International vs. domestic bioenergy supply chains for co-firing plants: The role of pre-treatment technologies

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International vs. domestic bioenergy supply chains for co-firing plants: the role of pre-treatment technologies

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Co-firing of solid biomass in existing large scale coal power plants has been supported in many countries as a short-term means to decrease CO_2 emissions and rapidly increase renewable energy shares. However, many countries face challenges guaranteeing sufficient amounts of biomass through reliable domestic biomass supply chains and resort to international supply chains. Within this frame, novel pre-treatment technologies, particularly pelletization and torrefaction, emerged in recent years to facilitate logistics by improving the durability and the energy density of solid biomass. This paper aims to evaluate these pre-treatment technologies from a techno-economic and environmental point of view for two reference coal power plants located in Great Britain and in Italy. Logistics costs and carbon emissions are modelled for both international and domestic biomass supply chains. The impact of pre-treatment technologies on carbon emission avoidance costs is evaluated. It is demonstrated that, for both cases, pre-treatment technologies are hardly viable for domestic supply. However, pre-treatment technologies are found to render most international bioenergy supply chains competitive with domestic ones, especially if sourcing areas are located in low labour cost countries. In many cases, pre-treatment technologies are found to guarantee similar CO_2 equivalent emissions performance for international compared to domestic supply chains.

Keywords: biomass supply chain, international logistics, carbon equivalent emissions, torrefaction, pelletization, bioenergy, co-firing

Nomenclature

BP	Black Pellets
BR	Brazil
C	Wood Chips
CDAC	Carbon Dioxide Abatement Cost

CAPEX	Capital Expenditure
EC	Export Country
F	Feedstock
GB	Great Britain
HFO	Heavy Fuel Oil
IT	Italy
IC	Import Country
kgd	dry kilogram
kWhe	electrical kilowatt-hour
L	Long-distance supply chain
LHV	Lower Heating Value
LCOE	Levelized Cost of Electricity
mc	Moisture content
MZ	Mozambique
my	Mass Yield
OPEX	Operational Expenditure
S	Short-distance supply chain
SI	Slovenia
td	dry tonne
US	United States
WP	White Pellets

1 Introduction

In many Western countries, co-firing of solid biomass and coal has been supported by renewable energy schemes as a means to obtain rapid and significant decreases in GHG emissions. Up to 2010, more than 230 power plants had experienced some co-firing activity, most of them in the US and northern Europe [1]. Several European countries, in addition to the

US, already offer policy incentives or have mandatory regulations to increase renewable's share in the electricity sector. Some of them also support programs aimed at creating biomass supply chains outside the EU [1,2].

In Great Britain the Renewable Obligation (RO) has been one of the main support mechanisms for large-scale renewable electricity projects. Suppliers are obliged to supply a percentage of their electricity from renewable sources, which increases year on year. A penalty is imposed on suppliers who do not meet the targets. Correspondingly, the Office of Gas and Electricity Market (Ofgem) issues Renewable Obligation Certificates (ROCs) to electricity generators in relation to the amount of eligible renewable electricity they generate. In essence, this operates to the effect that suppliers can buy and sell their way out of the renewable requirement. This is the current support mechanism for biomass co-firing and is open for new installations until the year 2017, providing ROCs in eligible operators for a duration of 20 years [3]. In other EU countries, including Italy [4], Germany and Austria [5] no specific incentives for biomass co-firing are currently foreseen.

While forestry biomass withdrawal in Italy is not sensibly smaller than the EU average, Italy is in the lowest ranks in Europe as to primary energy consumption from solid biomass [6], and heavily depends on imports to meet current demand [7]. The situation in Great Britain is similar, with even smaller contribution of solid biomass to primary energy consumption: 0,22 m^3 equivalent of pro capita consumption in Italy against 0,10 m^3 in Great Britain [8]. Thus, for both countries co-firing could improve their biomass contribution to the renewable national energy production and utilization mix, provided that imports, even from distant countries, are economically feasible and overall sustainable. Demonstrating the economic and environmental performance of long distance biomass supply chains for large scale plants is a challenge for policy makers and for energy companies, faced with economic risk of supply as well as with social acceptance issues, especially in countries with less experience in biomass use, such as Italy and Great Britain [9]. However, to the best of the authors' knowledge, comparative assessments of local and overseas supply chains can be hardly found in literature, with the exception of [10], which dates back to 2005.

Within this frame, novel pre-treatment technologies, particularly pelletization and torrefaction of pellets, emerged in recent years to improve durability and energy density over long distance solid biofuels transportation. While biomass pelletization is a well established and commercially practiced process [11], torrefaction is a relatively new and emerging technology, which consists of a thermal treatment process in which the biomass material is subjected to a temperature in the range of 200–350°C in reducing or possibly slightly oxidative atmosphere, during a sufficiently long residence time [12]. Previous research has identified some advantages and issues of torrefaction, particularly in comparison to pelletization, as summarized in Table 1.

Table 1 Comparison of torrefaction and pelletization pre-treatment technologies.

The limited experience with torrefaction at pilot and industrial scale is the major concern about this technology. On the other hand, Table 1 shows that, compared with traditional wood pellets, the combined torrefaction and pelletization process has significant potential advantages; in particular, the enhanced bulk and energy density results in more efficient transportation. Better mechanical and hydrophobicity properties further reduce the need for expensive storage solutions. Hence, torrefaction in combination with pelletization has the potential to improve the economic performance of long distance biomass supply chains, provided that the additional CAPEX and OPEX of this emerging, energy intensive technology are compensated by corresponding cost savings in the logistics [18,19].

The role of pelletization in long distance biomass logistics has been investigated by several authors [20,21], also in comparison with other pre-treatment alternatives such as pyrolysis and considering regional and overseas supply chains [10,22]. On the other hand, only recent studies compare torrefied pellets (also called black pellets) with traditional pellets (white pellets), considering long distance logistics case studies [23–26] and introducing a supply chain configuration perspective [19,27]. For this reason, Ehrig et al. [5], who first demonstrated that long distance solid biomass supply for co-firing could be a viable GHG reduction policy option for the EU, call for additional research on supply chain configurations and economics, as well as on the environmental impact of torrefaction, since only white pellet supply chains are investigated in their study.

This paper contributes to fill these research gaps by aiming to investigate:

1. how torrefaction at biomass sourcing sites may affect the economic and carbon equivalent emission performance of long distance supply chains;
2. whether torrefaction and pelletization may play a role in short-distance supply chains;
3. how do domestic and international supply chains compare in terms of cost and emissions performance.

For this purpose two cases of reference plants will be examined in different national contexts, i.e. Italy and GB, as those countries are characterized by low shares of solid biomass in the primary energy mix and therefore have a high potential for increase. International and local biomass supply chain scenarios are configured, i.e biomass flows and properties are quantified, capacities and input-output flows of treatment plants are determined both for long and short distance supply chains, as well as collection, transportation and storage requirements. For long distance supply chains black pellets and white pellets scenarios are considered, whereas for short distance supply chains wood chips are also evaluated. Section 2 describes the case studies discussed in this paper. Alternative supply chain configurations are modelled on a spreadsheet simulation model as illustrated in section 3, which presents the economic and environmental parameters used as model inputs for the two case studies. In section 4, the least cost configurations for international and local supply chains are evaluated, and the performance of short and long distance supply chains is compared, considering also their contribution to the economic and environmental performance of produced electricity and corresponding costs of CO_2 avoidance. In section 5, the sensitivity of the model results to the most influential uncertain parameters is analysed, while general conclusions and directions for future research are derived in section 6.

2 Case studies

To enable comparison of long distance (L) and short distance (S) supply chains delivering biomass to large coal co-firing plants in a global context, two reference co-firing plants in GB and Italy were selected as end users. The location of the base reference plant is assumed to coincide with existing plants in GB (Drax Power Station in Selby) and in Italy (A2A power station in Monfalcone). The Selby power station has already converted several of its units to use biomass pellets, it is the biggest in GB and is located near to the port of Immingham, an important harbour for pellets trade. In Italy, Monfalcone is selected as a coal power plant of comparable size as Selby, and because of technically successful past experiences of co-firing.

Both reference co-firing plants are modelled with the same reference capacity to enable a fair comparison of results. The reference capacity has been fixed at 600 MW, which is in accordance with reference values often used in literature [28,29] and reflects industrial practice, as it is very close to the real capacity of a single unit in Selby (645 MW according to [30]) and the overall capacity of Monfalcone (664 MW according to [31]).

The long distance international supply chain options examined are mapped in Figure 1.

Figure 1 Representation of import & export countries and shipping routes.

The green dots represent the location of import harbours, i.e. Immingham for Selby and port of Koper in Slovenia, for Monfalcone. In both cases, energy conversion plants are situated within 50-70 km from the harbours. Figure 1 also shows the exporting countries selected and the respective harbours considered for long-distance biomass supply, i.e. Brazil (port of Belem), South East US (port of Savannah) and Mozambique (port of Nacala). These choices are in agreement with the selection criteria proposed in [2] and [27]. Export as well as import ports are large ports with existing terminals for wood pellets or at least other biomass or wood products. South America and Africa are widely expected to become significant exporters of biomass to the EU. A future high level of EU biomass demand is expected to result in investments in pellet plants, short rotation crop and tree plantations, such as eucalyptus, in regions such as Brazil, Uruguay, West Africa and Mozambique [2]. Similar considerations are presented in [1], where the expectations are that up to 5% of total biomass use in 2020 could be sourced by international trade, with North America, Africa, Brazil and Russia as the major suppliers.

For the European countries of concern data on forest biomass distribution is available from National Inventories, particularly [32,33] for softwood availability in Scotland, [34] for biomass from arboreal origins in different Italian provinces, and [35] for the allowable cut of forestry biomass in Slovenia. Available data on technical biomass withdrawal potentials were imported in ArcGis, and used first to build up a supply area, gradually including locations farther to the plant once the potential of the closest ones was exhausted. Secondly, ArcGis was used to determine a weighted median centre, where the reference location of the centralized collection point was set, and to calculate the average transport distance from the withdrawal area to the collection point. This approach allows to estimate the proportion of national territory needed to feed reference plants with local forest biomass. For regional supply, limitations in European forest biomass potentials lead to remarkable average distances from centralized collection points to power plants: 443 km for Scotland, 275 km for Northern Italy, and 153 km for Slovenia.

3 Supply chain modelling

The generic supply chain structures of all scenarios examined in this work are modelled as in Figure 2. Delivery of biomass as black pellets (BP) and white pellets (WP) is considered for both short and long distance supply chain types, while wood chips (C) are examined only in short distance supply chains. In fact, previous studies [26,36,37] concluded that wood chips are not economically viable on long distance supply chains, and a preliminary evaluation for the case studies of concern led to similar results.

Figure 2 Structure of long and short distance supply chain scenarios for C, WP and BP.

To model the supply chain structures represented in Figure 2 for the case studies at hand, a spreadsheet based simulation model was developed to evaluate energy and mass flow balances, properties of feedstock, costs and CO_2 equivalent emissions of alternative supply chain configurations. A supply chain configuration is defined for the purposes of this work as a combination of one of the supply chain structures presented in Figure 2 with a particular biomass origin and destination country. The inputs and output parameters of the simulation model are reported in Figure 3 for each supply chain stage, with reference to long distance supply chains only for simplicity of representation. A simplified version of Figure 3 applies for short distance supply chains, where port logistics and overseas transport stages are omitted and chipping is considered as the treatment option. Inputs and outputs for common stages between long and short distance supply chains are the same.

Figure 3 I/O diagram of long distance supply chain.

The output of every stage of the supply chain consists of:

- an economic evaluation of the CAPEX and OPEX related to the single stage activity considered (e.g. chipping, handling, storage);
- an environmental assessment (in terms of $kgCO_2eq$) related to the single stage activity consumption of fuel (electricity, diesel, HFO or natural gas).

At the end all the output results of every single stage are added to obtain the total cost and emissions of the supply chain.

The simulation model is based on following assumptions:

- Mass losses for the supply chain stages are adapted from [5,10,20,21], while mass yield of torrefaction and pelletization processes is derived from [24].
- Mass yield of drying in the case of C is derived from the evaluation of water losses and the amount of wood used for drying the chips from 40% to 20 % moisture content: the value of drying to a 20% moisture level has been adopted from [38] as the best practice

in biomass direct co-firing in order to ensure seamless biomass conversion together with coal in the coal utility boiler.

- Fuels represented in Figure 3 vary depending on supply chain stage. Diesel and electricity are considered for handling and storage. Trucks are fuelled with diesel, trains use electricity or diesel fuel depending on locally available infrastructure, and ships operate on HFO. For all pre-treatment options, except for the torrefaction process, drying is considered to be fuelled with biomass, rather than with fossil fuels, as in [5]. In the case of torrefaction, extra thermal power to support drying and torrefaction processes is being put into the process partly by natural gas and partly by combustion of extra feedstock, as reported in [39]. When the pre-treatment is pelletization, only electricity emissions are considered as the combustion of biomass for drying is considered renewable, while in the case of torrefaction emissions from electricity and natural gas are considered. Emission factors are derived from [40] for diesel and HFO, from [41] for natural gas, and from [42–44] for electricity generation in each country.
- The assessment of electrical efficiency reduction due to biomass co-firing is based on the evaluation performed for black pellets by [25], who, like [24], assume that combustion efficiency for black pellets equals that of white pellets combustion.
- It is also assumed that wood chips combustion is performed at the same efficiency as pellets. Since some authors [45,46] claim that black pellets combustion efficiency may be higher than white pellets or wood chips combustion, this assumption is conservative, and the adopted values tend to favour chips and white pellets over black pellets.
- The final supply chain stage analysed in this work is pulverising the biomass delivered at the co-firing plant and feeding it to the boiler. To define and calculate biomass requirements, direct co-firing is selected among the various available technologies [47]. For direct co-firing, biomass is pre-mixed with coal, and the fuel blend is fed to the furnace using the existing firing equipment, i.e. without significant additional investments. As a consequence, this technology is the most popular [37,41] and has therefore been selected for this study. A limitation of direct co-firing is in the share of biomass which can be treated, i.e. only percentages up to approx. 5-10% on an energy basis. For this reason, a 8% co-firing rate was assumed in this paper, which is in line with similar analyses in literature [48].
- For wood chips and white pellets, milling should be performed in two stages, with mills dedicated to wood grinding before mixing with coal [39,47]. In this case, additional investments to perform co-firing include handling, storage and pulverizing before co-

feeding in the boiler. On the other hand, black pellets have properties that closely match those of low-grade coal [23]. This allows using the same equipment at the co-firing plant and, as a consequence, no additional investment cost for milling [14,16,49].

Data and sources about the co-firing plants are reported in Table 2.

The properties of wood chips before drying, mainly considered for short supply chains and available at the roadside are reported in Table 3, while the properties of treated biomass (WP, BP and dried C) are summarized in Table 4.

Table 2 Reference co-firing plant characteristics.

Table 3 Properties of biomass before treatment, after chipping at the roadside.

Table 4 Properties of pellets (short and long supply chain) and chips (only short supply chain) after treatment.

Transportation pathways and relevant cost models were implemented separately for each supply chain configuration. For each power plant location, international long distance supply chains from Brazil, Mozambique and South US are modelled. For short distance supply alternatives, the forests of Scotland are chosen for supplying Selby, while for Monfalcone two alternative sourcing areas are considered for local supply, i.e. Northern Italy and Slovenia. Combining all sourcing and pre-treatment options examined yields 20 alternative configuration scenarios, described in Table 5, where ISO codes are used as abbreviations for country names.

Table 5 Summary of all cases studied.

3.1 Long-distance supply chains

The long-distance supply chain scenarios are based on the following assumptions:

- As feedstock is considered available at the roadside, the feedstock cost includes harvesting, collection and, if specified, also storage. Feedstocks considered are based on the prevalent biomass sources in each supply country: hardwood (eucalyptus) for Brazil and Mozambique, softwood for US.
- Biomass is chipped at the roadside and then transported to the pre-treatment facilities.
- Different first transport stage options are assumed depending on regional infrastructure conditions: for Brazil, transport to the port is done by truck for an average assumed distance of 100 km [10], while in South US and Mozambique biomass transfer is a combination of truck (20 km) and diesel train (100 km), in agreement with the assumptions by [55–57] for the same or similar countries.
- The pre-treatment plant is located next to the export port.

- For overseas shipping, a handymax bulk carrier with capacity of 45000 t and 56250 m^3 is used, as this is a ship type that can access smaller ports and usually has on-board loading capability. Due to the lower bulk density of pellets compared to the marginal cargo density of the ship (800 kg/m^3), volume is the restrictive factor in the sea transportation stage, leading to suboptimal utilisation of the ship weight capacity.
- The sea transportation cost has been calculated analytically as a time charter by adding a daily charter rate, the fuel cost and other major operational costs (port and canal fees) [25].
- Once arriving at the import ports, the ship is unloaded and the pellets are transferred to the reference coal power plant by electric trains.

Economic, technical and environmental input data used for the logistics model are summarized in

Table 6,

Table 7 and Table 8 respectively. All costs and prices, collected from several sources and in various currencies, are first converted in Euro using the average yearly exchange rates from [58] and then adjusted in 2016 values using the industrial producer price index [59].

The average shipping distance between export and import ports is reported in

Table 9.

Table 6 Model input data: transport parameters.

Table 7 Model input data: storage and chipping parameters.

Table 8 Model input data: electricity emission factors, biomass and fuels prices.

Table 9 Average distance between the ports in nm (nautical miles) and km.

3.2 Short-distance supply chains

To configure short supply chains it is assumed that:

- Pelletization and torrefaction pre-treatment options are performed at a centralized collection and storage point before the transportation to the final user.
- Also for wood chips a centralized pre-treatment is assumed, which consists only of drying wet chips from 40% to 20% moisture content [38].

- Costs and emissions for harvesting, collection and first handling incorporate truck transport to local collection points, where pre-treatment is performed.
- The transportation mode from the collection point to the co-firing plant is selected depending on locally available infrastructure: thus, rail transport (electric train) is selected for Scotland and road transport (diesel truck) for both supply from Slovenia and North Italy.

Alternative configurations are also possible and could be considered in a spatially explicit analysis of local supply, which is however beyond the scope of current paper. The simplifications introduced here are deemed as conservative for the sake of local vs international comparison in that they tend to minimize costs and impacts of short supply chains.

4 Results and discussion

Economic and carbon emissions analysis has been performed for all supply chain configuration scenarios studied. The costs and the emissions associated with the supply chain are reported with respect to GJ of biomass delivered. In order to address the three main research questions and to facilitate presentation of the results for the 20 scenarios, the analysis focuses first on long distance supply chains, to assess whether torrefaction is economically and environmentally justifiable compared to pellets and to determine the best performing supply chain scenarios. Secondly, short supply chains are studied to establish which supply form (WP, BP or C) is preferable for each case. Finally, the best performing short and long distance options are compared to highlight the relationship between long and short distance supply alternatives.

4.1 Long distance supply chains

In order to have the same amount of thermal energy input for a co-firing plant with 8% of biomass on an energy basis, the quantity of biomass delivered at the final user changes depending on its energy content.

The initial and delivered quantities for all pre-treatment methods, considering the detailed supply chain stages are shown in Table 10. The amount of raw biomass needed for the international supply chains is significantly higher than for the wood chips local supply chains, due to the torrefaction and pelletization process energy requirements. For long distance supply in particular, the difference between L/BR and L/MZ&US initial biomass flow stems from the mass losses of the first transport stage, as the additional transhipment stage between truck and train in MZ and US increases the mass losses.

Table 10 Initial and final biomass flows.

4.1.1 Cost breakdown and comparison

In Figure 4, costs per GJ of biomass delivered are presented. The major contribution to the total supply chain cost is represented by cost of the biomass at the roadside (particularly in the US) and pre-treatment (especially for black pellets and in export countries with higher electricity costs).

Ship transport and export fees are the third highest cost element. These are significantly reduced for BP, compared with WP, due to higher energy density that leads to better utilisation of the ship cargo space. A major cost reduction in BP supply chains comes from removing the need for dedicated milling at the power station. The reduction in these three cost components, namely ship transport, export fees and milling at destination, compensates for the additional pre-treatment costs associated with the BP process. As a result, both for Italy and Great Britain and from all import countries, BP are the least cost option for biomass logistics, with savings ranging between 8,3 % (for L/BP/US-IT) and 12,2% (for L/BP/BR-GB) compared with the respective WP supply chains.

Figure 4 Cost breakdown for WP and BP on long distance supply chains.

These economic results whereby BP is less costly than WP in long distance supply chains are in agreement with the conclusions of [26,27,37].

As to country dependent differences, the examined supply chains have a comparable economical behaviour, with differences between L/WP and L/BP in the range of 12,23% and 10,75% respectively for BR-GB and BR-IT, 10,72 % for MZ-GB, 8,79 % for MZ-IT, 9,51% and 8,30% respectively for US-GB and US-IT. The best economic performance for supplying Italy is BP from Mozambique due to lower cost of biomass and electricity (Table 8), which affects operational costs of pre-treatment. Indeed, although the additional cost of passing through the Suez Canal has been incorporated in shipping costs, the cost of shipping from MZ to IT is comparable with the ones of L/BP/BR-IT and L/BP/US-IT thanks to the shorter shipping distance (

Table 9). The least cost long-distance supply chain to GB is the one supplying BP from Brazil. This is due to the lower cost of biomass and to the relatively shorter shipping distance compared to other supply chain configurations.

4.1.2 Environmental impact breakdown and comparison

Pre-treatment and sea transportation are also the phases with the highest impact on the CO_2 equivalent emissions of long distance supply chains, as highlighted in Figure 5. In the case of white pellets, also pulverisation at final plant has a significant impact, especially in Great Britain due to the higher carbon emission factor for electricity generation (see Table 8). International differences in electricity related emission factors remarkably affect the environmental impact of pre-treatment, particularly of the energy intensive torrefaction and pelletization process.

Figure 5 Emission factor breakdown for WP and BP on long distance supply chains.

Figure 5 shows that the emissions of the supply chain from US are significantly higher than from other supply locations, because of considerable indirect emissions associated with pre-treatment. The reason is that the electricity mix of US is based mainly on fossil fuels while the electricity produced in Mozambique and Brazil comes mostly from hydroelectric energy, which leads to a much lower electricity emission factor (Table 8). For this reason, Mozambique is the best sourcing area for both Italy and Great Britain from a carbon emissions perspective, followed by Brazil.

As a whole, the higher number of sea trips required yearly for WP compared to BP because of the lower density of WP, and subsequent sub-optimal utilisation of the ship cargo capacity, is such that additional environmental impact associated with the torrefaction process is compensated by lower sea transportation impact both in the Brazil and Mozambique cases. Also for supply chains of US origin, BP are preferable to WP, but this is mainly due to additional emissions for pulverising white pellets at the plant before co-firing them, rather than to gains in sea transportation and handling at the port related emissions alone. Thus, for all the long distance supply chains considered, delivering BP appears preferable to WP not only from an economic but also from an environmental point of view.

Comparing the results with the literature, it should be first observed that usually environmental impact results are hardly discussed to the same extent and depth as the economical ones. Some authors [24] found that WP and BP supply chains have similar emissions for supply chains from Canada and Finland to Spain. Other results [27,78] are aligned with the results of this work, as they found that logistics related carbon emissions are lower for BP than for WP on comparable sea transportation distances. None of them, however, considers explicitly country specific differences in electricity generation mix, which, as shown above, may cause great variations in the environmental impact of long distance supply chains depending on origin and destination.

4.2 Short distance supply chains

For short distance supply chains there is mixed evidence in the literature about the utility of pre-treatment [10,26,47]. The advantages of pre-treatment in terms of handling, transportation and storage and the related efficiency gains are less profound in short transportation distances. Thus an economic and environmental comparison among wood chips, black and white pellet short distance supply chains is performed.

4.2.1 Cost breakdown and comparison

As shown in Figure 6, the purchasing cost of biomass has the highest share on total costs, particularly in Italy. The situation in Great Britain (Scotland) is more favourable, while Slovenia seems the least cost regional sourcing option for Italy with any pre-treatment method.

Due to the low bulk density of wood chips, the stages of transport, handling and storage highly affect the costs of the wood chips (C) supply chain compared to pelletization based options. Nevertheless, because of high electricity costs in all short distance supply countries, pre-treatment is expensive and additional costs are not compensated by efficiency gains in logistics. Therefore C are less expensive than pellets in all the short distance supply chains examined. Differences between WP and BP delivered costs are minimal.

Figure 6 Cost breakdown for WP, BP and C on short-distance supply chains.

4.2.2 Environmental impact breakdown and comparison

The emissions of pre-treatment and pulverizing at the co-firing plant influence considerably the total emissions of the supply chain (Figure 7). This is due to the high emissions factors of electricity in the supply and importing countries (Table 8). Transport related emissions for C are sensibly higher than WP and BP due to the lower bulk density of wood chips and, as a consequence, to the higher number of trips necessary to supply the plant; however, these differences do not make up for the additional impact of pelletization-based processes, with the notable exception of Slovenia. In fact the carbon equivalent emission of the S/C/SI-IT supply chain is about 12 % higher than the S/BP/SI-IT, mainly because Slovenia has the lowest carbon emissions factor among the sourcing areas considered for local supply [79], and thus the environmental impact of pelletization and torrefaction is correspondingly reduced. It should nevertheless be stressed that, from an economic viewpoint, C remain the least cost option even for the S/SI-IT supply chain.

Figure 7 Emissions factor composition for WP, BP and C on local supply chains.

As a conclusion, in short distance supply chains the best option, both from an economic and an environmental perspective, is to deliver biomass as wood chips, irrespective of the geographical context. Therefore, wood chips will be considered as the reference short distance biomass supply chain for the comparison with long distance supply chains. For the case of Italy, wood chips from Slovenia will be considered as a reference, due to the lowest cost and lower emissions compared to supply from northern Italy.

4.3. Long vs short-distance supply chains

As a result of the previous discussions, a comparison between the best performing long-distance supply chains (BP) with the short-distance supply chains (C) is performed.

4.3.1 Cost comparison between L/BP and S/C

Figure 8 enables comparison of least cost options for the best performing short and long distance supply chains, which is C and BP respectively. It appears that BP long distance supply chains have lower biomass delivered cost compared to local C supply chains. Despite the higher overall transportation and handling cost, as well as significant pre-treatment cost, BP supply chains benefit from the lower biomass price and lack of additional milling requirement compared to C supply chains. It appears that the introduction of torrefaction makes long distance supply options considerably more competitive to short distance supply chains in both geographical contexts. For Great Britain, the best option appears to be to supply BP from Brazil that reduces cost by 0,83 €/GJ compared to the best C option. For Italy, the cost difference between the least cost long distance supply chain from Mozambique is significantly more profound compared to the local C supply from Slovenia, amounting at 1,77 €/GJ.

Figure 8 Cost structure comparison of international (BP) vs. local (C) supply chains.

4.3.2 Environmental impact comparison between L/BP and S/C

Figure 9 shows that, while the logistics related environmental impact of sourcing in the US is sensibly higher than that of local supply chains, both Brazil and Mozambique originated BP supply chains lead to lower emissions per GJ of delivered biomass than local supply chains, in both Great Britain and Italian cases. Again, this is primarily due to international differences in carbon emissions associated with electricity generation. The high electricity-related emission factors of Italy and GB increase the emissions of the milling stage in the case of delivering wood chips, while low emission factors in Brazil and Mozambique limit the environmental impact of energy intensive pre-treatment options such as torrefaction and pelletization. Ultimately, it is shown that long-distance biomass supply chains can lead to reduced greenhouse gas emissions of the overall supply system compared to short-distance alternatives, despite the increased transportation and processing involved, when the supply locations benefit from high availability of renewable energy.

Figure 9 Emission factor comparison of international (BP) vs. local (C) supply chains.

4.4 Competitiveness of co-firing and carbon dioxide abatement cost

In order to compare co-firing of biomass from various origins with other decarbonisation options for electricity generation, a useful figure of merit is the Carbon Dioxide Abatement Cost (CDAC). The CDAC can be regarded as the minimum incentive to be paid per unit of carbon equivalent emission avoided (€/tCO_2eq, similarly to EU ETS allowances and any form of carbon credit) in order to make a renewable or low carbon energy source competitive with its fossil alternative [52,53]. In particular, the CDAC of biomass co-firing equals the incentive for every unit of carbon equivalent emission avoided by co-firing that would make the corresponding levelized cost of electricity (LCOE, as defined in [52]) equal to the LCOE obtained from the same plant, when firing only coal.

In mathematical terms, the CDAC of co-firing is calculated with Eq. 1 (adapted from [53]), where E stands for emissions in tCO_2/kWh, C for combustion and SC for supply chain.

$$CDAC = \frac{\left(LCOE_{cofiring} - LCOE_{firing}\right)}{\left(E_{firing} - E_{cofiring}\right)_C + \left(E_{firing} - E_{cofiring}\right)_{SC}} \qquad \left[\frac{€}{tCO2}\right] \quad (1)$$

The first term of the denominator in Eq. 1 expresses the difference in emissions level from combustion at the power plant, calculated as the amount of coal burned in the coal firing and the co-firing scenarios annually multiplied by the emissions factor of coal combustion (2110 kgCO_2eq/t [25]) and then divided by the respective amount of electricity generated annually to reflect the effect of de-rating when co-firing biomass. Biomass does not contribute to the CO_2 emissions at the combustion stage as it is considered a renewable fuel. The second term of the denominator in Eq. 1 expresses the difference in emissions level from the fuel supply chain between the coal firing and the co-firing scenarios. For the coal supply chain emissions have been estimated as 4% of the coal combustion emissions, according to [80]. For the biomass supply chain, emissions have been calculated analytically for each stage of the supply chain (see Figure 3), considering the fossil fuel and electricity use, multiplied by the respective emissions factor. For the co-firing scenario, the total supply chain emissions consist of both coal and biomass supply chain emissions for the respective amounts of each fuel used. All emissions have been divided by the amount of electricity generated in each scenario. Regarding the numerator of Eq. 1, LCOE of the firing plant is the total annual cost of coal needed in a firing plant with 600 MWe output gained only from coal combustion divided by the total annual electricity produced. LCOE of the co-firing plant is instead the sum of total annual coal cost and biomass cost at the plant gate (assessed in this work), divided by the total annual electricity produced.

Figure 10 illustrates the emissions reduction in the cases studied (8% biomass co-firing) compared with a coal firing system with the characteristics of the base reference plant reported in Table 2. In other words, Figure 10 illustrates the denominator of Eq. 1 for the case of concern expressed in percentage terms.

Figure 10 CO_2eq emissions reduction with 8% co-firing compared to coal-firing plant.

These results show that co-firing is environmentally better than coal firing regardless of the type and origin of biomass used. From an emissions reduction viewpoint, the best case for long distance supply chains is L/BP/MZ-IT; indeed, the logistics from Mozambique to Italy have the lowest emissions. The best scenario among short-distance supply chains is BP delivered from Slovenia (S/BP/SI-IT). While differences between different supply chains are significant in relative terms (e.g. carbon equivalent emissions associated with L/BP/MZ-IT supply chain are about 1/3 of L/WP/US-IT, see Figure 5) and logistics chains are virtually the only cause of net carbon emission associated with bioenergy, it should be observed that their carbon equivalent impact is nevertheless an order of magnitude lower compared with that of coal, which is in the order of ca 90 kgCO_2eq/GJ of delivered chemical energy [81] against 4-13 kgCO_2eq/GJ as calculated for various solid biomass supply chains in the present work. As a result, substituting coal with biomass always leads to a considerable reduction in carbon emissions, in the order of 7 - 7,7% in relative terms for an 8% co-firing ratio, which in absolute terms for the reference plant would mean a notable range of avoided emissions between ca 285 - 309 ktCO_2eq/year depending on the biomass supply chain adopted.

Figure 11 compares the CDACs of the biomass supply chain configurations studied, i.e. WP and BP for long (L) supply chains, WP, BP and C for short (S) supply chains. Also from a carbon emission abatement costs point of view, BP is the best option for long distance supply chains with a CDAC cost range of 40-55 €/tCO_2eq, while wood chips have the lowest CDAC for short distance supply chains (50-60 €/tCO_2eq). The CDAC of international supply chains originating in Brazil and Mozambique is slightly lower than that of local supply chains even when using WP, but when BP is introduced long distance supply chains become even more efficient.

Nevertheless, the required incentive is high in all cases if one considers that, current carbon prices within the EU ETS are around 5-10 €/tCO_2 [82], and, even considering future scenarios proposed by [83], maximum expected carbon prices equal 32 €/tCO_2 for Italy and 24-27 €/tCO_2 for GB in 2020. Dedicated additional support schemes are therefore needed in any case to promote bioenergy in the form of co-firing.

Figure 11 Carbon dioxide abatement costs of 8% co-firing at plants of all scenarios studied.

5 Sensitivity analysis

In order to evaluate the potential impact of uncertainty on the most influential parameter values to the findings of this work, the results have been subjected to sensitivity analysis.

In particular, the main research focus is on the potential economic and environmental benefits of BP over WP (for long distance supply chains) or over supply of wood chips (for local supply chains). It has been demonstrated that, under the conditions considered, for all long distance supply chains BP are preferable to WP, and for most short distance supply chains wood chips are preferable to BP, both from an economic and a carbon emissions viewpoint. To quantify the dependence of these results on input parameters, it was chosen to determine switching values, i.e. the level of uncertain parameters that determine a reversal in this relationship. Similarly, since it was also found that some long distance BP supply chains are preferable to short distance wood chips supply, it was decided to determine switching values also for this relationship.

The switching values for supply chain costs are reported in Table 11 and for supply chain CO_2eq emissions in Table 12, respectively. To enable comparison, they are represented as the required percentage variations on the parameter baseline values to reverse the existing preference and a colour coding is added to highlight the parameters with the highest sensitivity, i.e. where a preference switch is induced by relatively small percentage variations. Red and orange cells, with percentage variation ranges of ± 0-20% and ± 20-50%, respectively, display the most sensitive results. White cells represent parameters that are not relevant to the particular supply chain and therefore cannot affect the switching decision (e.g. in Table 11, HFO price in short supply chains). Parameters in light blue or green, with percentage variation ranges greater than 200%, indicate limited sensitivity on the cost and environmental performance of supply chains, while for blue cells switching conditions are either reached for extremely high values, could not be reached at all, or are reached for variations in physical parameters which are beyond technically achievable ranges.

To simplify representation only some of the possible configurations are reported in Table 11 and in Table 12, based on economic performance ranges. In particular, for long-distance supply chains, the comparison between BP and WP in the cases of US-IT and MZ-IT is chosen because supply chain cost differences between WP and BP are maximum in the case of US-IT and minimum for MZ-IT. The same rationale is behind the selection of US-GB and BR-GB supply chains for the British case. To analyse switching between local and global supply chains, supply from US to GB and from MZ to IT are selected as extreme conditions, with US-GB having the lowest gap to local supply and MZ-IT having the highest gap to local supply from Northern Italy. BZ to GB and the comparison between US-IT and SI-IT supply chains are also presented as examples for intermediate performance differences.

5.1 Sensitivity of cost

In Table 11, switching values for supply chain costs are reported as percentage variations on the parameter baseline values used in the analysis.

Table 11 Switching values for supply chain costs, expressed as percentage variation from baseline values.

5.1.1 Effect of CAPEX, fuel and electricity price

As shown in Table 11, economic parameters such as fuel cost, electricity price and CAPEX could change significantly without affecting final decisions on the least cost biomass supply chain configurations. An increase around 130-170% in capital costs of torrefaction equipment or – equivalently – a reduction in its expected lifetime around 70-80% make WP more economical than BP for international supply but, at the same time, determine a switch from long distance to local bioenergy supply chains.

5.1.2 Effect of feedstock price

Biomass cost mainly affects decisions on supply origin: in most cases, an increase of about 40% in biomass unit cost in international origin countries is required to make local supply chains competitive for GB and a doubling in biomass cost is required for IT. Biomass cost also affects decisions on pre-treatments on local supply chains: the trade-off between the mass losses implied by torrefaction processes and energy density gains in the transport stage is such, that a reduction of biomass costs in the order of 22% is sufficient to make BP preferable to wood chips for local biomass supply chains from Slovenia to Italy. For GB, a more important reduction in biomass cost is required to attain similar switching conditions (78%), mainly because operational costs of torrefaction plants are higher in GB than in Slovenia due to higher electricity prices.

5.1.3 Effect of biomass properties

The most critical parameter for long distance supply chain performance is the biomass energy density, whose variations in the order of 10-15% determine a complete rearrangement of the supply chain configurations identified as least cost options in sections 4.1.1, 4.2.1 and 4.3.1. This means that, if the LHV of BP is just about 18-19 MJ/kg against a baseline LHV of 17 MJ/kg for WP, then WP are preferable to BP in long distance supply configurations. Similarly, if a LHV of ca 18-19 MJ/kg can be attained for WP against a baseline BP LHV of 21 MJ/kg, torrefaction becomes uneconomic compared with WP. Ultimately, it is the difference between energy densities of BP and WP that is the critical parameter. When comparing long and short distance supply chains, a similar sensitivity is observed on the biomass energy density. In the best performing scenarios, a reduction in BP energy density of 11% and 23% is needed to make the switch to local wood chips supply chain economically feasible for GB and IT respectively. In the latter case, the economic competitiveness of supplying BP from MZ to IT seems quite robust, since a reduction in BP energy density of about 23% would imply that the calorific value of BP would be lower than WP, which is not realistically possible.

On the other hand, based on the switching values analysis, the impact of bulk density on supply chain economics appears limited, mainly because even relatively small percentage variations, e.g. in the order of 20-50%, are out of realistically feasible ranges for BP or WP. For instance, Table 11 shows that for BP to become economically preferable to WP on long supply chains or for C based short supply chains to become preferable to BP based long supply chains, bulk density of black pellets should be diminished to values in the range of 300-500 kg/m^3, completely out of the reported range of BP bulk density (650-800 kg/m^3) [27]. The only exception is when the cost advantage of long distance over short distance supply chains is at its minimum, as in the case of L/BP/US-GB compared with S/C/GB, where the cost difference between local and international supply is just 0,2 €/GJ. In that case, delivering C from Scotland becomes a better choice than BP from US for a decrease of BP bulk density within a realistic range (i.e. 18%, as reported in Table 11, which corresponds to a bulk density of 656 kg/m^3).

5.2 Sensitivity of environmental performance

Moving on to the sensitivity analysis related to the environmental performance of the supply chains (Table 12), the energy density of biomass in any form appears to be the most critical parameter.

Table 12 Switching values for supply chain emissions, expressed as percentage variation from reference values.

5.2.1 Effect of biomass properties

Once again, variations in the order of 10% are enough to change some recommended configurations: for instance, for short supply chains, a 10-11% increase in BP energy density would make centralized torrefaction and pelletization a preferable option to wood chips from an environmental viewpoint for Northern Italy and GB respectively. Similarly, in the case of the S/SI-IT supply chain, where BP originally outperform C as to carbon equivalent emissions, variations in the order of 12-13% in the energy density (i.e. decreases in BP LHV or increases in C LHV, respectively) would make C the preferable option from an environmental viewpoint.

On the other hand, the environmental performance of long-distance supply chains is quite robust to variations in energy density: a reduction of BP energy density around 31-36% or equally an increase of WP energy density of 44-56% would be needed to render the WP supply chains more environmentally friendly than BP, which is beyond the technically reasonable uncertainty range. Only for the US based supply chain, a 9-10% decrease in BP energy density would be enough to make WP preferable to BP from a carbon emission viewpoint. On the other hand, environmental advantages of torrefaction are quite robust for Mozambique and Brazil. When comparing short with long-distance supply chains, it can be concluded that no reduction in energy density of BP within technologically reasonable range is sufficient to make wood chips based short supply chains preferable to long distance supply chains in terms of logistics related carbon emissions. Particularly in the case of supply chains from US, the opposite holds: there is no technically feasible increase in BP energy density that would make this supply chain more sustainable than local ones, mainly due to the level of the electricity emission factor in the US, which is sensibly higher than corresponding values for Brazil or Mozambique (see Table 8). Interestingly, the results are much more sensitive to energy density of biomass compared to its bulk density.

5.2.2 Effect of electricity emissions factor

Regarding the uncertainty in electricity emissions factors of importing countries, only the Italian electricity mix appears to have a high sensitivity and only with reference to imports from Slovenia. In that case, an 18% decrease in the Italian electricity emission factor would reduce the environmental impact of milling wood chips at the final plant enough to make C a more environmentally friendly solution than BP even for the short-distance supply chain between SI-IT.

Variations in electricity emission factors of exporting countries hardly affect pre-treatment options in long supply chains, with BP remaining always preferable to WP; however, they are the only element of uncertainty affecting the relationship between the environmental performance of long and short distance supply chains. For each export country, percentage variations in electricity emissions factors required for short distance supply chains to outperform long distance ones are substantial and hardly achievable in the short term; thus, configurations identified in this work as the least cost can be deemed robust. However, long distance supply chains with different origins may have remarkably different environmental performances. For instance, the US emissions factor, which currently exceeds the British one by about 7%, should be reduced to about the half for the L/BP/US-GB supply chain to become at least as sustainable as its local alternative S/C/GB, whereas a 160% increase of the BR electricity emissions factor, which is currently about 1/5 of the emissions factor of GB, would be required for the S/C/GB to become preferable to Brazilian BP. Thus, differences in the carbon emissions factors of electricity in different countries affect the relative environmental performance of long and short distance supply chains in a similar manner as differences in biomass costs affect economic performance.

Conclusions

A substantial increase in biomass co-firing in European countries poses the question of the sustainability and availability of the feedstock supply, which is expected to rely mainly on international supply chains originating overseas [2].

Within this context, the present work aimed at investigating how torrefaction at biomass supply locations may affect the economic and carbon emissions performance of long distance international supply chains, whether it may play a role in short-distance local supply chains and also, whether local or international biomass supply chains are preferable for the specific cases of co-firing in Italy and in Great Britain. Several supply chain scenarios were analysed, including pellets and torrefied pellets from three international supply locations (US, Brazil and Mozambique) and compared with local biomass supply chain alternatives.

One of the main findings of this work is that torrefaction has the potential to reduce the cost of international supply chains compared to the currently established practice of white pellets, due to the system-wide economies achieved, not only at the upstream supply chain and logistics, but also at the co-firing station where the processing needed is significantly reduced. This finding is aligned with the conclusions of [23, 27, 36], although applied in different geographical contexts. Moreover, torrefaction could also reduce the carbon emissions of the biomass supply chain compared to white pellets.

In the cases examined, the lowest CO_2eq emissions from the biomass supply chain were achieved by sourcing torrefied pellets from Brazil to Great Britain and torrefied pellets from Mozambique for Italy.

When examining local biomass supply chains, wood chips were preferable to white or black pellets, as the limited transportation distance and logistical efficiencies do not justify the additional cost related to pre-treatment of biomass. Furthermore, wood chips incurred the least carbon emissions in most of the local supply chain scenarios examined.

Interestingly enough, the above proposed international supply chains (based on torrefied pellets) performed better than the best local supply chain alternatives for both Great Britain and Italy, in terms of cost and carbon emissions. This result highlights the potential of international biomass trade to reduce the overall environmental impact and cost of biomass supply for co-firing. The main underlying reason for the environmental performance has to do with performing energy-intensive pre-treatment processes in countries with low electricity emission factors, such as Brazil and Mozambique.

Due to the fact that many of the parameters used in this work are subject to uncertainty, a sensitivity analysis was performed. The main parameter identified that could change the order of preference between supply chain configurations for both cost and carbon emissions was the difference in the energy density between white and black pellets, where a 10% change could change the ranking. For the rest of the parameters assessed, the identified order of preference appears quite robust. Therefore, interested stakeholders should place emphasis on specifying the true energy density of the pelletized or torrefied feedstock before making supply decisions.

This work contributes to academic knowledge and industrial practice by reinforcing the potential advantage of a novel biomass pre-treatment process for international biomass supply chains, namely torrefaction and pelleting, as it can lead to both cost and carbon emissions reductions compared to the current practice of white pellets and even compared to local biomass supply alternatives, for the cases examined. It is also the first research to compare the performance of international biomass supply chains with local ones for this range of pre-treatment options. It could also be useful to policy makers for informing decisions on support for renewable energy generation.

Finally, the authors would like to acknowledge that this work has some limitations. The investigation of different co-firing rates or, particularly, of alternative technologies enabling higher co-firing rates was out of the scope of this study, but is an important theme for future research. Many of the parameters used are quite volatile, and therefore the order of preference between the supply chains identified could change in the future, despite the sensitivity analysis proving a good robustness of the findings to individual parameter value changes. Even more, the dynamic nature of the systems examined could also alter the results (i.e. the electricity mix in European countries is bound to become more renewable in the future and the average carbon emissions fluctuate every year). Additionally, although international biomass supply chains are the sensible way forward for the countries examined in this work, due to the inherent limitation of domestic supply quantities, a potential future development of domestic biomass uses in the considered supply countries could introduce competition, therefore increasing prices and affecting availability of biomass. Furthermore, sustainability of biomass does not only involve carbon emissions, but also the land change and substitution of edible crops for biomass. These analyses are beyond the scope of this work, but are an interesting aspect that deserves more investigation in the future.

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Pelletization	**Advantages**	**References**
	· Well established and commercially practiced process; · High energy density compared with untreated feedstock and chips;	[11,14]
	Issues	
	· Energy intensive process. · Limited variety of biomass feedstock suitable for pelletization. · Pellets require special treatment and dedicated equipment (e.g. milling and feeding) for co-firing in existing coal power stations. · Pellets are not water resistant, must be stored in protected environment or silos.	[11,19]
Torrefaction in combination with pelletization	**Advantages**	
	· Could be applied to a wide variety of feedstock (softwood, hardwood, herbaceous, waste) Compared with traditional pellets, torrefied pellets have: · Higher bulk and energy density; · Higher mechanical strength and lower dust formation; · Better hydrophobicity and reduced biological degradation, resulting in no need for covering and for expensive storage solutions; · Homogeneity and grindability properties similar to coal, therefore no need of dedicated milling and feeding infrastructure at coal power plants.	[11–18]
	Issues	
	· New and emerging technology, with limited industrial applications to date and high capital costs. · Limited data on process and pellet properties are available from a few pilot plants. · The process is more energy intensive than pelletization.	[11,12,14,15]

Table 1 Comparison of torrefaction and pelletization pre-treatment technologies.

Co-firing plant	**Unit**	**Value**	**Sources**
Nominal power	MWe	600	[50]
Capacity factor	%	85	[51–53]
Electric efficiency with 100% coal	%	38,74	[25]
Co-firing rate	%	8	[48]
Electrical efficiency with co-firing	%	38,18	[25]
Operating time	h/yr	7600	
Lifetime	yr	15	

Table 2 Reference co-firing plant characteristics.

Properties before treatment*	**Hardwood chips**	**Softwood chips**

Bulk density kg/m^3	317	224
LHV MJ/kgd	10,4	10,4
mc%	40	40
*sources: [54]		

Table 3 Properties of biomass before treatment, after chipping at the roadside.

Properties after treatment*	**BP**	**WP**	**C (hardwood)**	**C (softwood)**
Bulk density kg/m^3	800	575	317	224
LHV MJ/kgd	21	17	14,7	14,7
mc%	3	8,5	20	20
*sources: [12,26,27,54]				

Table 4 Properties of pellets (short and long supply chain) and chips (only short supply chain) after treatment.

Abbreviation	**Type of supply chain**	**Biomass delivered**	**Export country**	**Import country**
L/WP/BR-IT	Long-distance	White pellet	Brazil	Italy
L/WP/BR-GB	Long-distance	White pellet	Brazil	GB
L/BP/BR-IT	Long-distance	Black pellet	Brazil	Italy
L/BP/BR-GB	Long-distance	Black pellet	Brazil	GB
L/WP/MZ-IT	Long-distance	White pellet	Mozambique	Italy
L/WP/MZ-GB	Long-distance	White pellet	Mozambique	GB
L/BP/MZ-IT	Long-distance	Black pellet	Mozambique	Italy
L/BP/MZ-GB	Long-distance	Black pellet	Mozambique	GB
L/WP/US-IT	Long-distance	White pellet	South East US	Italy
L/WP/US-GB	Long-distance	White pellet	South East US	GB
L/BP/US-IT	Long-distance	Black pellet	South East US	Italy
L/BP/US-GB	Long-distance	Black pellet	South East US	GB
S/C/IT	Short-distance	Wood chips	North Italy	Italy
S/WP/IT	Short-distance	White pellets	North Italy	Italy
S/BP/IT	Short-distance	Black pellets	North Italy	Italy
S/C/SI-IT	Short-distance	Wood chips	Slovenia	Italy
S/WP/SI-IT	Short-distance	White pellets	Slovenia	Italy
S/BP/SI-IT	Short-distance	Black pellets	Slovenia	Italy
S/C/GB	Short-distance	Wood chips	Scotland	GB
S/WP/GB	Short-distance	White pellets	Scotland	GB
S/BP/GB	Short-distance	Black pellets	Scotland	GB

Table 5 Summary of all cases studied.

Main input parameter-transport	**Unit**	**Value**	**Source**
Truck transportation			
Chips: Nominal capacity-volume	m^3	130	[10]
Chips: Nominal capacity-weight	t	40	
Pellets: Nominal capacity-volume	m^3	80	[20]
Pellets: Nominal capacity-weight	t	35	
Loading/ unloading cost	€/m^3	0,543	[10]
Loading/ unloading speed	m^3/h	260	
Loading/ unloading consumption	l/h	7	[60]
Diesel consumption full load	l/km	0,5	[50]
Diesel consumption return trip (empty)	l/km	0,25	[61]
Average speed	km/h	65	[10]
Charter cost	€/km	0,92	
Train transportation			
Nominal capacity-volume	m^3	2500	[10]
Nominal capacity-weight	t	1000	
Loading /unloading cost	€/m^3	0,25	
Loading/ unloading speed	m^3/h	240	
Loading/ unloading consumption	kWhe/td	2,777	[20]
Diesel consumption (US & MZ)	MJ/t*km	0,5	
Diesel LHV	MJ/l	36,3	[55]
Electricity consumption (GB & IT)	kWhe/t*km	0,075	[61,84]
Average speed	km/h	75	[10]
Charter cost	€/km	7,92	[55]
Sea transportation			
Nominal capacity-volume	m^3	56250	[27]
Nominal capacity-weight	t	45000	
Loading time	t/h	700	[20]
Unloading time	t/h	300	
Loading/ unloading consumption	kWhe/td	11,08	
HFO consumption	t/km	0,04	
HFO cost	€/t	168,75	[62]
Average speed	knots	14	[63]
Charter cost	€/day	7326,58	[64]

Table 6 Model input data: transport parameters.

Main input parameter-logistics	**Unit**	**Value**	**Source**
Chipping at the roadside			
CAPEX	M€	0,33	[65]
Maintenance	% of CAPEX	20	
Diesel consumption	l/h	115,74	
Operating time	h/yr	5480	
Capacity	kg$_{\text{Raw Material}}$/h	83,5	
Labour cost	€/h	17,24	
Handling & Storage			
Electricity consumption	kWhe/MWh	0,25	[5]
Fuel consumption	l diesel/MWh	0,02	
Maintenance	% of CAPEX	3	[20]
Bunker-C			
mc loss (chips with mc >20%)	%/month	1,5	[20]
Size - volume	m^3	25000	
CAPEX	M€	2,12	
Silos-WP			
Size - volume	m^3	5000	[20]
CAPEX	M€	0,37	
Outdoor uncovered- BP			
Size - volume	m^3	3000	[20]
CAPEX	M€	0,03	
Handling & storage at final user			
Electricity consumption	kWhe/MWh	2,1	[5]
Pulverising at the plant: only for white pellet and wood chips			
Number of hammer mills	-	3	
CAPEX	M€	1,2	[20]
Lifetime yr	yr	15	
Load capacity	t/h	150	
Total power installed	kW	720	
Electricity consumption			
Wood chips	kWhe/t	116-118	[24,66]
White pellets	kWhe/t	50	

Table 7 Model input data: storage and chipping parameters.

Country dependent parameter	**Unit**	**Value**	**Source**
Biomass price			
Brazil	€/t	14,4	[10]
Italy	€/t	58,6	[67]
Mozambique	€/t	13,3	[23]
Slovenia	€/td	84,4	[68]
GB	€/td	69,1	[69]
US	€/t	17,8	[57]
Diesel price			
Brazil	€/l	0,77	[70]
Italy	€/l	1,31	
Mozambique	€/l	0,66	
Slovenia	€/l	1,13	
GB	€/l	1,41	
US	€/l	0,56	
Natural gas price			
Mozambique	€/kWh	0,025253	[71]
Italy	€/kWh	0,029335	[72]
Slovenia	€/kWh	0,031772	
GB	€/kWh	0,032552	
US	€/kWh	0,018142	[73]
Brazil	€/kWh	0,015508	Adapted from [73]
Electricity price			
Brazil	€/kWhe	0,0771	[71]
Mozambique	€/kWhe	0,0319	
Italy	€/kWhe	0,0896	[74]
Slovenia	€/kWhe	0,0693	
GB	€/kWhe	0,1425	
US	€/kWhe	0,0594	[73]
Port fees			
Brazil	€/m^3	8,62	Adapted from [27]
Mozambique	€/m^3	11,91	
US	€/m^3	8,45	
GB	€/t	7,5	[75]
Italy	€/t	5	[76]
Electricity emission factor			
Brazil	KgCO$_2$eq/kWhe	0,109907	[44]
Italy	KgCO$_2$eq/kWhe	0,435266	
Mozambique	KgCO$_2$eq/kWhe	0,000492	[42]
Slovenia	KgCO$_2$eq/kWhe	0,316025	[42,43]
GB	KgCO$_2$eq/kWhe	0,548402	[44]
US	KgCO$_2$eq/kWhe	0,586667	

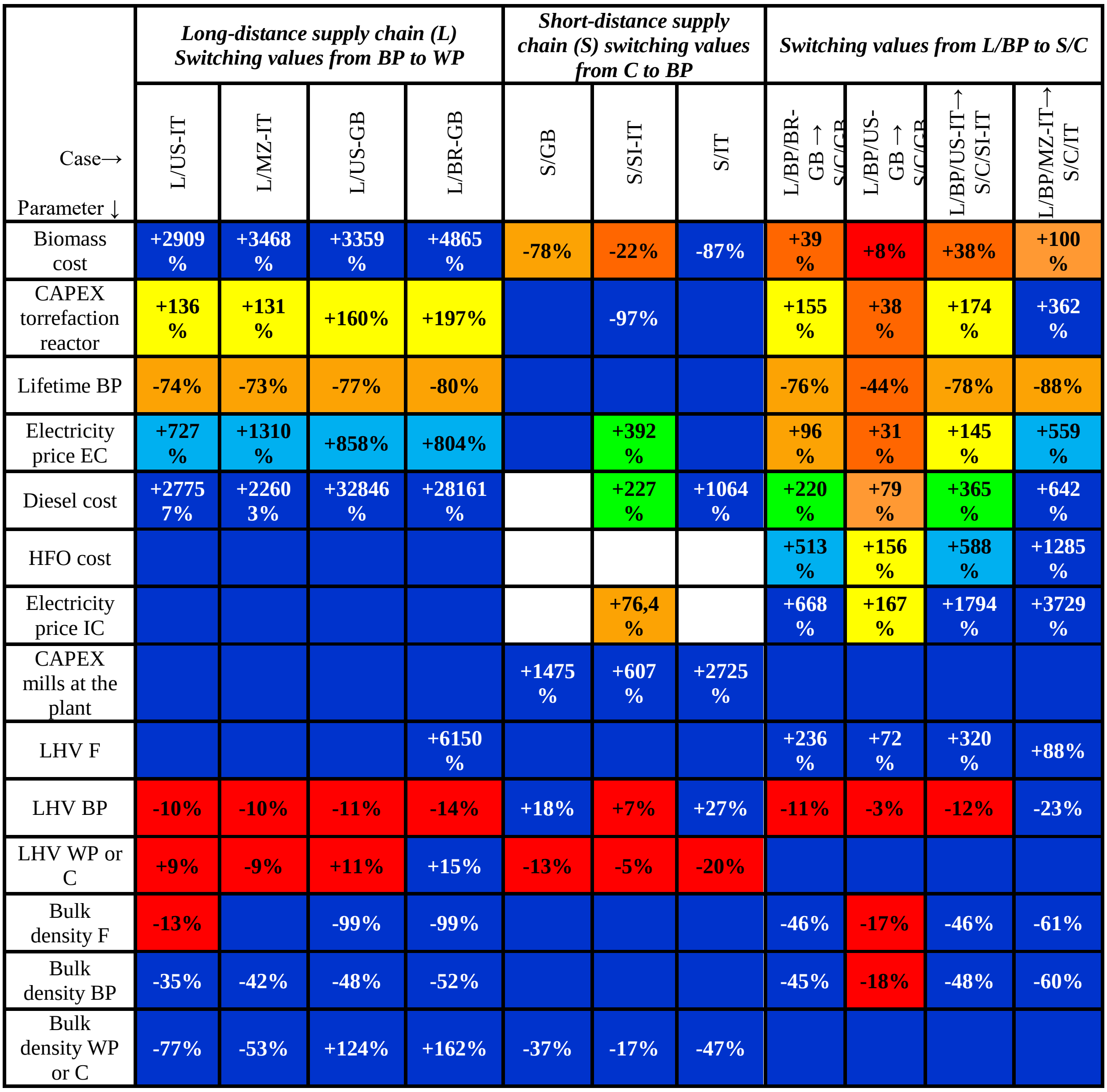
Table 8 Model input data: electricity emission factors, biomass and fuels prices.

Distance between the ports *	**GB- port of Immingham**		**Slovenia- port of Koper**	
	nm	km	nm	km
Brazil – port of Belem	5766	10678,6	6228	11534,3
Mozambique – port of Nacala	7817	14477,1	5540	10260,1
South East US- port of Savannah	4752	8800,7	5824	10786,1
* sources:[77]				

Table 9 Average distance between the ports in nm (nautical miles) and km.

	Biomass mass flow required at power plant (kt/yr)	Biomass flow required at collection stage (kt/yr)		
		L/BR	L/MZ&US	S
BP	139,23	435,33	439,68	400,27
WP	171,99	430,78	435,09	396,09
C	198,90			264,79

Table 10 Initial and final biomass flows.



Case→ Parameter ↓	*Long-distance supply chain (L) Switching values from BP to WP*				*Short-distance supply chain (S) switching values from C to BP*			*Switching values from L/BP to S/C*			
	L/US-IT	L/MZ-IT	L/US-GB	L/BR-GB	S/GB	S/SI-IT	S/IT	L/BP/BR-GB → S/C/GB	L/BP/US-GB → S/C/GB	L/BP/US-IT→ S/C/SI-IT	L/BP/MZ-IT→ S/C/IT
Biomass cost	+2909%	+3468%	+3359%	+4865%	-78%	-22%	-87%	+39%	+8%	+38%	+100%
CAPEX torrefaction reactor	+136%	+131%	+160%	+197%	🟦	-97%	🟦	+155%	+38%	+174%	+362%
Lifetime BP	-74%	-73%	-77%	-80%	🟦	🟦	🟦	-76%	-44%	-78%	-88%
Electricity price EC	+727%	+1310%	+858%	+804%	🟦	+392%	🟦	+96%	+31%	+145%	+559%
Diesel cost	+27757%	+22603%	+32846%	+28161%	⬜	+227%	+1064%	+220%	+79%	+365%	+642%
HFO cost	🟦	🟦	🟦	🟦	⬜	⬜	⬜	+513%	+156%	+588%	+1285%
Electricity price IC	🟦	🟦	🟦	🟦	⬜	+76,4%	⬜	+668%	+167%	+1794%	+3729%
CAPEX mills at the plant	🟦	🟦	🟦	🟦	+1475%	+607%	+2725%	🟦	🟦	🟦	🟦
LHV F	🟦	🟦	🟦	+6150%	🟦	🟦	🟦	+236%	+72%	+320%	+88%
LHV BP	-10%	-10%	-11%	-14%	+18%	+7%	+27%	-11%	-3%	-12%	-23%
LHV WP or C	+9%	-9%	+11%	+15%	-13%	-5%	-20%	🟦	🟦	🟦	🟦
Bulk density F	-13%	🟦	-99%	-99%	🟦	🟦	🟦	-46%	-17%	-46%	-61%
Bulk density BP	-35%	-42%	-48%	-52%	🟦	🟦	🟦	-45%	-18%	-48%	-60%
Bulk density WP or C	-77%	-53%	+124%	+162%	-37%	-17%	-47%	🟦	🟦	🟦	🟦

Parameter value change in % compared to baseline:

🟥	± 0-20%
🟧	± 20-50%
🟧	± 50-100%
🟨	± 100-200%
🟩	± 200-500%
🟦	> ± 500%
🟦	unreachable
⬜	independent

Acronyms

EC = Export Country

IC = Import Country

F = Feedstock: wet, after chipping at the roadside.

Table 11 Switching values for supply chain costs, expressed as percentage variation from baseline values.

Case → Parameter ↓	*Long-distance supply chain (L) Switching values from BP to WP*				*Short-distance supply chain (S) switching values from C to BP*			*Switching values from L/BP to S/C*			
	L/US-IT	L/MZ-IT	L/US-GB	L/BR-GB	S/GB	S/SI-IT	S/IT	L/BP/BR-GB→ S/C/GB	L/BP/US-GB → S/C/GB	L/BP/US-IT→ S/C/SI-IT	L/BP/MZ-IT→ S/C/IT
Electricity emission factor EC	**+103%**		**+121%**	**+1247%**		**+23%***		**+161%**	**-47%**	**-73%**	**+39887%**
Electricity emission factor IC	**-79%**		**-69%**			**-18%***		**+246%**			**+725%**
LHV F	**+17881%**		**+21054%**	**+6150%**		**+342%**		**+369%**			**+430%**
LHV BP	**-9%**	**-36%**	**-10%**	**-31%**	**+11%**	**-12%***	**+10%**	**-29%**	**+45%**	**+92%**	**-39%**
LHV WP or C	**+10%**	**+56%**	**11%**	**+44%**	**-10%**	**+13%***	**-9%**				
Bulk density F								**-97%**			**-97%**
Bulk density BP	**-39%**	**-58%**	**-48%**	**-60%**	**-100%**	**+182%***		**-57%**			**-61%**
Bulk density WP or C	**+60%**	**+405%**	**+116%**	**641%**		**-99%***	**-33%**				

***Only for Slovenia: switching values from BP to C

3

Parameter value change in % compared to baseline:

🟥	± 0-20%
🟧	± 20-50%
🟧	± 50-100%
🟨	± 100-200%
🟩	± 200-500%
🟦	> ± 500%
🟦	unreachable
⬜	independent

Acronyms

EC = Export Country

IC = Import Country

F = Feedstock: wet, after chipping at the roadside.

Table 12 Switching values for supply chain emissions, expressed as percentage variation from reference values.

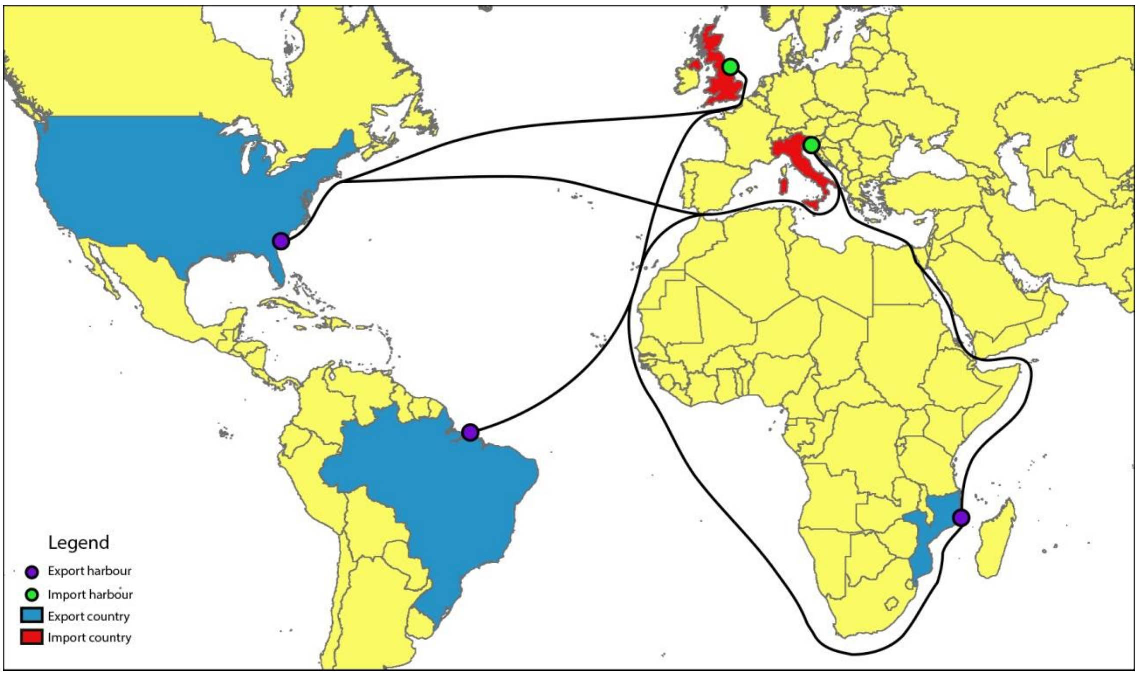


Figure 1 Representation of import & export countries and shipping routes.

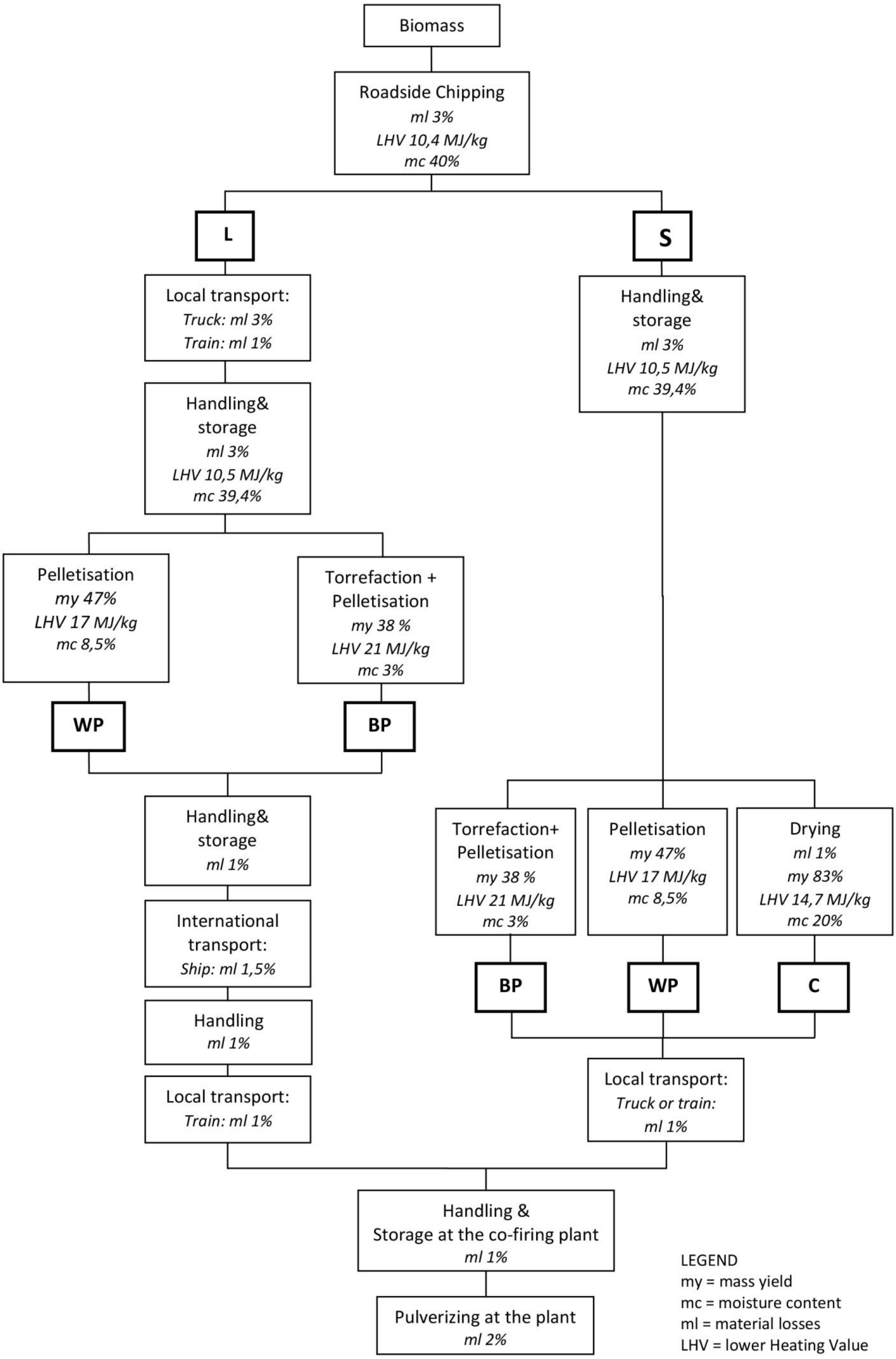


Figure 2 Structure of long and short distance supply chain scenarios for C, WP and BP.

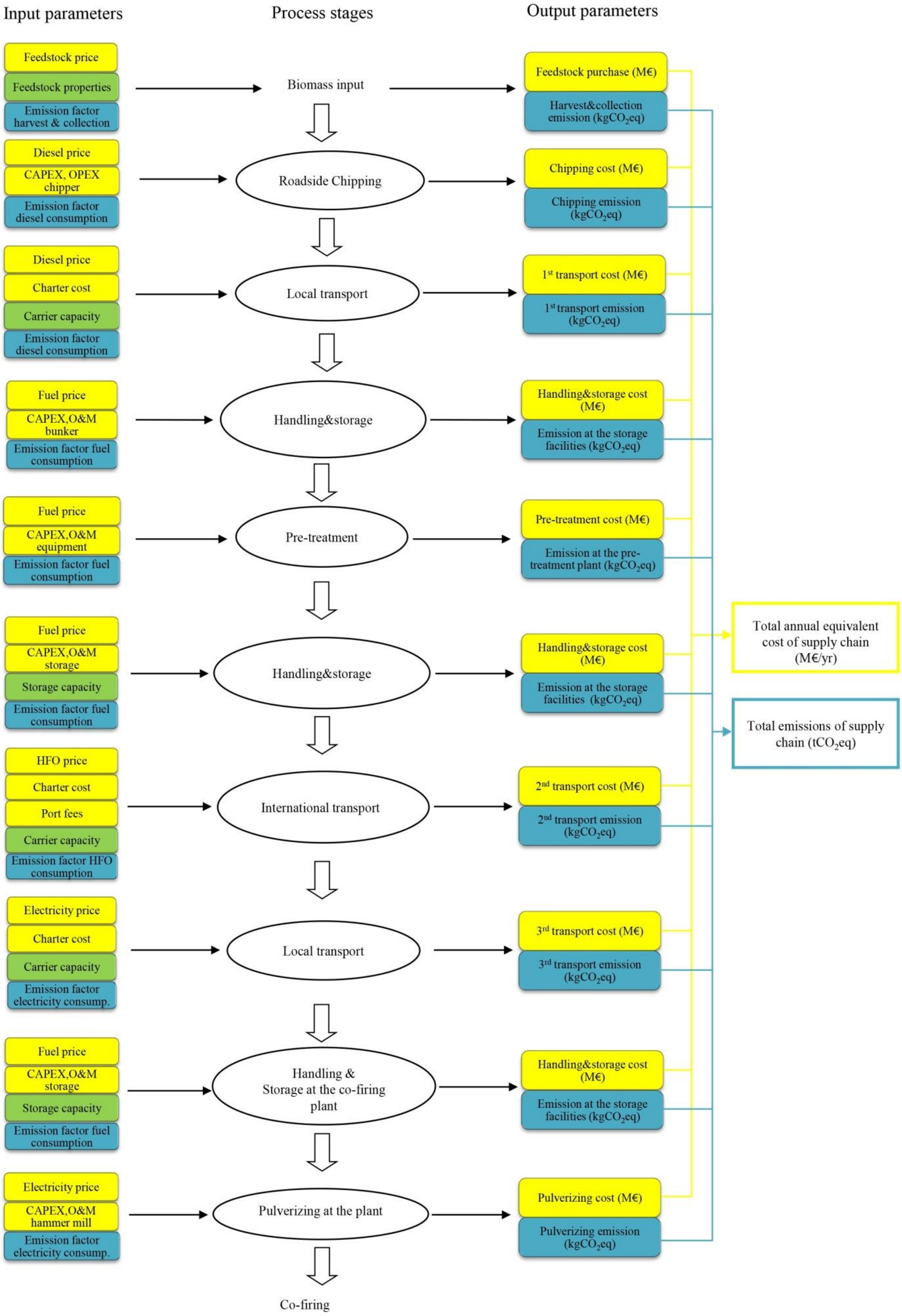


Figure 3 I/O diagram of long distance supply chain.

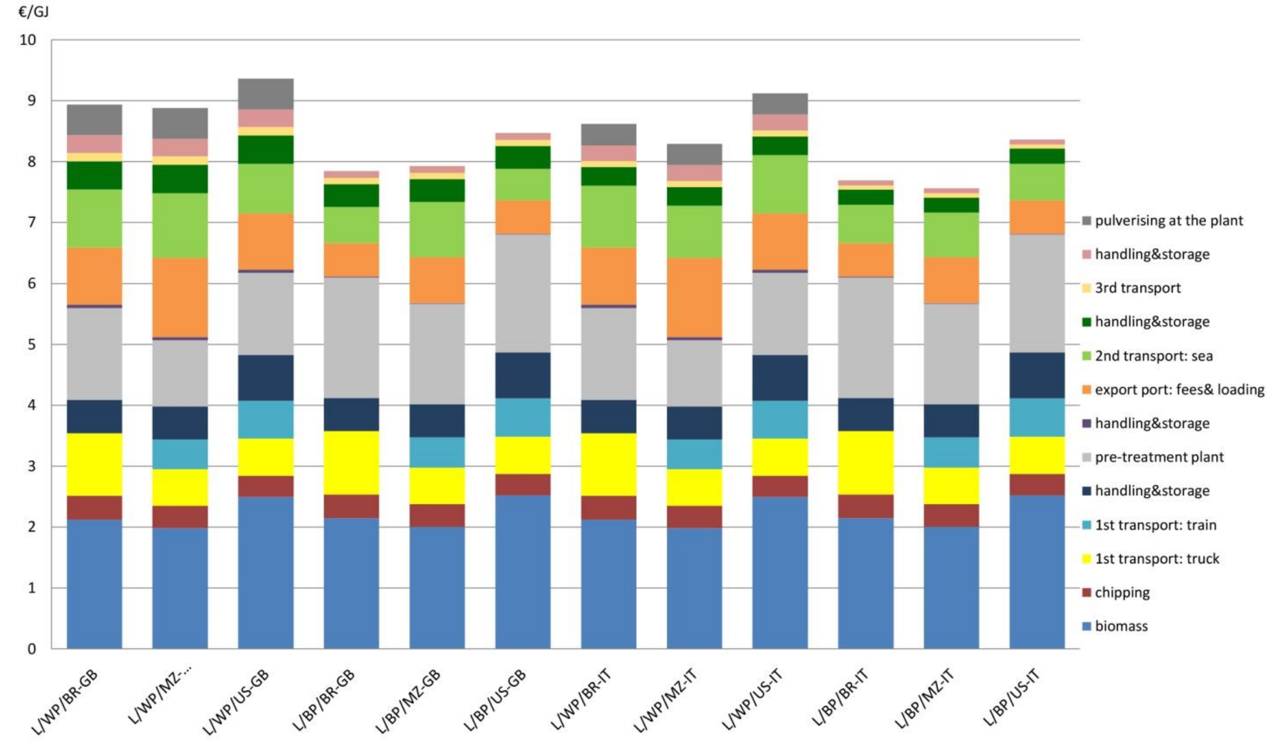


Figure 4 Cost breakdown for WP and BP on long distance supply chains.

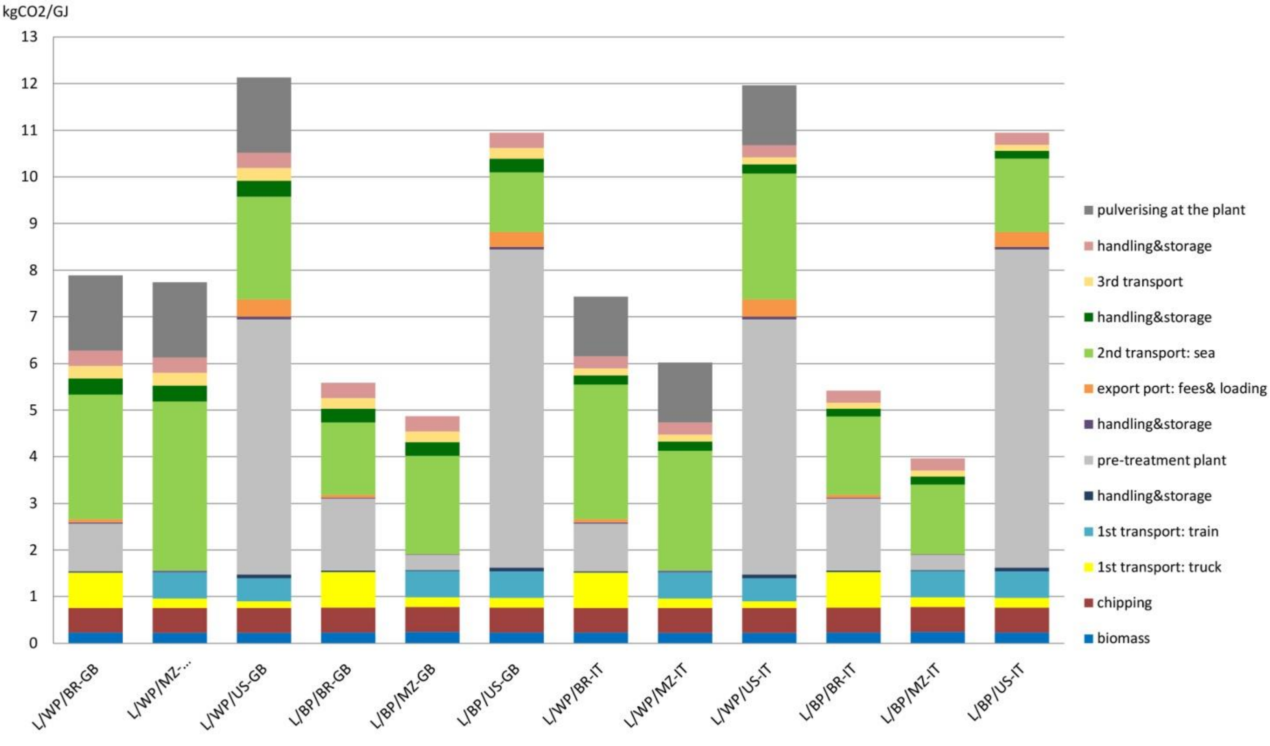


Figure 5 Emission factor breakdown for WP and BP on long distance supply chains.

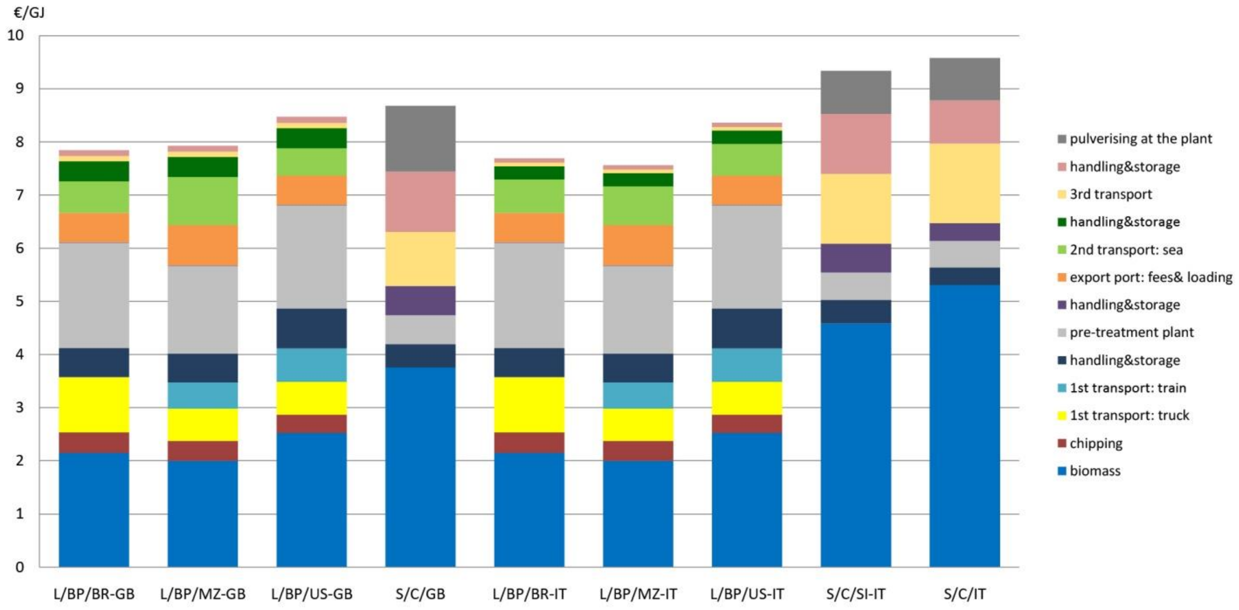


Figure 6 Cost breakdown for WP, BP and C on short-distance supply chains.

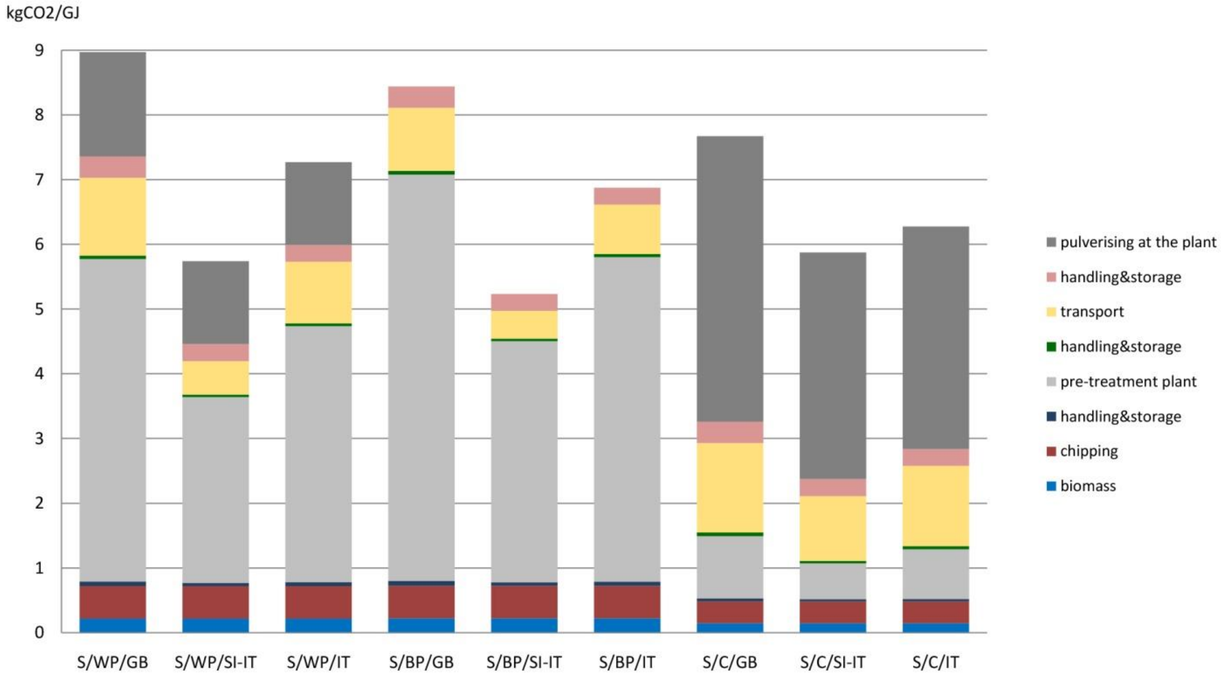


Figure 7 Emission factor composition for WP, BP and C on local supply chains.

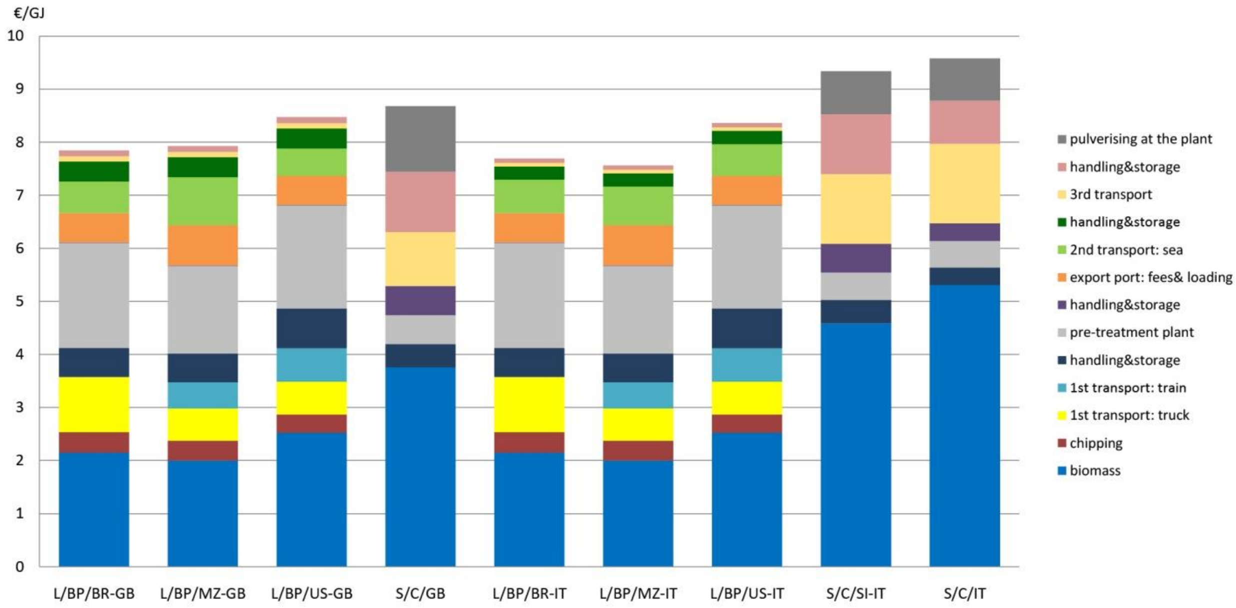


Figure 8 Cost structure comparison of international (BP) vs. local (C) supply chains.

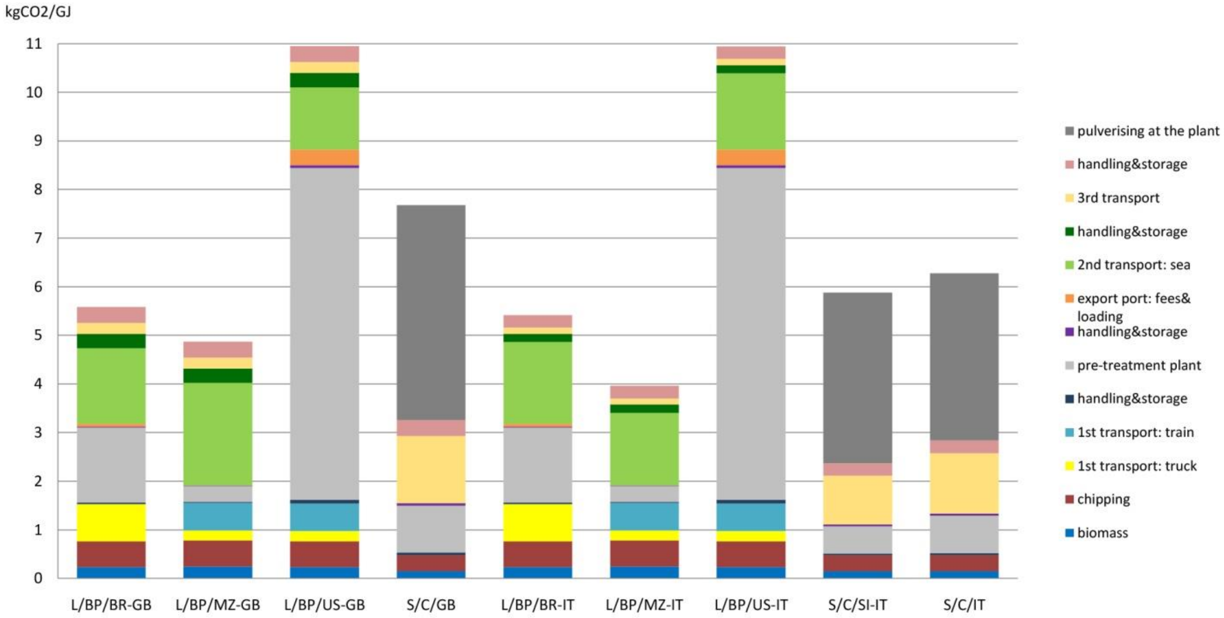


Figure 9 Emission factor comparison of international (BP) vs. local (C) supply chains.

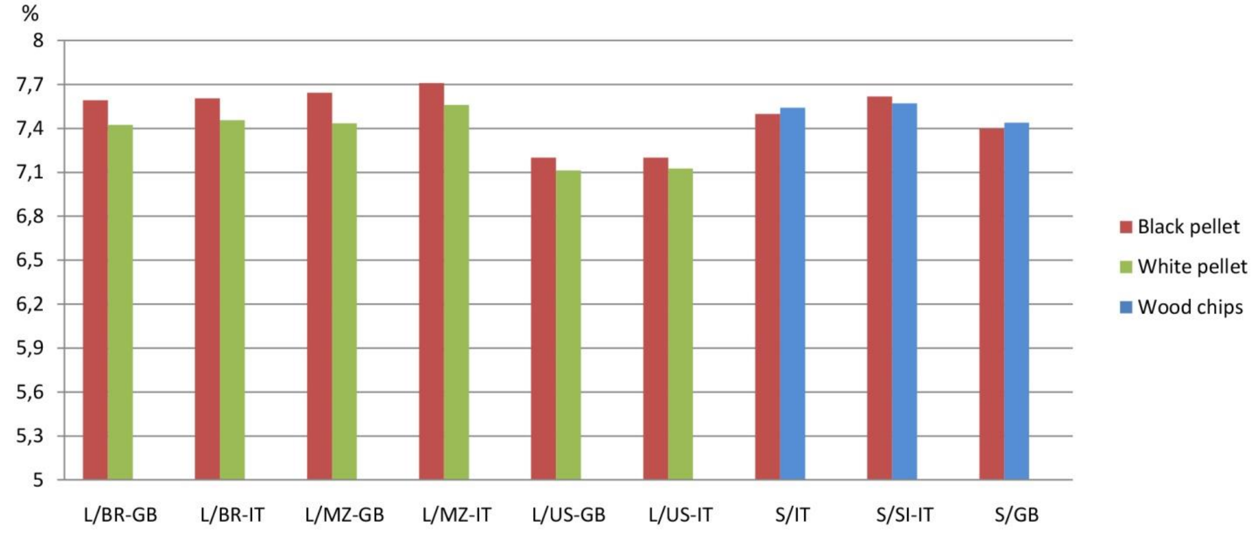


Figure 10 CO_2eq emissions reduction with 8% co-firing compared to coal-firing plant.

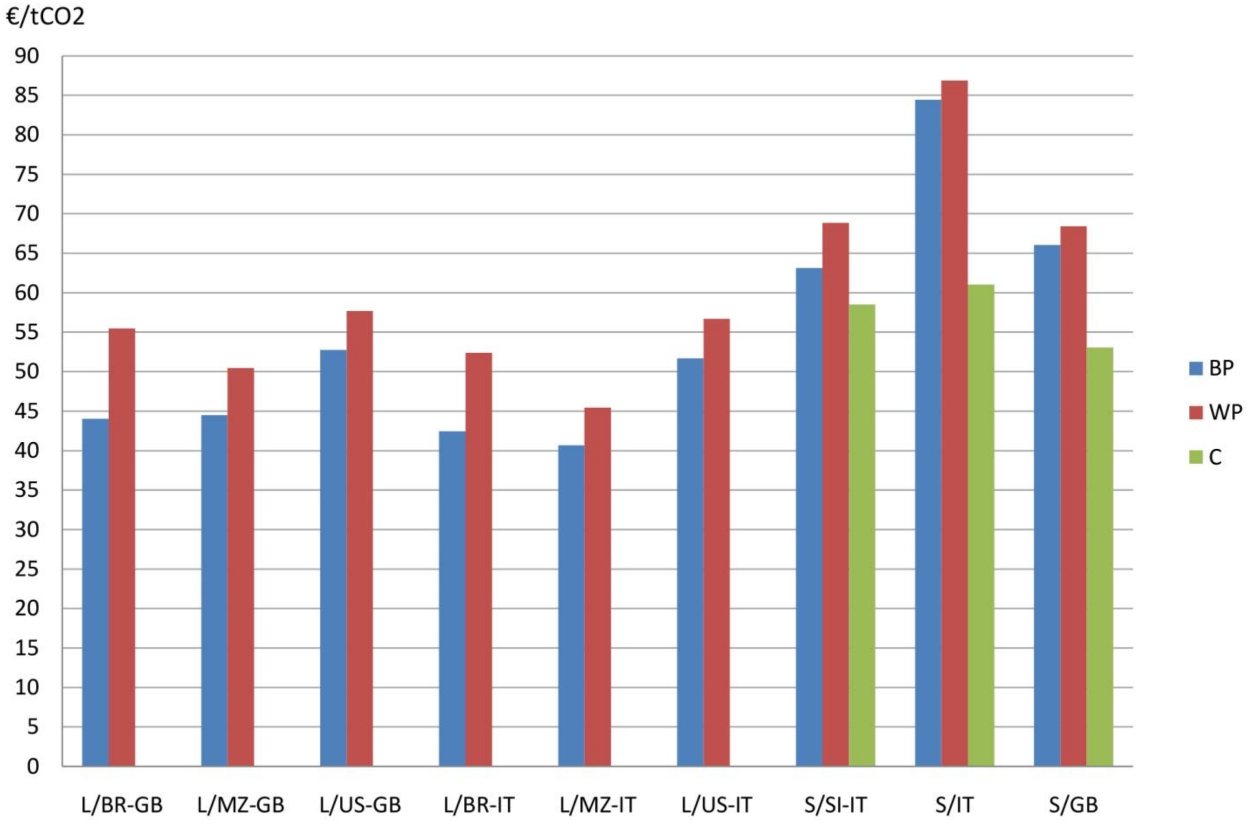


Figure 11 Carbon dioxide abatement costs of 8% co-firing at plants of all scenarios studied.