Renew, reduce or become more efficient? The climate contribution of biomass co-combustion in a coal-fired power plant

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HIGHLIGHTS

- Coal mining is more energy and CO_2 efficient than biomass production.
- Co-combustion of 60% biomass with coal doubles mass transport compared to 100% coal.
- Low co-combustion levels reduce GHG emissions, but the margins are small.
- Total supply chain efficiency is the highest for the coal reference at 41.2%.

ARTICLE INFO

ABSTRACT

Within this paper, biomass supply chains, with different shares of biomass co-combustion in coal fired power plants, are analysed on energy efficiency, energy consumption, renewable energy production, and greenhouse gas (GHG) emissions and compared with the performance of a 100% coal supply chain scenario, for a Dutch situation. The 60% biomass co-combustion supply chain scenarios show possibilities to reduce emissions up to 48%. The low co-combustion levels are effective to reduce GHG emissions, but the margins are small. Currently co-combustion of pellets is the norm. Co-combustion of combined torrefaction and pelleting (TOP) shows the best results, but is also the most speculative.

The indicators from the renewable energy directive cannot be aligned. When biomass is regarded as scarce, co-combustion of small shares or no co-combustion is the best option from an energy perspective. When biomass is regarded as abundant, co-combustion of large shares is the best option from a GHG reduction perspective.
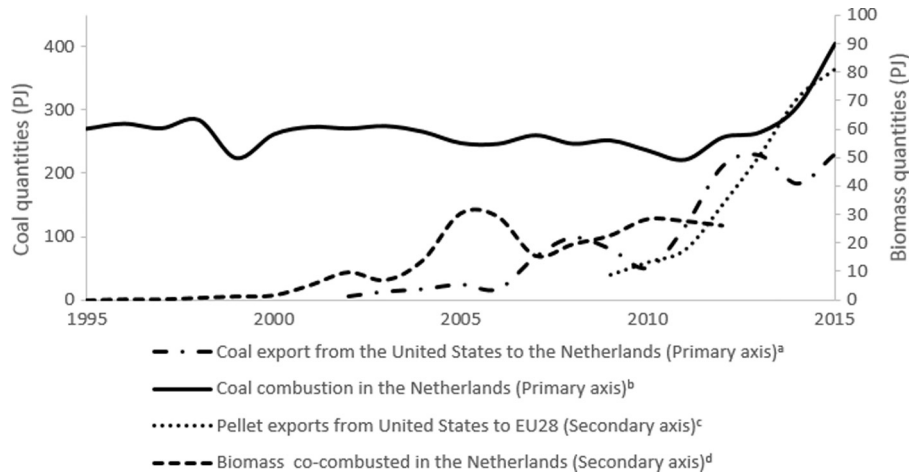
1. Introduction

During the last hundred years, pulverised coal combustion has been widely applied for electricity generation [1]. More recent, deregulation of the European power sector [1], low coal prices and a plethora of inexpensive emission certificates have increased the lock-in effects of pulverised coal firing in the EU. Currently, technological innovation is applied as a means to decrease the environmental impact of coal combustion, by increasing the boiler efficiency, co-combustion with biomass or carbon capture and storage [1].

The renewable energy directive (RED), [2] as constituted by the European Commission (EC), emerged from increasing awareness about climate change. Hence, the focus is on the reduction of greenhouse gas (GHG) emissions, by using indicators as: increased use of renewable energy sources, energy saving and more efficient use of energy. Biomass has the largest contribution to renewable energy production in the European Union (EU); almost two-thirds of the primary production of renewable energy originates from biomass [3]. Despite criticism on the actual sustainability of biomass for energetic purposes [4,5] biomass is often co-combusted in coal-fired power plants in the Netherlands. Fig. 1 shows the quantity of biomass co-combusted in the Netherlands from 1995 until 2012. The annual co-combusted biomass quantities after 2005, were directly related to the Dutch subsidy structures [6]. During the last decade a tenfold increase in coal exports from the United States (US) to the Netherlands has taken place, up to 230 PJ in 2015. In the same period, the domestic consumption of coal in the Netherlands for electricity generating purposes increased with approximately 60% up to 400 PJ in 2015. Pellet exports from the US to the EU28 increased with a factor nine since 2009 up to 81 PJ in 2015. The amount of imported pellets was

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Fig. 1. Coal exports from the United States to the Netherlands (PJ), coal quantities combusted for electricity production (PJ), pellet exports from the United States to the EU28 (PJ) and co-combusted biomass in the Netherlands (PJ). (a) [14] (b) [15] (c) [16,17] (d) [18].

equal to the domestic consumption in 2011 in the Netherlands. Assuming that the imports are evenly distributed over the domestic consumption, then about 40% of the consumed pellets in the Netherlands originated from the US. This corresponds to roughly 7 PJ, which is 25% of the co-combusted pellets in the Netherlands. The Dutch Energy Agreement for sustainable growth [7] has put a maximum on biomass co-combustion of 25 PJ in 2020. This maximum underlines that the debate regarding the environmental sustainability and optimal application of biomass is still ongoing.

Biomass is a rather dispersed resource [8] and generally available in regions with low energy and material demand. This low regional demand results in the need for transport to more material and energy intensive regions. The larger part of the co-combusted biomass in the Netherlands originates from North America [9]. Giuntoli et al. showed that low energy densities of biomass result in lower transport efficiencies compared to e.g. coal [10]. The logistic disadvantages of biomass can be reduced by applying pretreatment to increase the energy density (MJ kg^{-1}).

When biomass is applied for co-combustion, a supply system complementary to that of coal has to be designed. However, the impact of the biomass supply chain on the total system performance is often neglected. This is in line with Iakovou et al. whom state that little research focuses on supply chain issues, whilst taking the whole supply chain into account [11]. Lin et al. showed that long distance transportation of wood pellets is economically feasible [12], just as Uslu et al. showed that biomass transportation could be economically and energetically feasible under certain conditions [13]. However, the actual net quantities of renewable electricity from biomass co-combustion and the related greenhouse gas (GHG) emissions of long distance supply chains are still unsure, since conversion is not taken into account by Uslu et al. [13] and Lin et al. [12] only focus on the economic aspects of biomass supply, which at least in the Netherlands has a strong relation with subsidy structures [6].

Therefore, within this article a chain analysis with a variety of biomass supply chain scenarios, including different pretreatment technologies and different co-combustion levels, was performed. The aim of this analysis is to determine the effectivity of different pretreatment technologies, different levels of biomass co-combustion and conversion on the RED indicators, GHG emissions, the energy efficiency, energy consumption and renewable energy production, when the whole supply system is taken into account. Currently, co-combustion of pellets is the norm in the Netherlands. This research studies the effect of co-combustion of different shares of poplar wood chips, torrefied wood chips, pellets and combined torrefaction and pelleting (TOP). The analysis

indicates whether renewable energy from biomass co-combustion results in energy saving, increased energy efficiency and finally a reduction in GHG emissions compared to the combustion of coal.

This paper continues with a methodology section describing the qualitative and quantitative aspects of the supply chains. Subsequently, the supply chain scenarios are discussed after which the results are presented. Furthermore, a discussion section, finalised with a sensitivity analysis, and a general conclusion are presented.

2. Methodology // system components

There are two separate upstream supply systems, which merge at the midstream conversion stage (Fig. 2). Coal is first mined, transported to a harbour and subsequently transported overseas to the port of Rotterdam in the Netherlands. Poplar is produced, harvested, chipped and dried (up to 20% moisture on a wet basis) on the production site, before the wood chips are transported to a harbour. At the harbour, no further pretreatment, or torrefaction, or pelleting or TOP is applied. Subsequently, the biomass is transported overseas with a Supramax bulk carrier (in line with [10]) and grinded together with coal at the coal-fired power plant. The coal and biomass are co-combusted on the Maasvlakte where the GDF Maasvlakte pulverised coal-fired power plant is located. This power plant is theoretically able to co-combust up to 60% biomass [19]. Fig. 2 gives an overview of the system boundaries of this research and the design of the supply chain scenarios, which are further elaborated upon in Fig. 3. The midstream part of the biomass supply chain is equal to the coal supply chain, where both feedstocks are grinded and combusted for electric power production. In the following, the individual steps in the supply chains are discussed. This section further elaborates on the calculation of the energy use in transport, the conversion efficiency, the calculation of the share of renewable electricity produced, the 12 supply chain scenarios, and the coal supply chain reference scenario.

For ease of comparison 1 MJ$_{electric}$ output was taken as the functional unit for all supply chain scenarios. This results in demand driven supply chains scenarios. Hence, the calculated conversion efficiency and the energy content of the pre-treated biomass determine the required quantities of biomass.

2.1. Coal mining

The first step in coal supply is mining of the resource. Ditsele and Awuah-Offei provide a life cycle analysis of the impact of mod-
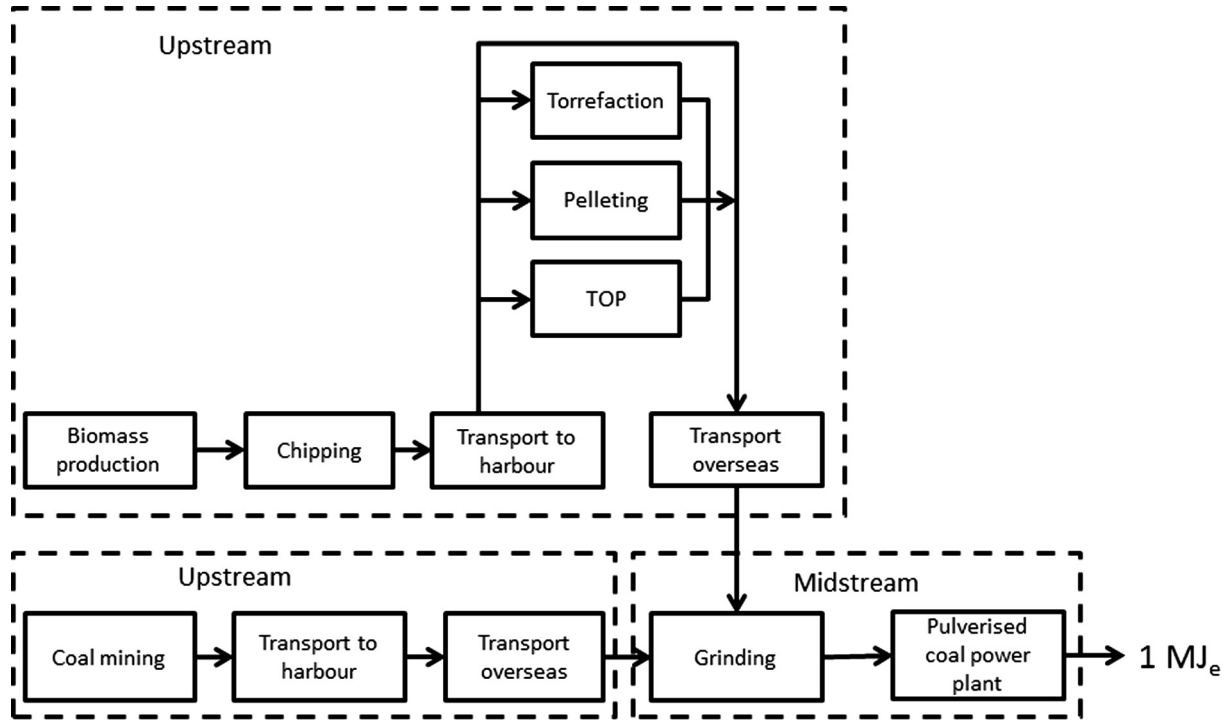
Fig. 2. Overview of the system boundaries of the analysed supply system for biomass and coal.
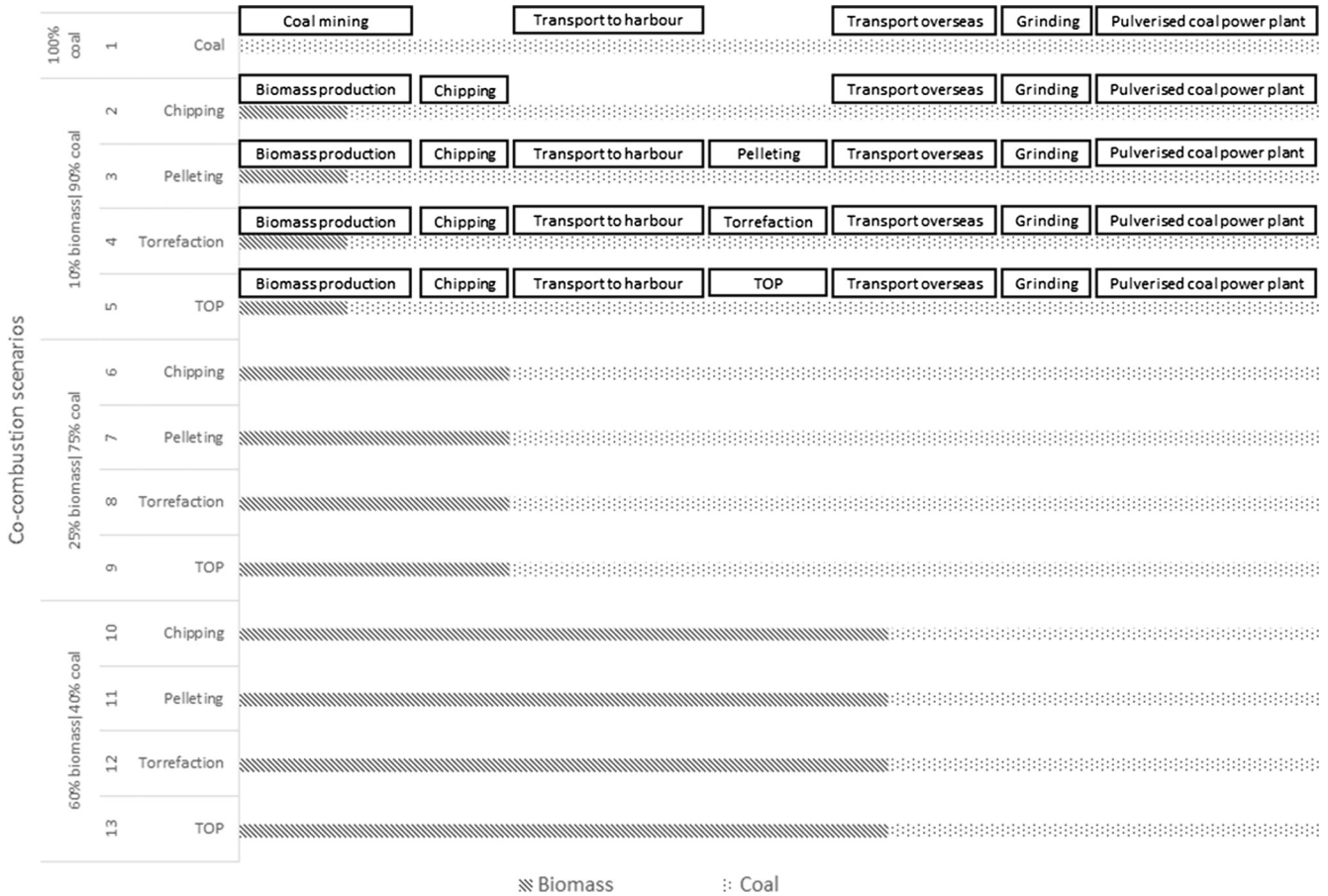
Fig. 3. Overview of the analysed coal-based reference and biomass co-combustion supply chain scenarios.

Table 1
Energy consumption and GHG emissions of coal mining and biomass production (data taken from Ditsele and Awuah-Offei [20] and Miedema et al. [21]).

Fuel		Low	Average	High	Unit
Coal	Energy consumption	97	124	181	MJ t^{-1} coal
	GHG emissions	38	62	92	kg CO$_2$ eq. t^{-1} coal
Biomass	Energy consumption		656		MJ t^{-1} biomass
	GHG emissions		65		kg CO$_2$ eq. t^{-1} biomass

Table 2
The energy losses and required fossil inputs for different types of biomass pretreatment and the energy consumption for grinding of coal and pre-treated biomass.

Pretreatment	Energy losses	Fossil input	Total	Grinding			Unit
				Low	Average	High	
Coal				18[d]	74	130[e]	MJ t^{-1}
Chipping		249[a]	249	360	3240	4201	MJ t^{-1}
Pelleting		464[b]	464	42	750	1500	MJ t^{-1}
Torrefaction	1400	616[c]	2016	36[c]	648	1260[b]	MJ t^{-1}
TOP	1400	695[c]	2095	22	389	756	MJ t^{-1}

[a] [30].
[b] [13].
[c] [8].
[d] [31].
[e] [32].

ern surface coal mining facilities in the United States (US) [20]. The data from this paper are suitable for this analysis, since it provides an overview of the distribution of energy use and emissions of different coal mining situations and it focuses on bituminous coal, which is suitable for conversion in a pulverised coal-fired power plant. The bituminous coal is suitable for grinding further down the supply chain. The coal in the analysed supply chains originates from the US and is suitable for conversion to electricity in the Netherlands. Fig. 1 shows that coal import from the US to the Netherlands is a recent and increasing trend. The data from Ditsele and Awuah-Offei [20] is cradle-to-gate data, where the gate is the mine gate. It therefore represents the first block in Fig. 2 (i.e., coal mining). Energy use and GHG emissions of coal mining are presented in Table 1.

2.2. Biomass production

For comparability with the reference scenario the biomass production system is located in the US, which is in line with [9]. As underlined by Fig. 1 and elaborated upon in the introduction, the amount of co-combusted pellets in the Netherlands, originating from the US is about 25% of the total. Therefore, the same transport logistics can be applied. The intensive production system for woody lignocellulosic biomass is applied [21]. These systems were originally developed for European production sites [22]. For the purpose of this research they are suitable, since biomass yields, inputs and energy densities of the biomass are in the same range. The intensive woody lignocellulosic biomass production system includes ploughing and preparation, crop protection, fertiliser application (nitrogen), harvesting, forwarding biomass to the roadside, chipping and loading of the biomass on a truck. Combined data for the energy use and GHG emissions of biomass and coal production are presented in Table 1.

2.3. Biomass and coal pretreatment

This paper analyses three pretreatment technologies for biomass, namely torrefaction, pelletisation and TOP. Transporting biomass in the form of pellets from the United States is the norm. The transport of pellets is compared with the transport of wood chips, torrefied wood chips and TOP in order to find whether one type of pretreatment is energetically and environmentally advantageous compared to pellet transport and co-combustion. In these assumed cases that the production of wood chips, torrefed wood chips, pellets and TOP is taking place in the US before actual overseas transport. Furthermore, grinding or pulverisation of coal and biomass is taken into account at the coal-fired power plant in the Netherlands.

2.3.1. Pellets

Pelletisation is a proven technology, since 650 pelletisation plants produced roughly 10 million tonnes of pellets in Europe in 2009 [23]. Pelleting or densification is applied to increase the bulk (kg m^{-3}) [24] and energy density of biomass for more efficient transport. For a more extensive overview of the pelleting technology this paper refers to Mani [24] and Uslu et al. [13]. The applied data for pelleting is presented in Table 2.

2.3.2. Torrefied wood chips

Torrefaction was not yet a commercially feasible technology in 2011 [25]. This is underlined by Koppejan et al. [26], whom identified over 40 torrefaction initiatives aiming to prove the economic and technological viability of the technology. The diffusion of torrefaction took off in this period and at the end of 2012 a number of torrefaction plants was commissioning, but not yet producing commercial volumes [27]. Currently, 65 companies are working on torrefied biomass on a global level [28]. Torrefaction is a thermal process with temperatures ranging between 200 and 300 °C. The advantages of torrefied wood chips with respect to untreated biomass are, a hydrophobic nature, due to loss of hydroxyl groups [29], and the absence of biological activity, which makes storage in an ambient atmosphere possible. Torrefied wood has a more constant product composition, which makes the subsequent conversion process easier to control. The applied data for torrefied wood chips are presented in Table 2.

2.3.3. Combined torrefaction and pelleting (TOP)

There is not yet a substantial market for TOP, but it could become a successor of pelletisation and torrefaction, due to high energy efficiency [33] and due to the fact that this product has the combined advantages of pelletisation and torrefaction. Therefore, it shows an increase in bulk and energy density. It has a

hydrophobic nature and requires less energy for grinding, when compared to pellets or chipped biomass. Prior to size reduction and densification of biomass in the pelleting process, the biomass is torrefied, after which densification is applied. Due to similarities in both the torrefaction and pelleting process, both processes can be combined efficiently [33]. The applied data for TOP is presented in Table 2.

2.3.4. Grinding

Before the feedstock can be fed to the burners of the power plant, it is grinded or pulverised. Grinding results in a constant particle size [29], which makes it possible to co-combust biomass with coal. The energy requirement for grinding of raw biomass is higher than the requirement for grinding of coal [8,29]. Torrefaction, e.g. may increase the grindability [29], which makes it suitable for co-combustion in a pulverised coal-fired power plant [34,35]. Therefore, pretreatment of biomass can be an option to increase the grindability of biomass in order to reduce the effects on boiler deterioration and maintain high conversion efficiency.

The energy consumption of the applied biomass pretreatment technologies are taken from literature and presented in Table 2. Aebiom states that passive drying is possible up to 20% on a wet basis [36]. Seasoning or drying is therefore done passively, by storing poplar wood chips under cover; the energy requirements for storage are not taken into account. Wood chipping is executed with a diesel driven engine [37]; for diesel a value of 74.1 g CO_2 - eq. MJ^{-1} [37] is applied. Torrefaction, pelleting and TOP are based on natural gas. For natural gas a value of 56.1 g CO_2 eq. MJ^{-1} [37,38] is applied. For torrefaction and TOP losses in energy content of the biomass fuel are included and assumed to be the equal (i.e. 10% of the energy content). Hence, during torrefaction about 10% of the energy content of the biomass is applied for the torrefaction process [34]. However, the fossil energy inputs differ for torrefaction and TOP (Table 2). The energy consumption for torrefaction and TOP are the nominal values provided by Batidzirai et al. [8]. The applied data for biomass and coal grinding is presented in Table 2.

The energy consumption data for grinding of woody lignocellulosic biomass and coal are given in Table 2. The data for torrefaction are taken from Batidzirai et al. [8] and are in the same range as data provided by Repellin et al. [39]. Tumuluru et al. argue that grinding energy of wood chips can be decreased with 70–90% when torrefaction is applied [29]. Based on the available data for torrefaction the energy consumption for grinding of wood chips was estimated. This paper assumes that grinding energy of torrefied woodchips is 10%, 20% and 30% of the energy required for grinding of chipped wood for respectively the low, average and high case. TOP has the most coal like properties and is therefore assumed to be the closest to coal. Grinding energy for pellets is assumed to be between torrefied wood chips and regular wood chips. Grinding is driven by electric power. The average Dutch energy mix was applied to calculate GHG emissions for grinding. The applied value is 114 g CO_2 eq. MJ^{-1}.

2.4. Technical possibilities for biomass co-combustion in Dutch pulverised coal power plants

The Dutch Energy Agreement for sustainable growth aims to close five of the ten coal fired power plants currently in operation [7]. This means that the GDF Maasvlakte, Amer 9, Hemweg 8, RWE-Eemshaven and MPP3 are theoretically available for co-combustion. The conversion efficiencies of these plants are: 46%, 40%, 41%, 46% and 46%, respectively [40,41], personal communication with Benders [42,43]. This paper applies a conversion efficiency for pulverised coal of 42%. Warringa et al. provide data based on their own calculations that give an estimate of the maximum

share of biomass that can be co-combusted in these power plants. These values are respectively: 60%, 50%, 40%, 20% and 20% [19].

2.5. Modal energy intensity of transport modes

The low bulk density (< 750 kg m^{-3}) of biomass causes maritime transport to be volume limited [10]. Based on data from Giuntoli et al. we argue that this also holds for truck transport when bulk densities are smaller than 300 kg m^{-3}. The low bulk densities combined with low energy densities of biomass, make biomass transport from an energetic point of view uncompetitive with liquid or gaseous fossil alternatives transported through pipelines. Coal has a high energy and bulk density and is therefore not volume limited when it comes to transport.[1] When there is a volume limitation for biomass or a lower energy density compared to coal, the fossil inputs for biomass transportation are larger than for transport of coal per unit of energy transported. The modal energy intensity (MJ/tkm) was estimated for 40t trucks with a net payload of 26t and a volume of 90 m^3 and for the Supramax bulk carrier with 57000t deadweight tonnage and a payload of 54000t. A linear relation between mass load and energy consumption was assumed. Giuntoli et al. provide modal energy intensities (corrected in order to include return trips) for the 40t trucks and Supramax bulk carrier [10], which were applied to determine two linear functions expressing the energy consumption of transport with different mass load or bulk density. Table 3 gives the required data (i.e. energy and bulk densities) to calculate the volume limitations. Subsequently, the modal energy intensity data from Giuntoli et al. [10] were applied to determine two linear functions describing the energy use for transport. This was combined with the data on volume limitations in order to estimate the modal energy intensity of both the truck and Supramax loaded with coal or biomass with different energy and bulk densities, due to pretreatment. These specific results are presented in Appendix A. The GHG emissions from transport are based on the assumption that trucks are diesel driven and the Supramax bulk carrier uses heavy fuel oil (HFO). For HFO a value of 82.6 g CO_2 eq. MJ^{-1} (calculated with data from Giuntoli et al., 2015) [10] is applied.

2.6. Conversion efficiency

Modern coal-fired power plants have electric conversion efficiencies over 46%. When biomass is co-combusted in a coal-fired power plant the overall efficiency decreases, due to deterioration of the boiler efficiency [44]. Pronobis and Wojnar, provided the experimental boiler efficiency of the co-combustion of coniferous wood biomass [45]. In this article the reduction in boiler efficiency is equal to the reduction in conversion efficiency. Pretreatment of biomass, like torrefaction and TOP, results in a biogenic feedstock of which the chemical composition is more similar to coal. Therefore, this article argues that more pretreatment results in less deterioration of the boiler efficiency and thus a smaller decrease in overall process efficiency. Therefore, a 1% conversion efficiency drop for every 10% increase in co-combusted biomass was applied for wood chips (Eq. (1)). This is in line with the data from Pronobis and Wojnar [45]. Torrefaction and TOP are assumed to have similar combustion performances after grinding. Pellets have lower moisture content than wood chips and are therefore assumed to have a combustion performance between wood chips and torrefied wood/ TOP. Therefore, a higher conversion efficiency was applied for pellets, torrefied wood chips and TOP (Eqs. (2) and (3)). Based on these assumptions and the data from Pronobis and Wojnar [45],

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[1] Assuming an average bulk density of 825 kg m^{-3} for coal; transport by bulk carrier and truck are both mass limited, since the bulk density is larger than 750 kg m^{-3} and 300 kg m^{-3} respectively.

Table 3
Input data for coal and biomass after different types of pretreatment.

	Energy density		Bulk density			
		Unit	Low	Average	High	Unit
Coal[a]	30	MJ kg^{-1}	800	825	850	kg m^{-3}
Chipping	14	MJ kg^{-1}	200[a]	325	450[a]	kg m^{-3}
Pelleting	17,7[a]	MJ kg^{-1}	500[a]	575	650[a]	kg m^{-3}
Torrefaction	18	MJ kg^{-1}	230[a]	265	300[b]	kg m^{-3}
TOP	18,4	MJ kg^{-1}	750[a]	800	850[a]	kg m^{-3}

[a] [13].
[b] [29].

Eqs. (1)–(3) were developed to calculate the conversion efficiencies of wood chips (1), pellets (2) and torrefaction and TOP (3).

$$f(x)_{\text{Wood chips}} = -10x + b \qquad (1)$$

$$f(x)_{\text{Pellets}} = -7,5x + b \qquad (2)$$

$$f(x)_{\text{Torrefied chips/TOP}} = -5x + b \qquad (3)$$

where x is the fraction of biomass co-combusted on an energy basis and b is the conversion efficiency of coal, which is in this case set at 42%. GHG emissions are determined by using a value of 94.1 g CO_2 eq. MJ^{-1} [37] bituminous coal combusted.

2.7. Net renewable power production

We developed Eq. (4) to calculate the share of renewable power production in the total supply chain compared to a conventional reference chain with coal.

$$E_{\text{renewable power}}(\%) = \frac{E_{\text{biomass}} - (E_{\text{supply chain}} - E_{\text{reference chain}})}{E_{\text{supply chain}}}$$
$$* 100\%$$
$$(4)$$

where

E_{biomass} = The energy contained in the biomass,
$E_{\text{supply chain}}$ = The energy consumption in the whole supply chain,
$E_{\text{reference chain}}$ = The energy consumption in the coal reference chain.

2.8. Supply chain scenarios

Thirteen supply chain scenarios were analysed, which are graphically represented in Fig. 3. The stacked horizontal bars show the shares of biomass and coal in the different scenarios. The blocks show the different supply chains. The supply chains for route 6–9 and 10–13 are equal to the supply chains for route 2–5. Scenario 1 is the 100% coal supply chain reference scenario, where only coal is combusted. Scenarios 2–13 apply co-combustion of biomass. The shares of biomass vary from 10% to 60% on an energy basis. Routes 2–5 co-combust 10% biomass and vary the applied pretreatment technologies which are chipping only, chipping and pelleting, chipping and torrefaction and chipping and TOP, respectively. This is the same for routes 6–9 and 10–13 in which 25% and 60% are co-combusted, respectively. For all supply chain scenarios the transport distances by truck and Supramax bulk carrier are set at 100 km and 8000 km respectively.

3. Results

In the following section the results are presented. First, the biomass and coal requirements are calculated and expressed in

kg MJ$_e^{-1}$ output. Second, the supply chain components are presented in three groups, namely, production of biomass and mining and coal, transport and pretreatment. These results are expressed in MJ MJ$_e^{-1}$ output and g CO_2 eq. MJ$_e^{-1}$ output. The result section is finalised with an analysis of the whole chain and a summation of the results.

3.1. Biomass and coal requirements

Based on the conversion efficiencies (Eqs. (1)–(3)), the energy density of the different fuels and the energy losses for torrefaction and TOP (Table 2), the biomass and coal requirements are calculated for all thirteen supply chains per MJ$_e$ output (Fig. 4). These results show that with larger biomass fractions, the amount of biomass that has to be transported increases per MJ$_e$ output. The differences in biomass demand, within the 10%, 25% and 60% supply chain scenarios, are due to pretreatment related energy losses in the biomass and the differences in conversion efficiency. The supply chain scenarios where 60% biomass is co-combusted require two times more mass to be transported than the 100% coal reference supply chain scenario.

3.2. Biomass production and coal mining

The feedstock production part of the supply chains with 10%, 25% and 60% biomass show an increase in energy consumption of respectively a factor 2, 4 and 8 compared to the coal reference (Fig. 5). The black dashed lines show the biomass and coal emissions. These are all fossil emissions related to the production and harvesting of biomass and mining of coal. The emission reduction through the combustion of biomass is taken into account in the combustion stage of the supply chain (Section 3.5). Fig. 5, therefore, represents the emissions related to fossil inputs required for biomass production and harvesting. The coal GHG emissions decrease, since the demand for coal decreases with increasing biomass demand. Emissions from biomass production and coal mining are in the same range per tonne raw product. The low energy density of biomass therefore results in higher emissions per unit of energy produced. This effect becomes larger when increased quantities of biomass are co-combusted at the cost of coal. In the 25% and 60% supply chains the total GHG emissions are roughly twice as high as the reference.

3.3. Biomass and coal pretreatment

Fig. 6 shows the energy losses in biomass due to torrefaction and TOP, the fossil energy input required for biomass pretreatment and the related fossil emissions. The energy requirement for biomass pretreatment is in the same range as biomass production (Fig. 5) and transport by Supramax bulk carrier (Fig. 9). This also holds for the related GHG emissions.

Fig. 7 shows that the grinding performance of biomass is worse than the grinding performance of coal. Especially chipped wood
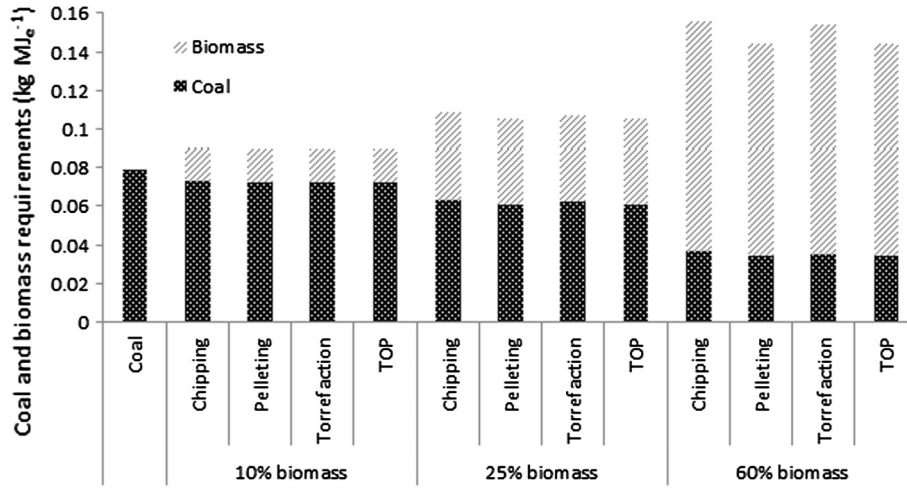
Fig. 4. The biomass and coal requirements before pretreatment, for all 13 supply chains. Biomass quantities are on a dry basis (i.e. 20% moisture content).
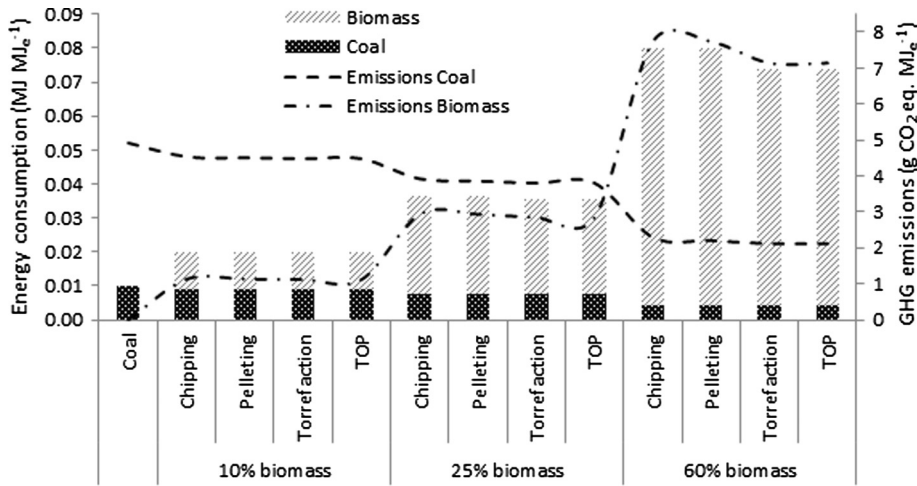

Fig. 5. Energy consumption and GHG emissions for biomass production and coal mining for all 13 analysed supply chain scenarios.
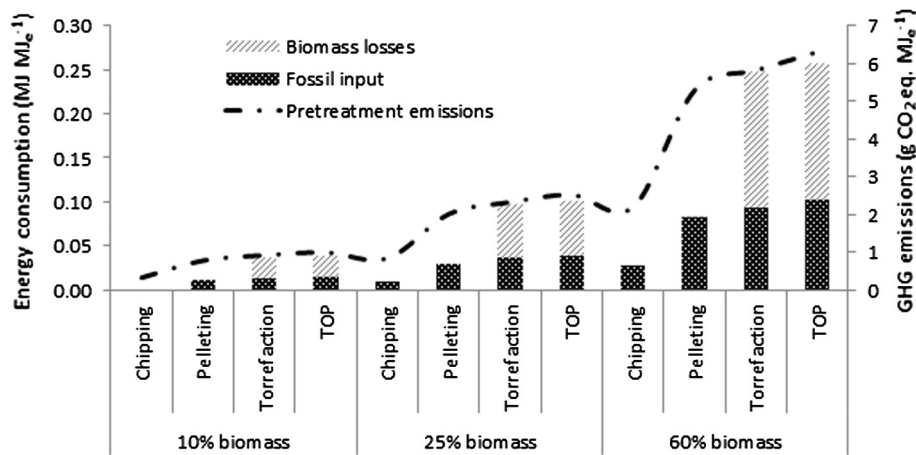

Fig. 6. The energy consumption for biomass pretreatment, the accompanied energy losses in biomass and the GHG emissions related to biomass pretreatment. Values for pelleting, torrefaction and TOP also include chipping energy and emissions.
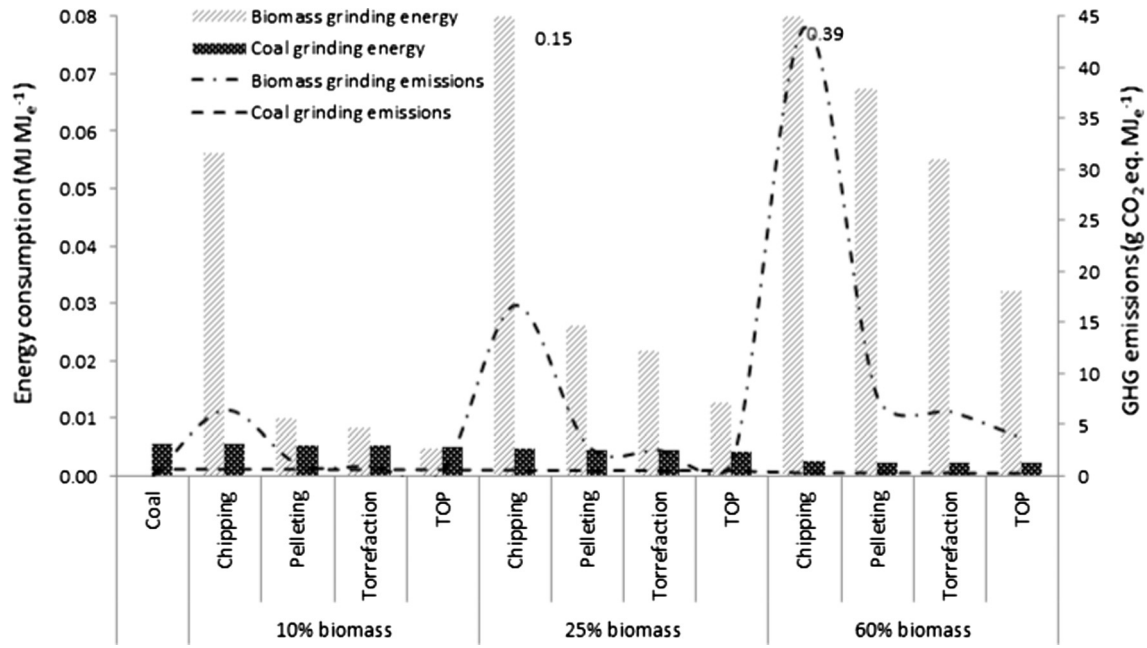
Fig. 7. The energy consumption and GHG emissions related to biomass and coal grinding. The primary vertical axis is adjusted in order to clearly display the coal related values; the high values for chipping in the 25% and 60% supply chains are therefore presented with labels.
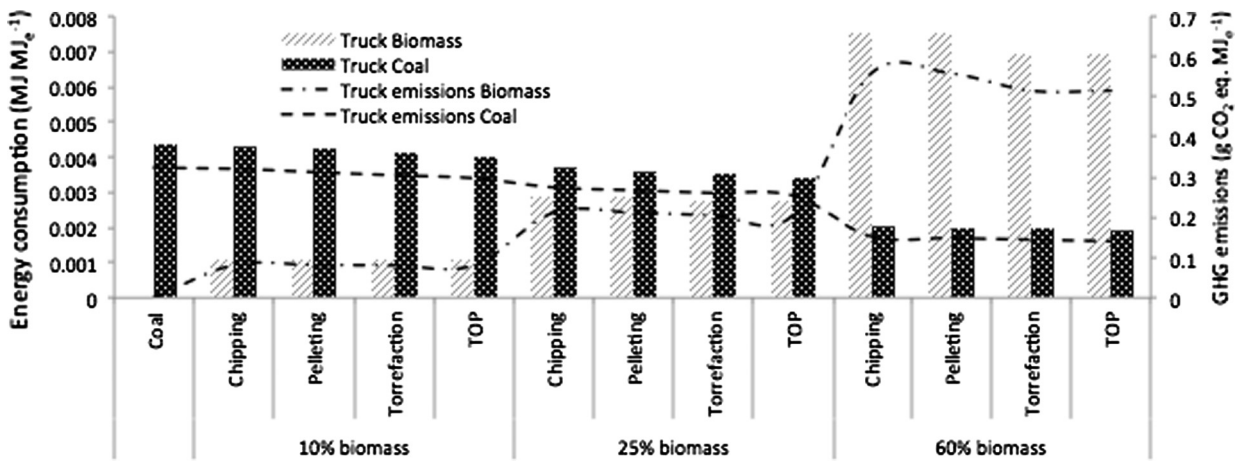

Fig. 8. The energy consumption and GHG emissions related to transport of coal and biomass by truck.
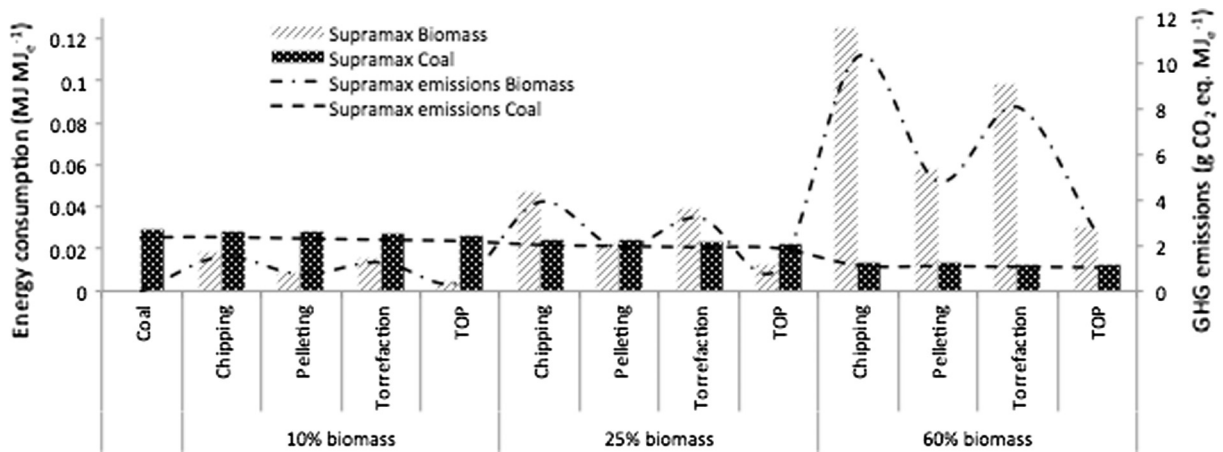

Fig. 9. The energy consumption and GHG emissions related to transport of coal and biomass by Supramax.

shows large outliers compared to coal and more intensively pre-treated biomass. A 9:1 coal to biomass energy ratio results in energy requirements for grinding, which are roughly similar for biomass and coal (i.e. when chipping is left out of the equation). More intensively pre-treated biomass shows a doubling in GHG emissions in the 10% supply chains scenarios, the 25% and 60% show an approximate increase of a factor 5 and 10, respectively compared to the coal supply chain reference scenario.

3.4. Transport performance by truck and bulk carrier

The calculations and results for the modal energy intensity of the two transport modes are presented in Appendix A. Load limitations for biomass are taken into account by applying the modal energy intensities from Fig. A.1 for coal and biomass transportation. Fig. A.1 displays the calculated energy consumption of a 40t truck and Supramax bulk carrier for coal, wood chips, torrefied wood chips, pellets and TOP. Transport energy is displayed in Figs. 8 and 9. In all scenarios it becomes clear that the total energy consumption increases, compared to the 100% coal reference. Furthermore, Fig. 9 shows that TOP technology can reasonably compete with the coal reference for the 10% and 25% scenarios, during overseas transport. Fig. 9 clearly shows the effect of the load limitations for chipping and torrefaction, during overseas transport, due to the low bulk density, especially in the 25% and 60% biomass chains.

3.5. Energy consumption and emissions of the whole supply chain

Fig. 10 shows that in every biomass supply chain scenario the overall system efficiency decreases compared to the combustion of the 100% coal chain. TOP has the best performance, but when substantial quantities (i.e. 60% biomass) are co-combusted the system performance decreases with 7% compared to the reference. The other biomass supply chain scenarios have even lower system efficiency. Appendix B gives a detailed overview of the average total energy consumption and GHG emissions related to the whole supply chains excluding conversion into electric energy. The energy consumption for conversion can be calculated by taking the reciprocal value of the conversion efficiencies, which can be derived from Eqs. (1)–(3). The vertical axis starts at 1 MJ, since this is the part of the total energy used in the process to have 1 MJ$_e$ output.

3.6. Summation of results

Fig. 11 displays the performance of the indicators from the RED; energy reduction/consumption, energy efficiency and the share of renewable energy, which should result in a decrease in GHG emissions. It shows that when 10% biomass is co-combusted, the energy consumption of the supply chains increases in the same order of magnitude. Co-combustion of 10% chipped wood results in a 4% decrease in GHG emissions and a 4% increase renewable power. TOP has the best performance with a decrease in GHG emissions of 7.5% and little over 6.5% renewable energy. The differences are quite small in the 10% biomass supply chains scenarios. The performance of wood chips becomes worse on a larger scale.

TOP has the smallest increase in energy consumption and the smallest decrease in overall energy efficiency. In the 60% supply chains scenarios, TOP co-combustion leads to a 48% decrease in GHG emissions and an increase of 35% in renewable energy. Furthermore, the results show that, when biomass is co-combusted there is always reduced energy efficiency and increased energy consumption. Therefore, the indicators from the RED cannot be aligned in the case of biomass co-combustion. There is a reduction in GHG emissions, since biogenic emissions are not accounted for, and an increase in renewable energy, but the energy efficiency decreases and the energy consumption increases.

4. Discussion

Only direct energy use is taken into account in this paper, since this is the most important part. The inclusion of indirect energy may however, alter the results. The design of the supply chains of coal and biomass differ in the feedstock production stage and the biomass pretreatment stage. Therefore, these two parts of the chain determine the potential difference in results, due to exclusion of indirect energy. It is probable that the inclusion of indirect energy therefore has a negative effect on the system performance of the biomass chains, since this also requires the construction and maintenance of pretreatment facilities. On the other hand there are the coal mining facilities, which have to increase production when biomass is not co-combusted. Also, the low and high values for grinding (Table 2) deviate more from the average value, than other input data. This is due to a large variety in the available data in literature. Despite that, we argue that the average values are representative. Furthermore, when it comes to the calculated conversion efficiencies (Eqs. (1)–(3)); there was no data available about the effect of biomass pretreatment and co-combusted quantities on power plant performance. Based on the data from Pronobis and Wojnar [45] we argue that our estimates are reasonable. Hence, we took a maximum reduction in conversion efficiency of 1% for every 10% biomass co-combusted as a worst case for wood chips.

There is no supply chain scenario where co-combustion leads to energy savings or to a more energy efficient supply system. Co-combustion of biomass has a positive effect on CO_2 reduction on the full chain level. Low co-combustion levels, as considered in the Netherlands, are effective, but contribute little to the reduction of GHG emissions. TOP has the best performance, since the amount of renewables is the highest, the decrease in GHG emissions is the largest, the increase in energy consumption is the lowest and the energy efficiency shows the smallest decrease. However, TOP is also the most speculative, since there is currently no substantial market. A fair trade-off between the indicators of the RED is difficult to establish in the case of biomass co-combustion, since biogenic energy is approached as freely available (i.e. without taking possible scarcity issues into account) and biogenic emissions are approached as having no net impact. Global warming potentials are expressed in terms of 100 years and replacement of harvested biomass and thus sequestration of the CO_2 emissions from biomass is not guaranteed. Focussing on one indicator from the RED may not necessarily lead to the most effective supply system for GHG emission reduction. Hence, this article shows that in all scenarios two (energy consumption and energy efficiency) of the three indicators perform worse than the reference coal supply chain scenario.

The system is demand driven (hence, the functional unit of 1 MJ$_e$ output); the required quantities of biomass are therefore determined by the calculated conversion efficiencies based on Eqs. (1)–(3). The results show that at an increasing scale (from 10% to 60% co-combustion) the production of renewable power becomes less efficient. In our scenarios this means that every additional unit of biomass co-combusted is converted a little less efficient. Thus, co-combusting 10% biomass on six locations results in more renewable power than co-combusting 60% biomass in one location. For the reduction of GHG emissions this effect is reversed, since higher shares of biomass require relatively larger quantities of biomass at the cost of coal. Table 4 gives an overview of this effect for our scenarios. It shows that for increasing levels of co-combustion, the reduction in GHG emissions increases when additional units of biomass are co-combusted. It also shows that
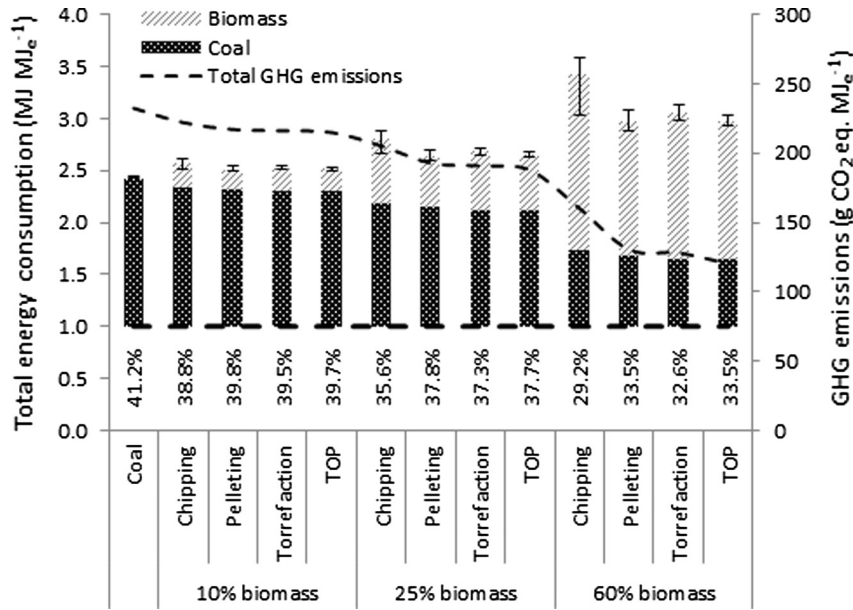
Fig. 10. The total energy consumed for 1 MJ_e output in the whole supply chain including conversion. The graph starts at 1 MJ, in order to include the part of the feedstock that is converted to electric energy. The labels refer to the overall supply chain efficiency including conversion of the feedstock; the error bars represent the high and low values for the supply chain scenarios.
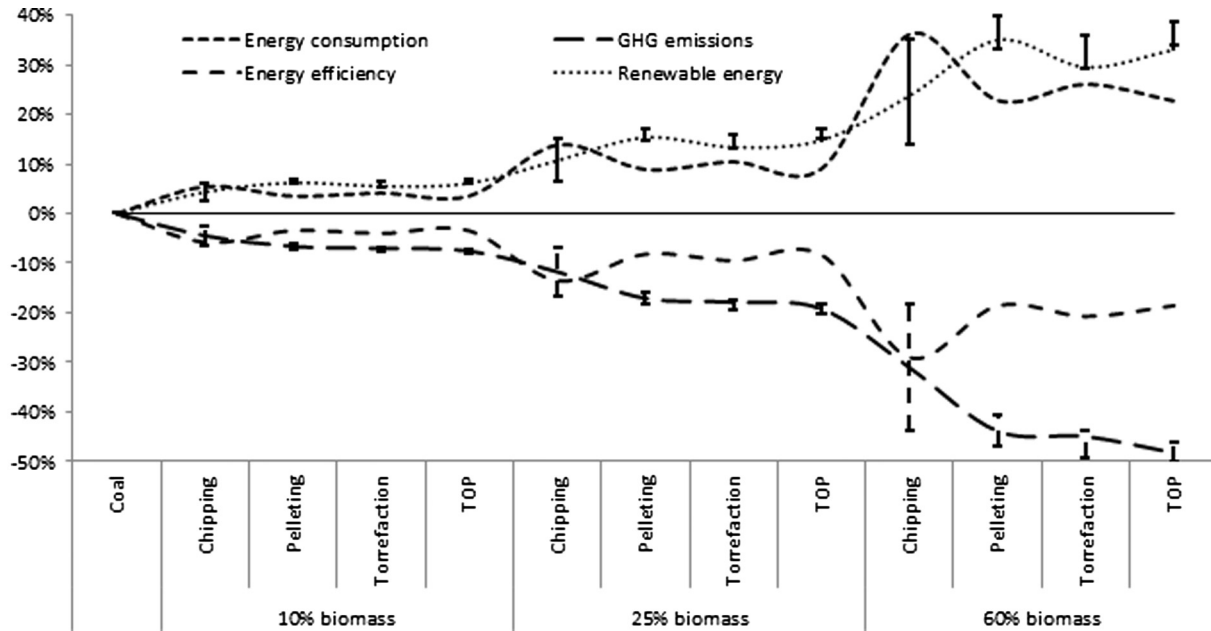

Fig. 11. The relative change in GHG emissions, energy consumption, energy efficiency and renewable energy, compared to the 100% coal reference chain.

Table 4
Performance of the different scenarios per MJ of biomass expressed for GHG emissions and renewable electricity.

	Scenarios			
	10%	25%	60%	Unit
Chipping	−42,38	−43,10	−43,38	g CO2 eq. $MJ_{biomass}^{-1}$
Pelleting	−63,33	−63,75	−63,75	
Torrefaction	−67,46	−67,74	−67,90	
TOP	−72,78	−72,86	−72,92	
Chipping	0,19	0,18	0,17	$MJ_{renewable}$ $MJ_{biomass}^{-1}$
Pelleting	0,27	0,26	0,24	
Torrefaction	0,24	0,24	0,23	
TOP	0,27	0,26	0,25	

for every additional unit of biomass co-combusted the amount of renewable energy decreases. Increasing the share of co-combusted biomass results in an increase in performance when it comes to GHG emission reduction; it results in a decrease in performance when looking at the amount of renewable energy production. This phenomenon is worth mentioning, but in this article it is negligible. A quadratic or exponential decrease in conversion efficiency, instead of a linear decrease can cause this effect to increase, when larger biomass fractions are co-combusted. Data addressing the effect of biomass co-combustion on conversion efficiency was difficult to find and requires more research, since it could change the results of this article. Our data are in line with [44,45]. However, Li et al. present discrepancies in boiler efficiency for co-combustion of torrefied biomass that show a quadratic relation, which could worsen the abovementioned effects [46].

4.1. Sensitivity analysis

Despite some large variations in the estimated energy consumption, especially grinding (see Table 2), but also for coal mining and transport by bulk carrier, Fig. 11 shows that the error bars are in the order of a few percent. The negative values for the error bars were constructed by taking the high values for the supply chain scenarios combined with a 2% conversion efficiency drop ((i.e. *b* in Eqs. (1)–(3)). The positive values for the error bars were constructed by taking the low values for the supply chain scenarios combined with a 2% conversion efficiency increase. By this approach, the most extreme cases are shown. The error bars in Fig. 11 show that the range in the results is small except for chipped wood. Chipping is, together with torrefaction, subject to substantial load limitations in overseas transport and chipping has the worst grinding performance. Furthermore, the conversion efficiency of wood chips is assumed to be the lowest.

5. Conclusion

This paper analysed the performance of supply chains for biomass co-combustion in a pulverised coal power plant. From an energy and GHG emissions perspective, the production stage of biomass cannot compete with bituminous coal mining. Coal mining is more energy and CO_2 efficient than biomass production, harvesting and chipping. However, in our case we allocated all fossil inputs and emissions related to biomass production to the supply system.

Energy consumption and GHG emissions related to biomass pretreatment have the worst performance in the cases of TOP and torrefaction; this also holds when the losses in energy content of the biomass are neglected and only the fossil input is taken into account. Despite a reduction in the energy requirement for grinding due to biomass pretreatment, the energy consumed for the grinding of biomass is higher than the grinding energy of coal. From a whole chain perspective TOP performs the best, because the conversion efficiency to electricity is higher and the transport requirements are lower.

The mass load limitations for the chosen transport modes are the largest for chipped and torrefied wood when it comes to truck transport. For transport over water pellets are also limited by mass, therefore, only TOP can directly compete with coal transportation. The effect of the mass load limitations of chipped and torrefied wood are the most prominent in transport by bulk carrier. Furthermore, there is an increase in transport related GHG emissions for all scenarios.

Results indicate that the three indicators, renewable energy, energy efficiency and energy reduction cannot be aligned in the case of biomass co-combustion. The energy efficiency decreases in all supply chains; the energy consumption increases in all supply chains. Wood chips, torrefied wood chips, pellets and TOP, in the 10% supply chains scenarios, show a decrease in emissions and a positive value for renewable energy, but the effect is little. This suggests that the introduction of bioenergy in the energy system does not necessarily lead to a system where energy is saved or used more efficiently and there is also no guarantee that the optimal reduction in GHG emissions is established. This is in line with Pierie et al. whom emphasise that the application of a renewable resource is not always the most environmentally sustainable solution [47]. The low co-combustion levels are effective to reduce GHG emissions, but the margins are small. When including indirect energy, the possibility of a larger conversion efficiency drop than calculated and chain components performing worse than expected may result in a negligible GHG reduction or even an increase compared to the coal supply chain reference.

The indicators from the RED cannot be aligned (Fig. 11); this is emphasised by Table 4. When biomass is regarded as scarce, one should focus on the most efficient use of biomass and thus on co-combustion of small quantities, or no co-combustion at all. When biomass is regarded as abundant, one should focus on GHG reduction and thus on co-combustion of large shares of biomass.

Acknowledgements

Appendix A. Calculation of the modal energy intensity and load limitations

The modal energy intensities are assumed to be linear to the mass load. Based on the data from Giuntoli et al. [10] the energy

Table A.1
The maximum load (tonne) of truck and Supramax bulk carrier for coal and biomass for low, average and high bulk densities.

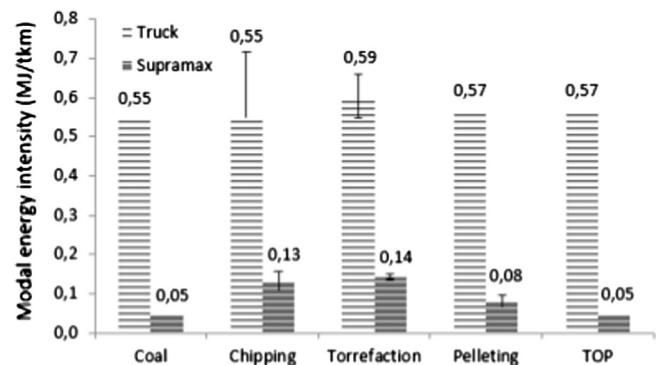|		Coal	Chipping	Torrefaction	Pelleting	TOP
Maximum load (tonne)						
	Low	26	18	21	25	25
Truck	Average	26	26	24	25	25
	High	26	26	26	25	25
	Low	54,000	14,400	16,560	36,000	54,000
Supramax	Average	54,000	23,400	19,080	41,400	54,000
	High	54,000	32,400	21,600	46,800	54,000

Fig. A.1. Calculated modal energy intensity for truck and bulk carrier when transporting coal, wood chips, torrefied wood chips, pellets or TOP. The labels in this figure refer to the specific modal energy intensity for truck or Supramax and not to the error bars.

consumption for transport by truck and Supramax bulk carrier are calculated to be, respectively;

$$f(x)_{Truck} = -2.1 * 10^{-2}x + 1.1(0 \leqslant x \leqslant 26) \tag{A.1}$$

$$f(x)_{Supramax} = -2.8 * 10^{-6}x + 0.2(0 \leqslant x \leqslant 54x10^3) \tag{A.2}$$

where x represents the (limited) mass load (in tonne) and $f(x)$ the modal energy intensity (in MJ/tkm). Table A.1 gives the maximum mass loads for low, average and high bulk densities of coal, wood chips, torrefied wood chips, pellets and TOP. When the mass load is smaller than the net payload (26t for trucks and 54000t for the bulk carrier), the load is volume limited. The difference of 1t load between coal and pellets and TOP is due to specific truck requirements for pellet transport. This paper applies a value of 1t for these requirements in line with Giuntoli et al. [10]. The transport of wood chips with a low bulk density is volume limited, just as the low and average bulk densities of torrefied wood chips. For overseas transport by Supramax, there is a volume limitation for chipped wood, torrefied wood chips and pellets for low to high bulk densities. The average bulk densities in Table 3 were applied to calculate the maximum mass loads for a 40t truck and the Supramax bulk carrier. These mass loads (Table A.1) represent x in Eqs. (A.1) and (A.2). With Eqs. (A.1) and (A.2), the modal energy intensity was determined for both transport modes. These values are presented in Fig. A.1; error bars are included when relevant i.e. where volume limitations are present (see also Table A.1). The modal energy density for trucks with woodchips is applied for this research, since further pretreatment is executed at the harbour, before overseas transport.

Appendix B. Overview of the energy consumption and GHG emissions in the supply chain scenarios
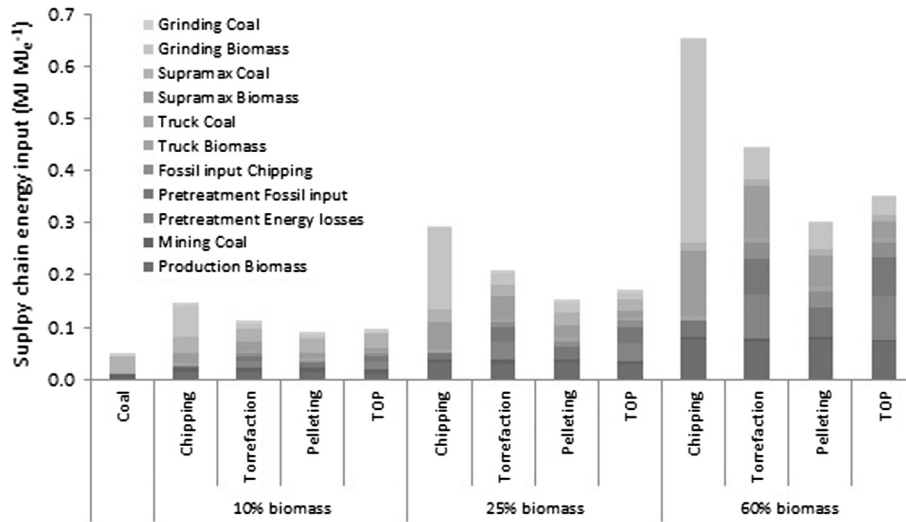
Figs. B.1 and B.2.

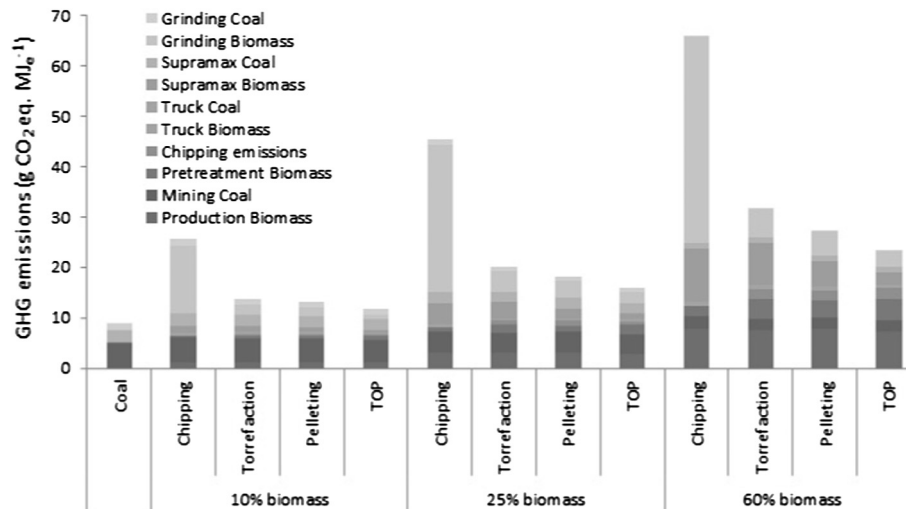**Fig. B.1.** Detailed overview of the supply chain energy consumption without conversion.

Fig. B.2. Detailed overview of the supply chain GHG emissions without conversion.

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