Energy Proceedings ISSN 2004-2965
Vol 27, 2022

Impacts of the Energy Transition on CO_2 Emission From Conventional Coal-fired Power Plants.

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ABSTRACT

The energy generation sectors in many countries around the world are experiencing a great transition period, moving away from fossil-based electricity to cleaner energy sources. Due to regulated emission limits and the integration of renewable energy sources, coal-fired power plants are heavily affected in terms of reduced operating hours and material life-time, lower efficiencies, higher operational expenses, and earlier retirement. By combining both literature review and analyzing real-time operational data from coal-fired power plants, this paper aims to provide an overview on:

- The commercial and technological impacts of the energy transition in Europe (with a focus on Germany)
- CO_2 emission during stationary operations at two lignite-fired power plants.
- CO_2 emission during Start-up processes at a hard coal-fired power plant.
- Potentials for reducing emission as well as lowering operational expenses.

Keywords: coal-fired, power plants, CO_2 emission, renewable energy sources, energy transition.

NONMENCLATURE

Abbreviations	
RES	Renewable Energy Sources
EEG	Eneuerbarer-Energien-Gesetz
EU ETS	European Union Emission Trading Scheme
DIN	Deutsches Institut für Normung
HR	Heat Rate
ems	Emission
OPEX	Operational Expenses

1. INTRODUCTION

With the threat and damages from global warming becoming increasingly apparent and relevant, multiple countries are making comprehensive changes to their energy generation sectors. From the multitude of paths towards carbon neutrality, Germany has chosen to phase out its coal-fired power plants fleet and increase the input from renewable energy sources (RES) such as wind and solar power to its electricity grid. After more than 20 years since the introduction of the Renewable Energy Act (in German: Eneuerbarer-Energien-Gesetz) in 2000, positive changes in terms of CO_2 emission can be observed in the country's energy sector, with emission in 2019 having fallen by 35.1% compared to the level in 1990 and the input from RES in 2021 dominates in ten out of 16 German states [1]. As a result, Germany is selected to highlights the accomplishments and challenges brought about by a transition of the energy sector.

Traditionally, coal-fired power plants were designed to operate at predictable load patterns with low variability [2], meaning they were optimized to run at base load as efficiently as possible [3]. The increase in the share of volatile energy sources in the grid forces the coal-fired power plants to be more flexible to adapt to a greatly varying load profile and thus giving rise to challenges not accounted and compensated for during the design phase, such as more Star-ups, Shutdowns (for definition see section 4), unplanned unavailability, operations in low-efficiency min- to part-load region, higher specific CO_2 emission, higher strain and damage on high-pressure components, etc. This paper, by means of literature analysis, first gives an overview on the current state of the energy transition in Germany in terms of CO_2 emission. Then, by analyzing real-time operational data from three coal-fired power plants, the techno-economic impacts on coal-fired power plants along with measures to mitigate these impacts will be discussed in details.

2. COMMERCIAL AND TECHNOLOGICAL EFFECTS

2.1. Merit order rating and CO_2 certificate trading

Figure 1 and 2 show the share of electricity production from various sources in Germany in November 2010 and 2021. It can immediately be seen that the input from wind and solar power has increased sharply, while the share of coal-fired electricity has been reduced considerably, with periods of almost no production. As mentioned before, due to the nature of RES being volatile and unpredictable, conventional power stations, including coal-fired plants, now operate in a load-following manner, in which they are to supplement the output of RES by either ramping/starting up to compensate for the residual demand that RES cannot provide at the time [3], or ramping/shutting down due to unforeseen over-generation from RES. The Renewable Energy Act heavily favors RES by giving their output feed-in priority into the grid. As a result, the average output from hard coal-fired power plants fell from around 15 GW to 6 GW, and that of lignite-fired plants decreased to 12 GW from 14 GW. Consequently, this is equivalent to around 320 million tons less CO_2 per year [4]. Additionally, hard coal power plants no longer cover the peak-load demands, that roll is being filled by gas-fired units.

Another factor which hinders the operation of coal-fired power units is the mechanism of CO_2 certificate trading. In 2005, the European Union established in the EU Emission Trading Scheme (EU ETS), a cap-and-trade system, with the goal of reducing CO_2 emission by imposing a tax based on the amount of emission from the allowances holder. The number of certificates (or allowances) available each year continuously decreases, along with the emission cap. Additionally, the price per certificate has been rising continuously since 2018, to roughly 70 € per ton CO_2 emitted at the end of 2021 [5]. Companies also face heavy fines if their emission exceeds the amount allowed in the certificates they have in possession [6]. This incentivizes companies to implement measures to reduce their total carbon emission, otherwise they will suffer economically from rising CO_2 prices.

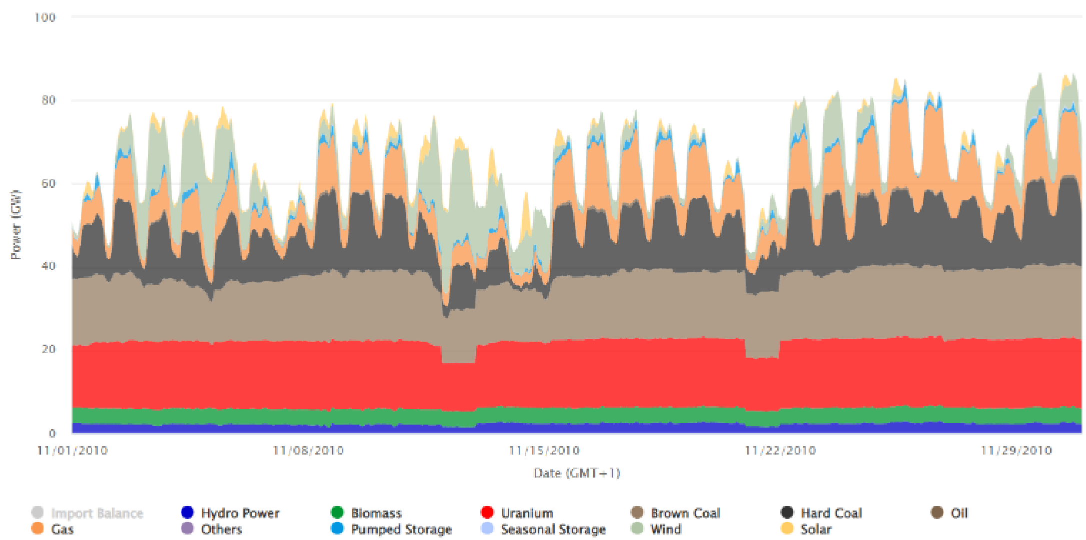

Fig. 1 Electricity production in Germany in November 2010 [7]

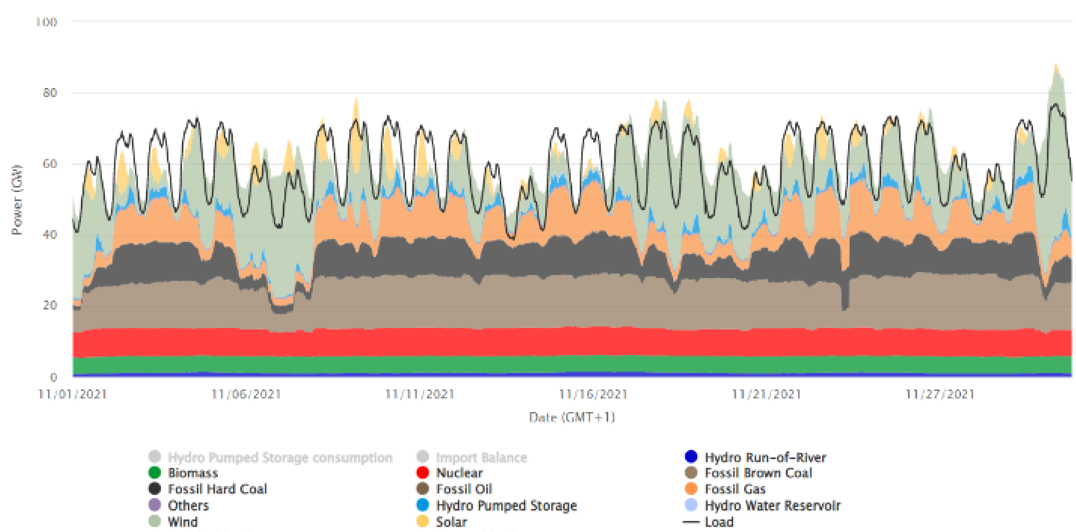

Fig. 2 Electricity production in Germany in November 2021 [7]

The European Green Deal, presented in December 2019 and adopted officially in July 2021 as the 2030 Climate Target Plan, proposed raising the emission reduction target to 40% to 50% compared to 1990's level. According to Pietzcker et al., this implies a further tightening of the already stringent EU ETS [8]. The results of their study predict net zero emission to be achieved in 2040, CO_2 certificate price to rise to 150€ per ton by 2030, with the sharpest increase occurring between 2021 and 2030. At the same time, coal phase out is likely to be completed by 2030.

The deployment of (conventional) power plants in the market is determined by the variable costs of each power plants, the lower these costs are, the more the plants will be utilized. These cost are determined by fuel prices, plant efficiency, and cost of CO_2 certificates in the European Trading System [9]. This results in the so-called merit order rating, which shows the priority order in which power plants can feed their produced energy into the grid. Figure 3 provides comparison of the merit order between low/no CO_2 price and high CO_2 price. An increase in the CO_2 price will push the emission-heavy technology to the right of the curve, giving way to less carbon-intensive technology to take priority in terms of dispatch order [10]. RES will of course be at front of the bidding stack, not only because they are favored by the EEG, but also due to the fact that they have no fuel cost and are not directly affected by changes in CO_2 price.

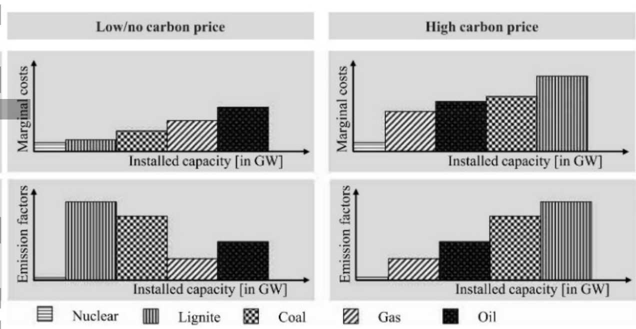

Fig. 3 Merit order at low and high CO_2 prices [10]

2.2. The situation in Germany

In the Germany, there was a drop of 46.1 million tons of CO_2 (5.4%) between 2018 and 2019. The energy sector had the highest share of emission in 2019, at 31.9%, however, it also experienced the largest reduction amount from 309 million tons of CO_2 in 2018 to 258 million tons in 2019 [1]. As impressive as these achievements may seem, the rate at which the energy transition is progressing was still not enough to meet 40% CO_2 reduction by 2020 and will not be enough to reach the newly adopted target of 55% by 2030, therefore, more action and policies are needed [11].

If there is one lesson to learn from the energy transition in Germany, it would be that in order for the process to succeed, strong climate- and energy-related policies need to be introduced. It is a long -term commitment, and it is political and societal as much as it is technological. The cooperation between different fields with a common goal of reducing the impact humanity has on the climate is absolutely vital for its success [11]. All of the required technologies for a renewables-based electricity system, and to achieve carbon-neutrality may already be readily available [9].

2.2.1. Lignite characteristic in Germany

Germany is the world's largest lignite coal miner, with the majority of the product being used directly for the power plants. There are three major lignite mining regions in Germany: Rheinland, Lausitz, and Mitteldeutschland. The coals from these regions vary in terms of Sulphur contents, and because Sulphur content has an influence on fuel's net calorific value (NCV), it also affects the net calorific value/carbon ratio [12].

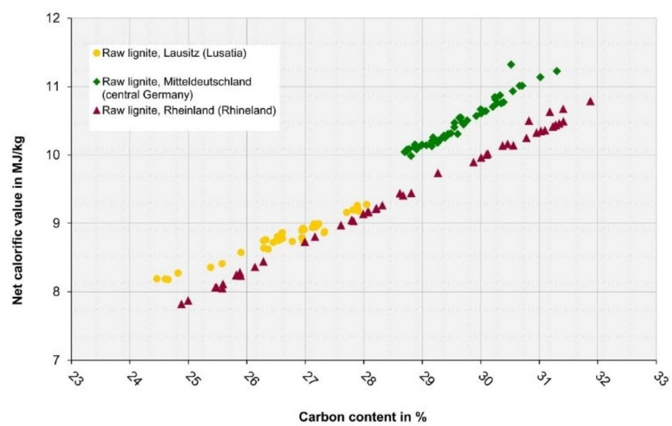

Fig. 4 NCV vs carbon content of lignite in Germany [12]

The lignite in Germany has net calorific values ranging from 7.8 MJ/kg to 11.3 MJ/kg (figure 4). For use in the public electricity sector, the emission factor of the lignite coal is 110.8-111.7 tons CO_2/TJ [12]. This translates to 800 to 965 g CO_2 per kilowatt hour electricity (gCO_2/kWh_{el}) for common lignite-fired power plants. For state-of-the-art plants, the emission factor is slightly better, from 791 to 953 gCO_2/kWh_{el} [2]. Lignite contributes around 47% of emission in the German power sector and is therefore incompatible with the targets of 80% GHG reduction by 2050 [11].

2.2.2. Hard coal characteristics in Germany

Unlike lignite, which is mined from and used directly in Germany for power generation, the share of domestically mined hard coal that is used in Germany has been decreasing. Back in 1990, the share of domestically mined hard coal in Germany was 81.3%, in 2016, that number was only 12.5% [12]. With the closure of the last hard-coal mine at the end of 2018, Germany now relies solely on import hard-coal for its electricity generation [12]. Due to the fact that hard coals are being imported from various sources, the carbon content and consequently the NCVs also vary greatly depending on the origin. Overall, the NCVs of hard coal used in Germany ranges from 21 to 32 MJ/kg with most averaging around 25 MJ/kg (figure 5).

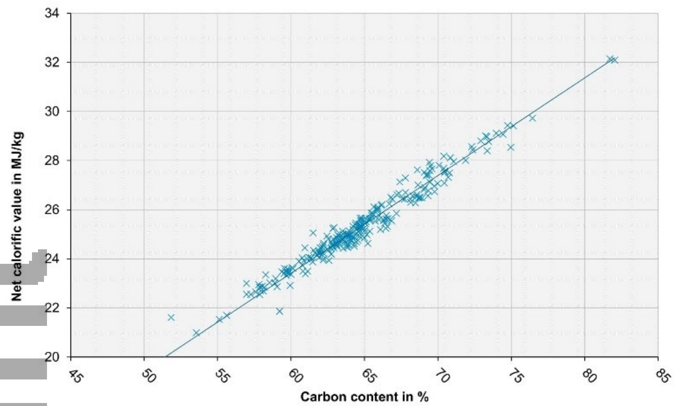

Fig. 5 NCV vs carbon content of hard coal used in Germany [12]

In terms of CO_2 emission, on average, common hard coal-fired power plants produce 756-814 g CO_2/kWh_{el} while state-of-the-art plants emit 707-761 g CO_2/kWh_{el} [2]. From an economic perspective, it is advisable to phase out hard coal-fired power plants before lignite-fired ones due to higher fuel price and the increasing cost for CO_2 certificates. From a climate protection view however, hard coal is the cleaner of the two coal-fired options, so it makes little senses to opt for phasing out hard coal and extending the service life of lignite-fired power plants.

2.3. Flexible operations and CO_2 emission

According to Agora Energiewende [2], "the flexibility of a power plant can be described as its ability to adjust the net power fed into the grid, its overall bandwidth of operation and the time required to attain stable operation when starting up from a Standstill." From this definition, three parameters of flexibility can be arbitrarily formulated: **Minimum load rate** (henceforth **min load** or **min-load**), **ramp rate**, and **Start-up time**.

2.3.1. Min load

Load rate is defined as the current electrical energy output of the power plant divided by the designed base output. It is calculated simply as follow:

$$Load\ Rate = \frac{P_{el,act}}{P_{nominal}} * 100\% = \frac{E_{el,act}}{E_{nominal}} * 100\% \quad (1)$$

Min load can be understood as the minimum load rate at which a power plant can operate without incurring stability issues. It is often seen as the most important criteria for flexible operation of power plants [13]. By avoiding total Shutdown of the power plant, fuel- and emission-intensive Start-ups can be avoided, and consequently the amount of CO_2 decreases. This might seem counter-intuitive, because no CO_2 will be emitted during periods of total Shutdown. However, power plants require a large amount of input heat during Start-up processes just to reach operational status [2], which leads to more fuel being burnt and more CO_2 being emitted while little to no useful energy is being produced. Consequently, while overall emission might decrease with total Shutdown of the power plants, the specific CO_2 emission (g/kWh_{el}) will increase substantially after each Shutdown and Start-up cycle.

"For instance, a hot Start-up at a 750 MW hard coal-fired power plant requires approximately 1,820 MWh of thermal energy. This is about the same quantity required to operate the power plant at nominal load for approximately an entire hour. The fuel needed for the Start-up translates into roughly 620 tons of CO_2 emissions. [2]"

There is also a trade-off in terms of plant efficiency when it comes to flexibilization as the efficiency of the power plants decrease alongside load reduction, which also means more CO_2 being produced for the same amount of electrical energy generated. On average, reducing the power output by 20% will result in a drop of 2% to 5% in efficiency. Therefore, there is a need for balance between flexibility and efficiency [2].

This efficiency-reducing effect of lowering min load should be evaluated over the entire operation period and not just during periods with lowest efficiency. When done so, the overall efficiencies of the power plants are much closer to their designed value , and as a result, the benefits of reducing min load in terms of CO_2 emission outweigh its drawbacks [2]. Furthermore, one study pointed out that as the share of RES in the grid increases, reducing min load will lead to a decrease of CO_2 emission (figure 6). This is especially true for electricity systems with low penetration of RES. On the contrary, if a system includes coal-fired power plants with high min-load values, increasing the share of RES might increase the level of CO_2 emission. This means that the integration of RES must be accompanied by efforts to optimized existing coal-fired power plants for flexible operations with reduction of min load being the criterion of highest priority.

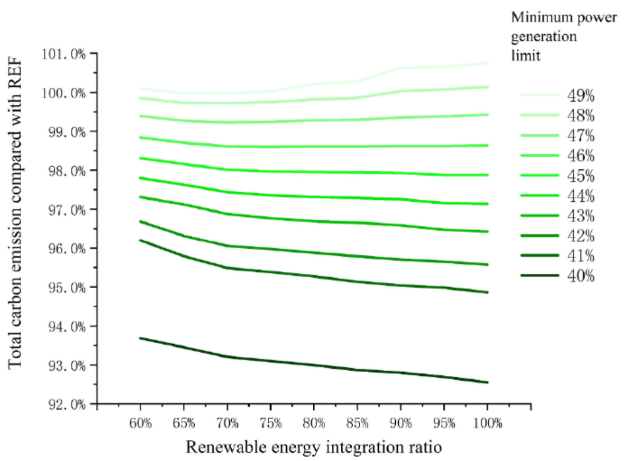

Fig. 6 RES ratio vs CO_2 emission at various min load levels [14]

2.3.2. Ramp rate

Ramp rate indicates how quickly a power plant can adjust its output to meet the requirement of the grid. High ramp rates ensure fast reaction to changes in the market condition. According to [15], it is calculated with the following formula:

$$\omega = \frac{|P_{el,t} - P_{el,t-1}|}{\Delta t * P_{nominal}} \tag{2}$$

Typically, the ramp rate of a power plant depends on the technology or the generation of the plant itself. In terms of CO_2 emission, unfortunately, one study has found a positive correlation between high ramp rate and the amount of CO_2 emission (figure 7). Additionally, rapid changes in temperature result in thermal stress for plant components [2]. These drawbacks must be accepted to improve the ramp rate of coal-fired power plants since they now mostly operate in load-following condition and are seen as secondary sources of electricity.

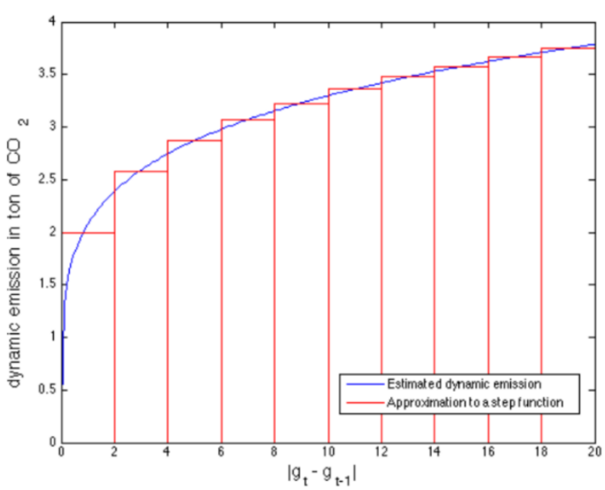

Fig. 7 CO_2 emission plotted against absolute difference in power output between two time points [15]

2.3.3. Start-up time

Finally, Start-up time indicates the time it takes from the moment the plant starts its operation until it reaches minimum load [2]. Start-up time varies among different generations of power plants and also depends of the type of Start-up process that a power plant undergoes. Start-up processes are classified according to how long the plant has been out of operation before beginning of operation. Three types of Start-ups, defined by Gostling in 2002 [16], are adopted for use throughout the industry:

- Hot Start-up: The plant has been out of operation for less than eight hours;
- Warm Start-up: The plant has been out of operation between eight and 48 hours;
- Cold Start-up: The plant has been out of operation for longer than 48 hours.

Of the three processes, cold Start-ups have the potentials to cause the most damage to plants components due to large temperature differences that occur during Start-up [2]. Another disadvantage of frequent Start-up is the consumption of expensive ignition fuels, such as oil, which can also release harmful soot and heavy hydrocarbons [17] to the environment. As the penetration of RES increases, Start-up processes will occur with greater frequency. Therefore, it is necessary to adopt appropriate measures to not only protect the components of the power plants within their remaining lifetime, but also to reduce the emission of harmful by-products of the combustion process.

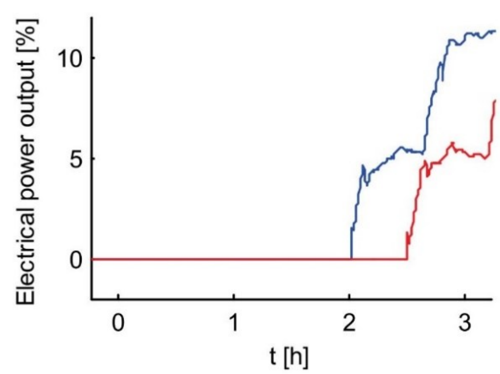

Fig. 8 Comparison of electrical output against time duration at a STEAG power plant from beginning of Start-up to synchronization of the turbine. Blue: Automated, Red: Manual [18]

Common measures implemented to improve flexibility in terms of Start-up operations include: Accurate and reliable control of Start-up fuel; model-based thermal stress calculator; automated Start-up; Start-up optimization; improved ramping. Experience after Start-up optimization at one of the coal-fired power plants owned by STEAG GmbH shows faster pressure build-up, quicker Start-up and synchronization of the turbine, and hence less oil and coal consumptions when compared to manual Start-up processes under similar initial conditions [18].

2.4. *Effects of frequent load changes on boilers (and other high-pressure components)*

Most coal-fired power plants in Germany belong to the older generation, averaging between 27.3 and 30.4 years per MW when weighted with capacity and around 32.9 when weighted with the number of units [19]. These plants were designed before the emergence of the flexibility requirements stemming from the integration of the RES, and thus the basic criterion for selection of materials for pressure parts of boilers was creep resistance [17]. Creep damage occurs when components run at high temperature (approximately 450°C or above) and high pressure for a prolonged period of time, and the higher the temperature and pressure, the higher the degree of creep damage. Standard design guidelines such as DIN EN 12952-3 suggest that thick-walled boiler components are needed to contain the fluid within to ensure safe operation. Alternatively, more expensive materials of higher quality will be needed.

Nowadays, coal-fired power plants are forced to adapt to an increasingly varying load pattern and as a result, the pressure components experience steep temperature transients across the material's thickness and high number of Start-up and Shutdown cycles [20]. These components are designed to withstand only a certain number of Start-up/Shutdown cycles within their lifetimes. In this new operating condition, as the number of load changes also increases (as will be discussed in section 4.2), the share of fatigue damage increase. Fatigue damage in this context is defined as thermal stress from cyclic non-uniform heating across the thickness of the components' wall.

When factoring in the interaction between creep and fatigue damage, the critical damage D_{CR} is a non-linear function of creep and fatigue damage, and is smaller than one [21]. This significantly reduces the region of allowable damage (figure 9). As the share of RES and subsequently the number of load cycles for coal-fired power plants increases, the proportion of fatigue damage in high-pressure components also increases. Considering the strategy of increasing boilers' flexibility, the expected time of remaining operation should be taken into account [17].

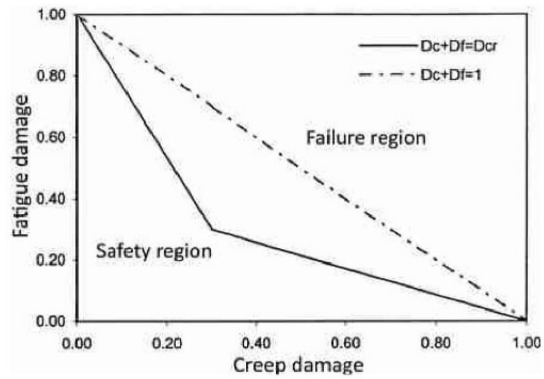

Fig. 9 Damage evaluation [17]

3. CO_2 EMISSION DURING OPERATIONAL PHASES AND REDUCTION POTENTIALS

Data to investigate CO_2 emission in steady-state operation phases in the year 2020 was taken from two lignite-fired power plants, henceforth named "Lignite 1" and "Lignite 2" and was provided by STEAG Energy Services GmbH [22]. Lignite 1 was built in the 1970s and will represent the power plants belonging to older generation using legacy technology. Lignite 2 was built in the 2010s and is used as an example for the latest technology available for coal-fired power plants in the market. These two power plants mix two types of lignite with different characteristics together for their operation.

3.1. *Calculation steps*

The following calculation steps were performed to evaluate the effects of load-following operations on lignite-fired power plants:

1. Fuel demand per hour or input heat flow, actual and reference [MJ/h]:
$$\dot{Q}_{in,act} = \frac{P_{el}}{\eta_{act}} * 3600;\ \dot{Q}_{in,ref} = \frac{P_{el}}{\eta_{ref}} * 3600$$
2. Carbon mass flow in coal 1 and 2, actual and reference [kg/h]:
$$\begin{cases} \dot{m}_{Ci,act} = \dot{m}_{i,act} * C\%_i \\ \dot{m}_{Ci,ref} = \dot{m}_{i,ref} * C\%_i \end{cases} \text{with } i = 1 \text{ or } 2$$
3. CO_2 emission per hour from coal 1 and 2, actual and reference [kg/h]:
$$\begin{cases} \dot{m}_{CO2,i,act} = \dot{m}_{Ci,act} * \frac{44}{12} \\ \dot{m}_{CO2,i,ref} = \dot{m}_{Ci,ref} * \frac{44}{12} \end{cases} \text{with } i = 1 \text{ or } 2$$
4. Total CO_2 emission per year, actual and reference [tons]:
$$\begin{cases} m_{CO2,total,act} = \frac{\sum \dot{m}_{CO2,act}}{1000} \\ m_{CO2,total,ref} = \frac{\sum \dot{m}_{CO2,ref}}{1000} \end{cases}$$

5. Total CO_2 saving potential per year: $\Delta m_{CO2,total} = m_{CO2,total,act} - m_{CO2,total,ref}$
6. Relative load percent: according to equation (1)
7. Classify all processes into 3 categories:
   - Min-load ($\%Load \leq 50\%$),
   - Part-load ($50\% < \%Load \leq 90\%$),
   - Full-load ($\%Load > 90\%$)
8. CO_2 saving potential:

$$\%reduction_{CO2} = \frac{\Delta m_{CO2,\text{total}}}{m_{CO2,\text{total},act}}$$

9. Fuel consumption actual and reference [tons/h]:

$$\dot{m}_{fuel,act} = \frac{\frac{P_{el}}{\eta_{act}}}{NCV_{mixed}} * \frac{3600}{1000}$$

$$\dot{m}_{fuel,ref} = \frac{\frac{P_{el}}{\eta_{ref}}}{NCV_{mixed}} * \frac{3600}{1000}$$

10. Fuel consumption difference [tons/h]:

$$\Delta\dot{m}_{fuel} = \dot{m}_{fuel,act} - \dot{m}_{fuel,ref}$$

11. Fuel saving potential:

$$\%reduction_{fuel} = \frac{\Delta\dot{m}_{fuel}}{\dot{m}_{fuel,act}}$$

12. Relative fuel consumption and CO_2 emission per MWh, actual and reference [tons/MWh]:

$$m_{fuel,rel.,\text{act}} = \frac{\dot{m}_{fuel,\text{act}}}{P_{el}};\ m_{fuel,rel.,\text{ref}} = \frac{\dot{m}_{fuel,\text{ref}}}{P_{el}}$$

$$m_{CO2,rel.,\text{act}} = \frac{\dot{m}_{CO2,\text{act}}}{P_{el}};\ m_{CO2,rel.,\text{ref}} = \frac{\dot{m}_{CO2,\text{ref}}}{P_{el}}$$

13. Relative fuel consumption and CO_2 emission difference [tons/MWh]:

$$\Delta m_{fuel,rel.} = m_{fuel,rel.,\,act} - m_{fuel,rel.\,,\,ref};$$

$$\Delta m_{CO2,rel.} = m_{CO2,rel.,\,act} - m_{CO2,rel.\,,\,ref}$$

14. Actual and reference heat rate [MJ/MWh]:

$$HR_{act} = \frac{Q_{in,act}}{E_{el,act}} HR_{ref} = \frac{Q_{in,ref}}{E_{el,ref}}$$

15. Design heat rates HR_{des} and efficiencies η_{des}: average of **reference** heat rates and efficiencies when the units are in full load operation
16. Average heat rates HR_{avg} and efficiencies η_{avg} : average of all **actual** heat rates and efficiencies
17. Min- and part-load heat rates and efficiencies $HR_{min,part}$ and $\eta_{min,part}$: average of all actual heat rates and efficiencies while relative load $\%Load < 90\%$.
18. Equivalent full load hours [h]:

$$t_{eq} = \frac{E_{el,act}}{P_{nominal}}$$

19. Capacity factors of the power plants [%]:

$$CF = \frac{E_{el,act}}{P_{nominal} * \Delta t}$$

3.2. Results and discussion

Heat rate and efficiency are heavily affected as the plants operate in lower load ranges. The difference between intended performance as determined in plant's design and actual values are higher when compared between older and new generations of power plants, 1,234.25 MJ/MWh for Lignite 1 and 390.67 MJ/MWh for Lignite 2. Average efficiencies in min- and part-load conditions are much lower compared to design values. As a result, average efficiencies across all load ranges are lower compared to the efficiency as per designed (i.e., during full-load operation) due to an increase in min- to part-load operations. It is worth noting that the changes in heat rates and efficiencies are not noticeable for Lignite 2 until the relative load drops below 70% (figure 10). Higher heat rates or lower efficiencies mean that the power plant has to consume more coal to produce the same amount of electricity, which leads to higher relative CO_2 emission overall and especially during min-load conditions (as can be seen in *Table 2*)

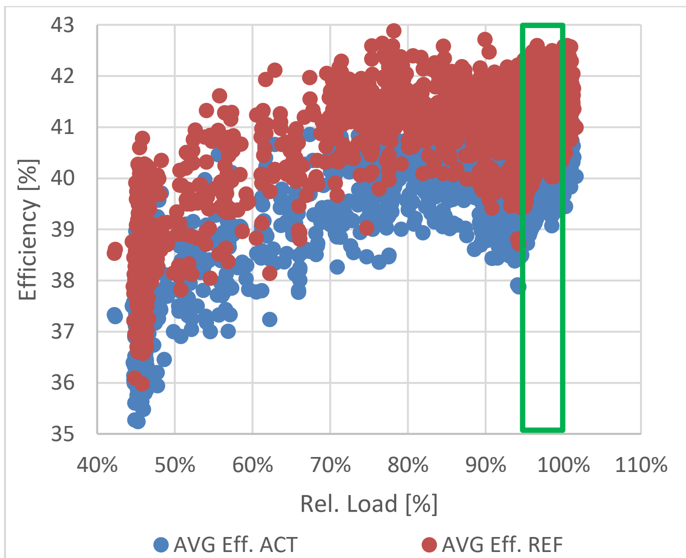

Fig. 10. Lignite 2's efficiency plotted against relative load. The green rectangle represents the load range that the power plant was designed to operate in.

Parameters	Unit	Lignite 1	Lignite 2
Design heat rate HR_{des} (reference full load)	[MJ/MWh]	9,622.65	8,630.49
Average heat rate HR_{avg} across the entire load range	[MJ/MWh]	10,856.90	9,021.16
Average heat rate during min- and part-load conditions $HR_{min,part}$	[MJ/MWh]	11,520.13	9,335.38
Design efficiency η_{des} (reference full load)	[%]	35.28	41.19
Average efficiency η_{avg} across the entire load range	[%]	33.22	39.94
Average efficiency during min- and part-load conditions $\eta_{min,part}$	[%]	31.37	38.62
Equivalent full load hours	[h]	2,042.48	4,680.50
Capacity factor	[%]	23.32	53.43

Table 1: Operational parameters at Lignite 1 and Lignite 2 across three load ranges (step 14 to 19 in section 3.1)

	Lignite 1			Lignite 2		
	Min-load	Part-load	Full-load	Min-load	Part-load	Full-load
Run time [h]	218 (9.86%)	259 (11.72%)	1,733 (78.42%)	434 (8.37%)	553 (10.67%)	4,196 (80.96%)
CO_2 ems. (SUM) [tons/year]	80,244	132,981	1,269,947	226,182	435,570	4,265,819
Rel. CO_2 ems. (AVG) [tons/MWh]	1.33	1.24	1.19	1.07	1.00	0.99
Rel. fuel con. (AVG) [tons/MWh]	1.20	1.16	1.12	1.09	1.01	1.01

Table 2: CO2 emission-related operational parameters (step 4, 12 in section 3.1)

The number of hours per year operating in full-load has been reduced from roughly 8000 as per designed to 1,733 hours and 4,196 hours for Lignite 1 and Lignite 2, respectively. When only steady-state conditions in a year are considered, the results are only 2,210 hours for Lignite 1 and 5,182 hours for Lignite 2. For the remaining time in the year, these power plants are either ramping up/down, or in Standstill states. In terms of total CO_2 emission, due to the fact that the power plants spent close to 80% of their steady operation time in full load condition, the CO_2 emission figures in this category are the highest among the three load categories. However, when comparing the relative CO_2 emission and associated fuel consumption across the three categories, min-load operation emits the highest amount of CO_2 per MWh produced. The gap between min-to part-load and full-load operation is higher for Lignite 1, implying that for this particular investigation, the older-generation power plant is more heavily impacted. This result coincides with the findings from de Groot (2017) [3].

3.3. Emission reduction potential

Potentials are identified by comparing measured or calculated steady-state operation parameters to reference values calculated in real-time using STEAG's EBSILON®Professional, a comprehensive physics-based software designed to model and simulate thermodynamic processes for the purpose of plant planning, design, and optimization.

In reality, an increase in heat rate (or decrease in efficiency) is unavoidable when the plants operate in non-optimal conditions. This is because of the drop in efficiency in the water-steam cycle (due to lowered steam temperature and pressure) while energy consumption of auxiliary devices remains relative unchanged [13]. Experience from practice shows that not all 100% of the potential identified by the thermodynamic simulation can be leveraged through operational and/or I&C optimization [22]. Assuming only half of the potentials for improvement in efficiency can be leverage, efficiency for all load ranges at Lignite 1 will be increase by 1.03% and at Lignite 2, 0.63%. The amount of fuel consumption and CO_2 emission reduction that follows the increase in efficiencies is summarized in the table below.

	Lignite 1			Lignite 2		
	Min-load	Part-load	Full-load	Min-load	Part-load	Full-load
CO_2 ems. difference [tons/year]	2,670	4,089	37,606	3,758	6,808	65,783
Fuel cons. difference [tons/year]	2,600	4,053	37,069	3,854	6,911	66,821
Fuel cons. or CO_2 ems. difference [%]	3.33	3.07	2.96	1.66	1.56	1.54

Table 3: Fuel and CO_2 saving potential after assumed optimization and retrofitting increase efficiency across all load range (step 5, 10, and 13 in section 3.1 but with new reference values)

4. CO_2 EMISSION DURING START-UP PROCESSES AND REDUCTION POTENTIALS

Data for this analysis was taken from a hard coal-fired power plants (henceforth known as HC) from 2015 to 2021 to evaluate CO_2 emission during Start-up phases.

The following process definitions (provided by STEAG [22]) are necessary for the analysis:

- Standstill defines the stationary state of the unit without operation of the boiler or steam turbine and therefore without production of useful electricity.

- Start-up begins with a triggering event that increases energy demand when compared to Standstill; ends with the synchronization of the generator into the electricity grid.

- Warm-up is the operation after synchronization, the unit is already generating useful energy, but the components have not fully reached operational conditions. As a result, this process has increased input energy demand compared to stationary process that produces the same amount of electricity.

- Shutdown: begins with the disconnection of the generator from the grid; ends with a triggering event putting the unit into Standstill.

4.1. *Data preparation steps*

1. Classify the time point in Mappe2 according to the processes recognized by the module;
2. Calculate daily relative load;
3. Sum up the CO_2 emission values from coal and oil for each process;
4. Sum up the CO_2 emission values for consecutive Start-up and Warm-up processes;
5. From given parameters, calculated the amount of heat input and fuel consumption;
6. Plot CO_2 emission m_{CO2} and heat input against duration Standstill $t_{Standstill}$;
7. Because raw data set was scattered, making it difficult to form meaningful conclusion, more filtering using statistical methods were required to obtain good data for use in analysis.

It is worth noting that this evaluation will focus on Start-up processes with less than 100 hours in Standstill mode since it is assumed that the downtime of power plants will decrease in the future following an increase in the frequency of the Start-up to Shutdown cycles. Another assumption is that this power plant is more advanced compared to other hard-coal power unit in service around the world, and might be able to reach sufficient generating capability to be able to synchronize with the grid sooner than its less modern counterparts, leading to less CO_2 emission per Start-up. As a result, CO_2 emission figures from Start-up and Warm-up are added together to make the evaluation more representative of the current state of hard coal-fired power plants in the world.

4.2. *Result and discussion*

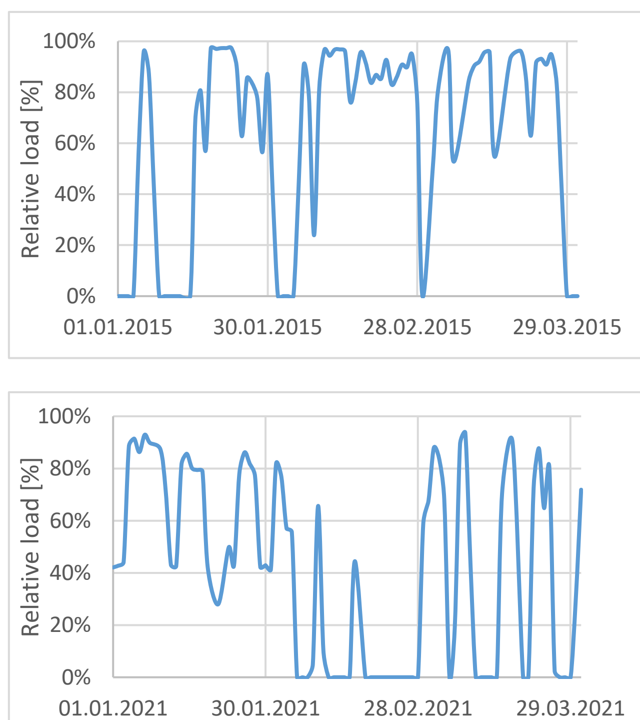

Fig. 11 Daily relative load of Q1 2015 (top) compared to that of Q1 2021 (bottom)

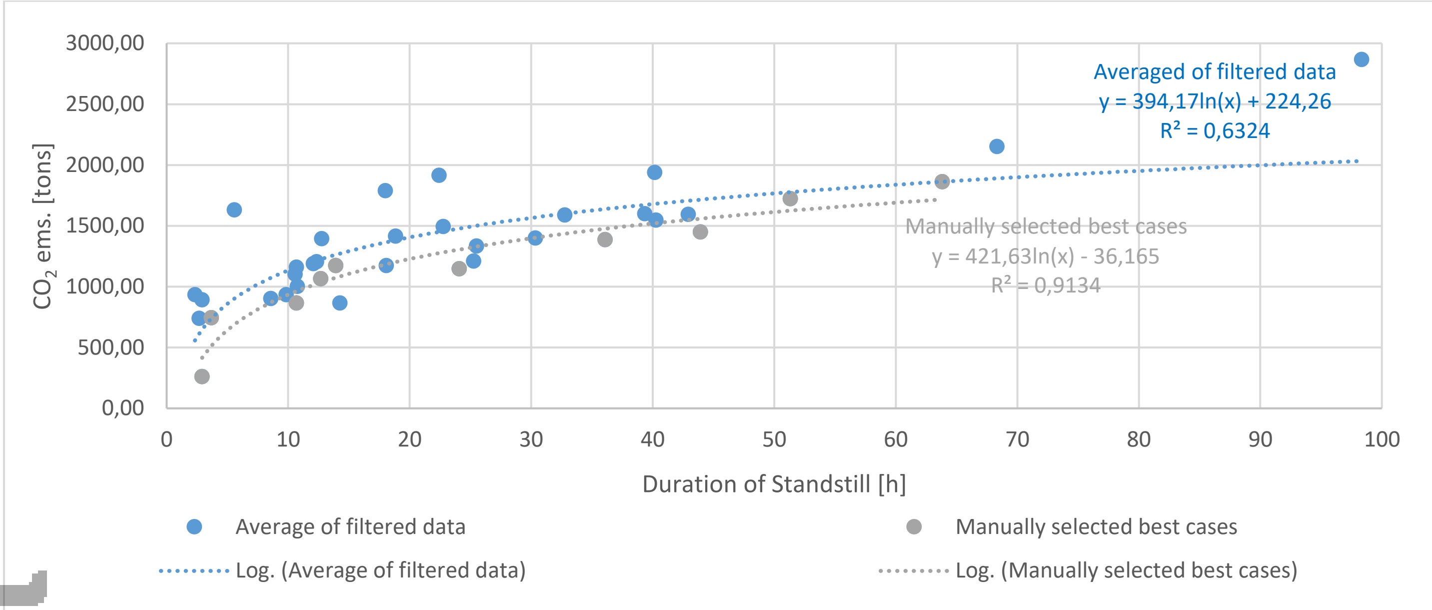

Fig. 12 Filtered CO_2 emission plotted against duration of Standstill

When comparing the relative load between Q1 2015 and Q1 2021, more instances of full load operations can be seen in Q1 2015. The power plant could maintain operation at full load condition for a longer period of time, possibly due to different market boundary conditions (such as lower input from RES). In Q1 2021, there was no stationary operation at full load condition, along with more cases of ramping up and down. Additionally, there were more Start-up and Shutdown operations, with a total of three cold starts having taken place between 12.02.2021 and 15.03.2021. This particular power plant was designed for 200,000 hours of full-load operation, with a maximum of one cold starts per year [23]. The differences between assumed and actual operational conditions highlight the need to not only optimized the power plants for flexible operations, but to also reduce the amount of relative CO_2 emission that follows each Standstill period. Furthermore, the increased number of Start-ups also leads to a rise in low cycle fatigue damage, which may affect remaining lifetime of the project. The current mode of operation differs greatly from what was assumed the design process.

Figure 12 shows the correlation between CO_2 emission and duration of Standstill after the data was filtered. Under 60 to 70 hours of Standstill, there is a strong correlation between duration of Standstill and the amount of CO_2 emission during the Start-up and Warm-up processes that follows afterward. There is also a large amount of data points that are below the best-fit curve, which represent potentials for the processes to be optimized further to reduce the amount of fuel consumption and subsequent CO_2 emission. Above the 70-hour mark, there is insufficient data to make a conclusion regarding the correlation between duration of Standstill and CO_2 emission as well as potential for reduction.

4.3. Reduction potentials

After filtered CO_2 emission is plotted against duration of Standstill, the grey dots in figure 8 was manually selected to represent best-case Start-ups that could occur after optimization of the process, while still remaining realistic. On average, CO_2 emission can be reduced by 183.21 tons per Start-up, which amounts to 11.40% of current actual emission.

The same instances of best-case Start-ups and Warm-ups are used to evaluate the amount of heat input and fuel consumption from oil and coal that can be saved by optimizing the system. The calculation to derive the saving potential includes the following steps:

1. Actual mass of coal consumption:

$$m_{coal,act} = \frac{m_{CO2,coal,act} * \frac{12}{44}}{C\%}$$

2. Actual heat input from coal and oil:

$$Q_{coal,act} = m_{coal,act} * NCV_{coal}$$

$$Q_{oil,act} = \frac{m_{CO2,oil,act}}{emf._{oil}}$$

$$with\ emf. = emission\ factor\ from\ oil$$

3. Actual volume of oil consumption:

$$V_{oil,act} = \frac{\frac{Q_{oil,act}}{NCV_{oil}}}{d_{oil,act}}$$

4. Actual total heat consumption:

$$Q_{total,act} = Q_{coal,act} + Q_{oil,act}$$

5. Best-fit curve from the best-case instances as calculated by Excel:

$$Q_{total,best} = 4620.3\ GJ * ln(t_{Standstill}/h) - 188.33\ GJ$$

6. Difference in heat total heat consumption:

$$\Delta Q_{total} = Q_{total,act} - Q_{total,best}$$

7. Assuming that the percentages of heat input from coal and oil do not change after optimization, the saving potentials from coal and oil are:

$$\Delta Q_{coal} = \Delta Q_{total} * \%Q_{coal}$$
$$\Delta Q_{oil} = \Delta Q_{total} * \%Q_{oil}$$

8. Fuel saving potential:

$$\Delta m_{coal} = \frac{\Delta Q_{coal}}{NCV_{coal}}, \Delta V_{oil} = \frac{\frac{\Delta Q_{total}}{NCV_{oil}}}{d_{oil}}$$

On average, if the assumed optimizations happen, the power plant can save approximately 70 tons of coal and 9,500 liters of oil per Start-up. These reduction in CO_2 emission and fuel consumption could save the power plant's owner and operator up to 236,000.00 € in operational expenses (OPEX) per year when calculated with the unit price of 2021 (available in the table below).

Expenditures	Reduction amount	Cost per unit (average 2021 value)	Budget savings [€/year]
CO_2 emission	2,320.61 tons/year	25 €/certificate	58,015.25
Coal consumption	879.12 tons/year	128.46 €/ton	112,931.76
Oil consumption	120,253 liters/year	0.54 €/liter	64,936.62

Table 4: Budget saving potentials resulting from assumed optimization

With CO_2 certificate in Germany soared to 78.00 € per ton at the end of 2021 (and is predicted to increase further at a faster rate), the additional cost due to non-optimal operation increase to more than 358,000.00 € per year with a further increase forecasted. Coal-fired power plants' owners and operators are under pressure to optimize the efficiency of not only min- to part-load operations, but also during the start-up processes that will undoubtedly occur at greater frequencies.

5. CONCLUSION:

Continuous operations at base-load, the primary assumed load conditions in the design phase of coal-fired power plants, are slowly being replaced, as a direct result of increasing integration of RES in the electricity grid, by load-following services, which include lower-than-optimal load, more Start-up, Shutdown cycles, higher strain on high pressure components, reduced service time, lower efficiency, higher relative fuel consumption and CO_2 emission. Due to time constraint, adding new coal-fired projects into the electricity mixed would not make sense from an economic perspective, as they will be either phased out completely or forced to operate in less efficient conditions to comply with emission regulation. Instead, the matured coal-fired generation technology should be further adapted and retrofitted to adopt its new role as a secondary source of electricity while its contribution to the grid slowly being taken up by less emission-heavy sources, such as wind, solar, and nuclear power. Considering eventual permanent shutdown (in Germany), priorities should be given to measures with short ROI (such as I&C upgrades and optimizations) to maximize the profit within the limited amount of time coal-fired power stations have left to operate. With the right methods chosen, power plants' owners and operators can witness reduced OPEX resulting from lower fuel consumption and CO_2 emission while alleviating the impacts of increasingly stringent market boundary conditions.

ACKNOWLEDGEMENT

Because this paper is a summary of my Bachelor thesis, I would like to first express my utmost gratitude for Professor Roland Span (Ruhr University Bochum) and Mr. Joel Wagner (STEAG Energy Services GmbH) for their guidance, supervision, and for having accompanied me throughout the preparation and writing of the thesis. Secondly, I am particularly grateful for the assistance given by my fellow students, colleagues at the Ruhr University Bochum and STEAG Energy Services GmbH. Last but never least, without the unending support and encouragement from my family and friends, I would not have been able to complete this project.

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