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Viability of Carbon Capture and Storage for German power generation sectors in 2030

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Abstract:

This work investigates the economic viability of Carbon Capture and Storage (CCS) technologies in the German power generation sector for the year 2030. While current German climate policy prioritizes CCS deployment in industrial sectors and does not actively promote its deployment in power generation, future system needs and evolving European CO_2 transport and storage infrastructure may alter this assessment. Using a scenario-based energy system optimization model, this study explores the conditions under which CCS-equipped power plants could become cost-competitive, focusing on fuel price and CO_2 price variations.

Keywords:

Carbon Capture and Storage; CO_2 emission price; Greenfield; GAMS

1. Introduction

1.1. CCS Technologies and their potential

CCS technologies are widely recognized as vital measures to mitigate the greenhouse gas emissions from hard-to-abate sectors, where direct electrification or renewable substitution is challenging. As per Intergovernmental Panel on Climate Change (IPCC) [1] projections, concurrent CCS implementation in industrial and fossil power generation units could help potentially realize the 1.5°C temperature limiting scenario by 2050 by cutting down cumulative emission by 45%. According to [2] over 40 commercial carbon capture CO_2 recovery plants are currently operating worldwide, with combined annual capture capacity of exceeding 45 million tonnes.

Three key technical pathways exist for the power generation units, namely, post-combustion capture, pre-combustion capture and oxy-fuel combustion. Post-combustion method utilizes chemical scrubbing to scrub CO_2 from flue gas, and this technology is ideal for retrofitting. Pre-combustion capture is typically integrated with a gasification unit to convert the hydrocarbon fuel to syn-gas and removes CO_2 before the fuel is fed into the boiler. Oxy-fuel combustion uses nitrogen depleted air for combustion and therefore enhances the CO_2 concentration in flue gas resulting in easier capture [3]. Once the CO_2 is captured from the emission source, moisture removal is done and it is compressed to supercritical state and then transported and stored in suitable geological infrastructures located deep beneath the ground. The recovered CO_2 from the CCS units finds its application in production of e-Fuels (kerosene, diesel, aviation fuel), chemicals (polymers, cleaning agents etc.) and building materials (bricks, paving stones) [4].

In Europe, multiple initiatives such as the Northern Lights (Norway) [5], Project Greensand (Denmark) [6], ARAMIS (Netherlands) [7] and projects Porthos (Netherlands) [8] demonstrate large-scale infrastructure development for transportation and storage of CO_2 which could trigger future CCS deployment in industrial and power sectors; although most current European CCS activities are oriented toward industrial decarbonization rather than power sector retrofits [9]. Cross-border CO_2 transport is also gaining momentum in Europe starting with the north-sea bordering nations. The German Federal government is also considering offshore CO_2 storage, whereas onshore CO_2 storage is still only permitted for research purpose [10].

1.2. Implementation of CCS in power sector

CCS has been deployed in variety industrial sectors; however, its technical performance and cost implication vary significantly from sector to sector. Industrial sources like steel, cement and chemical refining plants typically emit larger concentration of CO_2 compared to fossil power plants. This makes the CO_2 capture less energy intensive and cost effective for the former applications. For example, a recent study [11] says capture cost can be as low as €14–23 per tonne of CO_2 for concentrated sources such as ethanol production but rise to €38–114 per tonne for sources like power stations with diluted CO_2 streams. The energy penalty paid to capture CO_2 in fossil power plants reduces their efficiency. Depending on the CCS technology used and the existing efficiency of the fossil plant, an efficiency drop of 7-14% can be expected when CCS is implemented [12].

Studies by the European Commission's Joint Research Centre [13] show that adding CCS to a pulverized coal plant can increase the levelized cost of electricity by approximately 70–120% compared to an unabated plant, largely due to the energy penalty of capturing and compressing CO_2, increased capital costs for capture equipment, and additional operational costs. Nevertheless, estimating the true cost of CCS implementation in power sector is challenging due to limited data availability pertaining to costs of CCS value chain and limited real-world operation data, which leads to low and inconsistent learning curves [14].

1.3. Implementation of CCS in Germany

In 2024, Germany adopted the key principles for a "Carbon Management Strategy" [15] which paves the way for CCS policy framework for the industrial integration. According to this policy measures, there will be no large-scale deployment of CCS in the fossil power generation sectors along with their exclusion from access to CO_2 pipelines and CO_2 storage. Rather, CCS integration is stressed for the hard-to-abate industrial sectors (e.g., cement, steel, chemical etc.). To alleviate the emissions from the fossil power generations, "coal phase out" is planned by 2038 along with fast-tracked expansion plan for renewable energy sources (RES) generations. Despite Germany's ambitious plan to expand the RES capacity, the power supply still relies on dispatchable thermal generation to ensure energy security during low wind and no sun periods. Fossil power plants equipped with CCS represent a potential low-carbon secure option that could complement variable RES generation. The objective of this work is not to forecast the optimum technology mix for power generation in Germany for 2030, rather to explore the viability of investment in CCS technologies for power generation, subjected to instabilities in fuel prices and hike in CO_2 emission prices.

To accomplish this objective, a greenfield optimization models is built in GAMS considering the potential electricity demand in 2030, and it is used to determine optimal investments in 2030 under different CO_2 and fuel price levels.

2. Methodology

The greenfield investment model built in GAMS provides optimal investment decision for total six power generation technologies which includes two fossil power plants (Lignite and Gas combustion turbine), their CCS counterpart (Lignite with CCS and Gas combustion turbine plant with CCS), and two RES technologies (Wind onshore and PV). No particular CCS technology was assumed in this model, rather implementation of CCS is accounted for by incorporating reduction in 90% CO_2 emission from the reference fossil plant and a corresponding reduction in thermal efficiency. Two possible scenarios were analyzed to comprehend the investment decisions i.e., the RES technologies having fixed capacity (RES exogenous), where the corresponding RES capacity was considered to be the planned installation capacity for 2030 and in the other scenario, the capacity of RES technologies were optimally calculated by minimizing the total cost (i.e., RES endogenous).

2.1. Input parameters and their sources

The input parameters related to power plant availability factors, hourly demand, installed capacity, investment cost (IC), operation and maintenance cost (O&MC), fuel costs (FC), carbon emission costs (EC), technical lifetime, plant efficiency, carbon emission factors are adopted from open literature [16-20]. The availability factors for the conventional technologies were considered to be constant as 0.85, whereas the hourly Wind and Solar availability factors were taken from the Renewables Ninja [16] database for the reference year 2023. The PV and Wind capacities for the RES exogenous cased were considered to be 215 GW and 115 GW respectively and is taken from [17]. The electricity demand scenario considered for Germany in 2030 is according to the National Trend [18]. The hourly electricity demand data for 2030 are obtained from ENTSO-E database [18]. The technical input parameters for the six power generation technologies are given in Table 1.

Table 1. Technical input

Technology	Investment cost, €/MW	O&M cost, €/MWh	Fuel cost, €/MWh	Efficiency	CO_2 emission factor, tCO_2/MWh
Lignite	112514	7	2.3	0.447	0.383
Lignite with CCS	206425	34	2.3	0.312	0.0383
Gas	34324	3	27	0.393	0.201
Gas with CCS	80404	19	27	0.323	0.0201
Wind	88117	7	0	1	0
PV	42571	0	0	1	0

The resources used for input parameters are also charted in Table 2.

Table 2. Input parameters and their reference

Parameter/Data	Reference
Hourly demand of electricity	[18]
Wind and PV availability factor	[16]
PV and Wind target installation capacity for 2030	[17]
Investment cost, variable operation and maintenance cost, efficiency	[19]
Fuel price, carbon price	[20]

2.2. Mathematical formulation

The mathematical formulation of the objective function and the constraints are as follows:

The objective function is the total cost (TC) of operation of all the technologies combined together. The TC comprises of IC and variable cost (VC). The VC can be broken into individual cost components i.e., O&MC, FC and EC. The assumptions invoked in the model are:

- There is no upper limit for capacity building.
- There is no storage of electricity.
- Start-up functions and associated costs are not considered.
- Fixed O&M costs are not considered.
- There exist no minimum load criteria.
- The availability factors of the conventional technologies are constant.
- The CCS plants have CO_2 emission factors which are only 10% of their non-CCS counterpart.

The objective function can be expressed as:

$$min\ TC = \sum_{c} ic_c \cdot CAP_c + \sum_{r} ic_r \cdot CAP_r + \sum_{c,t,d} \left(vc_c \cdot G_{c,t,d}\right) + \sum_{r,t,d} \left(vc_r \cdot G_{r,t,d}\right) \quad (1)$$

where,

$$vc_c = omc_c + \frac{fc_c + CO2f_c \cdot CO2P}{\eta_c} \quad (2)$$

$$vc_r = omc_r \quad (3)$$

The linear optimization problem is subjected to the following constraints:

$$\sum_{c} G_{c,t,d} + \sum_{r} G_{r,t,d} = D_{t,d} \quad (4)$$

$$G_{c,t,d} \leq CAP_c \cdot af_c \quad (5)$$

$$G_{r,t,d} \leq CAP_r \cdot af_{r,t} \quad (6)$$

$$G_{c,t,d}, G_{r,t,d}, CAP_c, CAP_r \geq 0 \quad (7)$$

2.2. Scenario setup

Two key scenarios are analysed in this work. The first being the RES capacities modelled exogenously i.e., the installed capacities are already known for 2030, and only the capacities of the conventional technologies are optimized and revealed. The second scenario considers both RES capacities and conventional capacities to be endogenous i.e., the installation capacities are not known prior but rather are optimized and revealed. Under these two scenarios, CO_2 emission price and fuel prices are varied. Whereas the CO_2 emission price was varied from 100 €/t-CO_2 to 240 €/t-CO_2, the fuel price variations were staged as a combination of low and high prices for Lignite and Gas. The combinations ((low, low), (low, high), (high, low) and (high, high)) correspondingly refer to price levels of Lignite and Gas, e.g., the combination low, low refers to both low level's prices for Lignite and Gas. The range of key parameters are shown in Table 3.

Table 3. *Scenario setup*

Scenario	Parameters
RES exogenous	Case A: CO_2 emission price variation ▪ Wind capacity: 115 GW ▪ PV capacity: 215 GW ▪ Lignite price: 2.3 €/MWh ▪ Gas price: 27 €/MWh ▪ CO_2 emission price: 100-240 €/t-CO_2 Case B: Fuel price variation ▪ Wind capacity: 115 GW ▪ PV capacity: 215 GW ▪ Lignite price: 2.3-3.45 €/MWh ▪ Gas price: 27-40.5 €/MWh ▪ CO_2 emission price: 150 €/t-CO_2
RES endogenous	Case A: CO_2 emission price variation ▪ Lignite price: 2.3 €/MWh ▪ Gas price: 27 €/MWh ▪ CO_2 emission price: 100-240 €/t-CO2 Case B: Fuel price variation ▪ Lignite price: 2.3-3.45 €/MWh ▪ Gas price: 27-40.5 €/MWh ▪ CO_2 emission price: 150 €/t-CO_2

The low levels of the fuel prices are adopted from [20]. While the high levels are considered to be 50% higher than the corresponding low levels.

3. Results and discussion

3.1. Scenario: RES exogenous

3.1.1. Case A: CO_2 emission price variation

The influence of carbon emission price on the optimal investment on capacity building for the exogenous RES consideration is depicted in Fig.1. Out of the four conventional technologies, Lignite without CCS does not see any investment. Though, Lignite with CCS sees almost steady capacity building for all emission prices due to its lowest marginal cost amongst all conventional technologies across whole emission price range. As emission price increases, a part of the Gas capacity gets gradually replaced by the Gas with CCS owing to comparatively less increment in its marginal price. Nevertheless, the sum of the capacities for CCS and non-CCS technologies remains unchanged for the whole emission price range.

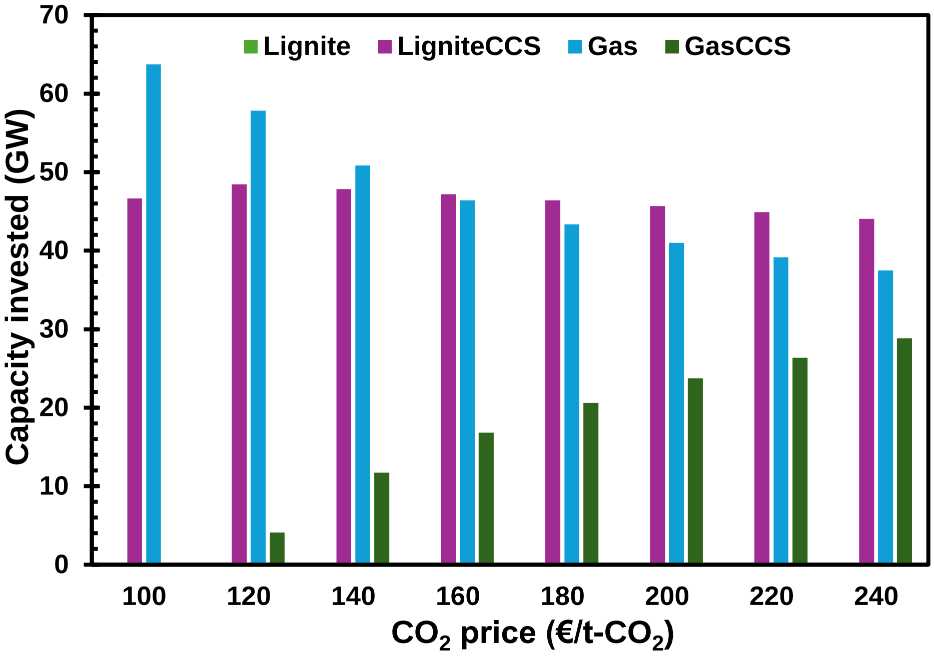

Figure. 1. *Influence of CO_2 emission price on investment*

The individual cost components and the cumulative CO_2 emission in 'million tonnes' (Mt) are plotted against the emission prices and is shown in Fig. 2. The cost components are represented in 'billion' (bn) unit.

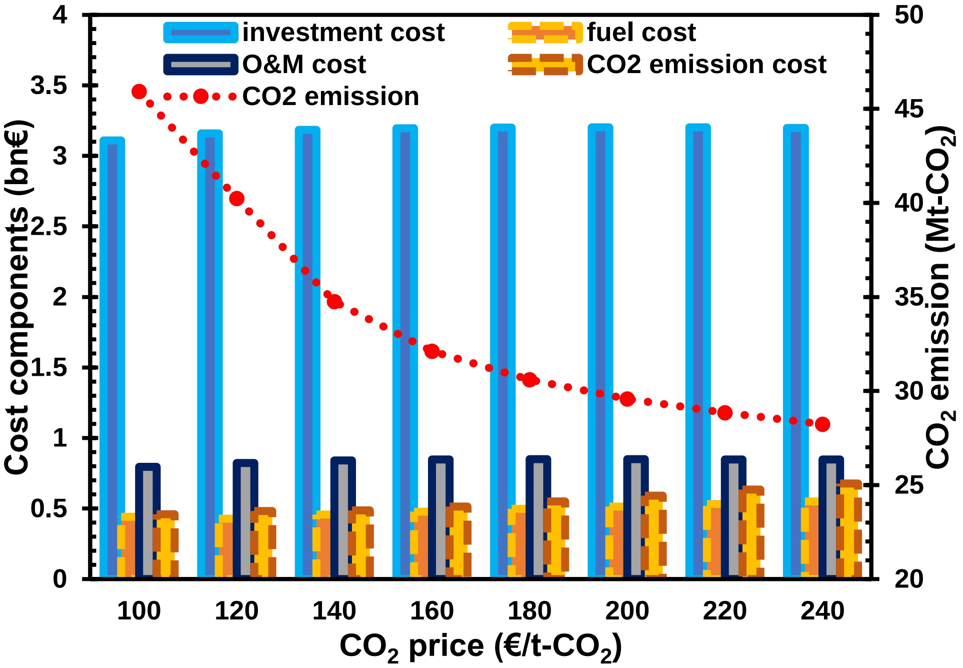

Figure. 2. *Influence of CO_2 emission price on costs components and total emission*

As carbon emission price is increased the O&MC and the IC remains almost unchanged, while the FC and the EC increases. The increase in FC can be attributed to the penetration of CCS technologies at higher emission prices, which offers inferior thermal efficiency compared to their non-CCS counterparts. It is a noteworthy that even though the EC rises with an increase in carbon emission price, the cumulative emission decreases monotonically from 45.9 Mt to 28.2 Mt as emission price is increased from 100 €/t-CO_2 to 240 €/t-CO_2. Such an observation is trivial as capacity building for CCS technologies would be favoured at higher carbon emission prices.

3.1.1. Case B: Fuel price variation

Figure 3 depicts the influence of fuel price variations on capacity invested. Once again, Lignite without CCS does not attract any investment due to its very high IC and high VC. It is interesting to observe that only in the case of a reduction in gas price (scenarios: low, low and high, low) drives investment in GasCCS; however, reduction in lignite price does not significantly influence capacity building of LigniteCCS. Such an observation is rational as despite considering equal percentage increment in prices for lignite and gas, the lignite price only increases by a little in magnitude.

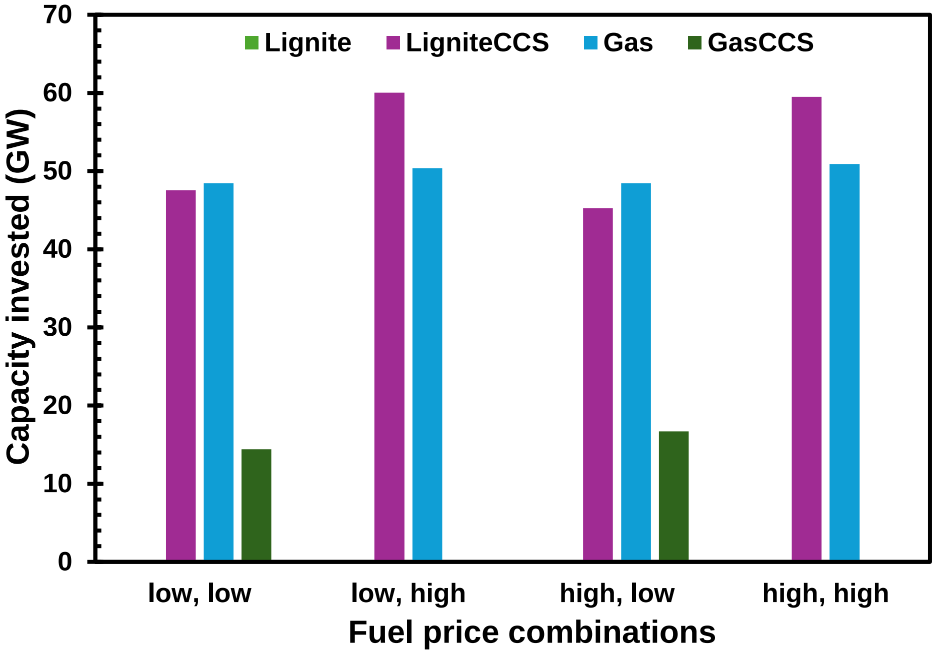

Figure. 3. *Influence of fuel price on investment*

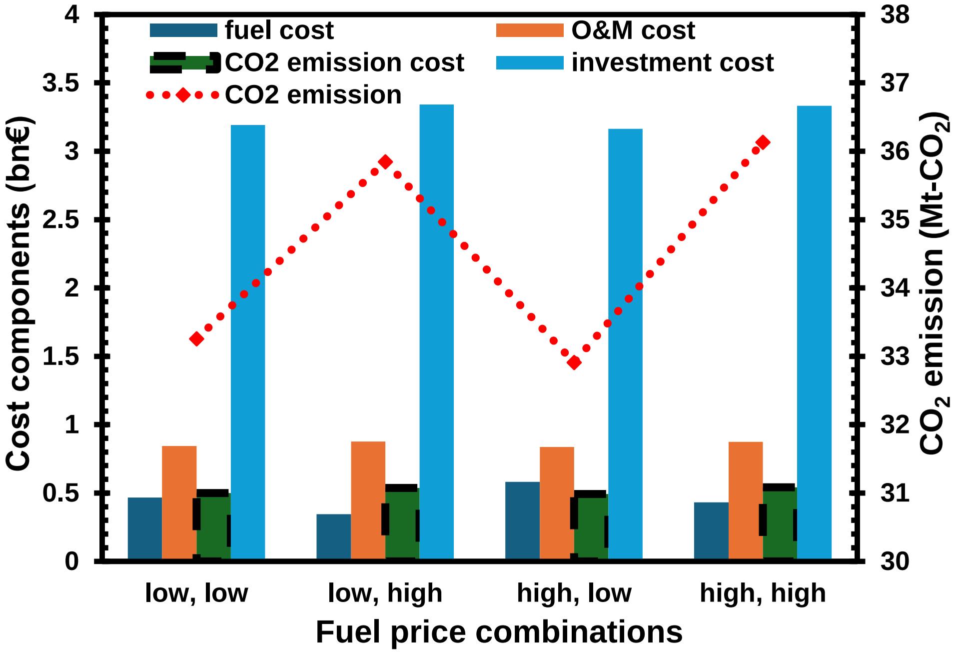

Figure. 4. *Influence of fuel price combinations on cost components and total emission*

Figure 4 shows the influence of four different combinations of fuel prices for Lignite and Gas on the individual costs and the total CO$_2$ emission. The O&MC and the EC remain almost unchanged in all four scenarios; whereas FC and investment are negatively and positively influenced by higher gas price scenarios (scenarios: low, high and high, high). The total emission is also positively influenced by an increase in gas price owing to cumulative increase in emissions from the Lignite with CCS plant, which sees approximately 10 GW expansion when gas price goes up.

3.2. Scenario: RES endogenous

3.2.1. Case A: CO_2 emission price variation

The influence of carbon emission price on the optimal investment on capacity building for the endogenous RES consideration is depicted in Fig. 5. Out of all the technologies, no capacity is invested for Lignite without CCS. This is obvious as the RES plants have much lower investment costs and very low marginal cost. In fact, PV plants have been modelled with zero marginal cost. With an increase in emission price from 100 €/t-CO_2 to 240 €/t-CO_2, the investment in capacity building for all conventional plants except for the GasCCS goes down. Although, Lignite with CCS experiences a tiny increase in capacity (~1.4%) when emission price increases from 100 €/t-CO_2 to 120 €/t-CO_2, beyond which its capacity building falls gradually. On the contrary, the investment for capacity building for the RES plants sees an upsurge with increase in emission price. In particular, the investment in Wind goes up by approximately 30% as emission price increases from 100 €/t-CO_2 to 240 €/t-CO_2.

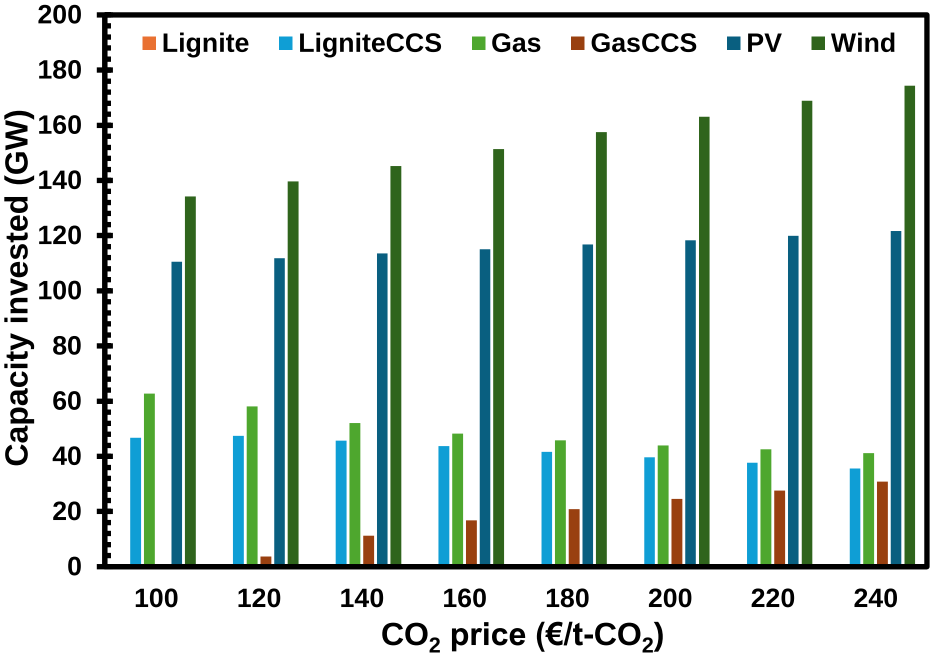

Figure. 5. *Influence of CO_2 emission price on investment*

Figure 6 illustrates the influence of emission price on the individual cost components and cumulative CO_2 emission. With an increase in emission price, the FC first decreases and then monotonically increases, whereas the O&MC first increases and then monotonically decreases. This observation can be attributed to an increase in the LigniteCCS capacity when emission price increases from 100 €/t-CO_2 to 120 €/t-CO_2.The EC goes down by a tiny amount when emission price increases from 120 €/t-CO_2 to 140 €/t-CO_2, as at this junction the capacity added to the GasCCS surpasses the cumulative capacity cut down combinedly from LigniteCCS and Gas without CCS. This has a direct implication on the emission as GasCCS has the lowest CO_2 emission amongst all considered conventional technologies. Beyond 140 €/t-CO_2 price and above the emission cost goes up monotonically. Investment cost demonstrates monotonically increasing pattern for the whole range of emission price. Nevertheless, the total amount of emitted CO_2 goes down from ~46.7 Mt to ~23.5 Mt as emission price is hiked from 100 €/t-CO_2 to 240 €/t-CO_2. This behaviour demonstrates CO_2 emission mitigation by combined RES and CCS penetration in the technology mix.

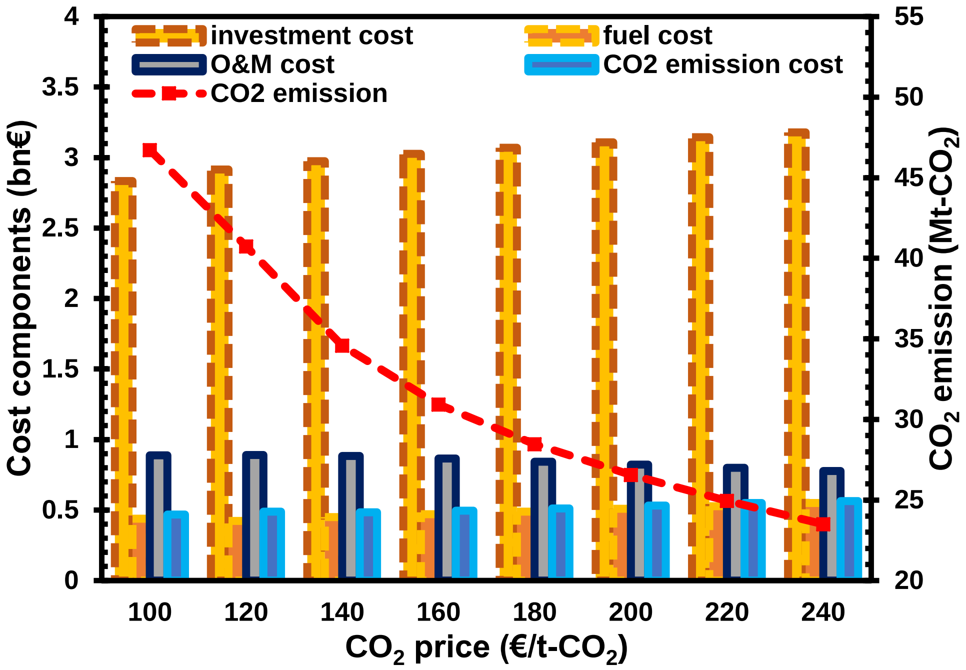

Figure. 6. *Influence of CO_2 emission price on individual cost components*

3.2.2. Case B: Fuel price variation

Figure 7 the shows the influence of fuel price variations on capacity invested. It can be observed that investment in GasCCS is earned only when gas prices are low (scenarios: low, low and high, low); on the contrary, investment in LigniteCCS is earned in all cases. This behaviour is logical as the change in magnitude of coal price from low level to high level is not significant compared to change in magnitude of Gas price. Penetration of PV in the technology mix remains almost unchanged in all cases of fuel price variation whereas Wind earns maximum capacity investment in scenario: high, low.

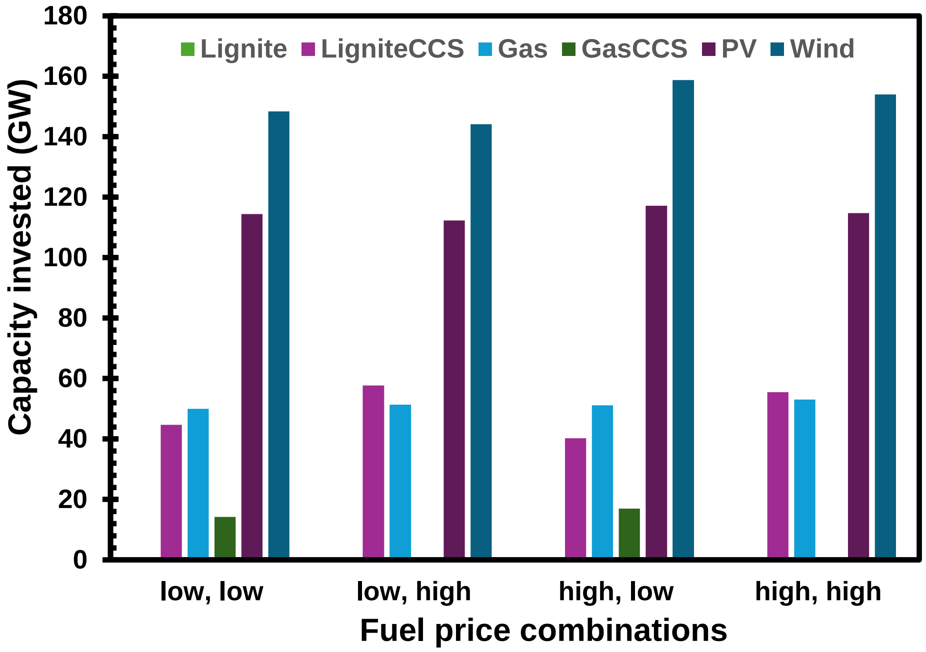

Figure. 7. *Influence of fuel price on investment*

Figure 8 illustrates the influence of four different fuel price combinations for Lignite and Gas on the individual costs and total CO_2 emission. The characteristics of the costs and CO_2 emission are analogous to the characteristics observed for the corresponding analysis performed for the RES Exogenous scenario.

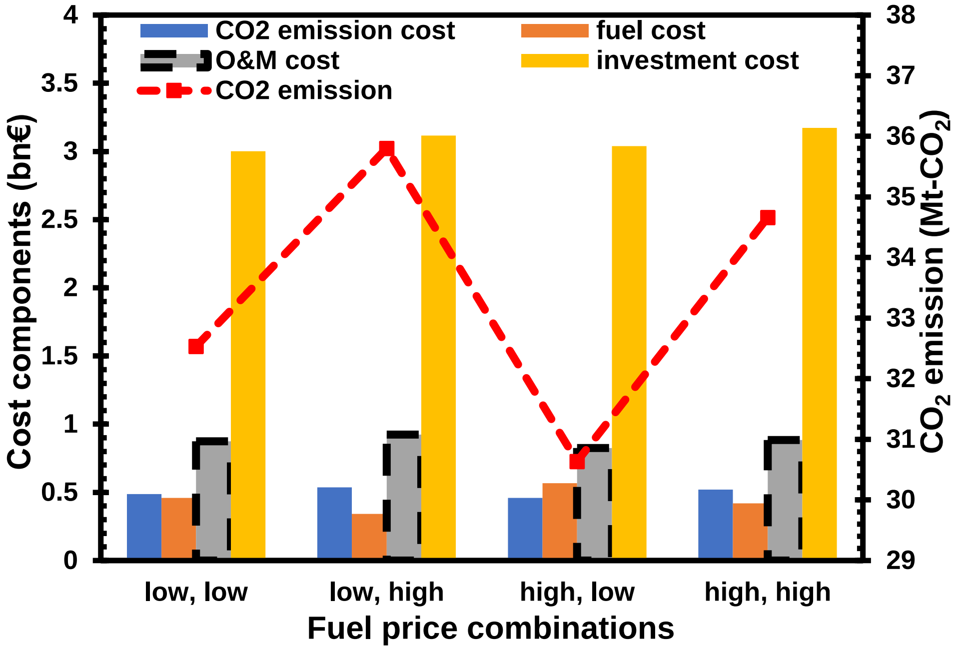

Figure. 8. *Influence of fuel price combinations on cost components and total emission*

3.3. Scenario comparison

3.3.1. Capacity investment

A capacity investment comparison was made between the RES exogenous and RES endogenous for different CO_2 emission prices and is depicted in Fig. 9.

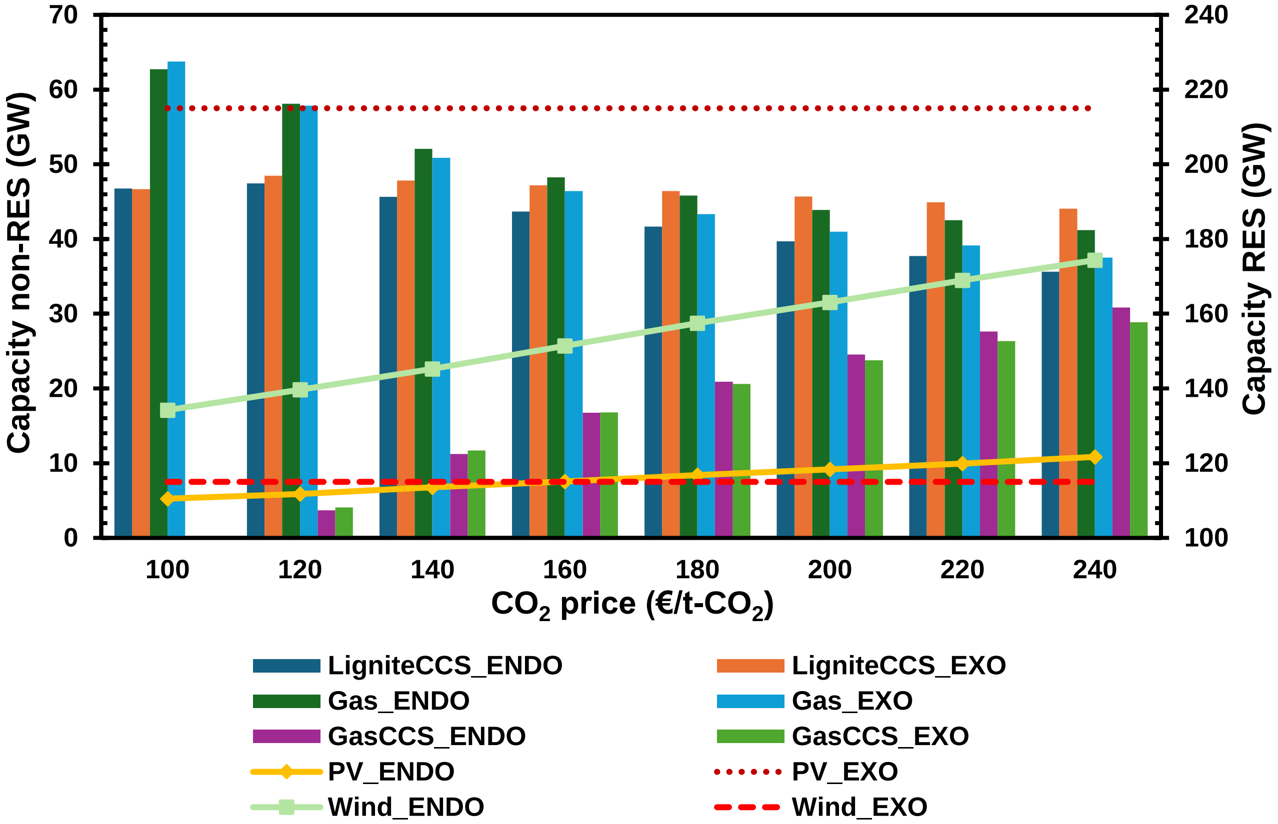

Figure. 9. *Comparison of capacity investment*

When RES capacities are considered endogenous, a large investment is directed towards Wind which is between 16.7%-51.6% higher than that of the exogenous capacity. Whereas, Solar PV sees declined capacity building (~45%) under endogenous scenario compared to its exogenous figure. Such an observation may be attributed to the non-zero availability factor for the Wind compared to Solar, which despite higher capital and O&M cost earns more investment. It is interesting to observe that the gas combustion turbine technology with and without CCS sees increase in capacity investment in endogenous case. On the other hand, the LigniteCCS sees decline in capacity investment under endogenous scenario.

3.3.2. CO_2 emission

Figure 10 illustrates the CO_2 emission levels attained for the RES exogenous and RES endogenous scenarios at different CO_2 emission prices. It can be observed that at CO_2 emission prices exceeding 140€/t-CO_2, the cumulative emission goes down drastically. This may be attributed to tremendous increase in Wind capacity as well as increase in GasCCS capacity.

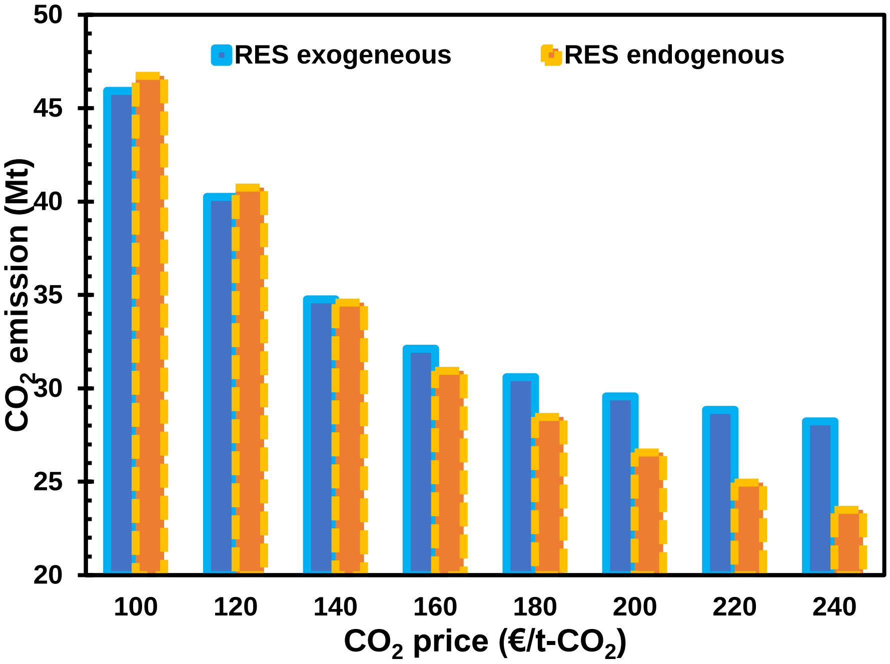

Figure. 10. *Comparison of CO_2 emission*

Conclusions

In this work a greenfield investment model is built in GAMS to forecast the optimum technology mix for power generation in Germany for the year 2030. Despite the coal phase out planned by 2038, the model assumes there could be new investment coming for Lignite plants with and without CCS. The model assumes only two conventional technologies i.e. Lignite and Gas combustion turbine with and without CCS. With the assumed low level of CO_2 emission price (100 €/t-CO_2) in 2030, investment in LigniteCCS is projected to be cost competitive, however, investment in GasCCS becomes cost competitive only beyond 120 €/t-CO_2. Despite the assumed high price for natural gas (i.e., 27-40.5 €/MWh), it remains attractive option for investment even without CCS. When RES capacities are considered endogenous, it reveals that more investment should be directed towards Wind installations compared to the existing plan for 2030. Despite invoking simplified assumptions in the model and inaccessibility to reliable cost data pertaining to CCS deployment in power generation sector, this model results can serve as a starting point for follow up studies with more rigorous technical input and diverse scenario analysis.

Nomenclature

af	Availability factor
CAP	Capacity of power plant, MW
CO2f	Carbon emission factor
CO2P	CO_2 emission cost, €/t CO_2

D	Demand of Electricity, MWh
EC	Total emission cost, €
fc	Unit fuel cost, €/MWh
FC	Total fuel cost, €
G	Generation from power plant, MWh
ic	Annualized investment cost of power plant, €/MW
IC	Total investment cost, €
omc	Operating and maintenance cost for power plant, €/MWh
O&MC	Total operating and maintenance cost, €
TC	Total cost, €
vc	Unit variable cost for power plant, €/MWh
VC	Total variable cost, €

Greek symbols

η	Efficiency of power plant

Abbreviations

CCS	Carbon capture and storage
GAMS	Generic algebraic modelling software

Subscripts

c	Conventional
d	Demand
r	Renewable
t	Time

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