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Evaluation of co-firing as a cost-effective short-term sustainable CO_2 mitigation strategy in Germany

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Abstract

Background: In order to achieve the German greenhouse gas reduction targets, in particular, CO_2 emissions of coal-fired power plants must be reduced. The co-incineration of biomass-based substitutes, here referred to as co-firing, is regarded as a highly cost-effective and short-term method of reducing CO_2 emissions in the electricity sector. Another advantage of co-firing is its ability to meet base load demands and offer controllability. In this paper, we, therefore, evaluate the effectiveness of co-firing as a CO_2 mitigation strategy in the German electricity sector by 2020.

Methods: We consider the co-firing of three different substitutes: wood chips, industry pellets and torrefied biomass. Likewise, a comparison with three alternative mitigation strategies is part of the evaluation. We use seven sustainability indicators covering social, ecological and economic aspects as the basis for the evaluation. These sustainability indicators are determined by means of a merit order model, which enables us to simulate the electricity market in 2020 on an hourly basis and adjust it based on the assumption of widespread implementation of co-firing or one of the alternative mitigation strategies.

Results: Our results show that all mitigation strategies have a significant potential to reduce the CO_2 emissions of the electricity sector. Compared with the alternative mitigation strategies, co-firing is characterised on the one hand by rather low mitigation potentials and on the other hand by low CO_2 mitigation costs. The co-firing of industry pellets appears to have the most advantageous combination of mitigation potential and mitigation costs.

Conclusions: The widespread implementation of co-firing with industry pellets until 2020 would have led to 21% reduction in CO_2 emissions on average. Nevertheless, it cannot be implemented immediately because time is needed for political decisions to be taken and, afterwards, for the technical retrofitting of power plants. Co-firing will, therefore, not be available to contribute to the achievement of the greenhouse gas reduction targets for the year 2020. However, our approach can be used to assess the contribution of the various CO_2 mitigation strategies to the ambitious mitigation targets for the year 2030.

Keywords: Co-firing, CO_2 mitigation strategy, Sustainable energy generation, Sustainability indicators, Merit-order model (MOM)

Background

During the UN climate conference in Paris in 2015, the world community agreed to the target of limiting global temperature rise to ideally 1.5 °C compared with the pre-industrial age. In order to determine Germany's contribution to this goal, the German government ratified the climate protection plan in 2016 and defined greenhouse gas (GHG) reduction targets. These targets aim to reduce Germany's GHG emissions by 40% by 2020 and 55% by 2030 compared with the base year of 1990. Despite numerous efforts to reduce GHG emissions, the current developments indicate that the GHG reduction target for 2020 will be missed. The latest climate protection report indicates that the target will be missed by 8% [1]. Nevertheless, the governing parties in Germany declared in their coalition agreement in 2016 the goal to reach the reduction target for 2020 as soon as possible. Indeed, the ambitious reduction target for 2030 also requires the establishment of immediate, sustainable and

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implementable measures for the reduction of GHG emissions.

One of the main contributors to German GHG emissions, which is, therefore, also a sector with a great GHG reduction potential, is the energy sector. In 2016, the energy sector emitted 332 megatonnes of CO_2 equivalents, accounting for 37% of the total German GHG emission. Within the energy sector, the main emitter of GHG is electricity generation in lignite- and hard coal-fired power plants, which amounts to 73% of the energy sector emission and 30% of the total German CO_2 emission [2].

One promising strategy to mitigate CO_2 emissions from coal-fired power plants is the partial substitution of coal with biogenic fuel surrogates, here named "co-firing". Co-firing is considered a highly cost-effective and short-term method of reducing CO_2 emissions from coal-fired power plants since existing plants can be used with low retrofitting efforts [3, 4]. The mitigation potential of co-firing is estimated as 950–1100 g_{CO2}/kWh_{el} if local biomass is co-fired in lignite-fired power plants and as 900–1000 g_{CO2}/kWh_{el} if it is co-fired in hard coal-fired power plants [5]. Worldwide, approximately 150 power plants have either been tested for co-firing or have permanently transformed their operations to co-firing [3]. In European countries such as the UK, Denmark and the Netherlands, co-firing has already been implemented as a CO_2 mitigation strategy. For example, Denmark and the Netherlands implemented subsidies as co-firing incentives in the range of 2.0–6.5 ct/kWh. Additionally, the Danish policies intend to transfer the co-fired plants gradually to 100% biomass plants [3]. This strategy has the advantages of providing, on the one hand, a near-term implementable CO_2 mitigation strategy for the energy sector and a gradual phase-out of coal-fired power plants and, on the other hand, the gradual development of the biomass supply infrastructure that is needed for the implementation of 100% biomass plants and other biomass technologies under development [6].

Nevertheless, the German climate protection plan does not consider co-firing as a CO_2 mitigation strategy, and subsidies were not provided for this technology [1]. Consequently, only a few coal-fired power plants in Germany are retrofitted with the co-firing technology presently, and the great potential of this technology to contribute to the achievement of the GHG reduction targets has not yet been exploited. Therefore, the aim of this work is to investigate the extent to which the implementation of the co-firing technology could have contributed to meeting the German GHG reduction targets for the year 2020 if it was implemented in the climate protection plan. For this purpose, we have evaluated the effectiveness of co-firing as a CO_2 mitigation strategy under the premise of sustainability criteria. To this end, we have developed a novel approach that allows us to assess the CO_2 mitigation potential of co-firing by the year 2020 on the basis of seven sustainability indicators addressing social, ecological and economic aspects. The central instrument for determining these sustainability indicators is a specifically developed merit order model (MOM) that allows us to simulate the electricity market in 2020 and adjust it assuming the widespread use of co-firing. The CO_2 mitigation potential of co-firing has also been evaluated by comparing it with three alternative CO_2 mitigation strategies for the energy sector with similar characteristics concerning power plant controllability.

Methods

Approach

In order to assess the effectiveness of co-firing as a CO_2 mitigation strategy and compare it with three alternative CO_2 mitigation strategies, we developed a new approach (Fig. 1) that takes into account different possible development pathways of the electricity market dynamics by 2020, the power plant operators' economic motivation to retrofit their power plants for co-firing or to apply one of the alternative mitigation strategies, the technical constraints of co-firing biomass-based substitutes in coal-fired power plants and the maximum available biomass potential in Germany. We assess the effectiveness of co-firing by evaluating seven sustainability indicators concerning social (one indicator), ecological (two indicators) and economic (four indicators) aspects.

We consider the dynamics of the electricity market by the usage of a MOM. Our MOM is based on data from the German electricity market in the year 2010. For this year, the most recent and complete dataset was available at the point in time when our MOM was implemented. The load profiles of the reference year 2010 were then adapted to the year 2020. We chose the year 2020 as target year since we wanted to answer in a retrospective way the question of whether co-firing would have been an effective measure to achieve the climate targets for 2020. Nevertheless, a big advantage of our method is the transferability of the model to a more recent database and to a target year in the distant future. To enhance reproducibility, we also describe our method in a very detailed way. In order to enable the consideration of various conceivable developments in the German electricity market, the MOM is simulated for eight scenarios that are based on eight different energy pathways.

For the simulation of the co-firing scenarios, we consider three different biomass refinement levels as substitutes: wood chips, industry pellets and torrefied biomass. In the scenarios, we distinguished between the technical potential, which corresponds to the maximum technically feasible potential, and the economic potential, which additionally includes the economic motivation of the power plant operator to implement the investigated CO_2

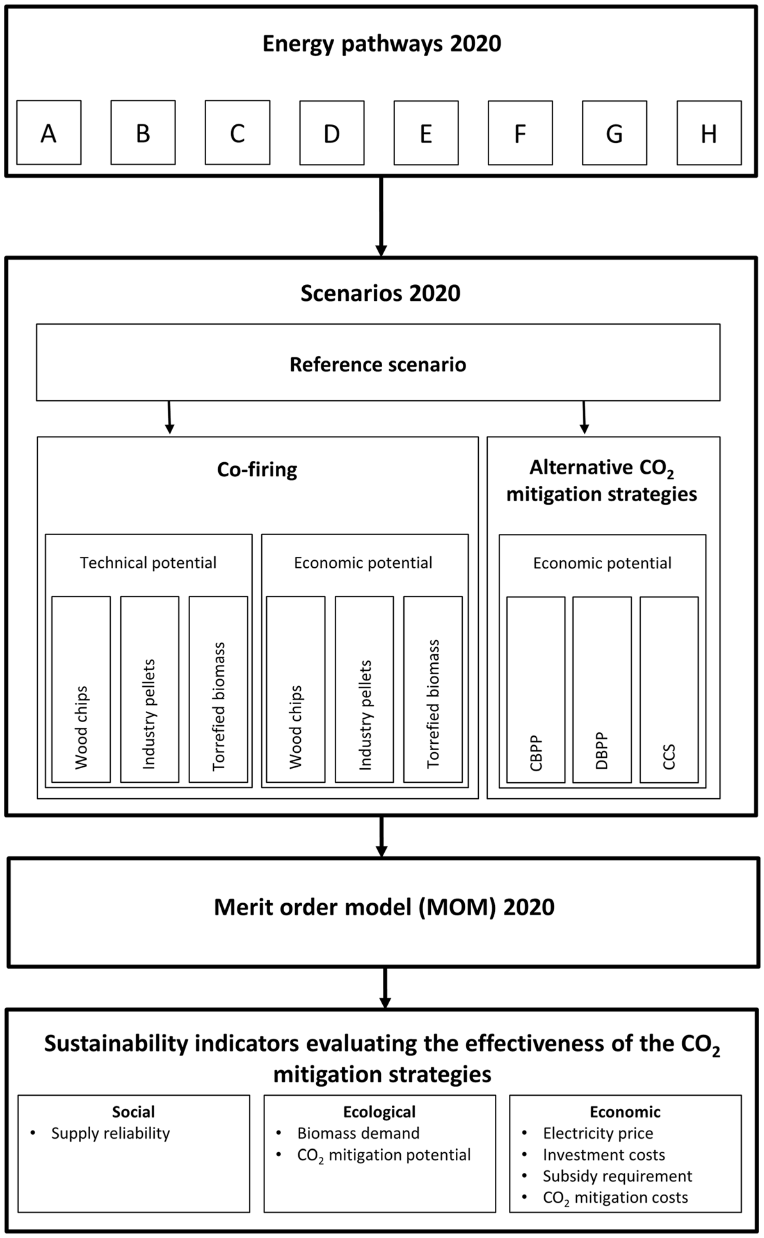

Fig. 1 Approach for evaluating the effectiveness of co-firing and alternatives as CO_2 mitigation strategies

mitigation strategy. The effectiveness of co-firing as a mitigation strategy is assessed by comparing it with three alternative CO_2 mitigation strategies with similar characteristics concerning power plant controllability. These alternative mitigation strategies are as follows: central biomass power plants (CBPP), decentralised biomass power plants (DBPP) and carbon capture and storage technologies (CCS).

Since the application of the different CO_2 mitigation strategies will not yet be profitable for power plant operators by the year 2020 [7], we determined the amount of subsidy requirements for each CO_2 mitigation strategy. These subsidy levels were taken into account in the economic potential scenarios.

Merit order model (MOM) 2020

MOMs are used for the prediction of electricity prices. On the spot market of the European Energy Exchange (EEX), the electricity price is determined according to the MO. For this purpose, the power plants are sorted by their marginal costs. On the left side of the MO, power plants that are independent of marginal costs, such as power plants that are remunerated according to the Renewable Energy Sources Act (EEG), heat-controlled combined cogeneration plants and waste-to-energy plants, are listed. These plants are followed by conventional power plants, starting with plants with low marginal costs, i.e. nuclear power plants, followed by hard coal and lignite-fired power plants, and finally gas- and oil-fired power plants. On the basis of this order, contracts are awarded at the spot market. The bid of the last power plant that is accepted determines the electricity price for the corresponding hour, and all previously concluded supply contracts are paid according to the marginal costs of this power plant [8].

Structure and database of the merit order model

The development of the MOM with a 1-h-specific resolution is based on the data from the German electricity market in the year 2010. The first step in the development of the model is to determine the demand load profile. Subsequently, the generation profiles from the power plants that are independent of marginal costs are identified. Furthermore, the load profiles from transboundary electricity transfer and the supply from pump- and seasonal-storages are taken into account. The residual load results from the difference between the demand load profile and generation profiles mentioned above and is covered by marginal cost-dependent conventional power plants according to the MO. Complemented by the fuel price, the CO_2 certificate price, the emission factors and the power plant availability, the MOM is able to make statements on the electricity price and the CO_2 emissions of the German electricity generation with a 1-h-specific resolution.

The determination of the different load profiles is based on different sources, which are illustrated in Table 1. In order to prevent misallocations resulting from different databases, we scale the specific load profiles to the stated annual values given by the BMWi [9].

Validation of the merit order model

The validation of the MOM is carried out in two stages. First, the MOM is validated based on real data of the year 2010. For this purpose, real data of the electricity demand, the electricity feed-in of marginal cost-independent power plants as well as the electricity imports and exports were implemented into the MOM, and the correlation between the electricity prices determined by the MOM and the real prices of the EEX spot market was validated. This approach was chosen following the procedure described in [16, 22, 23].

There is a very high correlation between the MOM and the EEX spot market regarding the average electricity prices, which show only a deviation of 0.7%. Referring to the hourly values, the correlation is still high with 70%, but there are systematic deviations in the peripheral areas of the demand profile. These are typical for MOMs though, and they occur in other published MOM studies as well [16, 22, 23].

Second, the MOM is validated based on the counterfactual scenario of Sensfuß [24] and the consideration of the described MO effect. This validation shows that the developed MOM is not only sufficient regarding statistical parameters (EEX spot market prices) but also regarding changing parameters such as the share of renewables. In order to validate the MOM with the counterfactual scenario, the assumptions regarding the generation structure and electricity prices of the counterfactual scenario by [24] are included in the MOM, and the resulting electricity price is compared with the results of Sensfuß [24]. The low deviation of 2.4% shows that there is a high correlation between our modelled MOM and the model of Sensfuß [24].

Transfer of the merit order model to 2020

For the simulation of the 2020 scenarios, the MOM input parameters need to be transferred to the year 2020. The validated MOM calculation algorithm remains unchanged. The input parameters for the corresponding load profiles are adapted as described subsequently.

The future composition of German power plants takes into account the decision to phase out nuclear energy, the shutdown of power plants that would have reached their technical lifespan of 35–40 years in 2020, and the construction of new plants that are already under construction or in the planning stage.

For the generation profiles of renewable energies, it is not possible to derive a forecast for the year 2020 on the basis of the real input parameters from the year 2010 due to the high growth rates during the year, the strong stochastic weather influences on real electricity production and the expected future expansion of renewable energies. For this reason, long-term mean values of wind distribution, solar radiation and water levels or water availabilities of rivers are used to estimate the future distribution of the renewable energy generation over a month or day (for sources see Table 1). The resulting synthetic load profiles are then scaled to the annual values of the electricity generation from renewable energies of the respective energy pathway.

If not explicitly stated in the respective energy pathway, the installed capacity of cogeneration plants is estimated by calculating the share of cogeneration capacity in the total installed capacity assumed in the DLR [25]. The electricity generation from cogeneration plants is determined in the same way.

Due to the changing energy sectors of Germany and its neighbours, the load profile of cross-border electricity transfers in 2010 can only be transferred to the future to a limited extent. Therefore, on the one hand, the assumption is made that the long-term average of transboundary

Table 1 Data source and database of the input parameters of the merit order model

Input Parameter	Source	Comments
Electricity demand	Grid data of transmission system operators [10–13] and selected regional network operators	Scaled to the annual values of BMWi (2013) [9]
Wind power	Grid data of transmission system operators	Scaled to the annual values of BMWi (2013) [9]
Photovoltaic	Grid data of transmission system operators	Scaled to the annual values of BMWi (2013) [9]
Run-of-river power stations	EEX Transparency (2011) [14]	Scaled to the annual values of BMWi (2013) [9]
Biomass	No published load profile available	Approach for the estimation of an idealised biomass load profile according to ISET (2009) [15]
Geothermal power	No published load profile available	Due to minor present and anticipated future significance not taken into account in the MOM
Waste-to-energy plants	No published load profile available	Assumption: constant base load production Annual values according to BMWi (2013) [9]
Heat-controlled cogeneration plants	No published load profile available, no data available on the installed capacity of heat-controlled cogeneration plants Bundeskartellamt [16]: sub-day distribution of the feed-in of heat-controlled cogeneration plants	Assumption: installed net capacity = 8800 MW_{el}
Transboundary electricity transfer	Grid data of transmission system operators	Scaled to the annual values of BMWi (2013) [9]
Pump- and seasonal-storages	EEX Transparency (2011) [14]	Scaled to the annual values of BMWi (2013) [9]
Marginal cost dependent power plants	List of all active power plants [17]	complemented by net installed capacity and efficiency from direct publications by power plant operators or assumption of data from technically comparable power plants
Emission factors	Regulations on allocation of GHG emission allowances (German: Verordnung über die Zuteilung von Treibhausgas-Emissionsberechtigungen) [18]	
Commodity prices	European Energy Exchange (EEX) Group; Energate [19, 20]	
CO_2 certificate prices	European Energy Exchange (EEX) Group [19]	
Plant availability	EEX Transparency [21]	

electricity transfer can be applied to the future; on the other hand, it is assumed that electricity exports take place primarily during the hours when the residual load is low in relation to its annual average. In the opposite case, electricity imports are assumed.

In order to determine the future load profile of pumped and seasonal storage facilities, the assumption is made that the load profile structure from 2010 can be adopted. The annual electricity production from hydropower corresponds to the data of the corresponding energy pathway. The model also assumes that the use of pumped and seasonal storage facilities is to be expected especially in times of high electricity prices.

Energy pathways

In order to represent a broad variance of possible development pathways of the energy sector, eight different and consistent energy pathways were taken into account in the simulations of the individual scenarios. The energy pathways are target scenarios that differ with regard to their objectives, on the one hand, and the development pathways for achieving these objectives, on the other hand (see Additional file 1: Table S1 for a detailed description of the eight selected energy pathways). For this reason, the pathways show differences concerning the assumed commodity prices, the electricity demand, the composition of the power plant park, the share of renewable energies in electricity provision, the composition of renewable energies and the transboundary electricity transfer.

The main criteria for the selection of the energy pathways were the complete availability of the input parameters needed for the MOM. However, missing information was complemented by other sources. All complementary sources for the energy pathways are in Additional file 1: Table S5-10. In addition, we standardised single input parameters in order to ensure the comparability of the simulation results. Table 2 lists the input parameters of the eight energy pathways A to H. Together with the load profiles modelled for the year 2020, the parameters of the individual energy pathways are implemented separately in the MOM.

Table 2 Comparison of the input parameters for the different energy pathways

Energy pathway	A	B	C	D	E	F	G	H
Electricity demand in 2020 (TWh)	578.7	635.1	569.2	573.0	573.0	573.0	580.0	592.0
Production capacity (GW)	167.9	188.6	169.1	196.3	196.3	196.3	196.3	196.3
Thereof conventional (%)	34.3	30.5	48.3	40.7	40.7	40.7	40.7	40.7
Thereof renewable (%0	65.7	69.5	51.7	59.3	59.3	59.3	59.3	59.3
Electricity generation (TWh)	588.7	625.2	578.9	563.5	563.5	563.5	563.5	568.0
Thereof conventional (%)	48.6	45.7	66.3	58.4	58.4	58.4	58.4	57.9
Thereof renewable (%)	51.4	54.3	33.7	41.6	41.6	41.6	41.8	42.1
Transboundary electricity transfer [TWh]	10.0	− 10.0	9.7	− 9.5	− 9.5	− 9.5	− 16.5	− 24
Commodity prices (€/GJ)								
Uranium	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lignite	1.85	1.85	0.44	N/A	N/A	N/A	N/A	N/A
Hard coal	9.27	9.27	2.49	2.99	3.51	4.30	3.51	3.51
Natural gas	15.33	15.33	4.98	6.35	7.29	8.43	7.29	7.29
Oil	N/A	N/A	N/A	16.02	17.54	19.47	17.54	17.54
CO_2 certificates prices (€/t)	38.00	38.00	20.00	20.00	23.00	27.00	23.00	23.00
Source	[26]	[26]	[27]	[25]	[25]	[25]	[25]	[25]

Scenarios 2020

The scenarios 2020 consist of the reference scenarios, the co-firing scenarios and the scenarios of alternative CO_2 mitigation strategies.

The reference scenarios reflect the modelled load profiles implemented in the MOM and combined with the eight energy pathways A-H without any other adaptations and intend to describe the electricity market in 2020 without co-firing. The co-firing scenarios reflect the retrofitting of the existing coal-fired power plants for co-firing biomass together with coal. The co-firing scenarios investigate, on the one hand, the technical potential resulting from the use of co-firing without considering economic motives. This is intended to determine the technical CO_2 mitigation potential of co-firing taking into account the technical constraint of the co-firing rates (Table 3) and the sustainable constraint of the maximum available biomass in Germany. On the other hand, the economic potential of co-firing is investigated. Whether the technical CO_2 mitigation potential of co-firing will actually be exploited depends above all on whether it represents an attractive economic alternative to pure coal combustion for power plant operators or not. Since in all cases, co-firing without subsidies is not competitive with pure coal combustion [7], we considered subsidies in all economic potential scenarios. Both the technical and economic potential scenarios of co-firing

Table 3 Characteristics of the considered biomass refinement levels

	Wood chips	Industry pellets	Torrefied biomass
Calorific value (MJ/kg)	9–10[c]	17[c]	19–22[c]
Maximum co-firing ratio (%)	10[a]	30[b]	50[c]
Reductionof efficieny (%)	9.4[a]	4.7[d]	0[d]
Maximum co-firing rate (%)	10	30	50
Fuel prices in 2020 (€/MWh)	27.27[e]	33.18[e]	36.87[e]
Transportation costs (€/MWh)	4.97[e]	6.85[e]	8.63[e]
Investment costs for retrofitting (€/MW_{el})	346,000[f]	154,000[f]	38,000[f]
Depreciation and debt services for retrofitting (€/MW_{el}*a)	37.85[g]	16.82[g]	4.21[g]
Allocation of biomass (hard coal) (€/MWh)	8.32[h]	3.7[h]	0.92[h]
Allocation of biomass (lignite) (€/MWh)	5.55[h]	2.47[h]	0.62[h]

[a][28][b][29][c][30][d]Assumptions based on [29–31]: torrefied biomass co-firing without performance loss; mean value of wood chips and torrefied biomass performance loss for industry pellets[e]Calculation according to the approach in Additional file 1: Table S2-4[f] [28, 32–34], Conversion rate of US Dollar to EUR, 1.3[g]Investment costs as annuity with an amortisation period of 15 years at 8% interest rate[h]Annuity allocated to biomass fuel consumption based on the mean hours of operation at full load of lignite (6814 h/a) and hard coal power plants (4547 h/a) as given in [27]

were simulated for three biomass types differentiated by the refinement level: wood chips, industry pellets and torrefied biomass. Their characteristics and fuel properties are given in Table 3.

Furthermore, the evaluation of the effectiveness of co-firing as a sustainable instrument to mitigate CO_2 emissions is discussed by comparing it with alternative CO_2 mitigation strategies. The alternative CO_2 mitigation strategies were selected based on the capability to reduce CO_2 emissions in the power sector, meet base load demands and offer controllability. Both the capability to meet base load demands and controllability are critical to the reliability and stability of the German power supply. Especially, the controllability is likely to become increasingly important as the installed capacity of wind power and photovoltaics will continue to increase without the prospect of storage technologies being available to buffer large amounts of electricity cost-efficiently by 2020 or 2030. Additionally, the alternative CO_2 mitigation strategies are characterised by long-term accountability. Their deployment can, thus, be demand-driven, and seasonal or intra-day load fluctuations can be balanced without the need to buffer excess electricity. Based on these criteria, the following three alternative CO_2 mitigation strategies were chosen: (1) the construction of new centralised biomass power plants fired exclusively with biomass (CBPP); (2) the construction of new decentralised biomass power plants with EEG-remuneration, which goes beyond the expansion postulated in the various energy scenarios but is limited to the use of 50% of the available biomass potential in Germany (DBPP); and (3) the retrofitting of coal-fired power plants with CO_2 capture technologies in order to store CO_2 in geological formations (CCS). An overview of all considered scenarios is presented in Fig. 1.

Determination of subsidy requirements

The economic scenarios for co-firing and the alternative CO_2 mitigation strategies are based on the assumption that the corresponding plants will be subsidised. Subsequently, the determination of the subsidy requirements is described for the different CO_2 mitigation strategies.

Subsidy requirements for co-firing

In order to determine the subsidy requirements of co-firing, first of all, the fuel price equivalent must be determined. The fuel price equivalent indicates the maximum price for biomass that in co-firing would lead to generation cost per unit of electricity equivalent to the cost of a pure coal-fired system [35]. The fuel price equivalent varies for the three different biomasses and for the different energy pathways. Due to the significant price differences between hard coal and lignite, two separate subsidy rates were determined for co-firing in hard coal- and lignite-fired power plants. The average efficiency of all hard coal- and lignite-fired power plants in the German power plant park was then used to determine a uniform minimum subsidy requirement for all hard coal- and lignite-fired power plants. In addition, a further 5% of this minimum subsidy requirement was granted as a conversion bonus. This bonus is intended to serve as compensation for the risks of the power plant operator and as a financial incentive to retrofit to co-fired plants.

Subsidy requirements for CBPP

The subsidy level for CBPPs is chosen in such a way that the economic disadvantages of pure biomass firing are compensated for in terms of the higher specific investment and marginal costs of electricity generation compared to coal firing. The values of investment costs and efficiencies of biomass and coal-fired power plants shown in Table 4 are used as a basis.

Subsidy requirements for DBPP

The EEG already provides a legal basis for the subsidies of electricity from DBPPs with a maximum installed capacity of 20 MW_{el}. The amendment to the EEG of 2012 also formulates the policy that biomass power plants are only subsidised if they generate at least 60% of their electricity in cogeneration mode. This requirement is taken into account in our simulation.

Subsidy requirements for CCS

Similar to the calculation of the subsidy level for CBPPs, the subsidy level for coal-fired power plants equipped with CO_2 separation technology is calculated. The subsidy level is based on the fact that both the cost of retrofitting and the higher marginal cost of electricity production due to the reduction in efficiency can be compensated for. Based on average power plants, the subsidy level was chosen in such a way that the additional investments within the assumed technical useful life of 25 years for retrofitting existing power plants and 40 years for the construction of new plants with a rate of return of 8% can be compensated for. Here, too, a distinction is made between the determination of the subsidy level for coal- and lignite-fired power plants, and a conversion bonus of 5% is granted.

Table 4 Investment costs and efficiencies of centralised biomass power plants and coal-fired power plants [36–38]

	Centralised biomass power plants fired with woody biomass	Coal-fired power plants
Specific investment costs (€/kWh_{el})	1374	950
Efficiency (%)	36	49

Biomass potential

We also examined whether the biomass required for the various scenarios will actually be available for energy use in a sustainable way. For this purpose, we determined the maximum sustainable annual biomass potential that will be available in Germany by 2020 according to the approach published in [35]. The results can be found in Table 5.

Sustainability indicators

Since Germany aims for an environmentally friendly, reliable and affordable energy supply, the effectiveness of CO_2 mitigation strategies cannot be compared only on the basis of the quantified CO_2 emissions [39]; rather, further sustainability indicators have to be considered for a comprehensive assessment. Thus, we define seven sustainability indicators for the comparison of the CO_2 mitigation strategies considering social, ecological and economic aspects (Table 6).

The first indicator addresses the social aspect of *supply reliability* and specifies whether the electricity demand can be met at any time. This is a prerequisite for all considered scenarios. The two ecological indicators are the *biomass demand*, defined as the yearly amount of biomass utilised for electricity generation in Germany, and the *CO_2 emissions*, defined as the total annual emissions from marginal power plants without combined heat and power plants. The first economic indicator, the *electricity price*, is the average annual price that results from the hourly simulated marginal cost based on the MOM simulations. The *investment costs* of the CO_2 mitigation strategies reflect the costs necessary to retrofit power plants for co-firing or CCS and for the construction of new CBPP or DBPP. The *subsidy requirements* are calculated based on the aforementioned approach. The *CO_2 mitigation costs* are specified for each scenario by combining the investment cost, the electricity price and any subsidy requirement that is needed for CO_2 emissions mitigation.

Table 5 Determination of the maximum sustainable annual biomass potential that will be available in Germany by 2020

Biomass potential (PJ)	2020
Additional use of forest wood	137
Remaining forest wood & weak wood	230
Industrial wood residues	81
Waste wood	76
Landscape conservation wood	8
Straw	116
Others	19
Short rotational plantations	588
Maximum sustainable annual biomass potential available in Germany by 2020	1.254

Table 6 Sustainability indicators

Description	Unit
Social indicator	
Supply reliability ensured?	Yes/no
Ecological indicators	
Biomass demand	PJ
CO_2 emissions	Million t/a
Economic indicators	
Electricity price	€/MWh
Investment cost	Million €
Subsidy requirement	€/MWh
CO_2 mitigation cost	€/t_{CO2}

Results

In this section, the simulation results of the different scenarios are given. Each subchapter deals with the influence of the individual scenarios on the different sustainability indicators.

Social indicator

Supply reliability

This subsection shows the influence of the different scenarios on the supply reliability. This influence is likely to be strongest when considering the technical potential of the different CO_2 mitigation strategies.

The co-firing of biomass in coal-fired power plants leads to a reduction in the overall capacity of the power plant park, as the efficiency of coal-fired power plants is reduced by the co-incineration of wood chips and industry pellets (see Table 3). Torrefied biomass does not lead to efficiency reductions since it has similar properties with coal. For the combustion of wood chips, the overall capacity of the power plant park is reduced by 0.74%, and for the combustion of industry pellets, it is reduced by 1.41%. Even though the co-firing of wood chips leads to a higher reduction in power plant efficiency than the co-firing of industry pellets, the reduction in the total power plant capacity is higher for the latter, as industrial pellets can be co-fired with a higher maximum proportion of the fuel mixture (see Table 3). Despite the marginal reduction in overall power plant capacity, the supply reliability is ensured for all co-firing scenarios at all times, even under the consideration of power plant unavailability.

The CBPP scenario is characterised by the construction of additional central biomass power plants. This increases the installed capacity by an average of 12.5 GW; thus, the supply reliability in this scenario is also strengthened.

The construction of additional DBPP also leads to an increase in installed capacity by 12.5 MW compared with the reference scenario. This ensures supply reliability in all energy pathways at all times.

The retrofitting of coal-fired power plants with CO_2 capture technologies leads to a reduction in the net electrical efficiency of the power plant. Therefore, in the CCS scenario, the installed capacity of the coal-fired power plants, and, therefore, that of the whole power plant park, decreases to such an extent that the supply reliability for the energy pathways A to C is no longer ensured. Since the supply reliability is a requirement that must be fulfilled at all times, the following analyses consider the construction of further coal-fired power plants. It is assumed that these coal-fired power plants are also equipped with CO_2 capture technologies.

Ecological indicators

Biomass demand

Figure 2 shows the biomass demand for the different scenarios compared with the maximum sustainable annual biomass potential that will be available in Germany by 2020, which was determined as 1254 PJ in [35]. For each scenario, the difference between the maximum and minimum values for the biomass demand of the various energy pathways is given. In addition, the mean value of all energy pathways is given for each scenario.

The reference scenario takes into account the required biomass demand for the number of EEG-subsidised DBPPs that based on assumption would be in existence by 2020. The value of the range of the other scenarios, therefore, indicates the sum of this amount and the biomass required by the adjustments of the respective scenarios. The CCS scenario does not show any extra biomass demand and is, therefore, not included in the figure.

Comparing the technical potential scenarios of co-firing with the reference, an increased demand for biomass is determined. Nevertheless, none of the scenarios exceeds the maximum sustainably available biomass potential. Only the combinations of torrefied biomass with the energy pathways A and B almost exploit the existing potential with a biomass requirement of 1233 PJ and 1239 PJ, respectively. This can be explained by the high share of renewable energies in the electricity generation of these energy pathways. It can also be observed that the demand for biomass increases with the degree of biomass refinement, as the maximum technically possible co-firing rate also increases (see Table 3).

The economic potential scenarios of co-firing show a reduction in biomass demand compared with the technical potential scenarios, since not all coal-firing power plants are retrofitted for co-firing when economic motives are taken into account.

Taking a look at the CBPP scenarios, it is observed that the construction of new central biomass power plants leads to a significant increase in biomass demand. Nevertheless, the sustainably available biomass potential will not be exploited.

The DBPP scenario was limited to a maximum consumption of 50% of the available biomass potential. This measure is intended to help minimise upheavals on the energy markets that could result from a significant increase in the installed capacity of power plants operating independently of marginal costs. Therefore, the increase in biomass demand in the DBPP scenario is lower compared with the CBPP scenario.

CO_2 mitigation potential

The simulation results of the annual CO_2 mitigation potential for the different scenarios are given in Fig. 3.

Figure 3 shows that the technical potential of co-firing in reducing CO_2 emissions is significant. The mitigation potential increases with the degree of refinement since the maximum co-firing rate also increases. In comparison with the reference scenario, CO_2 emissions can be reduced on average by 7% with the use of wood chips, by 36% with industry pellets and by 50% with torrefied biomass. Since not all coal-fired power plants are retrofitted for co-firing, when the economic motives of the power plant operators are taken into account, the technical mitigation potential discussed above cannot be fully exploited in the economic scenarios. Nevertheless, compared with the reference scenario, CO_2 emissions can be reduced on average by 4% for wood chips, by 21% for industry pellets and by 34% for torrefied biomass.

Compared with the reference scenario, the economic potential for reducing CO_2 emissions through the construction of new CBPPs is considerable. On average, this will reduce CO_2 emissions by 47%.

Also, the construction of additional DBPPs leads to a reduction in CO_2-emissions by 26% on average compared with the reference scenario. Since mainly gas-fired power plants with low specific CO_2-emissions are substituted by DBPPs and since the coal-fired power plants are still emitting their high specific CO_2 emissions, the mitigation potential of this scenario is by a factor of 2 to 5 lower compared with the co-firing of biomass in coal-fired power plants.

Finally, a significant reduction in CO_2 emissions of 32% compared with the reference scenario is observed for the CCS scenario.

Economic indicators

The aim of the economic evaluation is to determine the costs resulting from the different CO_2 mitigation strategies. Therefore, we determine the CO_2 mitigation costs as the last economic indicator. They result from the sum

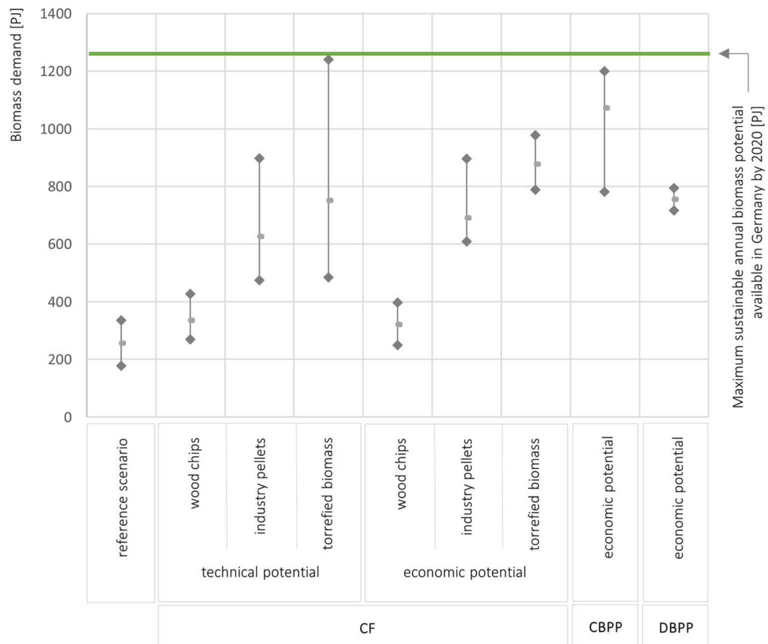

Fig. 2 Biomass demand incl. EEG-subsidised decentralised biomass power plants for the different scenarios

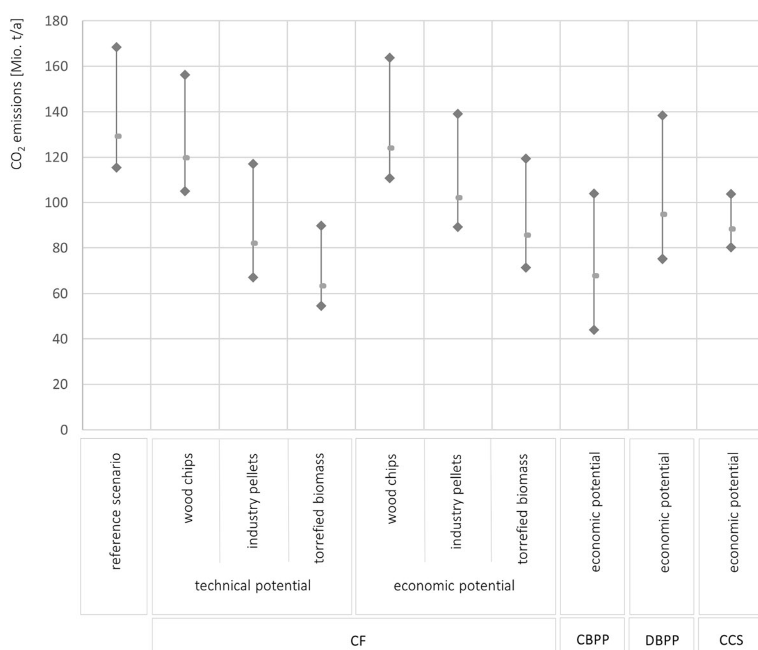

Fig. 3 CO_2 emissions of the yearly electricity generation for the different scenarios

of the subsidies granted for the respective CO_2 mitigation technology and the changes in electricity generation costs caused by the application of the respective mitigation strategies. The change in electricity generation costs reflects raw material costs, transport, depreciation and interest on necessary investments. Therefore, in the next section, we describe the investment costs required to adapt the power plant park in the various scenarios. These have an influence on the electricity price. Therefore, in the second section, we assess the scenarios' influence on the electricity price. Together with the change in power generation costs, the required subsidy levels influence the CO_2 mitigation costs. In the third section, thus, the influence of the scenarios on the required subsidy levels is presented. Finally, the results of the economic analysis are summarised in the last chapter, in which the influence of the scenarios on the CO_2 mitigation costs is presented.

Investment costs

The investment costs required to retrofit existing coal-fired power plants or build additional biomass power plants are shown in Figs. 4 and 5.

Before discussing the total investment costs, shown in Fig. 4, a brief discussion of the specific investment costs to retrofit coal-fired power plants for co-firing is provided. The specific investment costs relate exclusively to the part of the power plant output attributable to the use of biomass. They depend on the refinement level of the co-fired biomass. For co-firing of wood chips, industry pellets and torrefied biomass, the specific investment costs are 350,000 €/MW$_{\text{co-firing}}$, 150,000 €/MW$_{\text{co-firing}}$ and 40,000 €/MW$_{\text{co-firing}}$ respectively. Since the specific investment costs for wood chips are significantly higher compared with industry pellets and the maximum co-firing rate is lower for wood chips (10%) compared with industry pellets (30%) (see Table 3), accordingly, the total investment costs of wood chips are higher compared with industry pellets. Also, the total investment costs of co-firing with torrefied biomass are lower compared with the co-firing of industry pellets, which can be explained by the significantly lower specific investment costs for the co-firing of torrefied biomass.

The alternative CO_2 mitigation technologies require significantly higher investment costs than co-firing. For the construction of additional CBPPs, an investment cost of approximately 20 billion € is needed. The specific investment costs for DBPPs amount to approximately

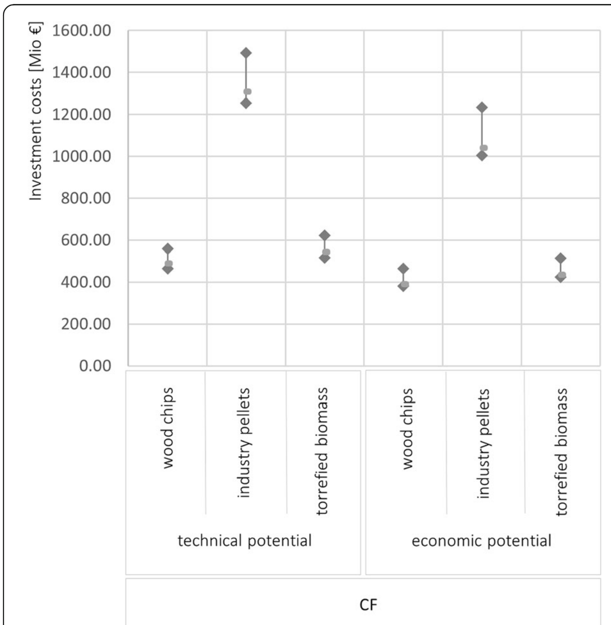

Fig. 4 Investment costs for the different co-firing scenarios

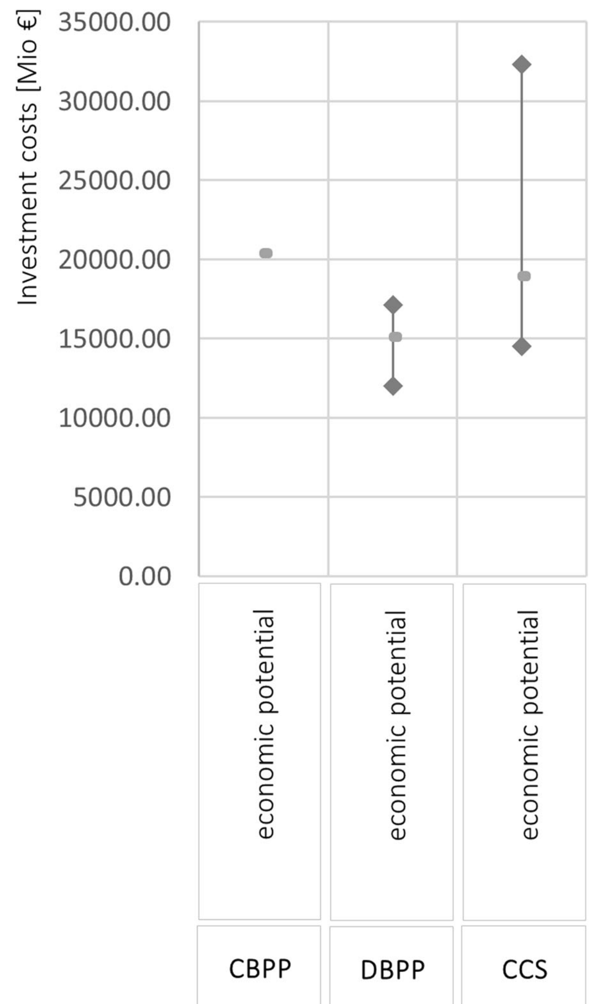

Fig. 5 Investment costs for the different alternative technology scenarios

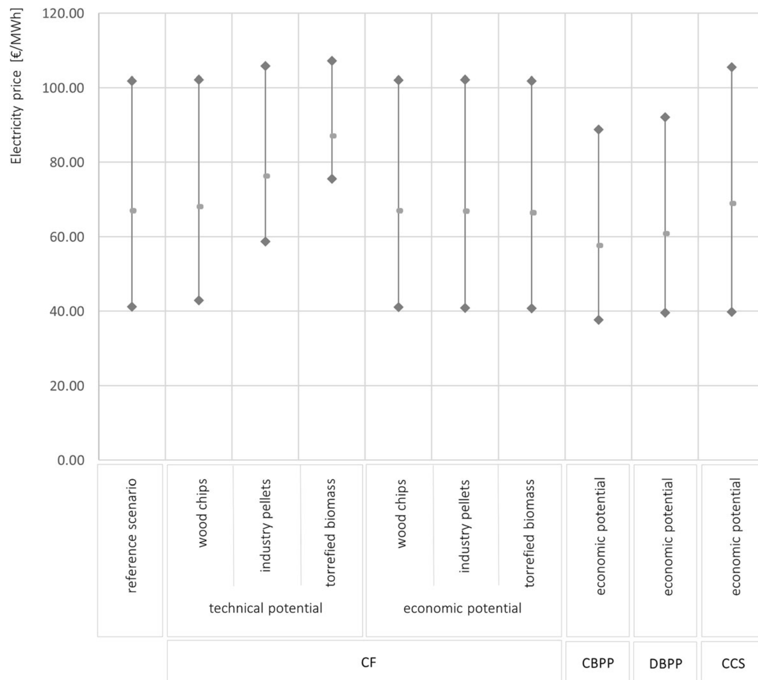

Fig. 6 Average simulated electricity price for the different scenarios

2.6 million €/MW$_{el}$. This leads to total investment costs of approximately 12 to 17 billion € for the different energy pathways. The total investment costs of the CCS scenario reach approximately 15 to 32 billion €.

Electricity price

The simulation results for the average electricity prices of the various scenarios are shown in Fig. 6.

The electricity price of the technical potential scenario of co-firing rises compared with the reference scenario. This is true for all types of biomass, and the reason is that the costs for biomass (including costs for commodities, processing, transportation and retrofitting) are higher than the costs for lignite and hard coal (see Table 3 and Table 2). The increase in the average electricity price for co-firing wood chips is small and continues to rise with the degree of biomass refinement. One reason for this is the costs for biomass that increase with increasing refinement level. Another reason is the maximum co-firing rate that also increases with increasing refinement levels.

If one considers the economic motivation of power plant operators to implement co-firing in their plants, co-firing will only take place if it leads, on the basis of the assumed subsidy levels, to the same or lower marginal costs compared with pure coal combustion. Therefore, the influence on the average electricity price is lower than in the scenarios excluding economic motives.

The CBPP scenario with assumed subsidies leads to a reduction in electricity prices. This can be justified by the additional generation capacities that can provide electricity at marginal costs comparable to those of modern hard coal-fired power plants. This leads to a shift in the intersection of the demand curve and MO towards power plants with lower marginal costs.

Also, the construction of additional DBPPs leads to a decrease in average electricity prices compared with the reference scenario. These power plants are covered by EEG subsidies and have priority feed-in. Considering the MO, DBPPs are, therefore, classified as independent of marginal costs. The increase in generation capacities that are independent of marginal costs leads to a decrease in residual load and, therefore, also to a shift in the intersection of the demand curve and MO towards power plants with lower marginal costs.

Retrofitting coal-fired power plants with CCS technologies leads to similar electricity prices compared with the reference scenario if subsidy rates are applied as given in Fig. 7.

Assumed subsidy requirements

Figure 7 shows the subsidy requirements for the different CO_2 mitigation strategies. Since the subsidy of DBPPs is already covered by the EEG, no subsidy requirements are determined here for this strategy.

On average, the subsidy requirements for co-firing are lower compared with the other two CO_2 mitigation

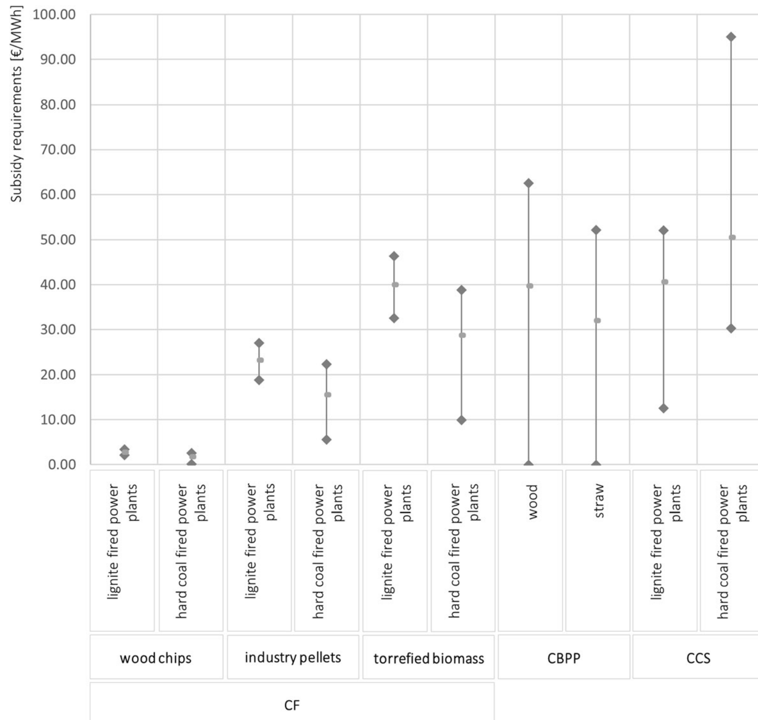

Fig. 7 Subsidy requirements for the different CO_2 mitigation strategies

strategies. The higher the refinement level of the co-fired biomass, the higher the need for subsidy becomes. In addition, it can be stated that the subsidy required for the substitution of lignite is higher than for the substitution of hard coal. This can be explained by comparing the difference between the prices of biomass and lignite and the difference between the prices of biomass and hard coal, whereby the former is larger.

The firing of wood in CBPPs requires similar subsidies as the co-firing of torrefied biomass in lignite-fired power plants. The subsidy requirements of firing straw in CBPPs are even lower. The firing of both, straw and wood, does not require any subsidy in energy pathways A and B.

The CCS scenario has on average the highest subsidy requirements. In contrast to the co-firing scenarios, here the retrofitting of lignite-fired power plants leads to lower subsidy requirements compared with the retrofitting of hard coal-fired power plants.

CO_2 mitigation costs

Figure 8 shows the CO_2 mitigation costs of the different scenarios. The CO_2 mitigation costs result from the sum of the change in electricity generation costs and the granted subsidy.

The scenarios for the evaluation of the technical potential of co-firing do not consider economic motivations and, therefore, does not involve subsidies. Thus, the CO_2 mitigation costs of these scenarios reflect the change in power generation costs only. These include the investment costs given in Fig. 5, the transportation costs of the biomass as well as the monetary effects of the change in the power plant efficiency and the shift within the merit order.

The CO_2 mitigation costs of the economic potential scenarios of co-firing are on average lower compared with the CO_2 mitigation costs of the technical scenarios. This result can be explained with the electricity prices given in Fig. 6. On average, the electricity costs are lower for the scenarios that reflect the economic potential, since in such scenarios less power plant operators are motivated to retrofit their power plants for co-firing. Therefore, the higher costs for biomass compared with coal have a lower impact on the electricity price. In both cases, the technical and economic scenarios, the CO_2 mitigation costs rise with an increase in the biomass' refinement level.

The change in power generation costs for the CBPP scenario includes the change in electricity prices given in Fig. 6, the expenditure for depreciation and interest and the additional costs for biomass compared with coal. Even though the CBPP scenario leads to a reduction in the average electricity prices, the CO_2 mitigation costs of the energy pathways A to H have positive values

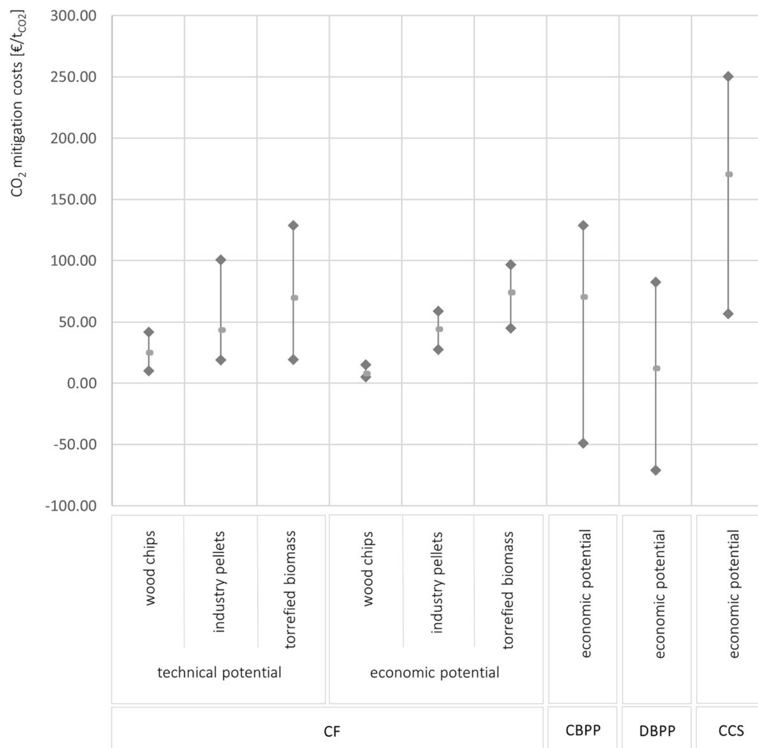

Fig. 8 CO_2 mitigation costs for the different scenarios

between 3.8 and 6.2 billion € and between 86 and 129 €/t_{CO2}, because of the required subsidy.

The CO_2 mitigation costs of the DBPP scenario result from the difference between the increase in the EEG levy and the reduction in the average electricity prices and lies between − 2.0 and + 2.5 billion €/a as well as − 71.0 and 82.5 €/t_{CO2}.

In the CCS scenario, the yearly expenses for the subsidy comprise the yearly expenditure for depreciation and interest, the costs for transportation and storage of the sequestered CO_2 and the monetary effects of the efficiency reduction. Compared with the other CO_2 mitigation strategies, the CCS scenario leads to by far the highest CO_2 mitigation costs.

Summary of results

The simulation results show that the potential for reducing the CO_2 emissions from electricity production in Germany is given by all investigated CO_2 mitigation strategies. Previous investigations demonstrated that in order to exploit at least part of the technically feasible CO_2 mitigation potential, it is necessary to subsidise the different technologies. Therefore, we investigated not only the technical potential but also the economically realistic potential, taking into account economic motives and assuming appropriate subsidies.

The economic CO_2 mitigation potential of the co-firing scenarios compared with the reference scenario varies widely between approximately 5 and 49 million t_{CO2}/a, depending on the selected biomass-based substitute and the considered energy pathway. With an average of 5 million t_{CO2}/a, the co-firing of wood chips has the lowest mitigation potential. As the refinement level of the biomass increases, the mitigation potential of the co-firing technology also increases due to the higher co-firing rates. The co-firing of torrefied biomass achieves a CO_2 mitigation potential of 43 million t_{CO2}/a on average. Through pure combustion of biomass in CBPPs, even more CO_2 emissions could be avoided. In this case, the CO_2 mitigation potential is 61 million t_{CO2}/a on average in comparison to the reference scenario. With respect to CO_2 mitigation potential, the combustion of biomass in DBPPs, with an average of 34 million t_{CO2}/a, lies between the potentials of co-firing of industry pellets and torrefied biomass. With an average of 41 million t_{CO2}/a, the conversion of existing coal-fired power plants to enable the use of CCS technologies achieves CO_2 mitigation potentials similar to the co-firing of torrefied biomass.

A different picture appears when looking at CO_2 mitigation costs. These are lower for co-firing compared with the alternative CO_2 mitigation strategies. The CO_2 mitigation costs increase with increasing refinement level of the biomass. The economic co-firing scenarios reach CO_2 mitigation costs of, on average, 8 €/t_{CO2} for wood chips, 45 €/t_{CO2} for industry pellets and 74 €/t_{CO2} for torrefied biomass. The CO_2 mitigation costs of pure biomass combustion in CBPPs are, on average, 71 €/t_{CO2} and are, therefore, comparable with those of the co-firing scenarios with torrefied biomass. Pure biomass combustion in DBPPs has relatively low CO_2 mitigation costs, with an average of 12 €/t_{CO2}, and is, thus, comparable with the co-firing of wood chips. Retrofitting existing coal-fired power plants with CCS technology leads by far to the highest average CO_2 mitigation cost, 171 €/t_{CO2}. This can be explained by both high investment costs and high subsidy requirements.

Co-firing is, therefore, a rather cost-effective technology for reducing CO_2 emissions. By comparing the CO_2 mitigation costs and the CO_2 mitigation potentials of the three different biomass-based substitutes, it becomes apparent that wood chips have the lowest CO_2 mitigation costs, but their CO_2 mitigation potential is very limited. The opposite is true for torrefied biomass. Therefore, the use of industry pellets currently appears to be the most advantageous combination of mitigation potential and mitigation costs. The rather low investment costs in retrofitting existing coal-fired power plants for co-firing of biomass is a further advantage of co-firing. Depending on the biomass used, the investment costs of the co-firing scenarios are, on average, 391 to 1042 million €. Thus, the average investment cost of the CBPP scenario is 20,357 million €, similar to that of the DBPP scenario with 17,137 million € and the CCS scenario with 32,326 million €, by a factor of 10 and 100 higher than those of the co-firing scenarios.

Discussion

Our approach enables the evaluation of the effectiveness of co-firing in comparison with three alternative CO_2 mitigation strategies considering seven sustainability indicators. It also allows, for the first time, the quantification of the CO_2 mitigation potential in a situation of widespread retrofitting of existing coal-fired power plants for co-firing. In this section, the limitations of our approach are discussed, particularly by assessing the influence of certain input parameters of our MOM by means of sensitivity analysis. Furthermore, the implications of our findings are discussed.

Sensitivity analysis of the developed MOM

The uncertainties of the MOM lie partly in the adaptation to the year 2020. Due to the fact that the German energy sector is undergoing a transformation as a result of the planned energy turnaround, forecasts of the electricity market in 2020 underlie considerable uncertainties. We address this uncertainty by performing each simulation on the basis of eight different energy pathways, each with different assumptions regarding commodity prices, electricity demand, composition of the power plant park and transboundary electricity transfer. In this way, each of the sustainability indicators will be given as a range that reflects the variance between the different energy pathways. Especially, the prices for biomass are difficult to predict due to their volatility in recent years [40, 41]. In order to investigate the influence of the fluctuation of biomass price, we conducted a sensitivity analysis. The sensitivity analysis is based on the energy pathway E combined with the scenario "economic potential of co-firing with the use of industry pellets". This scenario is characterised by medium assumptions regarding both commodity prices and the refinement level of the biomass. We applied a fluctuation range of ± 15%. The results of the sensitivity analysis are shown in Table 7. It is obvious that the influence of the fluctuating biomass price on the electricity price is small. Nevertheless, the deviation of the required subsidies is significant and, thus, constitutes CO_2 mitigation cost.

In our previous analysis, we assumed subsidies in order to investigate the economic potential of co-firing and other CO_2 mitigation strategies. An alternative way to increase the economic competitiveness of CO_2 mitigation strategies is to increase the prices for CO_2 certificates. We determined the required price level of CO_2 certificates by assuming that the marginal costs of electricity generation must be the same for the different CO_2 mitigation strategies and the pure coal combustion without CCS technology. The necessary CO_2 certificate prices determined in this way for energy pathway E are given in Table 8.

Subsequently, we discuss the effects of the increase in CO_2 certificate prices in comparison with monetary subsidies on several indicators. Also, we used the energy pathway E as an example (see Table 9).

The increase in CO_2 certificate prices leads to significant reallocations within the MO. Gas-fired power

Table 7 Sensitivity analysis for the price developments of industry pellets

Deviation of biomass price	− 15%	− 10%	− 5%	+ 5%	+ 10%	+ 15%
Deviation of electricity price (%)	0.16	0.09	0.04	− 0.07	− 0.13	− 0.16
Deviation of subsidy requirements (%)	− 22.86	− 15.88	− 7.87	7.98	15.79	23.7
Deviation of CO_2 mitigation costs (%)	− 21.67	− 15.22	− 7.63	7.38	14.78	22.5

Table 8 Necessary CO_2 certificate prices in order to achieve marginal cost parity in hard coal-fired power plants for energy pathway E

	CF, wood chips	CF, industry pellets	CF, torrefied biomass	CBPP		CCS
				Straw	Wood	
CO_2 certificate price (€/t)	95.0	100.0	99.0	60.0	75.0	40.0

plants benefit from higher CO_2 certificate prices compared with coal-fired power plants due to their lower CO_2 emission factor. This leads to a substitution of coal-fired power plants with gas-fired power plants. Since they cause higher electricity generation cost, the increase in CO_2 certificate prices leads in all scenarios to an increase in electricity generation costs, compared with the scenarios involving subsidies.

Likewise, the mitigation of CO_2 emissions can be explained partly by the reallocations within the MO. Another reason is the improved competitiveness of the different CO_2 mitigation technologies: The higher the price of CO_2 certificates, the more these technologies benefit from their reduced CO_2 emissions and the more frequently the plants equipped with these technologies are used. Due to increasing CO_2 certificate prices, CO_2 mitigation costs increase in all scenarios except the CCS scenario. The economic effects of rising CO_2 certificate prices on sectors such as the steel, cement and aviation industries, which are much more exposed to international competition than the domestic energy industry, are not taken into account in this analysis.

Implications of the findings

The pivotal indicator of the evaluation of the effectiveness of the planned CO_2 mitigation strategies is the CO_2 mitigation cost. In our study, the simulated CO_2 mitigation costs of the co-firing scenarios correspond mostly with literature estimates. Similar to our approach, Dena [34] assessed the co-firing of industry pellets with a co-firing rate of 10% and determined CO_2 mitigation costs of 27–89 €/t_{CO2}, which is similar to our simulated CO_2 mitigation costs, ranging from 19 to 100 €/t_{CO2} in the technical scenario and from 28 to 59 €/t_{CO2} in the economic scenario. Another study by McKinsey et al. [42] shows approximately 40 €/t_{CO2}, also similar to CO_2 mitigation costs for the co-firing of biomass. The comparison of the alternative CO_2 mitigation strategies with literature estimates is not straightforward for the co-firing scenarios. There are no literature estimates on the CO_2 mitigation costs for CBPP and DBPP, and the found literature estimates of CCS are much lower compared with our study. Whereas our simulations result in CO_2 mitigation costs of 60–250 €/t_{CO2}, the literature estimates are lower, approximately 30 €/t_{CO2} for lignite- and 50 €/t_{CO2} for hard coal-fired power plants [42].

From a retrospective perspective, the four CO_2 mitigation strategies could have contributed significantly to reducing CO_2 emissions in the energy sector and, thus, to achieving German GHG emission reduction target for 2020. The German government's goal is the mitigation of GHG by 40% by 2020 and 55% by 2030 compared with the reference year of 1990. In our study, the implementation of co-firing resulted in CO_2 reduction rates of 4% for wood chips, 21% for industry pellets and 34% for torrefied biomass considering the economic potential compared with our reference scenario. Considering the mitigated CO_2 emissions and the CO_2 mitigation costs, the co-firing of industry pellets is the most cost-efficient mitigation strategy. With respect to the CO_2 emissions of the German electricity generation, which amounted to 285.2 million t in 2017 [2], the co-firing of industry pellets could have led to CO_2 emission reduction of 60 million t if it had been implemented in time. The widespread use of CBPPs would have led to CO_2 emission reduction of 134 million t according to our findings. Regarding the use of DBPPs and the retrofitting of coal-fired power plants with CCS technology, reductions of 74 million t and 91 million t of CO_2 emissions respectively could have been achieved. However, these mitigations could only be achieved if the particular mitigation strategy is actually implemented. The implementation of co-firing requires a political decision supporting economic incentives that make them economically competitive. Afterwards, time is needed for the conversion of pure

Table 9 Effects of price increase of CO_2 certificates (CO_2 price) compared with monetary subsidies using energy pathway E as an example

Scenario	CF, wood chips		CF, industry pellets		CF, torrefied biomass		CBPP		CCS	
	Subsidy	CO_2 price	Subsidy	CO_2 price	Subsidy	CO_2 price	Subsidy	CO_2 price	Subsidy	CO_2 price
Average electricity generation costs (€/MWh)	58.29	119.34	58.16	126.81	57.68	125.09	48.6	95.12	60.54	76.68
Biomass demand incl. EEG plants (PJ)	309.4	345.4	634.9	514.5	827.0	489.6	1196.7	1025.4	749.8	245.5
CO_2 emissions (Million t/a)	114.9	70.5	94.6	60.7	75.9	54.5	45.2	22.9	85.3	29.9
CO_2 mitigation costs (€/t_{CO2})	7.2	73.9	51.7	92.8	78.5	268.7	106.1	112.8	159.2	66.7

coal combustion to the widespread use of co-firing. This is also true for the alternative mitigation strategies. Therefore, it will not be possible to exploit the abovementioned mitigation potentials by 2020. Only higher CO_2 certificate prices as shown in the sensitivity analysis can still lead to short-term CO_2 mitigations by 2020.

Regarding the year 2030 or the long-term, the implementation of co-firing technology in existing coal-fired power plants might be a cost-efficient CO_2 mitigation strategy. Facing the even higher reduction targets of the year 2030, the co-firing of industry pellets could play an important role as a bridging technology in order to mitigate the CO_2 emissions of the coal-fired power plants before their phase-out in 2038 [43]. Therefore, the inclusion of co-firing technology to the climate action plan should be considered.

In case of inclusion in the climate action plan, the big advantage of our presented approach lies in the transferability to other reference and target years and to further CO_2 mitigation strategies. In this regard, our approach can be easily updated to the year 2020 and transferred to the year 2030. The effectiveness of co-firing can be easily evaluated for the year 2030 by assessing the mitigation potential as well as the mitigation costs. Furthermore, additional CO_2 mitigation strategies can be evaluated and compared with co-firing scenarios.

Conclusion

All four analysed CO_2 mitigation strategies could have contributed significantly to meeting the German GHG reduction targets in 2020. Among the analysed CO_2 mitigation strategies, the co-firing of industry pellets has been identified as the most effective since it has the best combination of CO_2 mitigation potential and CO_2 mitigation costs. The widespread implementation of co-firing with industry pellets would have led to a reduction of CO_2 emissions by 21% on average and CO_2 mitigation costs of 45 €/t_{CO2} considering the economic potential on average. This would correspond to CO_2 emissions of 225 million t of the yearly electricity generation by 2020 if our reduction rate of 21% was transferred to the CO_2 emissions of the German electricity generation in 2017. Consequently, the implementation of co-firing with industry pellets would have led to CO_2 emission reduction of 38.5% compared with the base year 1990, which achieved almost the climate reduction targets of 2020 by considering solely electricity generation.

Co-firing with industry pellets is also the most preferable CO_2 mitigation strategy considering the other sustainability indicators. Compared with the alternative CO_2 mitigation strategies, co-firing is characterised first and foremost by low investment costs and also by the fact that it causes the least distortion within the MO. The electricity generation capacity currently existing in Germany is sufficient to meet the electricity demand. Therefore, capacity expansions such as those required in the scenarios involving the construction of additional CBPPs and DBPPs must be critically evaluated, as these may result in additional macroeconomic costs that have not yet been quantified. In this respect, biomass power plants should above all be built to replace today's coal-fired power plants at the end of their life span. The CCS technology is currently in the pilot and demonstration phase. In addition, the technology faces considerable rejection from civil society. Its widespread use in the power plant sector, therefore, appears rather unlikely in the immediate future. When economic motives are taken into account, the different CO_2 mitigation strategies will only be able to reduce CO_2 emissions if the economic conditions are changed. This can be achieved on the one hand by granting monetary subsidies and on the other by increasing the prices of CO_2 emission certificates. Our comparison of these two options gives an initial indication that CO_2 emissions can be reduced more cost-effectively by subsidies. In summary, co-firing appears to be the most efficient and fastest available technology for reducing CO_2 emissions in the near future, taking into account the CO_2 mitigation costs resulting from subsidies, the extensive investment costs of the alternative CO_2 mitigation strategies, the considerable distortions within the MO caused by the construction of additional CBPPs and DBPPs, and the current lack of market maturity of CCS technologies.

Nowadays, however, the necessary legal frameworks for monetary subsidies as well as the necessary infrastructures for the successful implementation of co-firing as a CO_2 mitigation strategy are missing in Germany. The consideration of different subsidy concepts and their analysis with regard to all resulting economic implications could be the focus of a subsequent study. The selected modular structure of the developed MOM makes such a study possible. Since the biomass price has a considerable influence on the CO_2 mitigation costs, a focus of future research should be the determination of cost reduction potentials in biomass cultivation, harvest and transportation. Emphasis could be laid on the optimisation of transport costs in relation to transport distances. In this regard, it would be interesting to determine at which transport distance the change to a biomass of higher refinement level is advantageous due to its higher energy density. For a more comprehensive assessment of the CO_2 mitigation potential of co-firing, future research works should consider not only the CO_2 emissions of combustion but also the CO_2 emissions from the entire upstream chain. In further studies, the extension of the observation period to 2050 and the combined consideration of co-firing and other CO_2 mitigation strategies should outline how the German climate protection goals for the year 2050 can be achieved.

However, in the end, it is up to policymakers to decide on the importance they attach to the mitigation of CO_2 emissions and to find solutions to keep the additional costs arising from subsidies acceptable for electricity consumers.

Additional file

Additional file 1: Table S1. Description of the eight energy pathways derived from Sachverständigenrat für Umweltfragen [26], Energiewirtschaftliches Institut an der Universität zu Köln et al. [27], DLR (Deutsches Zentrum für Luft- und Raumfahrt), IWES (Fraunhofer Institut für Windenergie und Energiesystemtechnik) and IfnE [25]. **Table S2.** Biomass prices for 2012 incl. Transportation [30, 41, 44–49]. **Table S3.** assumed annual biomass price increase [25, 40, 41, 44, 50, 51]. **Table S4.** biomass prices for 2020 incl. Transportation [40, 41, 44, 50, 51]. **Table S5.** Energy Pathway A: SRU – 509 GWh – standardized. **Table S6.** Energy Pathway B: SRU – 700 GWh – standardized. **Table S7.** Energy Pathway C: EWI – reference energy pathway – standardized. **Table S8.** Energy Pathway D-F: DLR – leading energy pathway 2011 A– standardized. **Table S9.** Energy Pathway G: DLR – leading energy pathway 2011 A' – standardized. **Table S10.** Energy Pathway H: DLR – leading energy pathway 2001 THG95 – standardized. (DOCX 77 kb)

Abbreviations

CBPP: Centralised biomass power plant; CCS: Carbon capture and storage technology; CF: Co-firing; CO_2: Carbon dioxide; DBPP: Decentralised biomass power plant; EEG: Renewable Energy Sources Act; EEX: European Energy Exchange; GHG: Greenhouse gas; MO: Merit order; MOM: Merit order model

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Authors' contributions

SK designed research, developed the MOM, the energy pathways and the scenarios; SK, AG and SW conducted the data collection, analysis and interpretation; AG & SW designed the concept of the article, AG derived the sustainability indicators, designed the visualisations and wrote most of the article. SW is the corresponding author and coordinated the collaboration; LS supervised the work and made substantial contributions to the conception of the research. All authors contributed to the revision of the article and approved the final manuscript.

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Availability of data and materials

All data generated or analysed during this study are included in this published article and its supplementary information files (Additional file 1).

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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