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International vs. domestic bioenergy supply chains for co-firing plants: the 1

2 role of pre-treatment technologies

Caterina Mauro^a, Athanasios A. Rentizelas^b, Damiana Chinese^{a,*} 3

^a Dipartimento politecnico di Ingegneria e Architettura, University of Udine, via delle Scienze 206, 33100 Udine, Italy.

456789 ^b Department of Design Manufacture and Engineering Management, University of Strathclyde, 75 Montrose Street, G1 1XJ, Glasgow, UK

* Corresponding author. E-mail address: damiana.chinese@uniud.it (D. Chinese)

Co-firing of solid biomass in existing large scale coal power plants has been supported in many 10 11 countries as a short-term means to decrease CO₂ emissions and rapidly increase renewable 12 energy shares. However, many countries face challenges guaranteeing sufficient amounts of 13 biomass through reliable domestic biomass supply chains and resort to international supply 14 chains. Within this frame, novel pre-treatment technologies, particularly pelletization and 15 torrefaction, emerged in recent years to facilitate logistics by improving the durability and the 16 energy density of solid biomass. This paper aims to evaluate these pre-treatment technologies 17 from a techno-economic and environmental point of view for two reference coal power plants 18 located in Great Britain and in Italy. Logistics costs and carbon emissions are modelled for 19 both international and domestic biomass supply chains. The impact of pre-treatment 20 technologies on carbon emission avoidance costs is evaluated. It is demonstrated that, for both 21 cases, pre-treatment technologies are hardly viable for domestic supply. However, pre-22 treatment technologies are found to render most international bioenergy supply chains 23 competitive with domestic ones, especially if sourcing areas are located in low labour cost 24 countries. In many cases, pre-treatment technologies are found to guarantee similar CO₂ 25 equivalent emissions performance for international compared to domestic supply chains.

26

27 Keywords: biomass supply chain, international logistics, carbon equivalent emissions, 28 torrefaction, pelletization, bioenergy, co-firing

29 Nomenclature

- 30 BP **Black Pellets**
- 31 BR Brazil
- 32 С Wood Chips
- 33 CDAC Carbon Dioxide Abatement Cost

34	CAPEX	Capital Expenditure
35	EC	Export Country
36	F	Feedstock
37	GB	Great Britain
38	HFO	Heavy Fuel Oil
39	IT	Italy
40	IC	Import Country
41	kgd	dry kilogram
42	kWhe	electrical kilowatt-hour
43	L	Long-distance supply chain
44	LHV	Lower Heating Value
45	LCOE	Levelized Cost of Electricity
46	mc	Moisture content
47	MZ	Mozambique
48	my	Mass Yield
49	OPEX	Operational Expenditure
50	S	Short-distance supply chain
51	SI	Slovenia
52	td	dry tonne
53	US	United States
54	WP	White Pellets
55		

56 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].

64 In Great Britain the Renewable Obligation (RO) has been one of the main support mechanisms 65 for large-scale renewable electricity projects. Suppliers are obliged to supply a percentage of 66 their electricity from renewable sources, which increases year on year. A penalty is imposed 67 on suppliers who do not meet the targets. Correspondingly, the Office of Gas and Electricity 68 Market (Ofgem) issues Renewable Obligation Certificates (ROCs) to electricity generators in 69 relation to the amount of eligible renewable electricity they generate. In essence, this operates 70 to the effect that suppliers can buy and sell their way out of the renewable requirement. This is 71 the current support mechanism for biomass co-firing and is open for new installations until the 72 year 2017, providing ROCs in eligible operators for a duration of 20 years [3]. In other EU 73 countries, including Italy [4], Germany and Austria [5] no specific incentives for biomass co-74 firing are currently foreseen.

75 While forestry biomass withdrawal in Italy is not sensibly smaller than the EU average, Italy 76 is in the lowest ranks in Europe as to primary energy consumption from solid biomass [6], and 77 heavily depends on imports to meet current demand [7]. The situation in Great Britain is 78 similar, with even smaller contribution of solid biomass to primary energy consumption: 0,22 m³ equivalent of pro capita consumption in Italy against 0,10 m³ in Great Britain [8]. Thus, for 79 80 both countries co-firing could improve their biomass contribution to the renewable national 81 energy production and utilization mix, provided that imports, even from distant countries, are 82 economically feasible and overall sustainable. Demonstrating the economic and environmental 83 performance of long distance biomass supply chains for large scale plants is a challenge for 84 policy makers and for energy companies, faced with economic risk of supply as well as with 85 social acceptance issues, especially in countries with less experience in biomass use, such as 86 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 87 88 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,

93 which consists of a thermal treatment process in which the biomass material is subjected to a 94 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 95 96 advantages and issues of torrefaction, particularly in comparison to pelletization, as 97 summarized in Table 1.

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

99 The limited experience with torrefaction at pilot and industrial scale is the major concern about 100 this technology. On the other hand, Table 1 shows that, compared with traditional wood pellets, 101 the combined torrefaction and pelletization process has significant potential advantages; in 102 particular, the enhanced bulk and energy density results in more efficient transportation. Better 103 mechanical and hydrophobicity properties further reduce the need for expensive storage 104 solutions. Hence, torrefaction in combination with pelletization has the potential to improve 105 the economic performance of long distance biomass supply chains, provided that the additional 106 CAPEX and OPEX of this emerging, energy intensive technology are compensated by 107 corresponding cost savings in the logistics [18,19].

108 The role of pelletization in long distance biomass logistics has been investigated by several 109 authors [20,21], also in comparison with other pre-treatment alternatives such as pyrolysis and 110 considering regional and overseas supply chains [10,22]. On the other hand, only recent studies 111 compare torrefied pellets (also called black pellets) with traditional pellets (white pellets), 112 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 113 114 long distance solid biomass supply for co-firing could be a viable GHG reduction policy option 115 for the EU, call for additional research on supply chain configurations and economics, as well 116 as on the environmental impact of torrefaction, since only white pellet supply chains are 117 investigated in their study.

- 118 This paper contributes to fill these research gaps by aiming to investigate:
- 119

1. how torrefaction at biomass sourcing sites may affect the economic and carbon 120 equivalent emission performance of long distance supply chains;

- 121 2. whether torrefaction and pelletization may play a role in short-distance supply chains;
- 122 3. how do domestic and international supply chains compare in terms of cost and 123 emissions performance.

124 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 125 126 primary energy mix and therefore have a high potential for increase. International and local 127 biomass supply chain scenarios are configured, i.e biomass flows and properties are quantified, 128 capacities and input-output flows of treatment plants are determined both for long and short 129 distance supply chains, as well as collection, transportation and storage requirements. For long 130 distance supply chains black pellets and white pellets scenarios are considered, whereas for 131 short distance supply chains wood chips are also evaluated. Section 2 describes the case studies 132 discussed in this paper. Alternative supply chain configurations are modelled on a spreadsheet 133 simulation model as illustrated in section 3, which presents the economic and environmental 134 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 135 136 short and long distance supply chains is compared, considering also their contribution to the 137 economic and environmental performance of produced electricity and corresponding costs of 138 CO₂ avoidance. In section 5, the sensitivity of the model results to the most influential uncertain 139 parameters is analysed, while general conclusions and directions for future research are derived 140 in section 6.

141 **2** Case studies

To enable comparison of long distance (L) and short distance (S) supply chains delivering 142 143 biomass to large coal co-firing plants in a global context, two reference co-firing plants in GB 144 and Italy were selected as end users. The location of the base reference plant is assumed to 145 coincide with existing plants in GB (Drax Power Station in Selby) and in Italy (A2A power 146 station in Monfalcone). The Selby power station has already converted several of its units to 147 use biomass pellets, it is the biggest in GB and is located near to the port of Immingham, an 148 important harbour for pellets trade. In Italy, Monfalcone is selected as a coal power plant of 149 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]).

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

157 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 158 159 of Koper in Slovenia, for Monfalcone. In both cases, energy conversion plants are situated 160 within 50-70 km from the harbours. Figure 1 also shows the exporting countries selected and 161 the respective harbours considered for long-distance biomass supply, i.e. Brazil (port of 162 Belem), South East US (port of Savannah) and Mozambique (port of Nacala). These choices 163 are in agreement with the selection criteria proposed in [2] and [27]. Export as well as import 164 ports are large ports with existing terminals for wood pellets or at least other biomass or wood 165 products. South America and Africa are widely expected to become significant exporters of 166 biomass to the EU. A future high level of EU biomass demand is expected to result in 167 investments in pellet plants, short rotation crop and tree plantations, such as eucalyptus, in 168 regions such as Brazil, Uruguay, West Africa and Mozambique [2]. Similar considerations are 169 presented in [1], where the expectations are that up to 5% of total biomass use in 2020 could 170 be sourced by international trade, with North America, Africa, Brazil and Russia as the major 171 suppliers.

172 For the European countries of concern data on forest biomass distribution is available from 173 National Inventories, particularly [32,33] for softwood availability in Scotland, [34] for 174 biomass from arboreal origins in different Italian provinces, and [35] for the allowable cut of 175 forestry biomass in Slovenia. Available data on technical biomass withdrawal potentials were 176 imported in ArcGis, and used first to build up a supply area, gradually including locations 177 farther to the plant once the potential of the closest ones was exhausted. Secondly, ArcGis was 178 used to determine a weighted median centre, where the reference location of the centralized 179 collection point was set, and to calculate the average transport distance from the withdrawal 180 area to the collection point. This approach allows to estimate the proportion of national territory 181 needed to feed reference plants with local forest biomass. For regional supply, limitations in 182 European forest biomass potentials lead to remarkable average distances from centralized 183 collection points to power plants: 443 km for Scotland, 275 km for Northern Italy, and 153 km 184 for Slovenia.

185 **3** Supply chain modelling

The generic supply chain structures of all scenarios examined in this work are modelled as inFigure 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.

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

193

194 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, 195 196 properties of feedstock, costs and CO₂ equivalent emissions of alternative supply chain 197 configurations. A supply chain configuration is defined for the purposes of this work as a 198 combination of one of the supply chain structures presented in Figure 2 with a particular 199 biomass origin and destination country. The inputs and output parameters of the simulation 200 model are reported in Figure 3 for each supply chain stage, with reference to long distance 201 supply chains only for simplicity of representation. A simplified version of Figure 3 applies for 202 short distance supply chains, where port logistics and overseas transport stages are omitted and 203 chipping is considered as the treatment option. Inputs and outputs for common stages between 204 long and short distance supply chains are the same.

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

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

207 – an economic evaluation of the CAPEX and OPEX related to the single stage activity
 208 considered (e.g. chipping, handling, storage);

an environmental assessment (in terms of kgCO₂eq) 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 andemissions of the supply chain.

- 213 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.

221 Fuels represented in Figure 3 vary depending on supply chain stage. Diesel and 222 electricity are considered for handling and storage. Trucks are fuelled with diesel, trains 223 use electricity or diesel fuel depending on locally available infrastructure, and ships 224 operate on HFO. For all pre-treatment options, except for the torrefaction process, 225 drying is considered to be fuelled with biomass, rather than with fossil fuels, as in [5]. 226 In the case of torrefaction, extra thermal power to support drying and torrefaction 227 processes is being put into the process partly by natural gas and partly by combustion 228 of extra feedstock, as reported in [39]. When the pre-treatment is pelletization, only 229 electricity emissions are considered as the combustion of biomass for drying is 230 considered renewable, while in the case of torrefaction emissions from electricity and 231 natural gas are considered. Emission factors are derived from [40] for diesel and HFO, 232 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.
- 240 The final supply chain stage analysed in this work is pulverising the biomass delivered • 241 at the co-firing plant and feeding it to the boiler. To define and calculate biomass 242 requirements, direct co-firing is selected among the various available technologies [47]. 243 For direct co-firing, biomass is pre-mixed with coal, and the fuel blend is fed to the 244 furnace using the existing firing equipment, i.e. without significant additional 245 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 246 247 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 248 249 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].
- 256 Data and sources about the co-firing plants are reported in Table 2.
- 257 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,
- 259 BP and dried C) are summarized in Table 4.
- 260 Table 2 Reference co-firing plant characteristics.
- 261 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.

270 Table 5 Summary of all cases studied.

- 271 3.1 Long-distance supply chains
- 272 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 m³
 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/m³), 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 summarizedin
- 296 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].

- 300 The average shipping distance between export and import ports is reported in
- 301 Table 9.
- 302 Table 6 Model input data: transport parameters.
- 303 Table 7 Model input data: storage and chipping parameters.
- 304 Table 8 Model input data: electricity emission factors, biomass and fuels prices.
- 305 Table 9 Average distance between the ports in nm (nautical miles) and km.
- 306
- 307 *3.2 Short-distance supply chains*
- 308 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].
 - 10

- 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.

323 **4 Results and discussion**

324 Economic and carbon emissions analysis has been performed for all supply chain configuration 325 scenarios studied. The costs and the emissions associated with the supply chain are reported 326 with respect to GJ of biomass delivered. In order to address the three main research questions 327 and to facilitate presentation of the results for the 20 scenarios, the analysis focuses first on 328 long distance supply chains, to assess whether torrefaction is economically and 329 environmentally justifiable compared to pellets and to determine the best performing supply 330 chain scenarios. Secondly, short supply chains are studied to establish which supply form (WP, 331 BP or C) is preferable for each case. Finally, the best performing short and long distance options 332 are compared to highlight the relationship between long and short distance supply alternatives.

333 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.

345 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).

350 Ship transport and export fees are the third highest cost element. These are significantly 351 reduced for BP, compared with WP, due to higher energy density that leads to better utilisation 352 of the ship cargo space. A major cost reduction in BP supply chains comes from removing the 353 need for dedicated milling at the power station. The reduction in these three cost components, 354 namely ship transport, export fees and milling at destination, compensates for the additional 355 pre-treatment costs associated with the BP process. As a result, both for Italy and Great Britain 356 and from all import countries, BP are the least cost option for biomass logistics, with savings 357 ranging between 8,3 % (for L/BP/US-IT) and 12,2% (for L/BP/BR-GB) compared with the 358 respective WP supply chains.

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

360 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 362 363 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% 364 365 and 8,30% respectively for US-GB and US-IT. The best economic performance for supplying 366 Italy is BP from Mozambique due to lower cost of biomass and electricity (Table 8), which 367 affects operational costs of pre-treatment. Indeed, although the additional cost of passing 368 through the Suez Canal has been incorporated in shipping costs, the cost of shipping from MZ 369 to IT is comparable with the ones of L/BP/BR-IT and L/BP/US-IT thanks to the shorter 370 shipping distance (

Table 9). The least cost long-distance supply chain to GB is the one supplying BP from Brazil.

372 This is due to the lower cost of biomass and to the relatively shorter shipping distance compared

to other supply chain configurations.

374 4.1.2 Environmental impact breakdown and comparison

Pre-treatment and sea transportation are also the phases with the highest impact on the CO₂ 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.

382 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 pretreatment. 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.

390 As a whole, the higher number of sea trips required yearly for WP compared to BP because of 391 the lower density of WP, and subsequent sub-optimal utilisation of the ship cargo capacity, is 392 such that additional environmental impact associated with the torrefaction process is 393 compensated by lower sea transportation impact both in the Brazil and Mozambique cases. 394 Also for supply chains of US origin, BP are preferable to WP, but this is mainly due to 395 additional emissions for pulverising white pellets at the plant before co-firing them, rather than 396 to gains in sea transportation and handling at the port related emissions alone. Thus, for all the 397 long distance supply chains considered, delivering BP appears preferable to WP not only from 398 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 406 variations in the environmental impact of long distance supply chains depending on origin and407 destination.

408 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.

414 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.

418 Due to the low bulk density of wood chips, the stages of transport, handling and storage highly 419 affect the costs of the wood chips (C) supply chain compared to pelletization based options. 420 Nevertheless, because of high electricity costs in all short distance supply countries, pre-421 treatment is expensive and additional costs are not compensated by efficiency gains in logistics. 422 Therefore C are less expensive than pellets in all the short distance supply chains examined. 423 Differences between WP and BP delivered costs are minimal.

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

425 4.2.2 <u>Environmental impact breakdown and comparison</u>

426 The emissions of pre-treatment and pulverizing at the co-firing plant influence considerably 427 the total emissions of the supply chain (Figure 7). This is due to the high emissions factors of 428 electricity in the supply and importing countries (Table 8). Transport related emissions for C 429 are sensibly higher than WP and BP due to the lower bulk density of wood chips and, as a 430 consequence, to the higher number of trips necessary to supply the plant; however, these 431 differences do not make up for the additional impact of pelletization-based processes, with the 432 notable exception of Slovenia. In fact the carbon equivalent emission of the S/C/SI-IT supply 433 chain is about 12 % higher than the S/BP/SI-IT, mainly because Slovenia has the lowest carbon 434 emissions factor among the sourcing areas considered for local supply [79], and thus the 435 environmental impact of pelletization and torrefaction is correspondingly reduced. It should

- 436 nevertheless be stressed that, from an economic viewpoint, C remain the least cost option even
- 437 for the S/SI-IT supply chain.

438 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.

445 *4.3. Long vs short-distance supply chains*

446 As a result of the previous discussions, a comparison between the best performing long-447 distance supply chains (BP) with the short-distance supply chains (C) is performed.

448 <u>4.3.1 Cost comparison between L/BP and S/C</u>

449 Figure 8 enables comparison of least cost options for the best performing short and long 450 distance supply chains, which is C and BP respectively. It appears that BP long distance supply 451 chains have lower biomass delivered cost compared to local C supply chains. Despite the higher 452 overall transportation and handling cost, as well as significant pre-treatment cost, BP supply 453 chains benefit from the lower biomass price and lack of additional milling requirement 454 compared to C supply chains. It appears that the introduction of torrefaction makes long 455 distance supply options considerably more competitive to short distance supply chains in both 456 geographical contexts. For Great Britain, the best option appears to be to supply BP from Brazil 457 that reduces cost by 0,83 €/GJ compared to the best C option. For Italy, the cost difference 458 between the least cost long distance supply chain from Mozambique is significantly more 459 profound compared to the local C supply from Slovenia, amounting at 1,77 €/GJ.

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

461 <u>4.3.2 Environmental impact comparison between L/BP and S/C</u>

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 467 factors of Italy and GB increase the emissions of the milling stage in the case of delivering 468 wood chips, while low emission factors in Brazil and Mozambique limit the environmental 469 impact of energy intensive pre-treatment options such as torrefaction and pelletization. 470 Ultimately, it is shown that long-distance biomass supply chains can lead to reduced 471 greenhouse gas emissions of the overall supply system compared to short-distance alternatives, 472 despite the increased transportation and processing involved, when the supply locations benefit 473 from high availability of renewable energy.

- 474 Figure 9 Emission factor comparison of international (BP) vs. local (C) supply chains.
- 475 4.4 Competitiveness of co-firing and carbon dioxide abatement cost

476 In order to compare co-firing of biomass from various origins with other decarbonisation 477 options for electricity generation, a useful figure of merit is the Carbon Dioxide Abatement 478 Cost (CDAC). The CDAC can be regarded as the minimum incentive to be paid per unit of 479 carbon equivalent emission avoided (€/tCO₂eq, similarly to EU ETS allowances and any form 480 of carbon credit) in order to make a renewable or low carbon energy source competitive with 481 its fossil alternative [52,53]. In particular, the CDAC of biomass co-firing equals the incentive 482 for every unit of carbon equivalent emission avoided by co-firing that would make the 483 corresponding levelized cost of electricity (LCOE, as defined in [52]) equal to the LCOE 484 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 tCO₂/kWh, C for combustion and SC for supply chain.

487
$$CDAC = \frac{\left(LCOE_{cofiring} - LCOE_{firing}\right)}{\left(E_{firing} - E_{cofiring}\right)_{c} + \left(E_{firing} - E_{cofiring}\right)_{SC}} \qquad \left[\frac{\epsilon}{tCO2}\right] \quad (1)$$

488 The first term of the denominator in Eq. 1 expresses the difference in emissions level from 489 combustion at the power plant, calculated as the amount of coal burned in the coal firing and 490 the co-firing scenarios annually multiplied by the emissions factor of coal combustion (2110 491 kgCO₂eq/t [25]) and then divided by the respective amount of electricity generated annually to 492 reflect the effect of de-rating when co-firing biomass. Biomass does not contribute to the CO₂ 493 emissions at the combustion stage as it is considered a renewable fuel. The second term of the 494 denominator in Eq. 1 expresses the difference in emissions level from the fuel supply chain 495 between the coal firing and the co-firing scenarios. For the coal supply chain emissions have 496 been estimated as 4% of the coal combustion emissions, according to [80]. For the biomass

497 supply chain, emissions have been calculated analytically for each stage of the supply chain 498 (see Figure 3), considering the fossil fuel and electricity use, multiplied by the respective 499 emissions factor. For the co-firing scenario, the total supply chain emissions consist of both 500 coal and biomass supply chain emissions for the respective amounts of each fuel used. All 501 emissions have been divided by the amount of electricity generated in each scenario. Regarding 502 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 503 504 electricity produced. LCOE of the co-firing plant is instead the sum of total annual coal cost 505 and biomass cost at the plant gate (assessed in this work), divided by the total annual electricity 506 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.

511 Figure 10 CO₂eq emissions reduction with 8% co-firing compared to coal-firing plant.

512 These results show that co-firing is environmentally better than coal firing regardless of the 513 type and origin of biomass used. From an emissions reduction viewpoint, the best case for long 514 distance supply chains is L/BP/MZ-IT; indeed, the logistics from Mozambique to Italy have 515 the lowest emissions. The best scenario among short-distance supply chains is BP delivered 516 from Slovenia (S/BP/SI-IT). While differences between different supply chains are significant 517 in relative terms (e.g. carbon equivalent emissions associated with L/BP/MZ-IT supply chain 518 are about 1/3 of L/WP/US-IT, see Figure 5) and logistics chains are virtually the only cause of 519 net carbon emission associated with bioenergy, it should be observed that their carbon 520 equivalent impact is nevertheless an order of magnitude lower compared with that of coal, 521 which is in the order of ca 90 kgCO₂eq/GJ of delivered chemical energy [81] against 4-13 522 kgCO₂eq/GJ as calculated for various solid biomass supply chains in the present work. As a 523 result, substituting coal with biomass always leads to a considerable reduction in carbon 524 emissions, in the order of 7 - 7,7% in relative terms for an 8% co-firing ratio, which in absolute 525 terms for the reference plant would mean a notable range of avoided emissions between ca 285 526 - 309 ktCO₂eq/year depending on the biomass supply chain adopted.

527 Figure 11 compares the CDACs of the biomass supply chain configurations studied, i.e. WP 528 and BP for long (L) supply chains, WP, BP and C for short (S) supply chains. Also from a

- 529 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 €/tCO₂eq, while wood chips have the lowest CDAC
- 531 for short distance supply chains (50-60 €/tCO₂eq). The CDAC of international supply chains
- 532 originating in Brazil and Mozambique is slightly lower than that of local supply chains even
- 533 when using WP, but when BP is introduced long distance supply chains become even more
- 534 efficient.

535 Nevertheless, the required incentive is high in all cases if one considers that, current carbon

536 prices within the EU ETS are around 5-10 €/tCO₂ [82], and, even considering future scenarios

- 537 proposed by [83], maximum expected carbon prices equal $32 \notin tCO_2$ for Italy and $24-27 \notin tCO_2$
- 538 for GB in 2020. Dedicated additional support schemes are therefore needed in any case to
- 539 promote bioenergy in the form of co-firing.
- 540 Figure 11 Carbon dioxide abatement costs of 8% co-firing at plants of all scenarios studied.

541 **5 Sensitivity analysis**

542 In order to evaluate the potential impact of uncertainty on the most influential parameter values543 to the findings of this work, the results have been subjected to sensitivity analysis.

544 In particular, the main research focus is on the potential economic and environmental benefits 545 of BP over WP (for long distance supply chains) or over supply of wood chips (for local supply 546 chains). It has been demonstrated that, under the conditions considered, for all long distance 547 supply chains BP are preferable to WP, and for most short distance supply chains wood chips 548 are preferable to BP, both from an economic and a carbon emissions viewpoint. To quantify 549 the dependence of these results on input parameters, it was chosen to determine switching 550 values, i.e. the level of uncertain parameters that determine a reversal in this relationship. 551 Similarly, since it was also found that some long distance BP supply chains are preferable to 552 short distance wood chips supply, it was decided to determine switching values also for this relationship. 553

The switching values for supply chain costs are reported in Table 11 and for supply chain CO₂eq 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 \pm 0-20% and \pm 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.

567 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 568 chains, the comparison between BP and WP in the cases of US-IT and MZ-IT is chosen because 569 570 supply chain cost differences between WP and BP are maximum in the case of US-IT and 571 minimum for MZ-IT. The same rationale is behind the selection of US-GB and BR-GB supply 572 chains for the British case. To analyse switching between local and global supply chains, 573 supply from US to GB and from MZ to IT are selected as extreme conditions, with US-GB 574 having the lowest gap to local supply and MZ-IT having the highest gap to local supply from 575 Northern Italy. BZ to GB and the comparison between US-IT and SI-IT supply chains are also 576 presented as examples for intermediate performance differences.

577 5.1 Sensitivity of cost

578 In Table 11, switching values for supply chain costs are reported as percentage variations on 579 the parameter baseline values used in the analysis.

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

581 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.

588 5.1.2 Effect of feedstock price

589 Biomass cost mainly affects decisions on supply origin: in most cases, an increase of about 590 40% in biomass unit cost in international origin countries is required to make local supply 591 chains competitive for GB and a doubling in biomass cost is required for IT. Biomass cost also 592 affects decisions on pre-treatments on local supply chains: the trade-off between the mass 593 losses implied by torrefaction processes and energy density gains in the transport stage is such, 594 that a reduction of biomass costs in the order of 22% is sufficient to make BP preferable to 595 wood chips for local biomass supply chains from Slovenia to Italy. For GB, a more important 596 reduction in biomass cost is required to attain similar switching conditions (78%), mainly 597 because operational costs of torrefaction plants are higher in GB than in Slovenia due to higher 598 electricity prices.

599 5.1.3 Effect of biomass properties

600 The most critical parameter for long distance supply chain performance is the biomass energy 601 density, whose variations in the order of 10-15% determine a complete rearrangement of the 602 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 17 603 604 MJ/kg for WP, then WP are preferable to BP in long distance supply configurations. Similarly, 605 if a LHV of ca 18-19 MJ/kg can be attained for WP against a baseline BP LHV of 21 MJ/kg, 606 torrefaction becomes uneconomic compared with WP. Ultimately, it is the difference between 607 energy densities of BP and WP that is the critical parameter. When comparing long and short 608 distance supply chains, a similar sensitivity is observed on the biomass energy density. In the 609 best performing scenarios, a reduction in BP energy density of 11% and 23% is needed to make 610 the switch to local wood chips supply chain economically feasible for GB and IT respectively. 611 In the latter case, the economic competitiveness of supplying BP from MZ to IT seems quite 612 robust, since a reduction in BP energy density of about 23% would imply that the calorific 613 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 614 615 chain economics appears limited, mainly because even relatively small percentage variations, 616 e.g. in the order of 20-50%, are out of realistically feasible ranges for BP or WP. For instance, 617 Table 11 shows that for BP to become economically preferable to WP on long supply chains 618 or for C based short supply chains to become preferable to BP based long supply chains, bulk 619 density of black pellets should be diminished to values in the range of 300-500 kg/m³, 620 completely out of the reported range of BP bulk density (650-800 kg/m³) [27]. The only 621 exception is when the cost advantage of long distance over short distance supply chains is at 622 its minimum, as in the case of L/BP/US-GB compared with S/C/GB, where the cost difference 623 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
- for range (i.e. 18%, as reported in Table 11, which corresponds to a bulk density of 656 kg/m³).
- 626 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.

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

631 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.

639 On the other hand, the environmental performance of long-distance supply chains is quite 640 robust to variations in energy density: a reduction of BP energy density around 31-36% or 641 equally an increase of WP energy density of 44-56% would be needed to render the WP supply 642 chains more environmentally friendly than BP, which is beyond the technically reasonable 643 uncertainty range. Only for the US based supply chain, a 9-10% decrease in BP energy density 644 would be enough to make WP preferable to BP from a carbon emission viewpoint. On the other 645 hand, environmental advantages of torrefaction are quite robust for Mozambique and Brazil. 646 When comparing short with long-distance supply chains, it can be concluded that no reduction 647 in energy density of BP within technologically reasonable range is sufficient to make wood 648 chips based short supply chains preferable to long distance supply chains in terms of logistics 649 related carbon emissions. Particularly in the case of supply chains from US, the opposite holds: 650 there is no technically feasible increase in BP energy density that would make this supply chain 651 more sustainable than local ones, mainly due to the level of the electricity emission factor in 652 the US, which is sensibly higher than corresponding values for Brazil or Mozambique (see 653 Table 8). Interestingly, the results are much more sensitive to energy density of biomass 654 compared to its bulk density.

655 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.

662 Variations in electricity emission factors of exporting countries hardly affect pre-treatment 663 options in long supply chains, with BP remaining always preferable to WP; however, they are 664 the only element of uncertainty affecting the relationship between the environmental 665 performance of long and short distance supply chains. For each export country, percentage 666 variations in electricity emissions factors required for short distance supply chains to 667 outperform long distance ones are substantial and hardly achievable in the short term; thus, 668 configurations identified in this work as the least cost can be deemed robust. However, long 669 distance supply chains with different origins may have remarkably different environmental 670 performances. For instance, the US emissions factor, which currently exceeds the British one 671 by about 7%, should be reduced to about the half for the L/BP/US-GB supply chain to become 672 at least as sustainable as its local alternative S/C/GB, whereas a 160% increase of the BR 673 electricity emissions factor, which is currently about 1/5 of the emissions factor of GB, would 674 be required for the S/C/GB to become preferable to Brazilian BP. Thus, differences in the 675 carbon emissions factors of electricity in different countries affect the relative environmental 676 performance of long and short distance supply chains in a similar manner as differences in 677 biomass costs affect economic performance.

678 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 CO₂eq 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. 717 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 718 chains, namely torrefaction and pelleting, as it can lead to both cost and carbon emissions 719 reductions compared to the current practice of white pellets and even compared to local 720 721 biomass supply alternatives, for the cases examined. It is also the first research to compare the 722 performance of international biomass supply chains with local ones for this range of pre-723 treatment options. It could also be useful to policy makers for informing decisions on support 724 for renewable energy generation.

725 Finally, the authors would like to acknowledge that this work has some limitations. The 726 investigation of different co-firing rates or, particularly, of alternative technologies enabling 727 higher co-firing rates was out of the scope of this study, but is an important theme for future 728 research. Many of the parameters used are quite volatile, and therefore the order of preference 729 between the supply chains identified could change in the future, despite the sensitivity analysis 730 proving a good robustness of the findings to individual parameter value changes. Even more, 731 the dynamic nature of the systems examined could also alter the results (i.e. the electricity mix 732 in European countries is bound to become more renewable in the future and the average carbon 733 emissions fluctuate every year). Additionally, although international biomass supply chains are 734 the sensible way forward for the countries examined in this work, due to the inherent limitation 735 of domestic supply quantities, a potential future development of domestic biomass uses in the 736 considered supply countries could introduce competition, therefore increasing prices and 737 affecting availability of biomass. Furthermore, sustainability of biomass does not only involve 738 carbon emissions, but also the land change and substitution of edible crops for biomass. These 739 analyses are beyond the scope of this work, but are an interesting aspect that deserves more 740 investigation in the future.

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	Advantages	References
	 Well established and commercially practiced process; High energy density compared with untreated feedstock and chips; 	[11,14]
	Issues	
Pelletization	 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]
	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: 	[11–18]
Torrefaction	Better hydrophobicity and reduced biological degradation,	
in	resulting in no need for covering and for expensive storage	
combination	• Homogeneity and grindability properties similar to coal,	
with	therefore no need of dedicated milling and feeding	
pelletization	Infrastructure at coal power plants.	
		[11 12 14 15]
	applications to date and high capital costs.	[11,12,14,13]
	• Limited data on process and pellet properties are available from a few pilot plants.	
	• The process is more energy intensive than pelletization.	

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 characterist	ics.		

Properties before treatment*	Hardwood	Softwood
	chips	chips

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

 *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		
* [10.04.07.54]						

*sources: [12,26,27,54] Table 4 Properties of pellets (short and long supply chain) and chips (only short supply chain) after treatment.

Abbraviation	Type of supply	Biomass	Export	Import
Abbreviation	chain	delivered	country	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-	Unit	Vəluo	Source
transport	Omt	v aluc	Source
Truck transportation			
Chips: Nominal capacity-	m ³	130	
volume		150	[10]
Chips: Nominal capacity-	t	40	[-~]
weight			
Pellets: Nominal capacity-	m ³	80	
Pollots: Nominal conscitu			[20]
weight	t	35	
Loading/unloading cost	€/m ³	0 543	[10]
Loading/ unloading speed	$m^{3/h}$	260	
Loading/ unloading	III / II	200	
consumption	l/h	7	[60]
Diesel consumption full load	l/km	0.5	[50]
Diesel consumption return trip	1./1	0, 2	
(empty)	l/km	0,25	[61]
Average speed	km/h	65	[10]
Charter cost	€/km	0,92	[10]
Train transportation			
Nominal capacity-volume	m ³	2500	
Nominal capacity-weight	t	1000	51.01
Loading /unloading cost	€/m ³	0,25	[10]
Loading/ unloading speed	m ³ /h	240	
Loading/ unloading	1 33 71 /4 1	0.777	
consumption	K w he/ta	2,777	[20]
Diesel consumption (US & MZ)	MJ/t*km	0,5	
Diesel LHV	MJ/l	36,3	[55]
Electricity consumption (GB &	kWho/t*km	0.075	[61.84]
IT)	K VV IIC/ L · KIII	0,075	[01,84]
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	
Unloading time	t/h	300	
Loading/ unloading	12Who/td	11.09	[20]
consumption	K W He/tu	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]

1011Table 6 Model input data: transport parameters.

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Main input parameter- logistics	Unit	Value	Source
Chipping at the roadside			
CAPEX	M€	0,33	
Maintenance	% of CAPEX	20	
Diesel consumption	l/h	115,74	[65]
Operating time	h/yr	5480	[03]
Capacity	$kg_{Raw Material}/h$	83,5	
Labour cost	€/h	17,24	
Handling & Storage			
Electricity consumption	kWhe/MWh	0,25	[5]
Fuel consumption	l diesel/MWh	0,02	[5]
Maintenance	% of CAPEX	3	[20]
Bunker-C			
mc loss (chips with mc >20%)	%/month	1,5	
Size - volume	m ³	25000	[20]
CAPEX	M€	2,12	
Silos-WP			
Size - volume	m ³	5000	[20]
CAPEX	M€	0,37	[20]
Outdoor uncovered- BP			
Size - volume	m ³	3000	[20]
CAPEX	M€	0,03	[20]
Handling & storage at final user			
Electricity consumption	kWhe/MWh	2,1	[5]
Pulverising at the plant: only for	white pellet and w	vood chips	
Number of hammer mills	-	3	
CAPEX	M€	1,2	
Lifetime yr	yr	15	[20]
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	

1017Table 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	€/1	0,77	
Italy	€/1	1,31	
Mozambique	€/1	0,66	[70]
Slovenia	€/1	1,13	[/0]
GB	€/1	1,41	
US	€/1	0,56	
Natural gas price			
Mozambique	€/kWh	0,025253	[71]
Italy	€/kWh	0,029335	
Slovenia	€/kWh	0,031772	[72]
GB	€/kWh	0,032552	
US	€/kWh	0,018142	[73]
Brazil	€/kWh	0,015508	Adapted from [73]
Electricity price			
Brazil	€/kWhe	0,0771	[7]1]
Mozambique	€/kWhe	0,0319	
Italy	€/kWhe	0,0896	
Slovenia	€/kWhe	0,0693	[74]
GB	€/kWhe	0,1425	
US	€/kWhe	0,0594	[73]
Port fees			
Brazil	€/m ³	8,62	
Mozambique	€/m ³	11,91	Adapted from [27]
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	KgCO2eq/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	
L. L	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]				

1021[* sources:[77]Table 9 Average distance between the ports in nm (nautical miles) and km.

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

1023 Table 10 Initial and final biomass flows.

	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			
Case→ Parameter ↓	LI-SU/L	LI-ZW/T	T/US-GB	L/BR-GB	S/GB	LI-IS/S	S/IT	L/BP/BR- GB → s./c/gr	L/BP/US- GB → s.rc/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	+2775 7%	+2260 3%	+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:

$\pm 0-20\%$
$\pm 20-50\%$
\pm 50-100%
$\pm100200\%$
$\pm 200-500\%$
$> \pm 500\%$
unreachable
independent

Acronyms

EC = Export Country

IC = Import Country

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

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

2

	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			
$\begin{array}{c} \text{Case} \\ \rightarrow \\ \text{Parameter} \\ \downarrow \end{array}$	LI-SU/J	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/SL-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											

Parameter value change in % compared to baseline:

EC = Export Country

IC = Import Country

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

	$\pm 0-20\%$
	$\pm 20-50\%$
	\pm 50-100%
	$\pm 100-200\%$
	$\pm 200-500\%$
	$>\pm 500\%$
	unreachable
	independent
Acronyms	

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



Figure 10 CO₂eq emissions reduction with 8% co-firing compared to coal-firing plant.



Figure 10 CO₂eq emissions reduction with 8% co-ming compared to coal-ming plant.

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