industry.

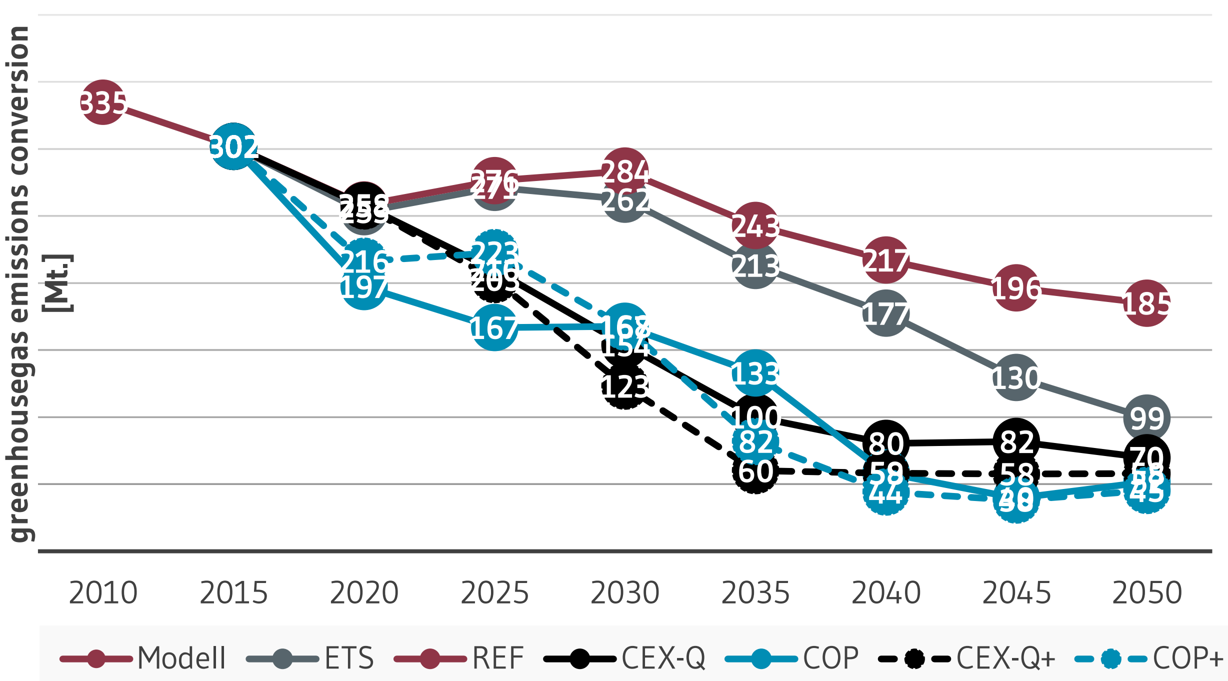

Figure 3 Greenhouse gas emissions of the Conversion Sector from 2010 to 2050 by Scenario

In comparison, the scenarios CEX-Q and COP and their corresponding adaptations with accompanying measures deliver very significant greenhouse gas reductions. The CEX-Q scenarios show a relatively uniform decline up to 2035 / 2040, corresponding to the decommissioning of coal-fired power plant capacities. Subsequently, the CEX-Q scenarios lose a great deal of momentum and emissions remain on a plateau, as no further capacities can be shut down from now on, meaning that the measure has been used to the full extent possible.
The COP scenarios, on the other hand, show a similar level, but a much more undulating course. This can be explained by the fact that above a certain CO2 price level, lignite and hard coal capacities are first pushed out of the system, while the shutdown of further capacities results only after a significantly higher price level.

- **Electricity generation by energy carrier**

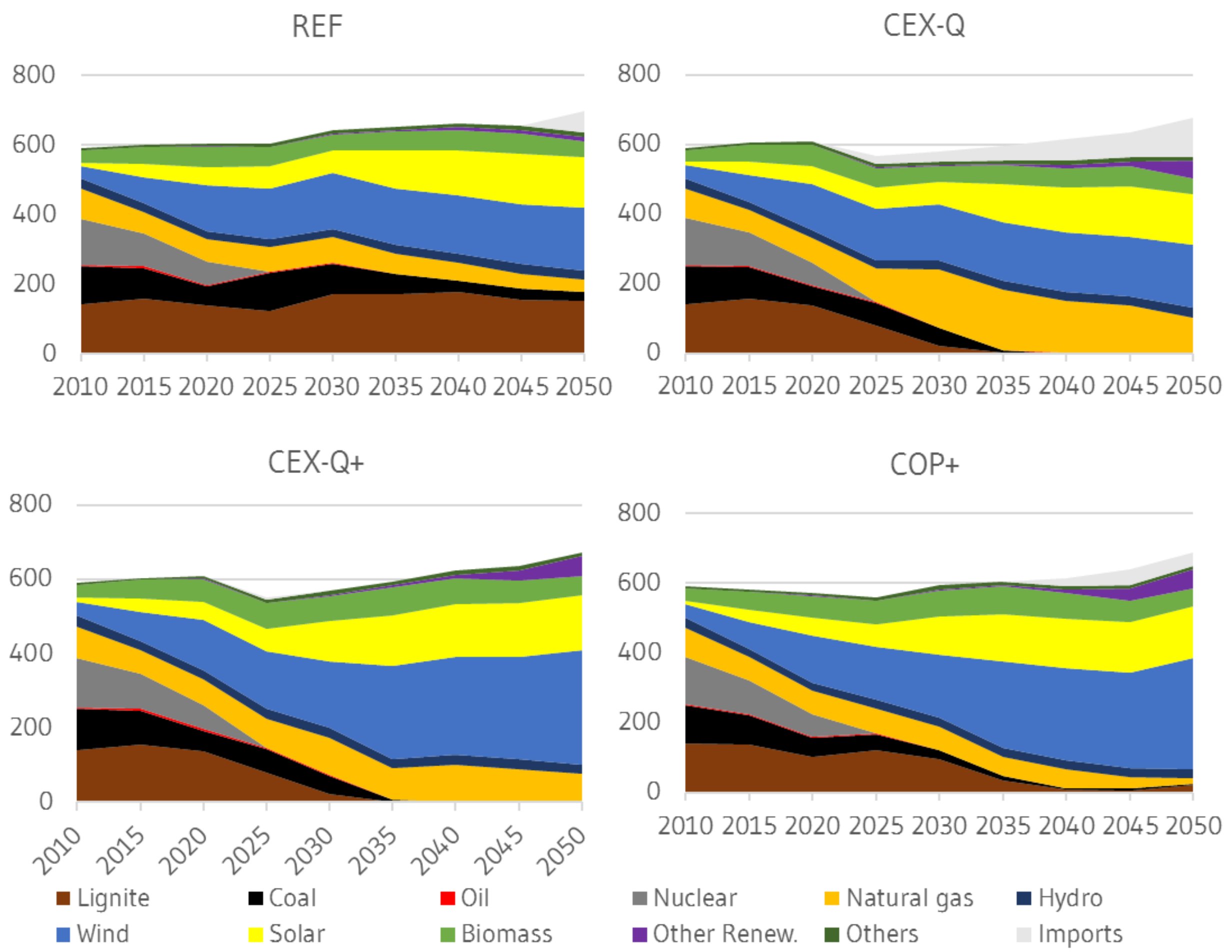

Figure 4 Electricity Generation by Energy Carrier and Scenario from 2010 to 2050

If we now take a closer look at the development of electricity generation in some scenarios, we can see that, in general, the level of electricity consumption is generally within a corridor of 550 to 650 TWh/a. What all scenarios have in common is that consumption levels will stagnate initially until around 2030 or even decline somewhat as a result of energy efficiency improvements. In the further course of time, there will then be a sometimes significant increase, due to the fact that further decarbonization of final energy consumption will then require electrification (e.g. by electric vehicles and heat pumps).

In the REF scenario we see an unbroken dominance of lignite use well into the future. The phase-out of nuclear energy will be compensated by increased use of lignite and hard coal. Only then will the use of wind power and photovoltaics increase sufficiently to displace at least hard coal to a large extent from electricity generation.

The CEX-Q scenario, in which the complete phase-out of the use of lignite and hard coal takes place by around 2035, represents a clear break in this respect. It is obvious here that compensation for the loss of electricity generation capacity is only to a small extent provided by renewable energies and that instead natural gas is mainly used as an energy source. While electricity generation from natural gas reaches its peak between 2030 and 2040, a significant decline in generation is already discernible by 2050. Also visible is a constantly rising block of electricity from electricity imports - this shows a possible dependence on imports which will be analyzed in more detail below.

In the CEX-Q+ scenario, on the other hand, we can observe a significantly higher use of wind power due to the accompanying measures. This significantly mitigates the interim high in natural gas electricity generation described in the CEX-Q scenario, and also means that domestic German electricity generation is sufficient to avoid provoking any further import dependency.

Finally, a look at the COP+ scenario shows that a CO2 minimum price can also lead to an early shutdown of coal-fired power generation. In contrast to the CEX-Q scenarios, the phase-out will take about 5 years longer until 2040, with the hard coal-fired power plants ceasing operation earlier and lignite use only ceasing subsequently. With regard to electricity generation from natural gas, a very low level is also visible here, which is comparable to the REF scenario - an interim high in the use of natural gas is thus ruled out, as the decommissioning of coal-fired power plants is in better alignment with the expansion of renewable energies. Electricity imports from abroad will be visible from 2040 onwards, but are generally at a rather low level.

- **The Waterbed Effect**

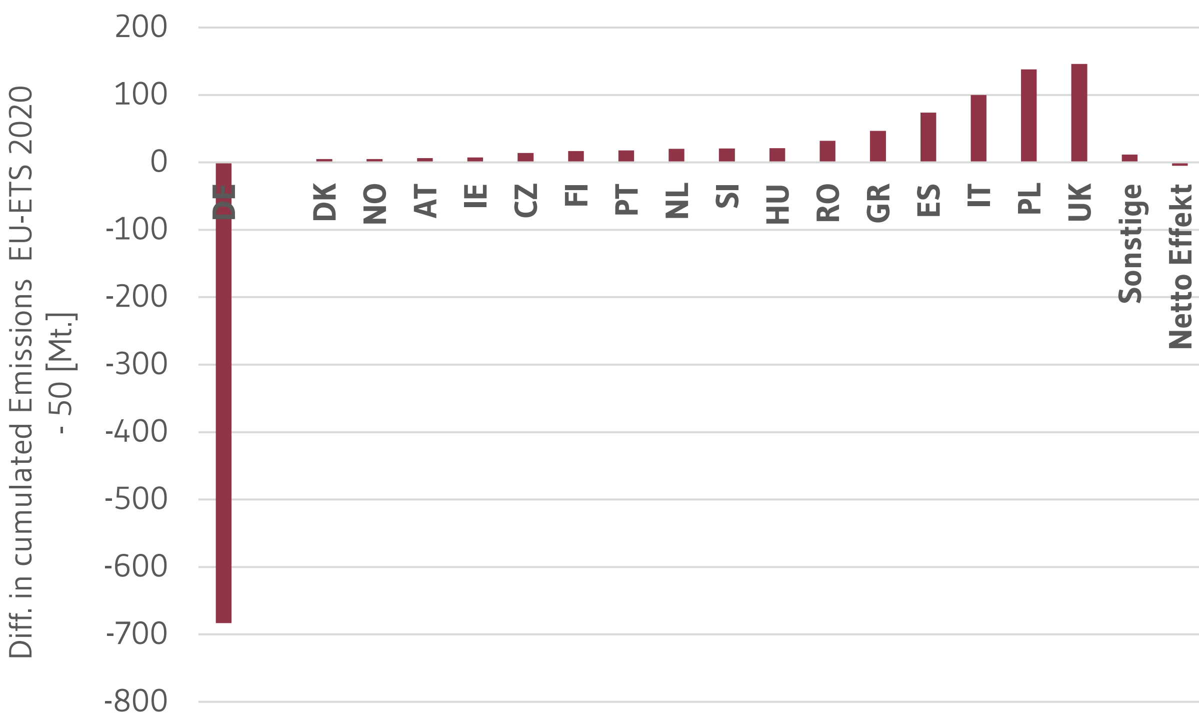

Figure 5 Redistribution of Greenhouse gas emissions within the EU-ETS by country due to the Waterbed Effect (Scenario CEX-Q)

A notable side effect of a rapid coal phase-out or a unilateral reduction of greenhouse gas emissions is the so-called waterbed effect. The accelerated phase-out of coal-fired power generation in Germany leads to the desired reduction of greenhouse gas emissions within Germany, but at the same time also reduces the demand for certificates in the EU ETS. This in turn lowers the price of certificates, which the other participating countries are seeing clearly. This in turn reduces the need to reduce emissions in these countries. Ultimately, there is a redistribution effect, which in our model leads to noticeable increases in emissions in the United Kingdom, Poland, Italy, Spain and Greece.
In total, the CEX-Q scenario for Germany results in cumulative emissions reductions of 680 Mt (2020 - 2050) compared with the REF scenario, but the resulting net effect in the ETS system is non-existent.
It can thus be stated that the unilateral withdrawal of coal without a corresponding certificate decommissioning would probably have no significant net effect. This shows that a coal phase-out scenario only with simultaneous certificate revocation is a sensible climate policy measure.

- **Electricity Import balance**

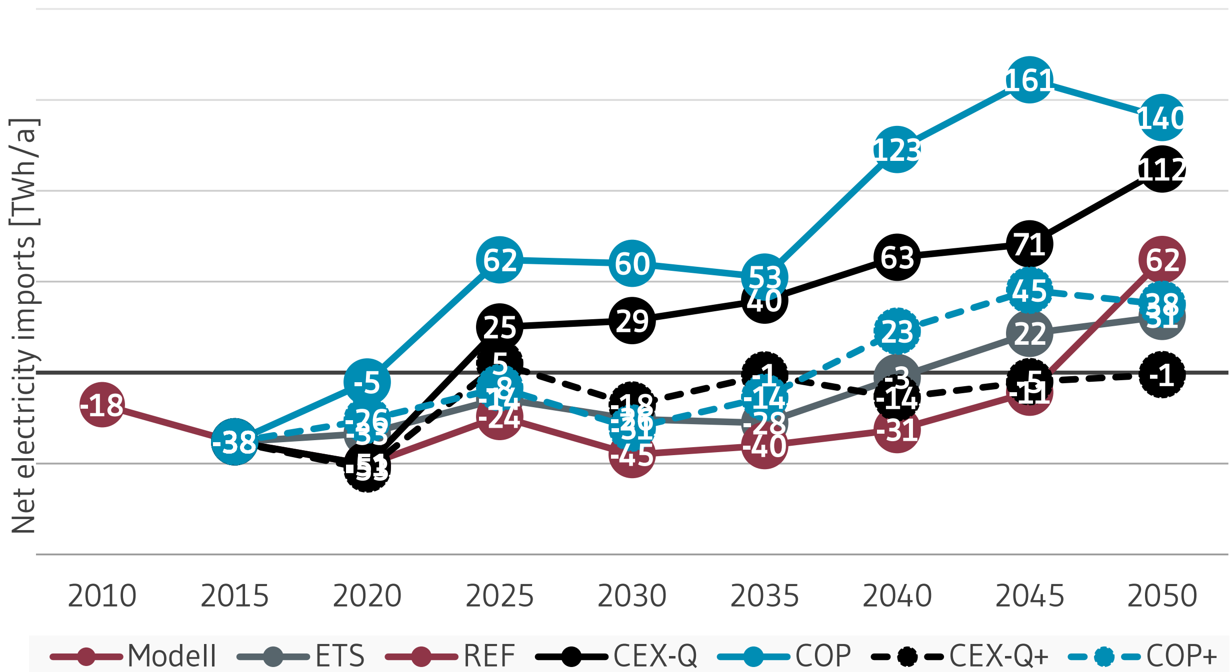

Figure 6 Net electricity imports of Germany by scenario from 2010 to 2050

As has already become apparent when looking at the electricity generation volumes, there can be very significant differences between the scenarios with regard to the import and export balance in electricity trading. At the lower end of the scale, with net exports high for a long time, are the ETS and REF scenarios - this represents a continuation, so to speak, of the current balance sheet situation. On the other hand, the scenarios CEX-Q and COP rank at the opposite end with significantly high net imports - here an import dependency of up to about 25% of domestic electricity consumption is achieved. The reason for this is that in the unilateral exit from coal, the loss of generation capacity from coal is compensated not only by natural gas power plants but also by foreign generation. We are benefiting from this effect through falling ETS certificate prices (keyword: waterbed effect). The COP scenario also indicates that electricity generation in neighboring countries is significantly cheaper.

Here, the scenarios with accompanying measures can ensure a significantly more balanced balance. On the one hand, the decommissioning of certificates raises the costs of electricity generation abroad relative to Germany to a higher level; on the other hand, an increased share of renewable energies in Germany also leads to a higher generation potential. The CEX-Q+ scenario therefore results in a fully balanced import balance, while the COP+ scenario at least significantly reduces foreign dependency and can thus be reduced to a normal level.

- **Natural Gas Primary Energy Consumption**

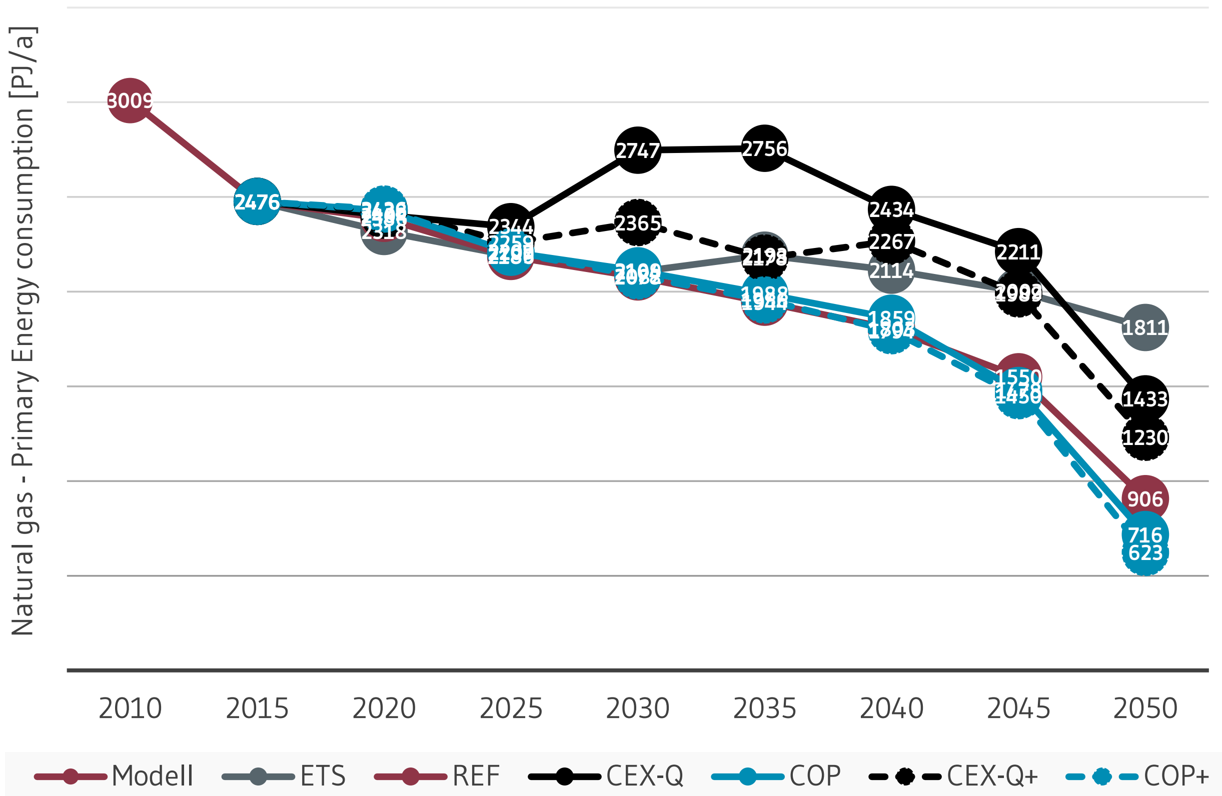

Figure 7 Primary Energy consumption of natural gas by scenario from 2010 to 2050

A look at the primary energy consumption of natural gas provides further interesting findings. When looking at electricity generation, it has already become apparent that the scenarios have a strong influence on electricity generation from natural gas - this is also clearly reflected in the primary energy demand. In general, it can be seen that natural gas use between 2020 and 2040 is on a slow downward trend, which will gain further momentum after 2040. In contrast, the CEX-Q scenarios, in which natural gas could experience a significant interim high between 2025 and 2045, show a strong deviation. So while the use of natural gas without CCS will no longer be compatible with ambitious climate protection efforts in the long term, there is a clear danger that an extensive natural gas infrastructure will be created for short periods of time, which will have to be shut down again before it reaches its natural lifespan. Here, too, it can be observed that the accompanying measures in the CEX-Q+ scenario are suitable for significantly mitigating this potentially unfavorable development.

- **District Heat Generation**

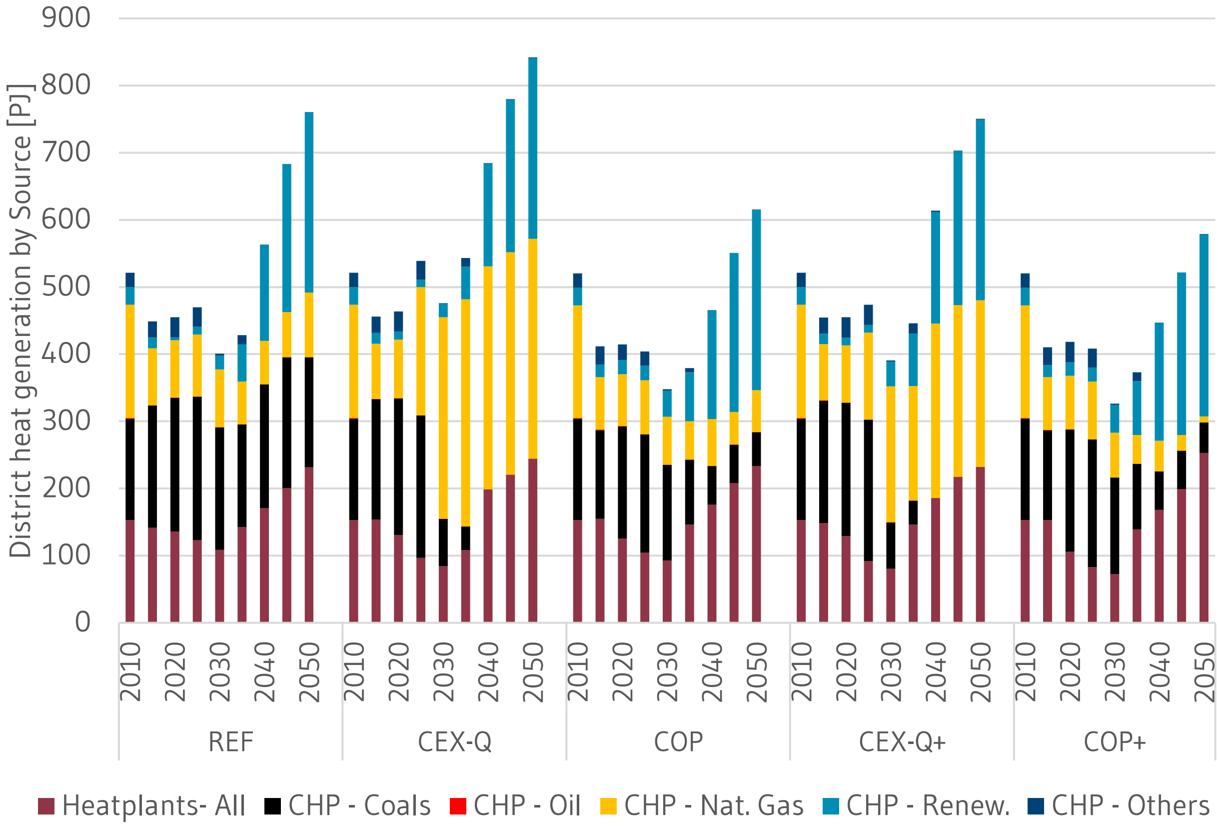

Figure 8 District Heat generation in Heat plants and Combined Heat and Power (CHP) in Germany by energy carrier

Another area in which the withdrawal of coal will have an impact is the heating market and the provision of local and district heating. In general, we can observe a similar trend here as in electricity generation. After initial stagnation or slight declines, attributable to increased energy efficiency in the use of space heating, a certain renaissance of district heating is taking place after 2030, driven by decarbonization efforts. This is based on the increasing use of large heat pumps and geothermal energy.

In the reference scenario, however, there is still extensive use of coal for district heating (CHP) until 2050. A generally comparable level can be observed in the CEX-Q scenario, where coal CHP plants are substituted by natural gas CHP plants - this results in the already described effect of the interim high of natural gas utilization around 2025 to 2045.

In contrast, a significantly lower level of district heating utilization can be observed with CO2 pricing (COP), accompanied by a lack of expansion of the natural gas CHP infrastructure. If one now considers the scenarios with accompanying measures, i.e. CEX-Q+ versus CEX-Q and COP+ versus COP, the course of generation from heating plants, coal-fired power plants and renewables is almost unchanged both times compared to the respective basic scenario. However, there are visible changes in district heating from natural gas CHP plants, which is slightly lower than in the respective basic scenarios. It can therefore be concluded that the accompanying measures reduce the economic efficiency of natural gas CHP plants and thus district heating in general compared with near-consumption generation, e.g. from heat pumps.

- **Resulting System Cost**

Scenario	**CEX-Q**	**COP**	**CEX-Q+**	**COP+**
additional costs compared to REF	165 Bn. €	351 Bn. €	272 Bn. €	393 Bn. €
+ back up preparedness (Sicherheitsbereitschaft)	17 Bn. €		17 Bn. €	
subtotal	182 Bn. €	351 Bn. €	289 Bn. €	393 Bn. €
- revenue from CO2-Price		– 128 Bn. €		– 110 Bn. €
SUM	182 Bn. €	223 Bn. €	289 Bn. €	283 Bn. €
per annum (30 a)	6 100 M. €	7 430 M. €	9 630 M. €	9 430 M. €

Figure 9 Additional System cost compared to REF-Scenario for Germany

Finally, if we consider the system costs incurred, it becomes clear that the pure CEX-Q coal exit scenario is by far the most economic scenario for the German energy system. The cumulated additional costs compared to the REF scenario amount to only about €165 billion - however, it should be noted that this scenario cannot have a net effect within Europe due to the waterbed effect and leads to a high import dependency and should therefore not be considered.
From the point of view of the actors in the energy system as the second most favorable scenario, the scenario CEX-Q+ with about € 272 billion follows. The COP and COP+ scenarios lag far behind, with additional costs of around €350-390 billion.
Here, however, it should be noted that the costs of the COP scenarios also include payments for emission rights, which in turn would be available at the state level as corresponding revenues and could be used for redistribution, subsidization measures or socially acceptable balancing of the additional burdens. It should also be taken into account that in the coal phase-out scenarios additional costs could be incurred through compensation payments for the consequences of the regulatory coal phase-out. Ultimately, a comparison of the two scenarios with accompanying measures reveals similar final costs of around €289 billion (CEX-Q+) and €283 billion (COP+), respectively, whereby the burden on individual actors can differ significantly and depends on the form in which the additional revenues from emission rights would be used. At the annual observation level, this results in additional costs of around €10 billion p.a. for the implementation of climate policy measures in the energy sector.

Discussion and Conclusion

We conclude that a German Coal phase-out can be an effective short-term measure on the road to climate protection (CEX-Q), which will result in the significant reduction of German conversion sector emissions. However negative side effects like rebound effects, the reduction of EU-ETS CO2 price (waterbed effect) and increased electricity imports would severely impact the long term effectiveness of such a scenario. Especially the replacement of coal in power generation and district heating by natural gas, albeit this has no long-term viability after 2040 as well as the redistribution of emissions within Europa call for accompanying measures like certificate revocation and the expansion of renewables, which as shown can significantly mitigate the undesirable side effects.
The accompanying measures lead to a reduction of rebound effects in electricity generation, as well a balanced electricity trade. EU-ETS certificate revocation in particular eliminates the transfer of emission quantities to other European countries (waterbed effect).

As an alternative to a withdrawal from coal under regulatory law we also analyzed the introduction of a minimum CO2 price as an alternative or additional instrument. This would lead to comparable outcomes, with less dependency on natural gas usage as well as reduced rebound effects.
The CO2 pricing scenario might possibly accompanied by lower government expenditure (compensation payments, renewable energy promotion) respectively higher revenues from emission rights trading which would possibly allow for a more equitable distribution of burdens.

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