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Production of Solid Sustainable Energy Carriers from Biomass by Means of Torrefaction

Deliverable No. D9.5

Deployment scenarios and socio-economic assessment of torrefied biomass chains. Part 2: Results

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1 Summary

1.1 Objective and content of this deliverable

The objective of this work is to describe and evaluate generic biomass-to-end-use chains based on torrefaction as well as scenarios up to 2030 with regard to social-, economic- and environmental criteria.

This deliverable builds upon other working papers published within the SECTOR-project. Especially the working papers from WP9 (D9.1-D9.4) contain additional explanations which represent presuppositions for this deliverable.

The focus of this report lies on the illustration of economic viability, GHG emissions and created jobs for torrefied pellets in contrast to comparative fossil based (e.g. coal etc.) and biobased (white pellets) fuels. Therefore, 22 different feedstock types selected by WP2 are computed to be processed to torrefied and white pellets under different framework conditions e.g. prices for country and scenario depending fossil fuel and labour. A set of transportation modes and distances is simulated to display the delivery of the solid bioenergy carriers to different types of end users for which the cumulated costs of the respective torrefaction based biomass-to-end-use chain is compared with the reference fuels. Not only costs but also GHG emissions and required labour (and consequently, jobs created) are calculated for every step throughout the entire biomass-to-end-use chain. This allows uncovering also small differences between the deployment of white and torrefied pellets.

The insights gained by investigating a large set of generic biomass-to-end-use chains are used to discuss literature based pellet scenarios in order to derive conclusions and recommendations about cost-efficient and environmentally sound deployment strategies for torrefied material and the torrefaction technology in general.

The general structure how to describe biomass-to-end-use chains was documented in the report D9.1 of this project (Kranzl et al., 2012) and is in line with recommendations on how to analyse different steps in torrefaction supply chains, see (Svanberg and Halldorsson, 2013). The different technological and logistical options considered for each step of the biomass-to-end-use chains are listed in detail in the next chapter.

Figure 1: Illustrative presentation of a biomass-to-end-use chain, from the biomass source to the biomass sink.

2 Methodology for the assessment of generic biomass-to-end-use chains

2.1 Calculation of generic solid biomass-to-end-use chains

In order to highlight the differences between the production of traditional- (white-) and torrefied pellets for the 22 different feedstocks identified in WP2 under different framework conditions for different regions of origin the biomass-to-end-use chain simulation tool **BioChainS** was used.

Generic biomass-to-end-use chains are calculated from the biomass source (biomass harvesting) over biomass supply to biofuel preparation (torrefied- and white pellets) and linked with different distribution steps (modes and distances) to the biomass sink (end user). Cropping and biomass production ̀is not considered in this study, harvesting is the first step calculated for cost and GHG emission calculations. However, assumptions for the biomass production step are drawn and simplifications for modelling purposes are discussed. (Annex I: Biomass harvest for pellet production and Annex V: GHG-model extension of BioChainS).

A full list of investigated feedstocks and their determining properties can be found in Annex I: Biomass harvest for pellet production. They range from logging residues and coniferous and broadleaved stem wood to bark and used wood, energy crops and agricultural residues. Feedstocks are differentiated according to their bulk density [kg/m³], moisture content [w-%] and net calorific value (NCV) [MJ/kg]. Furthermore, feedstock specific data based on WP2 and literature has been used regarding capital, fossil fuels and labour consumed for harvesting the feedstock and different levels of the value of the standing tree or crop (see Annex I: Biomass harvest for pellet production).

The mass balance of the torrefied and white pellets production process together with the feedstock properties determines the annual quantities of biomass needed to reach given capacities between 40 kt/a (kilo tons/year) and 1 Mt/a (million ton/year) solid biofuel output (documented in Annex II: Production plant sizes and supply distances for white- and torrefied pellets). Two distance types are considered for the supply distance of the raw biomass to the biofuel preparation plant and scaled according to the required input quantities depending on preparation plant size and feedstock properties. This approach ensures comparability and reduces uncertainties with regard to biomass yields, feedstock availability and infrastructure in the locality of the preparation plant. A sensitivity analysis and discussion of these factors can be found in (Annex II: Production plant sizes and supply distances for white- and torrefied pellets).

Cost calculations and energy and mass (E&M) balances for the solid biofuel production processes (torrefied- and white pellets) are adopted from results from WP3 and WP4 as well as from (Obernberger and Thek, 2010) (documented in Annex II: Production plant sizes and supply distances for white- and torrefied pellets). Next to scale dependent capital and maintenance costs, electricity consumption and heat demand for the drying process depending on the water content of the feedstock and labour demand in different salary classes are included for calculating costs and emissions. For the production of torrefied pellets the used cost factors represent actual estimations, no long-term assumptions about tribological properties of the used machinery and thus on a differentiating depreciation of the plant compared to a white pellet plant are considered. Also learning effects and efficiency improvements for the upcoming decades are neglected. However, it is assumed that an optimal utilisation of the technology can be achieved which is reflected in the assumption of an auto-thermal torrefaction process (documented in Annex II: Production plant sizes and supply distances for white- and torrefied pellets). Therefore an E&M balance including a feedstock dependent torrefaction degree [%db] which indicates the dry basis biomass share extracted in the form of torrefaction gas or dry basis mass loss is conducted for each biomass-to-end-use chain. The torrefaction process is considered to be auto thermal[1], thus we assume that by burning the torrefaction gas sufficient heat for the torrefaction process can be derived. The heat demand of the drying process depends on the feedstock´s moisture content and is considered to be covered by burning unprocessed biomass. E&M balances and other parameter for the biofuel production processes can be found in Annex II: Production plant sizes and supply distances for white- and torrefied pellets.

Prices for diesel (used for harvesting, supply and distribution), electricity (for the pellet production process and rail transport) and for labour (including different salary classes) are derived from official statistics (see Annex VII – data tables) for the different EU member states and world regions.

The permutation of the 22 feedstocks, two supply distance types, two biofuel production processes (white and torrefied pellets), five pellet plant output sizes and 30 different world regions respectively countries are computed and a list is generated containing costs, fuel- and labour consumption for every step for all 13,200 biomass-to-end-use chains. Figure 2: illustrates the generic biofuel production computation. Arrows indicate the sequence of data and databases used for the computation of the first step, the pellet production list containing generic biomass-to-end-use chain information until the pellet production plant excluding the distribution to the end user.

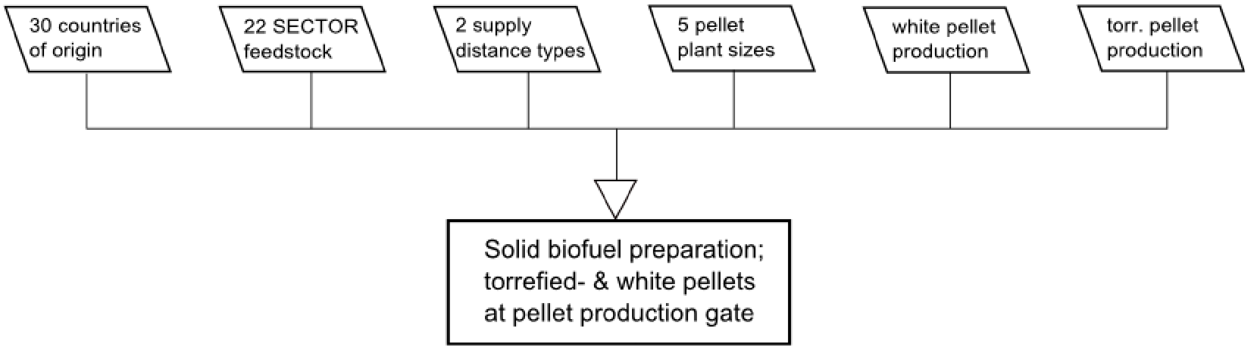

Figure 2: Generic biofuel production computation. Arrows indicate the sequence of data and databases used for the computation of the first step, the pellet production list containing generic biomass-to-end-use chain information until the pellet production plant

2.2 Transport considerations

For the generic computation of biomass-to-end-use chains only quantifiable parameters from literature or from the SECTOR-project partners were used. Parameters including hydrophobicity, durability and handling safety and the properties of produced pellets which will play a decisive role for large distance transportation (Annex III: Distribution considerations) and small scale combustion (ash content, slagging behaviour) could not be used for the computation (yet), further research is needed to derive conclusions about differences in performance and economic viability between torrefied and white pellets for the large set of considered generic biomass-to-end-use chains in this study.

Transportation capacities for commodities are either limited by volume or weight. The already mentioned feedstock supply (i.e. from raw biomass to the preparation plant), considered here solely by trucks, is restricted by the volume the feedstock takes up. On the other hand, the distribution of the densified pellets per rail containers or trucks is limited in the most cases by the maximum weight load of the vehicle. Shipping of densified material however again depends on the grade of densification since for this calculation for Ocean shipping a Panamax carrier with a maximum payload of 53.400 t and a capacity of 89.000 m³ (Baltic Exchange, 2011) is considered. For inland navigation data for a four-barges convoy set is used with a payload of 10.800 t and a capacity of 14.774 m³ (Hoefnagels et al., 2011). In other words, commodities with a bulk density exceeding 600 kg/m³ for ocean shipping and 730 kg/m³ for inland navigation can be treated similarly when calculating specific costs per transferred tonne of commodity while an unused payload for bulk densities below this threshold has to be considered. However, all transportation and handling steps of pellets in this report are simplified to be mass dependent and similar for torrefied and white pellets since differences are expected to be marginal. This simplification is supported, at least for ocean shipping, by the fact that only one out of five bulk density classification for white pellets according to EN 14961-1 is below 600 kg/m³ (Obernberger and Thek, 2010).

Again, capital costs, fuel and labour consumption for the transportation and (un-)loading have been acquired from literature for the transport modes truck, rail and shipping (see Annex III: Distribution considerations). This allows to calculate the capital, energy and labour intensive cost shares as well as to enable GHG emission calculations and labour utilisation considerations. Average transfer distances have been applied for ocean shipping (see Annex III: Distribution considerations) from other world regions (Russia, Canada, the US and Tanzania) to the EU. For the transport within these countries as well as for the distribution within the EU variable distances are calculated for all transport modes (see Annex III: Distribution considerations). Two further distribution distances are assumed to incorporate extra distribution needs with pellet trucks for small scale end users for space heating.

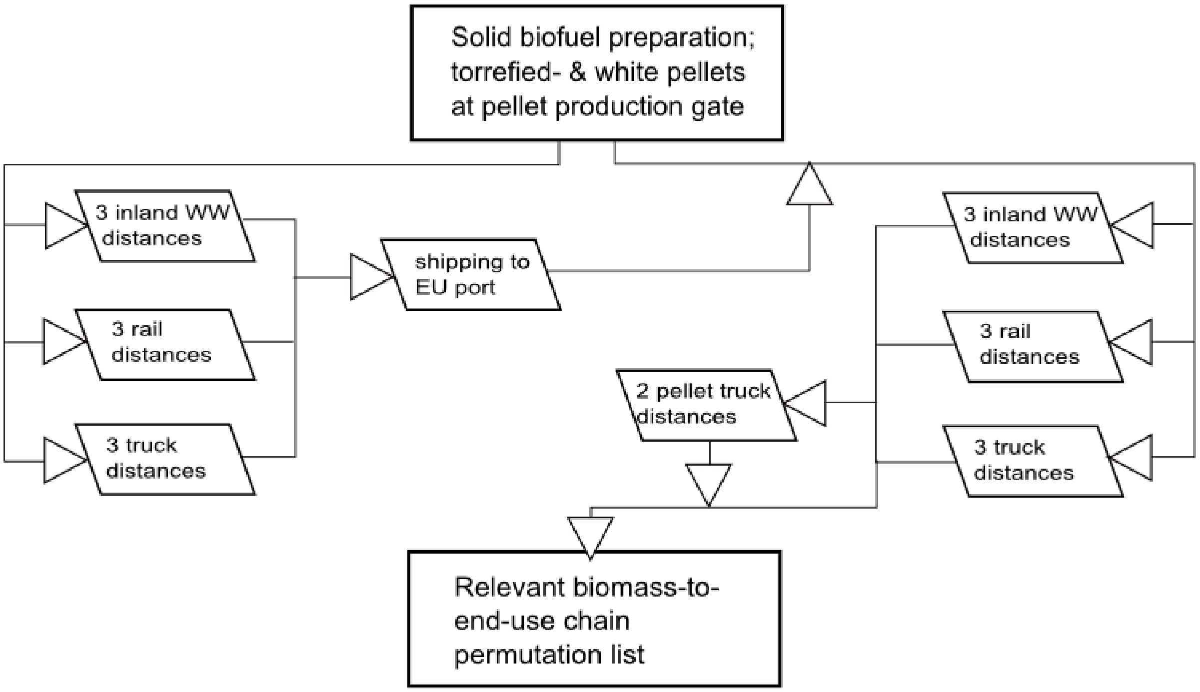

Figure 3: Generic biomass-to-end-use chain computation from pellet production to end use defined by distribution steps. Arrows indicate the sequence of data and databases used

2.3 End user specific system boundaries

Biomass-to-end-use chains are generically computed for two kinds of end use, (1) for large scale end use in large scale power, CHP and gasification plants and (2) for small scale space heating end use. While the generated list allows a direct comparison of torrefied and white pellets, the overall relevance and economic viability of pellets depends on the economic comparison with the reference fuels which are considered to be substituted. For the large scale end uses, the distribution to coal fired power or CHP-plants is considered as identical as the one to gasification plants for the production of electricity, heat or chemicals. For the small scale end uses the combustion in small-scale boilers or stoves for residential and commercial space heating and hot water preparation is investigated.

To not go beyond the scope of this paper and to be able to discuss insights on a European level, non-quantifiable factors for this level are not discussed. The public demand for renewables as well support instruments like feed in tariffs are cut out and costs for pellets are directly compared with coal prices in this study to provide an overall estimation of cost ranges and especially about the differences between white and torrefied pellets. Coal prices are obtained from the IEA price database (IEA and OECD, 2014) and directly used as reference and benchmark prices for the specific pellets costs adjusted by an average taxation (see Annex IV: Costs for end users and reference fuels). No further considerations about the coal-fired plant itself are included in the calculation even though cost advantages for torrefied pellets compared to white pellets or wood chips due to lower milling costs and better handling properties for higher co-firing shares than 10% can be achieved according to the most recent literature (“SECTOR D3.7 in press,” 2015).

For the gasification of pellets an example for fixed costs, energy and labour consumption is derived from literature (see Annex IV: Costs for end users and reference fuels). The aim is to derive specific costs and emissions of the produced syngas to be compared with prices for natural gas. Syngas form gasification is typically used in chemical industries, for the production of Fischer-Tropsch liquids, electricity and gaseous fuels (Hoffmann and Szklo, 2011).

For the deployment of pellets for small scale end use several reference systems are eligible. The EU average space heating is mainly performed in an ascending order with natural gas, heating oil, district heating, electricity and coal (Entranze database, 2014). According to their shares average heating prices are calculated and compared with the costs for the utilisation of pellets for the same purpose (see Annex IV: Costs for end users and reference fuels).

All comparisons are made for EU average end users since the focus lies on illustrating advantages and disadvantages of torrefied pellets compared to reference fuels in general rather than in the light of national details. Therefore the same inter-European transport distances are calculated for all pellet origins no matter if pellets and feedstock are produced in European countries or the production takes place on another continent and has to be shipped to a European port. Additional to the mentioned long distance transport which is simulated to take place using trucks, trains or inland water ways short distribution distances for the small scale pellet end users conducted by pellets trucks are considered (Annex III: Distribution considerations).

3 Results

3.1 Economics

The objective of this section is to discuss pellets chains under varying framework conditions and to identify the possible role of torrefaction for a large set of biomass-to-end-use chains. Therefore the created calculation of biomass-to-end-use chain permutations (as described in Chapter 2) was evaluated regarding its key parameters (Feedstock type, Origin, Preparation plant size, Preparation plant type, Distribution distances, End user type).

In order to assure comparability all permutations are calculated in pairs, each for torrefied- and white pellets. Therefore the evaluation of the key parameter can take place comparing torrefied- to white biomass-to-end-use chains at all stages. Biomass-to-end use chains only differing in the pellet process are furthermore called biomass-to-end-use chain pairs.

Biomass-to-end-use chain pairs allow illustrating the difference between white- and torrefied pellets for similar chains where only the preparation plant type (Traditional, i.e. white pellet production and torrefaction) are varied. On the one hand, the three to four times higher investment costs for the torrefaction reactor lead to higher deployment costs for pellets chains based on torrefaction compared to similar white pellet chains when costs are outlined per mass or volume. The increased energy densities and/or heating values of the torrefied product on the other hand ensure that the created cost differences are reduced or even switched in favour of the torrefied commodity when delivered to the end user. Two examples for biomass-to-end-use chains based on different feedstock are shown in Figure 4. Next to feedstock costs (indicated on the x-axis in the figure as “Biomass”), the preparation costs contribute the highest share to total deployment costs for the torrefied cases. For white pellets the distribution costs, from the preparation plant to the end user gate, have a higher impact than the preparation costs in both examples resulting in advantages for torrefied pellets when specific production costs become comparative for torrefied- and white pellets with regard to the energy content of the final product and scaling effects (see Excursus II) .

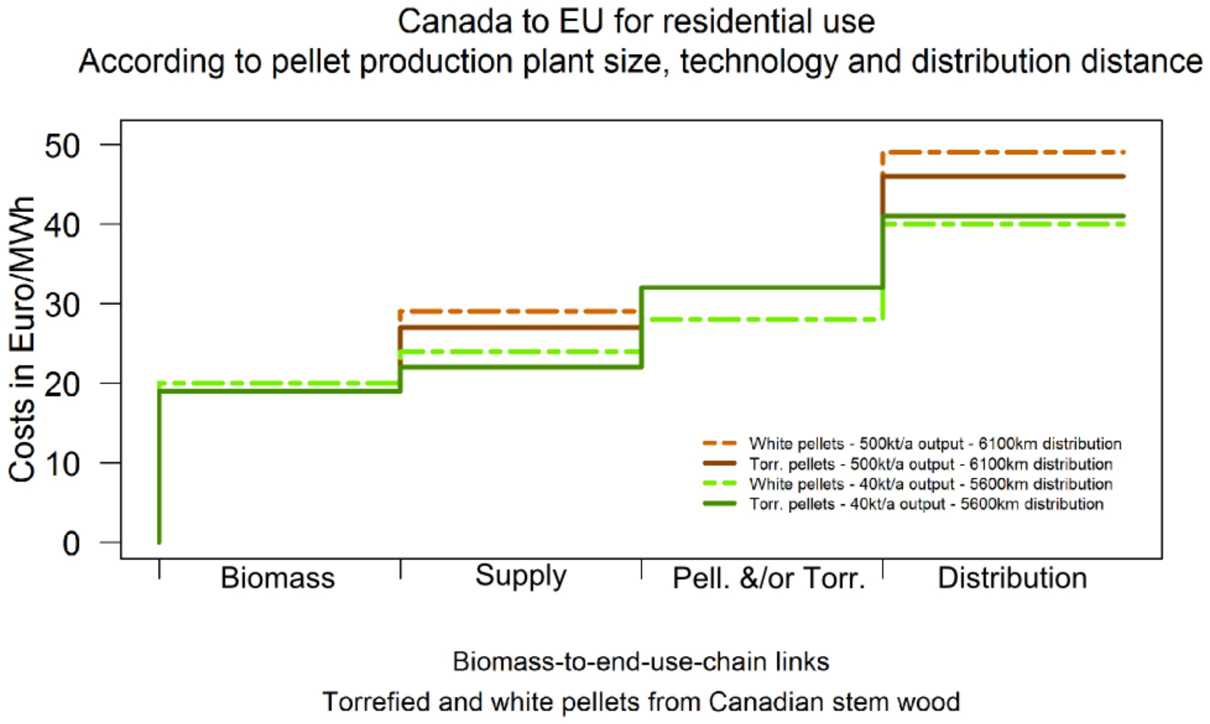

Figure 4: Two examples for biomass-to-end-use chain pairs: Specific costs are given regarding to the energy content of the final product.

The two sets of biomass-to-end-use chain permutations (for white and torrefied pellets) contain broad ranges of resulting costs for pellets at the end user. Pellet deployment costs are varying depending on the key parameters and thus on the feedstock used, supply- and distribution distances to be overcome and on the size and type of the pellet plant. The selection of distribution distances and pellet plant sizes is rather arbitrary, still conclusions about the comparison of both permutation sets reflecting the two families of the biomass-to-end-use chain pairs can be derived.

In Figure 5 the medians of the torrefied- and white pellet permutation sets for large scale and small scale applications are shown together with the 2nd and 3rd quartiles while leaving extreme values (1st and 4th quartiles) aside. Since the cost distributions do not reflect a list of existing biomass-to-end-use chain constellations the medians and quartiles should not be understood as a most likely cost that could occur. Rather, Figure 5 should illustrate the differences of white- and torrefied pellet costs compared to competitive fuel- and energy deployment for a large set of possibly relevant biomass-to-end-use chains.

Pellets for large scale demand can directly be compared with the industry prices for coal while pellets for small scale use have to be burned in a pellet boiler or stove for which running and capital costs (light green) are considered. Also running and capital costs for gasification of pellets (light blue) are shown. Higher process costs for torrefaction can be compensated by higher energy contents of the final product in the simulation.

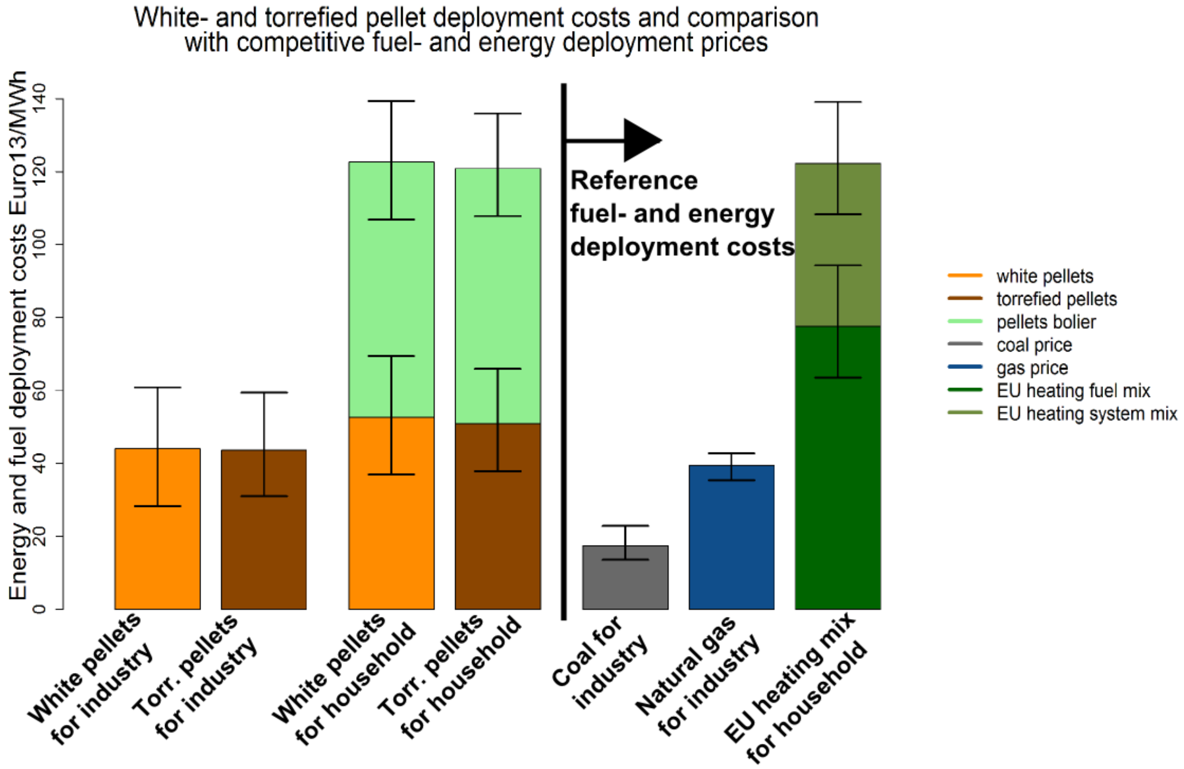

Figure 5: Medians and 2nd (lower part of error bars) and 3rd (upper part of error bars) quartiles of white pellets (WP) and torrefied pellets (TP) for large scale and household application. Deployment costs for pellets are directly compared with the industry prices for coal (grey) and natural gas prices (dark blue). For household pellets a pellet boiler (levelled costs in light green) is considered to compare the costs of heat deployment with an averaged heating fuel and system mix for the European Union. Quartiles for reference fuels result from country specific deviations.

Next to slight advantages for torrefaction for small scale end users and in general the comparability of small scale pellet heating systems and the reference EU heating mix three general conclusions can be derived. Firstly the total costs for torrefied and white pellets are comparable for the large set of permutations simulated, secondly the differences between white- and torrefied pellet and the EU heating mix for household are comparable as well and thirdly the deviations for the calculated torrefied chains to the illustrated median are principally smaller than for the white pellet permutation set. The smaller deviations to the medians of the torrefied pellets indicate advantages for more expensive biomass-to-end-use chains and disadvantages for cheaper ones.

In order to highlight biomass-to-end-use chains for which advantages for torrefaction can be expected, the cost differences of the biomass-to-end-use chain pairs are compared for all discussed chains: In Figure 6 and Figure 7 the deployment costs for identical biomass-to-end-use chains which only differentiate in the preparation type are averaged and plotted against the deviations from these averages. The negative deviation indicate cheaper white pellet deployment costs while for torrefied pellets the same deviation has to be added to the plotted average. Interesting to observe is a linear correlation for increasing average total deployment costs already presumed in the previous paragraph, which drives the deviations towards and beyond the break even line (in black). Above this break even line the torrefied counterparts become cost competitive with white pellets.

First in Figure 6 biomass-to-end-use chain pairs are coloured depending on the biomass feedstock type used. Feedstock types are explained in (Annex I: Biomass harvest for pellet production) and mainly differentiate by harvesting- and feedstock costs. For the most expensive feedstock type (care wood) a clear advantage for torrefied pellets can be outlined. The variation within the other feedstock types depending on the actual feedstock used and its moisture- and heat content as well as the country specific framework conditions like fuel and labour costs make it difficult to derive conclusions about the difference of torrefied and white pellet deployment.

In Figure 7 the dots are coloured with regards to their yearly biomass preparation plant output size reaching from 40kt/a to 1Mt/a for white or torrefied pellets. The explanation for the vertical shift towards economic advantages for torrefied chains with increasing pellet plant sizes can be found in the same scaling factors used for scaling capital costs for white and torrefied pellet plants which results in stronger effects on the production costs for more expensive technologies than for cheaper ones. Therefore production cost differences decrease for biomass-to-end-use chain pairs with increasing production plant sizes indicated by the vertical colour shift in Figure 7.

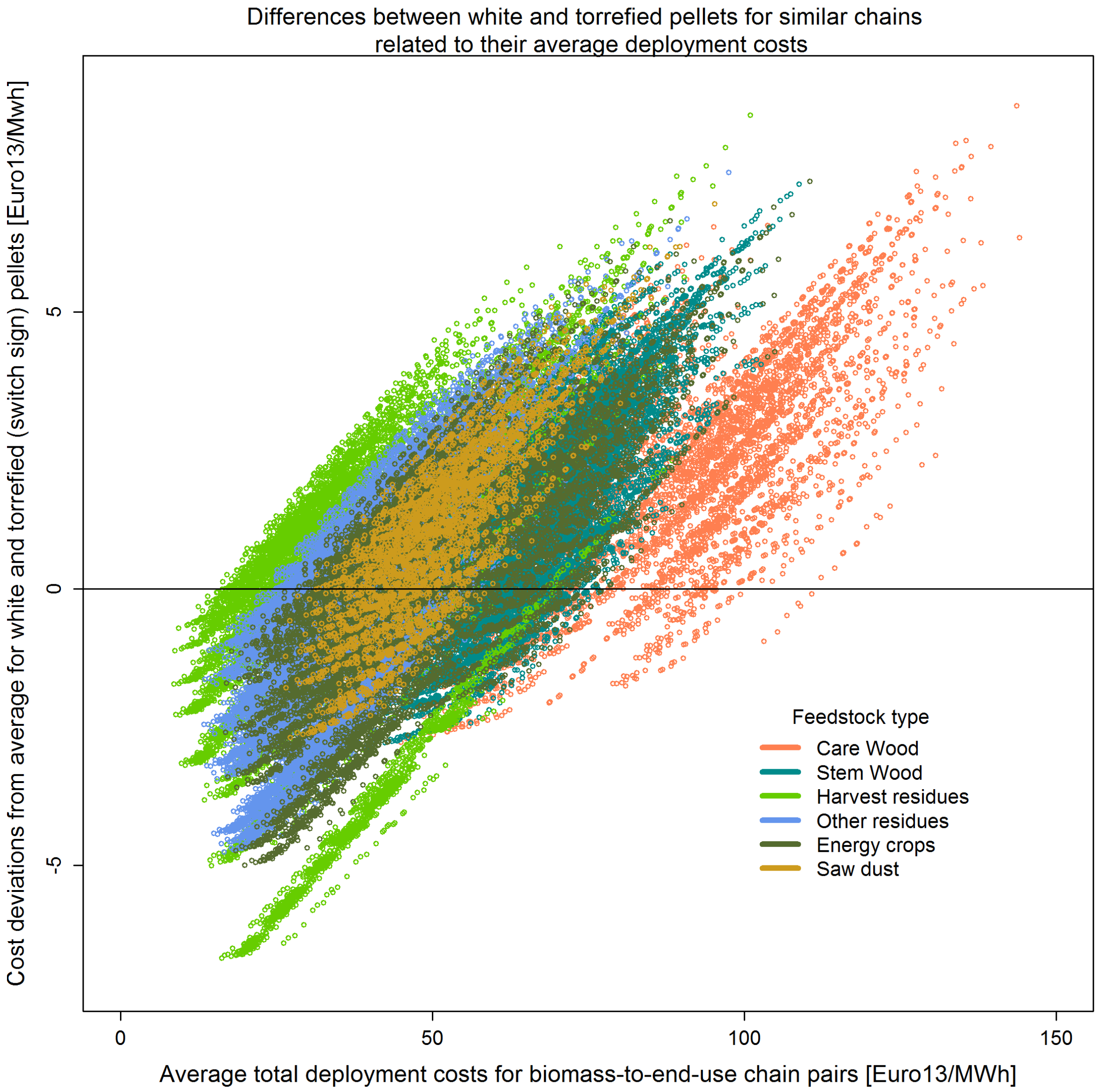

Figure 6: On the X-axis deployment costs are indicated averaged for every biomass-to-end-use chain pairs individually. The Y-axis shows the deviation to be added to obtain the respective white pellet deployment costs or subtracted to obtain the respective torrefied pellet cost (therefore cost deviation times two equal cost differences between white and torrefied pellets). Furthermore six feedstock types for varying harvest and feedstock costs are indicated with different point colours.

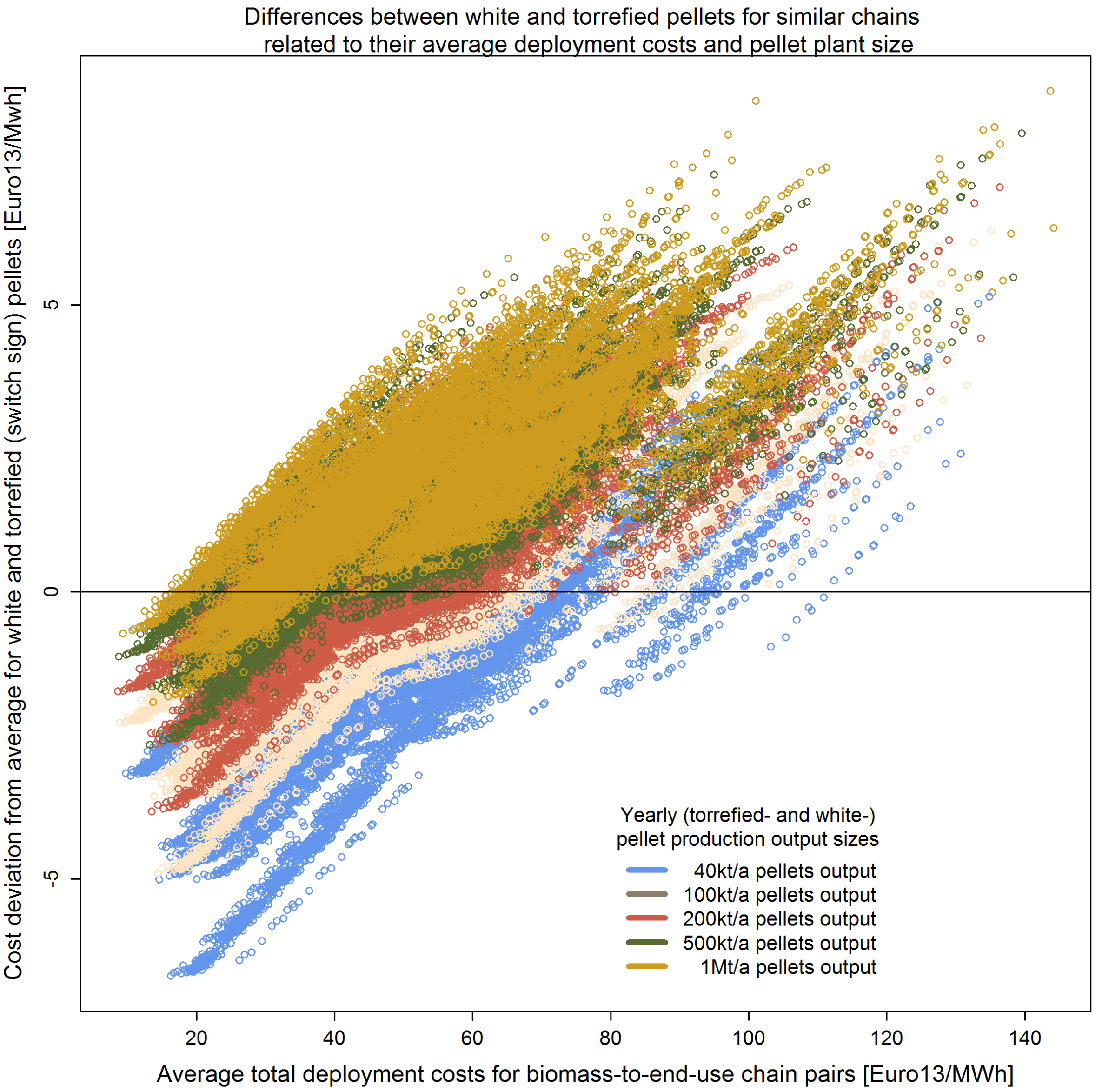

Figure 7: On the X-axis deployment costs are indicated averaged for every biomass-to-end-use chain pairs individually. The Y-axis shows the deviation to be added to obtain the respective white pellet deployment costs or subtracted to obtain the respective torrefied pellet cost (therefore cost deviation times two equal cost differences between white and torrefied pellets). Furthermore the yearly pellet plant output sizes which are similar for the calculated biomass-to-end-use chain pairs are indicated using different dot colours.

To summarise the results the impact of the different key parameters on 1) torrefied pellets costs and 2) on the difference to the white pellet counterparts[2] are illustrated in Figure 8 and Figure 9. In Figure 8 the example of torrefied saw dust pellets is used to illustrate their costs (number in the boxes) and cost differences (colours) for similar white pellet biomass-to-end-use chain constellations. The following key parameters are selected to discuss 8x6=48 constellations. They are based on two origin types (either North America or European continent), two supply distance types (explained in Annex II: Production plant sizes and supply distances for white- and torrefied pellets) and two pellet plant size types (smaller than

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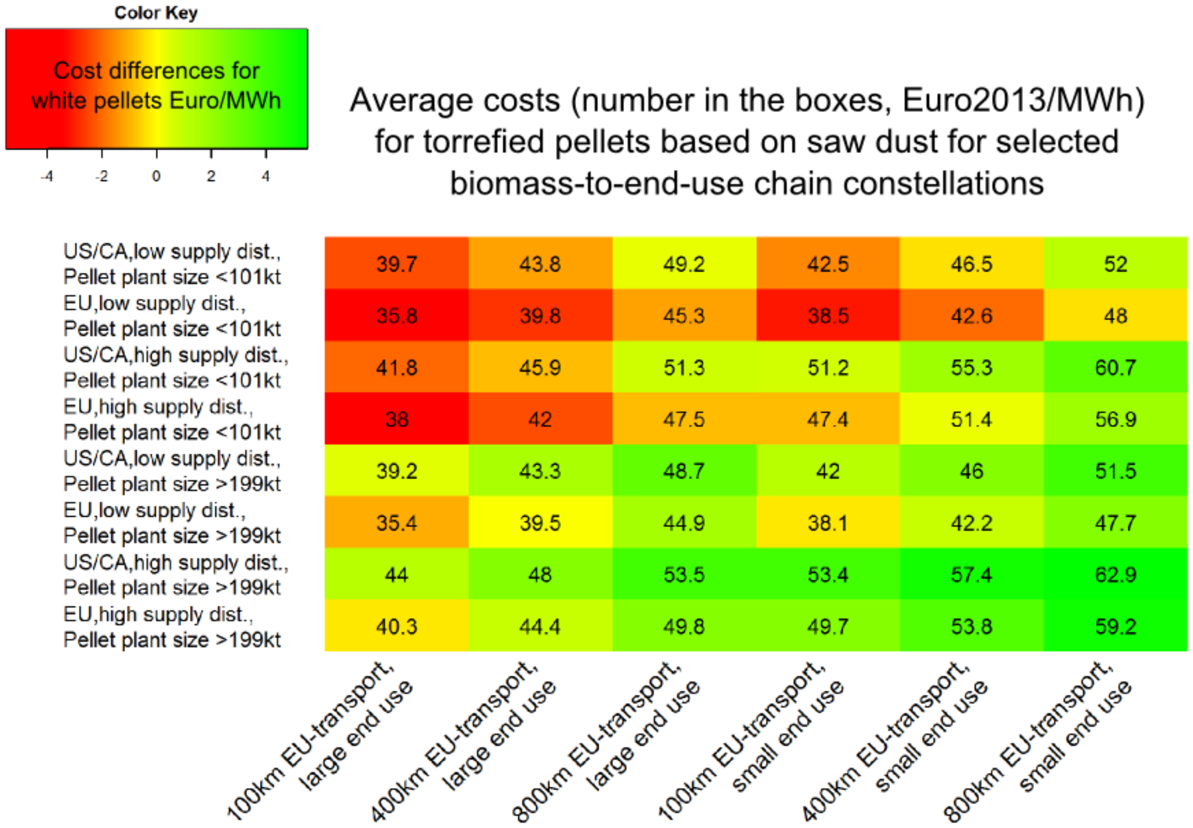
[2] two times the deviation from the mentioned averages of the biomass-to-end-use chain pairs used in the previous figures

101kt/a and bigger than 199kt/a) listed permuting on the y-axis. On the x-axis the permutations are combinations of distribution distance (from port or from pellet plant to end user) and end user type (small scale or large scale end users). Longer distribution distances for example can now be outlined as favorable for torrefaction especially when combined with larger pellet production plant sizes. However longer distances lead in general to higher costs. In (Calderon et al., 2013) bagged retailer pelle prices for Austria, France and Italy are mentioned for 2013 to were around 57€2013/MWh (including VAT).This price is further considered as a cost limit. The long-distance constellations which are most favourable for torrefaction (dark green and lower right part of Figure 8) could be effected considering such a limit for economic feasibility. Pellet production plant sizes bigger than 199kt (here 200kt and 500kt) result in cheaper torrefied pellet costs only for the considered low supply distances compared to pellet production plant sizes smaller than 101kt (here 40kt and 100kt output). This indicates varying optimal plant sizes for torrefaction and white pellet plants for varying feedstock yield, availability and accessibility combinations (see Annex II: Production plant sizes and supply distances for white- and torrefied pellets).



	100km EU-transport, large end use	400km EU-transport, large end use	800km EU-transport, large end use	100km EU-transport, small end use	400km EU-transport, small end use	800km EU-transport, small end use
US/CA,low supply dist., Pellet plant size <101kt	39.7	43.8	49.2	42.5	46.5	52
EU,low supply dist., Pellet plant size <101kt	35.8	39.8	45.3	38.5	42.6	48
US/CA,high supply dist., Pellet plant size <101kt	41.8	45.9	51.3	51.2	55.3	60.7
EU,high supply dist., Pellet plant size <101kt	38	42	47.5	47.4	51.4	56.9
US/CA,low supply dist., Pellet plant size >199kt	39.2	43.3	48.7	42	46	51.5
EU,low supply dist., Pellet plant size >199kt	35.4	39.5	44.9	38.1	42.2	47.7
US/CA,high supply dist., Pellet plant size >199kt	44	48	53.5	53.4	57.4	62.9
EU,high supply dist., Pellet plant size >199kt	40.3	44.4	49.8	49.7	53.8	59.2

Figure 8: Average costs for torrefied pellets based on saw dust for selected biomass-to-end-use chain constellations (see x- and y-axis). The difference for same constellations but without torrefaction step (white pellets) are indicated with colours from dark red (cheaper white pellets) to dark green (torrefied pellets are cheaper).

In Figure 9 relative frequencies of biomass-to-end-use chain pairs which 1) torrefied counterpart exhibit costs below 57 €2013/MWh and 2) the difference to the white pellet counterpart is positive (equals to cheaper torrefied pellets) are illustrated for all origins and feedstocks used in the simulation. The frequencies of the left block are related to the maximum frequency (used wood in Switzerland) with the origin on the European continent and the right block related to the maximum (Bark in Tanzania) of the remaining origins. Feedstock properties are described in (Annex I: Biomass harvest for pellet production) and country dependent energy and labour prices can be found in (Annex VII – data tables). Biomass-to-end-use chains are only calculated based on feedstock-origin combinations for countries where the respective feedstock is already in place or has an existent theoretical potential based on (Alakangas et al., 2013) and own estimations (especially for Eucalyptus and Paulownia no literature could be found). Higher feedstock and harvest cost for most of the woody biomass types result in respective average chain pair costs above the investigated limit and therefore have a lower frequency in this analysis. In contrary woody residues like used wood and bark have the highest frequency which means that they are cheap and probably applicable for torrefaction since cost advantages can be calculated frequently. The herbaceous biomass types exhibit mainly average frequencies; this is due to the fact that investment costs are higher than for woody biomass, according to data from WP3[3] (see Annex II: Production plant sizes and supply distances for white- and torrefied pellets).

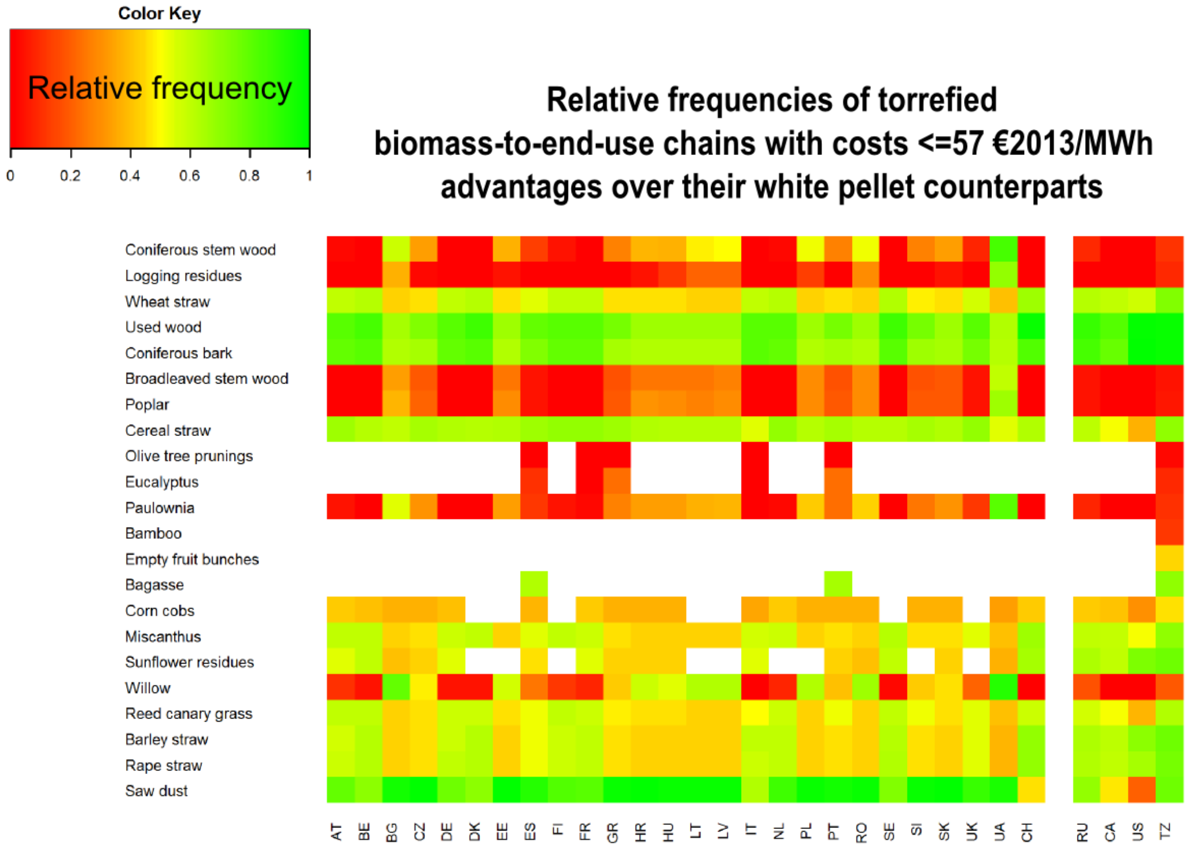


Figure 9: Generated biomass-to-end-use chain pairs with torrefied pellet costs below 57 €2013/MWh and cost advantages for the torrefied counterparts. The share of the key parameters occurring in the generated list are highlighted, lower shares up to 45% are coloured in red, shares around 50% +/-1 5% in yellow and above 55% in green. Shares for European origin chains are normalised using the maximum of generated chains with Europe as feedstock origin and shares for Russia, Canada, USA and Tanzania using the maximum of generated chains for these countries respectively.

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[3] Current developments in straw torrefaction through pre-pelletisation could lead to cost advantages for torrefaction. However this development could not (yet) be included in the simulation.

The purpose of this study was to compare costs of biomass-to-end-use chains for torrefied and white pellets. Therefore the absolute costs and the cost differences of these biomass-to-end-use chains with regard to a large set of key parameters are of special interest. The illustration of costs and cost differences have been enabled by making use of average costs of biomass-to-end-use chain pairs and their cost deviations (Figure 6 and Figure 7). A linear correlation of average costs and deviations could be determined and is further assessed theoretically in (Annex VI: Theoretical considerations). Clear advantages for torrefaction compared to white pellet counterparts for upscaling of the pellet production plant sizes can be observed (Figure 7 and Figure 8). Long distance transportation can be seen as another advantage if absolute costs stay affordable (Figure 8). In overall biomass-to-end-use chain pairs have to be discussed individually to draw conclusions about their average costs and deviations for torrefied and white pellets due to the high variability of these factors depending on country specific energy and labour prices, feedstock properties and costs, preparation plant sizes and supply and distribution requirements (Figure 8 and Figure 9).

3.2 GHG-emissions and jobs associated

CO2 emissions have been calculated for all biomass-to-end-use chain pairs. The coupling of BioChainS with emission calculations is explained in (Annex V: GHG-model extension of BioChainS).The step-wise calculation of ocurring emssions is illustrated for two examplary biomass-to-end-use chain pairs in Figure 10. Due to the transportation of pellets with higher heating values the specific emissions related to the heating value of the final product is always lower for torrefied- than for white pellets however the emission differences for the supply- and preparation steps are marginal in this example. The CO2-mitigation potentials of white- and torrefied pellets can be monetarised by illustrating the relation between cost- and GHG-mitigation differences regarding to coal prices and –emissions which is illustrated in the sensitivity analysis in Chapter 3.3.

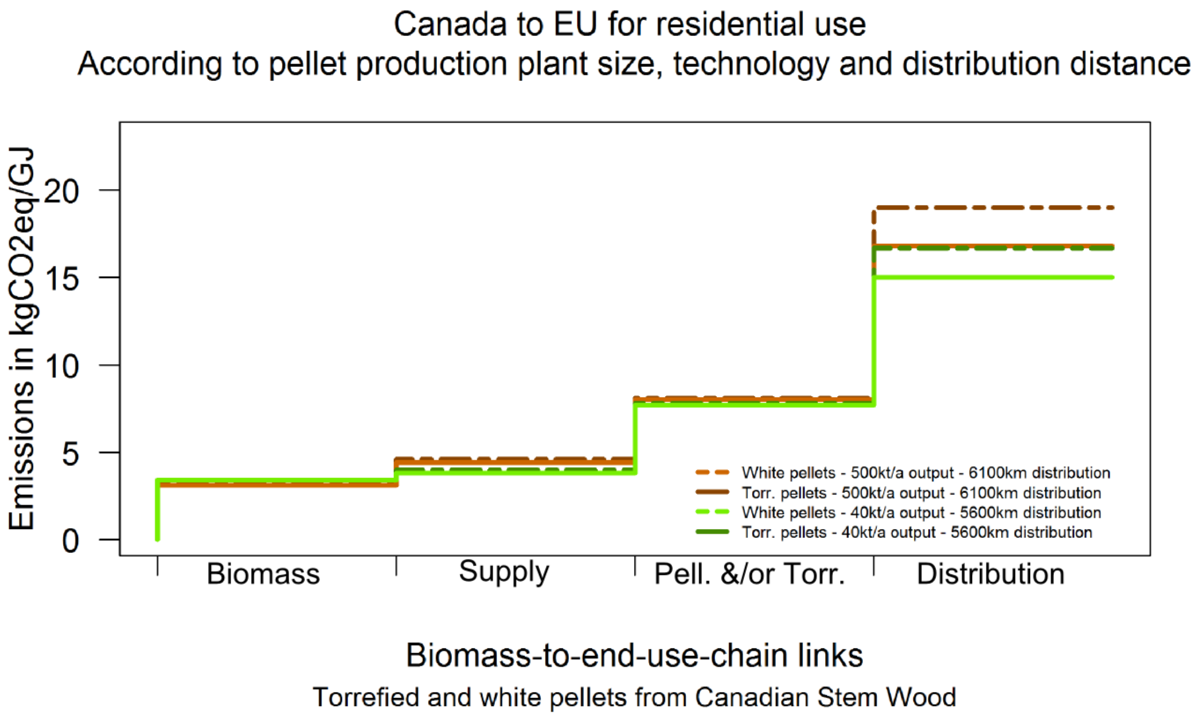


Figure 10: Final heating value specific CO2eq emissions for exemplary biomass-to-end-use chain pairs.

Labour consumption for torrefied products is in general lower than for white pellets if specified on the energy content of the final product. This is due to the fact that same labour demand for white- and torrefied pellet plants can be expected (see Annex II: Production plant sizes and supply distances for white- and torrefied pellets). A novelty value can be outlined for the used approach for the simultaneous calculation of costs with regard to energy- and labour consumption. This enables furthermore the direct and step wise calculation of labour hours necessary to deploy bioenergy. For white- and for torrefied pellets the simulation results in average labour consumption of 0.1 h_{Labour}/MWh and 0.06 h_{Labour}/MWh respectively. Throughout all investigated biomass-to-end-use chain pairs the differences between labour force used between white- and torrefied pellets account for 32% - 38%.

3.3 Sensitivities

In order to gain insights on the impact of particular parameters on the outcome of the calculation in BioChainS it is useful to vary individual parameters separately and to compare the results with regard to a base case. In contrary to the described concept of sensitivity analysis the investigated parameters rarely vary independently to other decisive parameters in reality. To investigate the variation of interdependent variables (like different fossil fuels) scenarios are used. Both approaches are used in this chapter.

This chapter is structured in two sections: Firstly sensitivities for the biomass premium paid additional to harvesting costs (reflecting the uncertainties regarding biomass feedstock prices), the investment costs for torrefaction plants and electricity, labour and diesel prices are discussed for one example or base case. Sensitivities for these parameters and the selected base case are calculated for all biomass-to-end-use chain steps based on torrefaction as well as the costs at the end user compared to the costs of a similar biomass-to-end-use chain for white pellets.

Table 1 illustrates sensitivities for the biomass-to-end-use chain computation in BioChainS. Additional to the sensitivities for an Austrian torrefaction base case the last column indicates the cost differences to a comparative biomass-to-end-use chain for white pellets. The negative difference in the base case of -1.75 €/MWh indicates white pellets costs of 56.42 €/MWh. In this case only a reduction of the investment costs for torrefied pellets result in cost advantages for torrefaction. The incorporation of a biomass premium is explained in (Annex I: Biomass harvest for pellet production) it consists of a factor multiplied with fuel- and labour price dependent harvesting costs. The variation of this factor with +/-30% result in feedstock cost changes (premium and harvesting) of +/-20% and the highest variations for total costs for the end users of +/-15%. At the same time the variation of the feedstock premium factor results in around -50% and +25% for the difference to comparable white pellet (WP) biomass-to-end-use chain total costs for end users. Furthermore important to mention is the sensitivity of distribution cost for varying electricity and diesel prices. This is because of the simplification, that the base case already consists of a weighted average of transport modes used to overcome the 400km inter-European transport (see Annex III: Distribution considerations) calculated for this example.

Parameter	Base case	Unit	Change	Feedstock costs	Supply costs	Prep. costs	Dist. costs	Total costs at end user	Unit	Additional costs TP vs WP €/MWh
Base case				43,21	2,59	10,53	1,85	58,17	€/MWh	-1,75
Feedstock-premium	1,5	times harvest.	+30%	1,20	1,00	1,00	1,00	1,15	*base	-1,17
			-30%	0,80	1,00	1,00	1,00	0,85	*base	-2,33
Electricity	106,3	€/MWh	+50%	1,00	1,00	1,14	1,01	1,03	*base	-1,72
			-50%	1,00	1,00	0,86	0,99	0,97	*base	-1,79
Labour	31,4	€/h	+50%	1,11	1,24	1,00	1,14	1,10	*base	-1,22
			-50%	0,89	0,76	1,00	0,86	0,90	*base	-2,28
Invest	22,5	M€	+30%	1,00	1,00	1,21	1,00	1,04	*base	-4,00
			-30%	1,00	1,00	0,79	1,00	0,96	*base	0,50
Diesel	107,4	€/MWh	+50%	1,04	1,09	1,00	1,14	1,04	*base	-1,51
			-50%	0,96	0,91	1,00	0,86	0,96	*base	-2,00

Table 1: Sensitivity analysis for an Austrian biomass-to-end-use chain based on broadleaved stem wood, a torrefaction plant size of 100kt/a output and a distribution distance of 400km for large scale end users. Additional a column indicates the price differences to comparative biomass-to-end-use chains for white pellets. The negative difference in the base case of -1.75 €/MWh indicates white pellets costs of 56.42 €/MWh. In this case only a reduction of the investment costs for torrefied pellets result in cost advantages for torrefaction.

In the second section of this chapter relations between coal, natural gas and oil prices from the 650ppm POLES scenario (JRC, 2014) are adapted to produce realistic increases of prices of the fossil fuel portfolio for 2030. To obtain the same sort of sensitivities we aim for in this section for decreased fossil fuel prices the percentile increases are mirrored with a negative sign. For HFO (heavy fuel oil) and diesel a 1:1 correlation with oil (crude oil) is assumed. Variations are also used for price decreases and correlation between fossil fuels and electricity is estimated roughly (see Table 2). Sensitivities in this section are calculated for GHG-mitigation costs for co-firing in coal fired power plants as well as for the general cost comparison with reference fuels.

Prices	Variation
Oil	+/- 60%
Coal	+/- 50%
Gas	+/- 20%
Diesel	+/- 60%
HFO	+/- 60%
Electricity	+/- 40%

Table 2: Positive variations for oil, coal and natural gas are similar to price increases in the 650ppm POLES scenario between 2010 and 2030 (JRC, 2014). For HFO and diesel a 1:1 correlation with oil is assumed. Variations are also used for price decreases and correlation between fossil fuels and electricity is estimated roughly.

In Figure 9 averaged CO_2-mitigation costs for the different feedstock- and pellet types are illustrated for co-firing in coal-fired power plants together with the averaged European coal price for 2013 (IEA, 2014) and a variance of 50%. Upper price levels for coal match with the 650ppm POLES scenario (JRC, 2014). For the feedstock types stem wood, care wood and saw dust (as explained in Annex I: Biomass harvest for pellet production) advantages for torrefaction can be outlined if CO_2 avoidance is financially rewarded. Due to higher investment costs for the torrefaction of the other feedstock types a price increase for coal would be necessary for torrefied pellets to become competitive with white pellets.

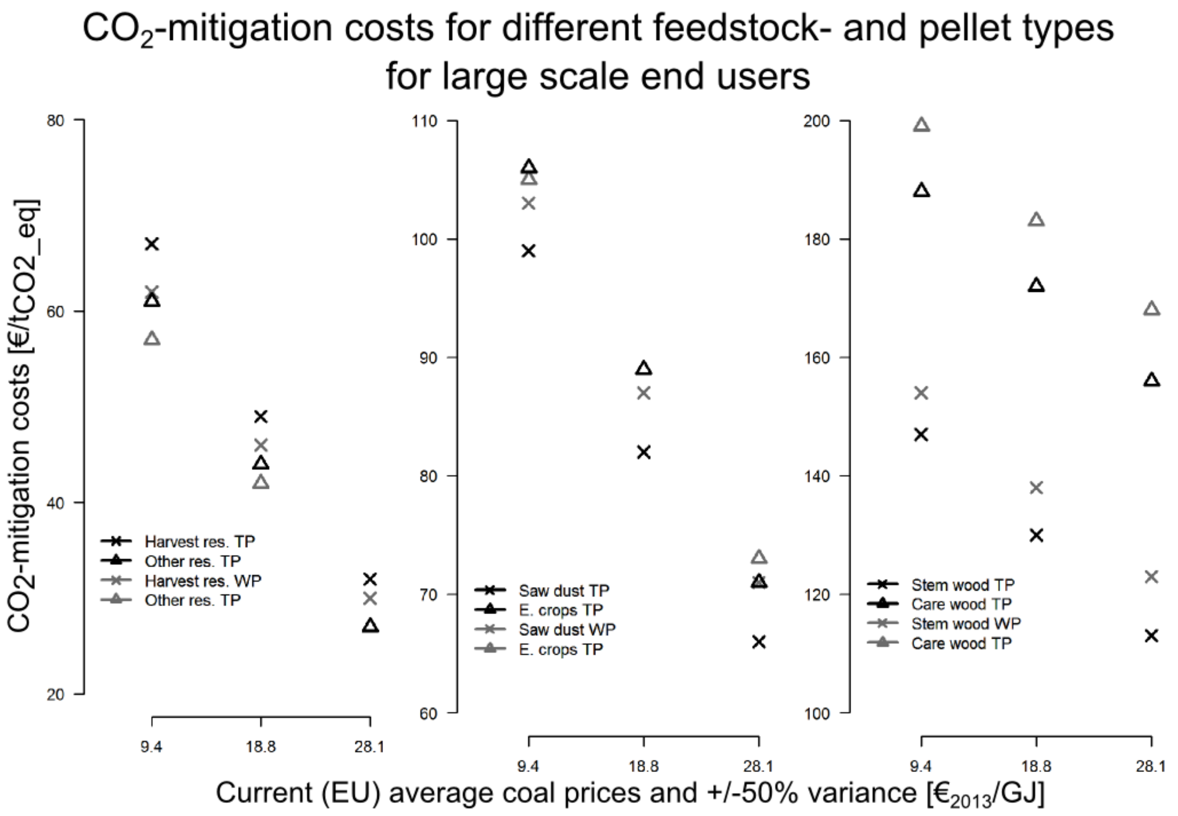


Figure 11: Average CO_2-mitigation costs for the different feedstock- and pellet types (for large scale end users) and a 50% variance to the averaged European coal price in 2013 (IEA, 2014).

According to Table 2 also diesel and electricity prices for production and other reference fuels are varied for this section of the sensitivity analysis chapter. Deployment costs of the pellets are compared with competitive fuel- and energy deployment prices in Figure 12 similar to Figure 5. This increased fossil fuel price scenario outline advantages for torrefied and white pellets for small scale end users compared to the European space heating average mix (described in Annex IV: Costs for end users and reference fuels). Dependencies between fossil fuel (and electricity) prices for the biomass-to-end-use chains are simulated in BioChainS due to diesel and electricity consumption for cropping, harvesting, supply, preparation and distribution.

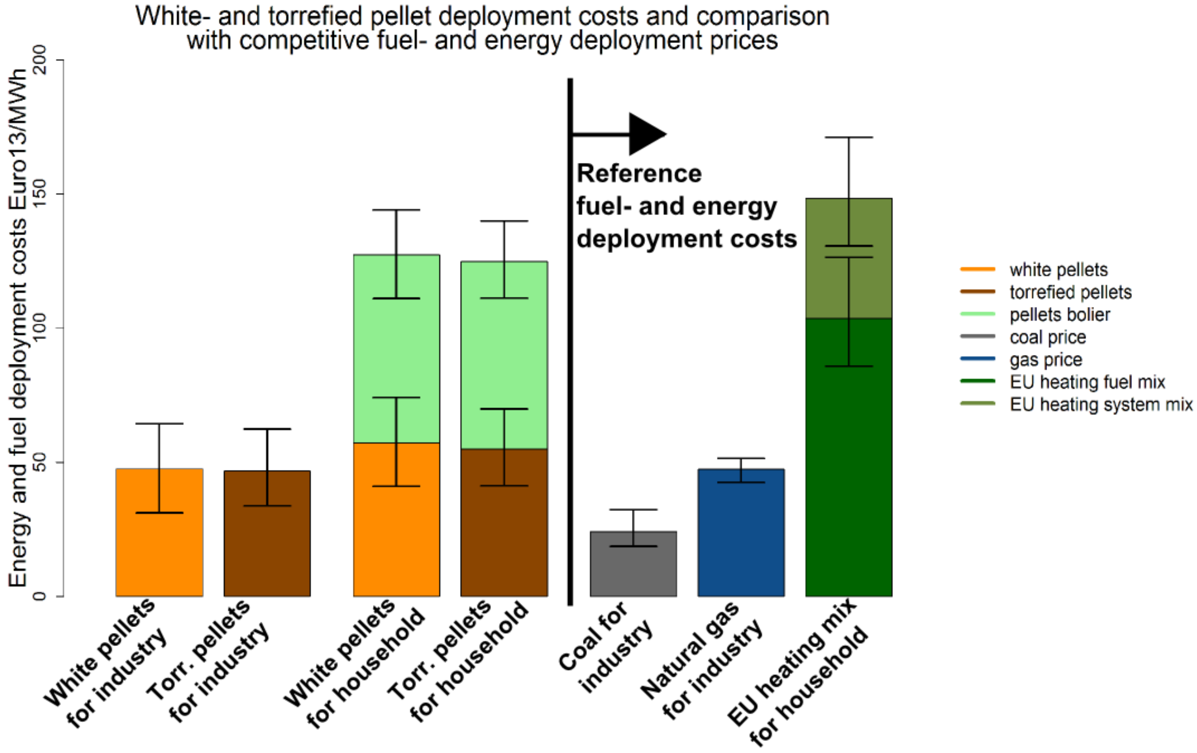


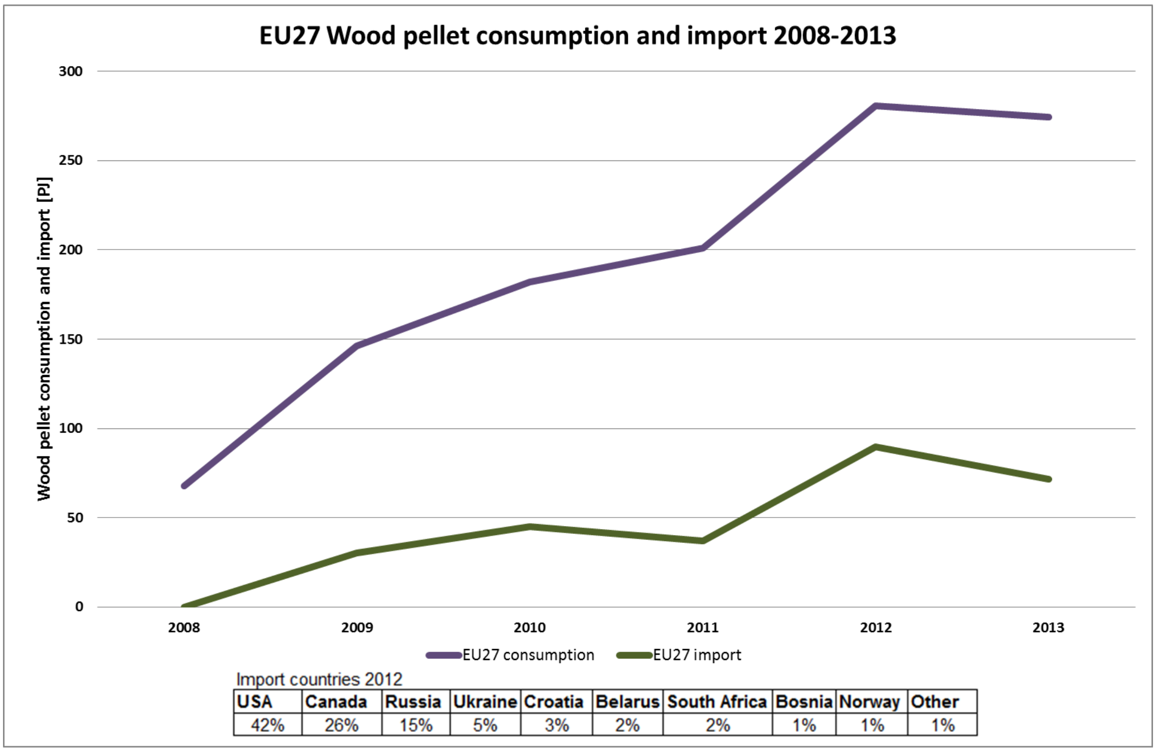
Figure 12: Medians and 2nd (lower part of error bars) and 3rd (upper part of error bars) quartile of white pellets (WP) and torrefied pellets (TP) for large scale and household application. Deployment costs for pellets are directly compared with the industry prices for coal (grey) and natural gas (dark blue). For household pellets a pellet stove (levelled costs in light green) is considered to compare the costs of heat deployment with an averaged heating fuel and system mix for the European Union. Quartiles for reference fuels result of country specific deviations. Prices of reference fuels are increased according to related levels from the 650ppm POLES scenario (JRC, 2014) for 2030.

4 Scenarios discussion

4.1 Pellets, status quo

Statistics on wood pellet production and trade are available in statistical databases (EUROSTAT, 2014a) and (FAOSTAT, 2014) as well as in statistical reports (Calderon et al., 2013). Figure 13 illustrates the consumption in the EU27 and imports from third countries for wood pellets based on (EUROSTAT, 2014a) converted to its energy content. Between 2009 and 2012 the consumption of pellets grew by 25%/a, the import from third countries is fluctuating. In 2012 the main importers where the US, Canada and Russia with 42%, 26%

and 15%, further importing countries can be listed in an descending order as Ukraine, Croatia, Belarus, South Africa, and other countries (Calderon et al., 2013). (EUROSTAT, 2014a) furthermore indicates a decrease for the consumption in 2012 and 2013, while using the production, import and export from (FAOSTAT, 2014) results in an increase of the EU27 consumption of 10% in the period 2012-2013. Differences in the data bases cannot be explained, however (EUROSTAT, 2014a) is further used for the scenario discussion.



Import countries 2012

USA	Canada	Russia	Ukraine	Croatia	Belarus	South Africa	Bosnia	Norway	Other
42%	26%	15%	5%	3%	2%	2%	1%	1%	1%

Figure 13: Wood pellet consumption and imports of the EU27 calculated using data from (EUROSTAT, 2014a) for production, imports- and exports from third countries and a conversion factor of 17.5 GJ/t. The share of import countries in 2012 are based on (Calderon et al., 2013).

In Figure 14 the 2012 wood pellet consumption per end user type is illustrated for selected countries. It can be observed that consumption is mostly either based on power generation (United Kingdom, Netherlands and Belgium) or heat generation for small scale and commercial end users (e.g. USA, Italy, Germany, Austria and France). Only the markets in Denmark, Poland and Sweden are mixed. The shares for small scale and commercial heating are estimated to be 77% and 23% respectively and pellet demand is mainly driven by small scale end users globally.

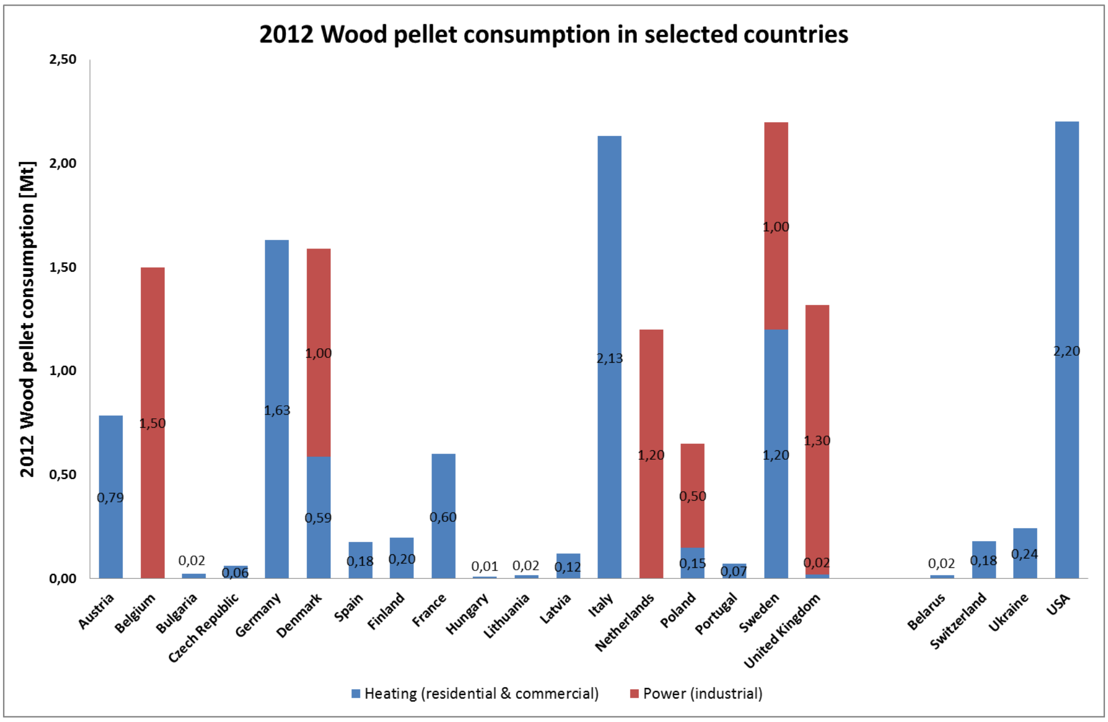


Figure 14: Wood pellet consumption for different end user types in 2012 based on the AEBIOM-statistical report (Calderon et al., 2013).

Pellet consumption is mainly based on wood pellets using saw dust as a feedstock. Agropellets are mainly used for co-firing in coal fired power plants and are not an option for small scale heating yet. Used feedstocks next to different kind of straws are for example miscanthus, grain, olive stones and sun flower husks. “Statistics and market figures of agropellets are hardly available”, estimations in (Cocchi et al., 2011) state a production and consumption of these types of pellets of around 0.43 Mt in the EU27 in 2009 plus 0.19 Mt produced in the Ukraine for the main consumption in power plants in Poland. (Cocchi et al., 2011)

Capacities and production of EU27 wood pellet production plants are put side a side with the number of plants in (Calderon et al., 2013) for the year 2012. According to these values around 500 plants with an average capacity of 37 kt/a and an average utilisation rate of 67% where running in 2012. Average plant sizes are slightly bigger in Canada and the US with 72 and 46 kt/a respectively and average work loads of 75% and 71% respectively.

The development and 2012 data for pellet consumption and trade are further used in Chapter 4.2 to create scenarios up to 2030 to discuss possible impacts of the torrefaction technology.

4.2 Deployment scenarios

A comparative table for magnitudes of EU pellet consumption in 2020 can be found in (Cocchi et al., 2011) reaching from 28 Mt/a to 80 Mt/a and showing an internal estimation in the same paper of yearly 35 Mt pellet consumption. Scenarios can be furthermore obtained from the EU wood study (Mantau et al., 2010) illustrating 32.5 Mt for household heating consumption and more up to date studies of the Pöyry consulting group (e.g. Kokko, 2012) which estimates 35 Mt with the difference that a majority of 20 Mt could be used for power production in 2020.

In (Mantau et al., 2010) the development of wood pellets for the small scale consumption are discussed for the time range 2010-2030 based on supply potentials of saw dust and demand potential depending wood pellet import estimations. According to this study a small scale pellet consumption of 32.5 Mt and 40 Mt in 2020 and 2030 respectively could be met by 21.5 Mt and 27 Mt domestic productions based on saw dust and 11 Mt and 13 Mt imports from third countries respectively.

Pöyry consulting (Kokko, 2012) estimates a pellet consumption for heating of around 13 Mt (including residential and commercial heating) and a demand for power generation of around 22 Mt and 20 Mt for 2020 and 2030 respectively mainly consumed in the north west of Europe (Mergner, 2014). An “end of the support scheme for UK projects” is expected to result in the stagnation and slight decrease of large scale wood pellet consumption between 2020 and 2030 (Mergner, 2014).

Out of these studies three distinct storylines have been constructed to determine the impacts of torrefaction under different framework conditions:

A “high scenario” discusses a pellet consumption growth resulting in similar small scale pellet consumption rates as described in (Mantau et al., 2010) for 2020 and 2030 and extra pellet demands for large scale, mainly coal-fired power plants similar to the (Mergner, 2014) levels are added. This would equal a yearly 16% growth for the time range of 2013-2020 and for the second decade from, 2020 till 2030, a 3%/year growth resulting in a 3.8 fold increase of the total yearly European pellet demand in the period 2013-2030.

The “moderate scenario” discusses similar small scale pellet consumption rates described in (Mantau et al., 2010) for 2020 and 2030, a stagnating power plant demand from 2012 onwards and a fade out for this large scale sector after 2020. This would equal a yearly 10% growth for the time range of 2013-2020 and for the second decade, from 2020 till 2030, a 2%/year growth resulting in a 2.4 fold increase of the total yearly European pellet demand in the period 2013-2030.

In the “low scenario” the import of wood pellets for small scale consumption outlined in (Mantau et al., 2010) is neglected and only the domestic production is used for household consumption. This would equal a steady growth of 3%/year between 2013 and 2020 and stagnation afterwards resulting in an 1.2 fold increase of the total yearly European pellet demand in the period 2013-2030.

In Figure 15 the discussed storylines are coupled with the statistical data described in chapter 4.1. In the “high-“, “moderate-“ and “low scenario” the European pellet consumptions grows from around 300 PJ in 2013 to 340, 650 and 1050 PJ in 2030 respectively. The main drivers in all scenarios are residential and commercial heat consumers for 2020 and 2030 and only in the high scenario the pellet consumption for co-firing is existent and around 34% of the total European consumption in 2030. In this scenario up to 350 PJ/a pellets would end up in co-firing. Compared to a European coal consumption of approximately 12.000 PJ in

2010 (Kokko, 2012) this pellet consumption would account to an average EU-wide 3% co-firing share.

Determining factors for the deployment of torrefaction are now according to Chapter 3 next to the willingness to pay from the end users and therefore the end user type, the feedstock type used for the production of the demanded pellets, the average pellet plant capacities and transport distances, thus for example the share of imported pellets to domestically produced pellets. None of these factors could be simulated for the future pellet market within this work package, still a qualitative discussion of these factors with regard to the presented scenarios will be conducted to illustrate the application of the main findings of Chapter 3.

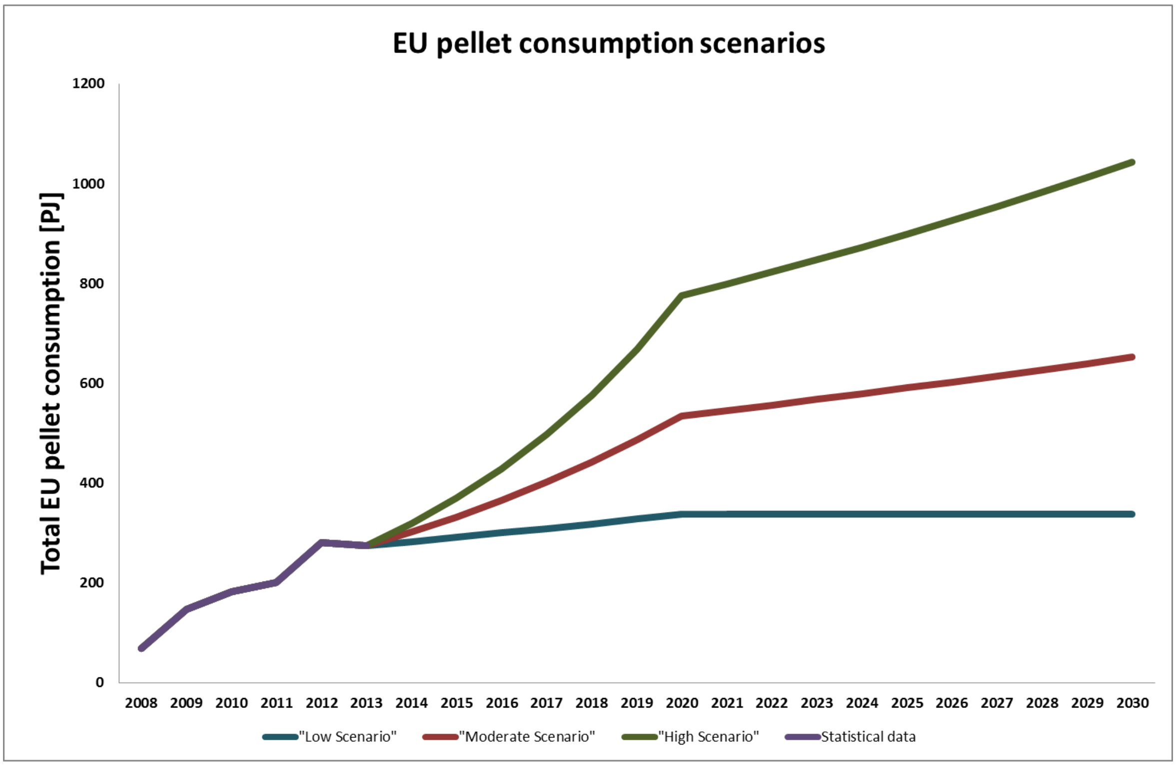


Figure 15: EU pellet consumption scenarios based on (Cocchi et al., 2011), (Mantau et al., 2010) and Pöyry consulting and own estimations respectively considerations for differing framework conditions for the diffusion of the torrefaction technology.

In the **low and in the moderate scenario** the pellet consumption of domestically produced pellets is based on the projected saw dust potentials of the member states (Mantau et al., 2010). Thus the main feedstock is expected to stay saw dust for both scenarios, the additional small scale demand in the moderate scenario is estimated to be either covered by imported pellets, or domestically produced pellets based on other woody biomass. Two types of this other woody biomass fraction have to be differentiated, woody feedstock that is cheaper than saw dust (e.g. used wood and bark) covering some of the stagnating co-firing demand until 2020 and stem wood (coniferous or broadleaved) which could be used for an upper price range of the pellets used for heating.

For the **low scenario** torrefaction is only assumed to play a minor role for particular cases where pellet production out of saw dust is economic more viable for pellet production plant sizes clearly exceeding the todays average production plant size of 40 kt. Torrefaction plants based on saw dust and a pellet output size of 100 kt/a (2.1 PJ/a torrefied pellets at full load) could contribute to around 0.6% of the total European demand in 2030 each if used to the full capacity. However comparing the deviation for torrefied and white pellets from their average pellet deployment costs illustrated in Figure 16 reveals that simulated torrefied biomass-to-end-use chain pairs based on affected characteristics (saw dust feedstock up to 100kt/a) only become competitive in the upper price range therefore a theoretical share of 1-2% for torrefied pellets is considered to be produced where the availability of saw dust is high and pellets are produced also for longer transport distances on an solely domestic EU market.

In the **moderate scenario** the demand exceeds the potential supply based on domestic saw dust. Thus additional feedstock are considered to be used; 1) cheaper saw dust chains for co-firing for which torrefaction is assumed to play no role 2) more expensive feedstock like coniferous or broadleaved stem wood, which is assumed to be processed largely in 100-200 kt/a torrefaction plants (2.0 – 4.2 PJ/a torrefied pellets at full load) and 3) imported pellets also partly based on torrefaction. In this scenario 15 to 35 domestic torrefaction plants depending on size and feedstock type could cover around 10% of the pellet demand for small scale end users (10% of 650 PJ_{2030}) making more expensive feedstock economic viable through upscaling in 2020 and 2030. The competitiveness for torrefied pellets for these biomass-to-end-use chain characteristics is illustrated in Figure 16 (Stem wood 200kt/a). Higher heating values of the final product also profit from longer transport distances, making it likely that imported pellets for heating is mainly based on torrefaction which would account to another 15 to 35 torrefaction plants outside Europe between 2020 and 2030 if the main share of imported pellets (50%-100% of 150 PJ_{2030}) is used for co-firing and based on feedstock in the lower price range (e.g. used wood and bark) and processed in 200 kt/a torrefaction plants marked as black crosses in Figure 16.

The extra consumption in co-fired power plants in the **high scenario** would demand a large share of pellets on the market which are among the lowest price range. Therefore larger scale pellet plants (100-200 kt/a) based on straw and other agricultural residues (e.g. sunflower husks, bagasse) would emerge. Due to higher cost differences between torrefied and white pellets for agricultural pellets than for wood based pellets the extra capacities would possibly not be based on torrefaction[4]. Compared to around 10 PJ/a in 2009 a consumption of domestic agricultural pellets of 70 PJ/a could cover 20% of the calculated co-firing demand in 2030 in this scenario (350 PJ_{2030}). The rest of the co-firing demand of 230 PJ in 2030 is considered to be covered by cheap imports and domestic production including a considerable share of saw dust. The intensified demand would lead to larger scale torrefaction plants based on saw dust and quality (stem-) wood for the consumption in heat applications but also imports of torrefied pellets for the same. Where applicable torrefaction plants with 200-500 kt/a torrefied pellets output could produce 4.0 PJ to 10.5 PJ/a torrefied pellets at full load each. A pellet demand for heating of around 700 PJ_{2030} could be possibly covered by around 500 PJ_{2030} of pellets based on saw dust and quality wood and 200 PJ_{2030} by imported pellets. Here 25 to 60 torrefaction plants inside Europe and due to a doubling of the imports compared to the moderate scenario and a higher share of imported pellets for the

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[4] This assumption represents the actual results of this study. Current developments in straw torrefaction could lead to higher agricultural residues torrefaction rates. However this development could not (yet) be included in the simulation and thus is also excluded from the scenario discussion.

more expensive household consumption up to 80 torrefaction plants for the EU import can be considered. The clear advantage for large scale pellet plants is illustrated in Figure 16 for saw dust and stem wood and a pellet output size of 500kt/a.

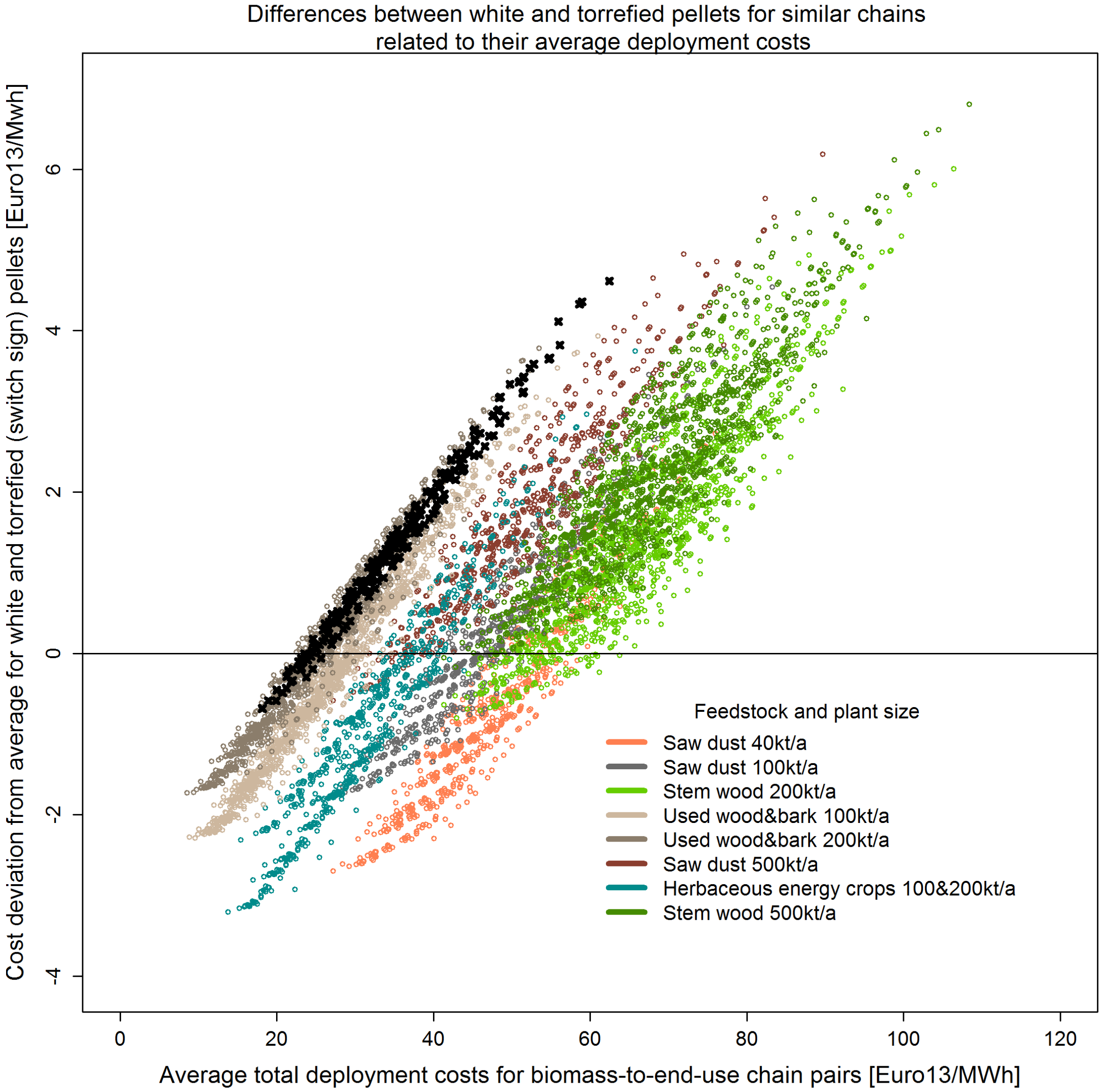

Figure 16: Biomass-to-end-use chains discussed in the deployment scenarios. On the X-axis deployment costs are indicated averaged for every biomass-to-end-use chain pairs individually. The Y-axis shows the deviation to be added to obtain the respective white pellet deployment costs or subtracted to obtain the respective torrefied pellet cost. Different feedstock and preparation plant sizes are indicated using different colours (see legend). Furthermore for pellet chains based on used wood and bark and a pellet production size of 200kt/a, the chains based on feedstock and production origin in Canada or the US are emphasized using black crosses.

Within the SECTOR project feedstock potentials for a vast amount of biomass types have been acquired (Alakangas et al., 2013). The domestic production of pellets based on agricultural residues of 70 PJ in 2030 accounts for around 10% of the cumulated straw residues (cereal, barley, wheat and oat) outlined in the mentioned report. Furthermore around 440 PJ pellets are considered to be based on domestic saw dust in 2030 in the high scenario. This would account for around 70 % of by-products and residues from the EU27 wood processing industries mentioned in (Alakangas et al., 2013) and reflect the assumption that all available saw dust is converted to pellets used for the scenarios in this report based on (Mantau et al., 2010). For additional stem wood and other wood feedstock around 210 PJ in 2030 are assumed for pelletisation in the high scenario. In (Alakangas et al., 2013) potentials of around 1440 PJ/a for stem wood of which currently around 600 PJ/a are used as fuel wood, a 520 PJ/ landscape management wood potential and another 1190 PJ/a primary forest residues potentials are mentioned. All potentials are outlined as technical potentials. The simulation of the economic potential share for pellets and subsequently for torrefied pellets is out of scope of this work package and the mentioned numbers should only serve for estimations of the theoretical feasibility of the outlined scenarios which thus can be described as theoretically feasible with regard to feedstock availabilities.

(Alakangas et al., 2013) furthermore discusses theoretical potentials exceeding the mentioned potentials in the previous paragraph for other biomass types including Miscanthus, Poplar, Reed Canary Grass and short rotation coppices. Even though theoretical biomass-to-end-use chain costs for these feedstock types are calculated for this report the author prefers to not include them specifically into the scenario discussion since their large scale application for the domestic production for bioenergy consumption can be seen as highly hypothetical.

To summarise the scenarios the selected biomass-to-end-use chain pairs were analysed for each scenario to derive conclusions about comparative cost savings if torrefaction is used to diversify the European solid bioenergy product portfolio. The medians for the deviations of the cost competitive biomass-to-end-use chains based on torrefaction from the biomass-to-end-use chain pair averages account for around 0.9, 1.3 and 2.0 €2013/MWh for the low, moderate and high scenario respectively. The cost savings compared to the white pellet counterparts (deviation to average times two) could therefore account for around 500 k€/PJ, 700 k€/PJ and 1 M€/PJ respectively. Cost savings could reach from 2 M€/a to 500M€/a according to the estimated torrefied pellet deployment in 2030 in the discussed scenarios. This result can only be seen as a rough estimation since econometric modelling of pellets and competitive fuels was out of scope of this work and various advantages and disadvantages for torrefied pellets compared to white pellets are not (yet) quantifiable.

5 Conclusions

The techno-economic evaluation of a realistic market diffusion of torrefaction for the pellet market in the upcoming decades is linked to considerable uncertainties and corresponding methodological challenges. This is due to the fact that the simulation of the market penetration and price formation of biomass for bioenergy in general asks for a sound understanding and computation of interdependencies with **1)** competitive energy commodities on the demand side and **2)** the different utilisation paths for land and biomass on the supply side. Pelletisation as a preparation step for biomass to obtain uniform, better tradable and standardised products is a rather new way of commoditisation compared to other energy and bioenergy products taking off mainly in Sweden and Germany according to (EUROSTAT, 2014a) only six years ago. The early stage of the development of this bioenergy carrier makes it difficult to simulate prices and quantities. This applies especially for differences induced through optimisation by torrefaction where differences between white- and torrefied commodities should be outlined.

However it is useful to estimate cost differences between traditional- and processes enhanced with torrefaction for varying key parameters including feedstocks already used for white pellet production in yet active countries as well as key parameters (feedstock, countries, production plant sizes, distribution distances and modes) that could potentially have a realistic connotation in the future for white and torrefied pelletisation. This was done successfully using the model **BioChainS** and technical and economic information produced within the SECTOR-project. It is important to stress that some not (yet) quantifiable parameters are left aside in the simulation even though they could play a crucial role for the deployment of torrefied pellets. Selected examples are grind ability and capacity effect costs for co-firing (explained in Annex IV: Costs for end users and reference fuels) and advantageous and disadvantageous performance differences for torrefied pellets for handling (Annex III: Distribution considerations). However first conclusions and recommendations for policy makers and stakeholders can be drawn mainly based on the impact of the differences in production costs and heating content of the final products white and torrefied pellets.

For **EU policy makers** following main findings have to be stressed.**1)** Optimisation of pelletisation through torrefaction can lead to considerable cost savings in scenarios where higher amounts of solid bioenergy carriers are deployed. Production cost differences for torrefaction are mainly outweighed in these scenarios by better unit scaling effects and thus higher optimal plant sizes as well as through the positive effect of higher heating values of the final product for longer transport distances and import from third countries. **2)** According to our analyses the argument regarding a diversification of the biomass for energy portfolio through torrefaction can be supported only to a certain extent at this stage of the research. Production costs of torrefied pellets depend on the density of the used feedstock. Here the utilisation for higher cost woody biomass can be beneficial if costs stay in an affordable range. For recycled wood cost savings can be expected but for herbaceous biomass no clear advantage for torrefaction can be outlined yet. Improvement for herbaceous biomass can be reached potentially through pre-pelletisation results for this constellation are expected in the beginning of 2015 within the SECTOR project (Chapter 3). **3)** CO_2 emissions of torrefied pellets are in general lower than for white pellets. Still advantages for torrefied to white pellet mitigation costs for co-firing cannot be found for all cases. Increasing coal and energy prices (also for production and transportation of pellets) but also increasing average mitigation costs between the two commodities in most cases result in lower mitigation costs for torrefied pellets (Chapter 3.2). **4)** The employment effects for white- and torrefied pelletisation is very similar if measured as pellet mass specific labour requirement. Thus, energy content specific staff hours used for their production is between 30% and 40% lower for torrefied pellets (Chapter 3.2). No conclusions can be derived at this stage of the research on how much this effect would be offset by higher pellet production through the deployment of torrefaction and about the effects on the employment of competitive energy and bioenergy deployment.

For the interested **industry** it should be highlighted that **1)** economic profitability of torrefaction is highly sensitive on the different key parameters of the entire biomass-to-end-use chain (Chapter 3). This can be explained by the example that the average supply distance depends on a combination of feedstock yield, -availabilities and –accessibilities and (also) size dependent E&M balance of the plant which should be optimised individually. **2)** Furthermore not only competitiveness to white pellets but also general economic viability has to be ensured. Therefore the example of increased transport distances can be favourable for torrefaction if, and only if the product stays in an affordable range for the end user. **3)** In general the production cost difference and the relation between the lower heating values is sufficient to roughly estimate the break even costs between torrefied and white pellets (see Annex VI: Theoretical considerations). **4)** Torrefaction can lead to considerable cost savings especially for large scale torrefaction plants and high quality feedstock (see Figure 12) due to higher scaling effects for the more expensive technology but especially also for lower quality woody feedstock.

A **final remark** outlines considerations about general risks and advantages of additional bioenergy preparation and commodity optimisation steps using an example for torrefaction: The torrefaction technology is applicable where a high demand makes larger scale pellet plants for more expensive feedstock economic viable. Thus torrefied pellets are considered to mainly cover the upper part of the pellets merit order in this example. On the one hand this placement induces risks for the torrefied pellet suppliers for varying cost-demand curves. On the other hand the diversification of the solid bioenergy portfolio would lead to a flattening of the pellet merit-order in general and thus to more stable pellet costs for the end users, especially for small scale consumption since torrefaction is more applicable for higher biomass-to-end-use chain costs. If this effect is desired risks should not only be kept in mind but also addressed and mitigation strategies investigated on policy and on investor sides.

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7 Annex I: Biomass harvest for pellet production

Profiles of selected raw materials are widely based on the deliverables from WP2. In (Lemus et al., 2013) biomass feedstock are listed which are or will be torrefied in either laboratory or pilot plant conditions within the SECTOR project. The list is transferred into the database of BioChainS including the, for the simulation important key parameters bulk density (BD), moisture content (MC) as received, gross calorific value (GCV) and information about harvesting and traded forms (see Table 3). Net calorific value (NCV) is calculated using the moisture content and the gross calorific value from the respective feedstock based on e.g. (Calderon et al., 2013):

$$NCV = \frac{GCV * (100 - MC) - 2.44 * MC}{100}$$

For this study we wanted to derive fuel and labour specific harvesting parameters to be able to generate harvesting costs under different framework conditions with regard to country of origins and fuel price scenarios. Therefore the SECTOR feedstock were nested into different harvesting forms, woody feedstock that is planted to be harvested directly for energy purposes (stem wood), woody feedstock that is harvested without cutting the respective stems (care wood), herbaceous biomass that is cropped and harvested directly for energy purposes (energy crops), agricultural residues that arise when agricultural biomass is harvested for other purposes (harvest residues) and other residues (other residues).

SECTOR code	Description used in WP2	Bulkdensity kg/m^3	Moisture w-%	GCV MJ/kg	NCV MJ/kg	Pilot testing in SECTOR	Nest defining harvesting form
1	Stem wood, conferous without bark	330	45	19,3	9,5	Yes	Stem wood
2	Logging residues, coniferous	300	45	19,2	9,5	Yes	Care wood
3	Straw, wheat (nordic)	180	15	17,6	14,6	No	Harvest res.
4	Used wood - post consumer, recycled	200	20	18,8	14,5	Yes	Other res.
5	Bark, coniferous	300	55	19,2	7,3	No	Other res.
6	Broadleaves, stemwood with bark	360	40	17,8	9,7	Yes	Stem wood
7	Poplar, with bark	340	40	18	9,8	Yes	Stem wood
8	Straw of cereal	100	12	17,8	15,4	Yes	Harvest res.
9	Prunings from olive trees - woddy bm	250	25	16,3	11,6	Yes	Care wood
10	Eucalyptus	340	40	18,5	10,1	Yes	Stem wood
11	Paulownia	340	40	18,6	10,2	Yes	Stem wood
12	Bamboo herbaceuos	300	20	16,9	13,0	Yes	Stem wood
13	Empty fruit bunches	300	67	13,0	2,7	No	Other res.
14	Bagasse Herbaceuos	130	50	16,7	7,1	Yes	Other res.
15	Corn cobs	300	20	13,0	9,9	No	Other res.
16	Miscanthus	200	16	17,6	14,4	No	Energy crops
17	Sunflower residue	200	11	19,1	16,7	No	Harvest res.
18	Willow	330	40	19,5	10,7	Yes	Stem wood
19	Reed canary grass	200	20	16,6	12,8	No	Energy crops
20	Barley straw	200	20	18,9	14,6	No	Harvest res.
21	Rape straw	200	20	18,2	14,1	No	Harvest res.
22	Saw dust	160	18	19,1	15,2	Yes	Saw dust

Table 3: Feedstock profiles from (Lemus et al., 2013). Bulk densities, Moisture content and gross calorific value (GCV) are averaged from the ranges given in the mentioned deliverable. Net calorific values (NCV) are calculated using moisture content and GCV. The nests defining the harvesting form are defined by the authors of this report and based on the description in the text.

In (Francescato et al., 2008) equipment for the harvesting and processing of woody biomass is specified regarding to its technical and economic parameter. For stem wood harvesting for bioenergy purposes the utilisation of a harvester with purchasing costs between 300 and 370 k€, a productivity of 8-20 solid m^3/h and a fuel consumption of 11-16 l/h is assumed. The hourly costs of around 90-120 €/h (without wages) have been corrected by an average fuel consumption using a diesel price of 1.3 €/l (Kühner, 2013). Using an average BD of around 330 kg/m^3 and the assumption that one labour hour is needed for one hour of operation the mass specific harvesting parameters equipment costs, fuel consumption and labour consumption could be calculated (Table 2).The harvested wood is forwarded to the road side using a forwarder and chipped at the road side for further transportation using a chipper. Care wood is considered to be processed similarly with the only difference that instead of the harvester a simple chainsaw is used. Chainsaw, forwarder and chipper data can also be found in (Francescato et al., 2008) and was transformed for the BioChainS database similarly as described for the harvester (Table 4).

For herbaceous biomass (energy crops and harvest residues) data from the BioBoost project was used (Kühner, 2013). After cutting and bailing biomass with a bailer, straw or energy crop bales are collected using a chaser and transported to road side. Again the data for this equipment was transformed into mass specific harvesting parameters, the productivity of the machinery and the average BD of the respective biomass (Table 2).

Harvesting form	Equipment costs €/t	Fuel use kWh/t	Labour use h/t
Stem wood	58,7	68,8	0,6
Care wood	90,4	63,3	3,1
Energy crops	13,0	21,2	0,1
Harvest residues	13,0	21,2	0,1
Other residues	0,0	0,0	0,0
Saw dust	58,7	68,8	0,6

Table 4: Harvesting forms and harvested feedstock and mass specific equipment costs, fuel consumption and labour consumption derived from (Francescato et al., 2008) and (Kühner, 2013). Equipment costs and labour use for care wood are higher than for stem wood since productivity of the assumed chain saw is much lower than for the automatized harvester. For other residues no costs are assumed. For saw dust same values as for stem wood are assumed since it is a product from stem wood.

No harvesting costs were assumed for the feedstock summarised under other residues. For saw dust the same harvesting parameters are used as for stem wood since it is assumed to be a product derived from stem wood.

Another parameter decisive for biomass feedstock costs is the cost for cultivation or the cost for the feedstock itself without harvest considerations. In literature this value is referred to as “standing tree value” for example for woody biomass (Francescato et al., 2008). It depends on several factors, for wood for example on the quality (trimmed throughout growing or not) and diameter. A similar parameter has also to be considered for energy crops since the cultivation requires labour, fuel and equipment. Furthermore for harvest residues for crops that are dedicated for other purposes the value of the standing crop is normally paid by the main purpose, still the value for the nutrients presented in the residues can lower the fertiliser costs for the following season if left on the field. No literature could be found on the relation between harvesting costs and cultivation costs. However the authors of this report assume that cultivation is similarly dependent on equipment, fuel and labour use as is the harvesting. Therefore a simplified factor of +50% of the resulting harvesting costs are assumed for the cultivation costs of the stem wood feedstock (SECTOR code 1 and 6), the woody energy crop feedstock (SECTOR code 7,10,11,12 and 18) and for the herbaceous energy crops (SECTOR code 16 and 19). Even though extra standing crops costs would occur for the harvesting residues no extra costs beside the harvesting costs are assumed for these biomass types. No extra costs are added to the harvesting costs of care wood and saw dust and no costs (also no harvesting costs) occur for the other residues biomass types in this study.

Using now for example the EU average for 2013 of 115 €/MWh diesel prices and 19 €/h labour prices result in harvesting costs for stem wood of 78 €2013/t and total biomass costs at road side of 117 €2013/t. However highest costs are assumed for care wood due to the low efficiency of the calculated chain saw of 157 €2013/t and the same cost for the biomass at the road side even though no extra standing tree values are assumed where the tree is kept standing. A standing crop value for energy crops is assumed in the contrary to harvesting residues. Bales for these commodities are calculated to cost 25 €2013/t and 17 €2013/t respectively. For saw dust the simplified assumption that harvesting costs are the same for stem wood and its residues but no extra standing tree value is cleared results in 78 €2013/t.

8 Annex II: Production plant sizes and supply distances for white- and torrefied pellets

Biomass harvested and pre-treated into bales or wood chips are considered to be loaded onto a truck to be transported (supplied) to the white or torrefaction pellet plant. In order to derive mass specific supply costs the BD of the feedstock had to be considered. Technical and economic data from (Hoefnagels et al., 2013b) for truck transport and the feedstock specific BDs described in (Annex I: Biomass harvest for pellet production) are used. Again values are derived which make it possible to distinguish between equipment costs and costs generated by fuel and labour consumption. Contrary to the harvesting costs, supply costs have to incorporate another dimension, namely the supply distance. However for the supply of the feedstock to the pellet plant also fixed, distance independent parameters have to be considered for the loading and unloading process. For the loading process fuel consumption of 7 litre diesel per hour are adopted from (Rotter and Rohrhofer, 2014) and the equipment is assumed to be operated by the driver of the supplier truck to load and unload the truck regardless to the handled feedstock within 0.5 hours. The range of the used parameters for the bulk densities according to Table 3 are listed in Table 5 for a truck of a capacity of 60m³ and one driver used for loading, unloading and supply.

	Equipment costs €/km*t	Fuel use kWh/km*t	Labour use h/km*t	Equipment costs fixed €/t	Fuel use fixed kWh/t	Labour use fixed h/t
Minimum	0,0251	0,1520	0,0008	0,6889	1,6373	0,0463
Average	0,0401	0,2434	0,0013	1,1028	2,6210	0,0741
Maximum	0,0902	0,5473	0,0030	2,4800	5,8942	0,1667

Table 5: Range for distance dependent and fixed equipment costs, fuel and labour use derived from (Hoefnagels et al., 2013b) and (Rotter and Rohrhofer, 2014) adjusted to a truck capacity of 60m³ and the bulk densities for the feedstock used in SECTOR.

Supply distances that have to be mastered in order to supply the feedstock from the road side storing location to the pellet production plant depend on several factors including infrastructure, inclination of the terrain, yields of the feedstock and its availability, input size of the pellet plants and logically the proximity of the pellet plant to the feedstock source. A simplified assumption is made to stay close to realistic transport distances plus to enable the generic biomass-to-end-use chain calculation in BioChainS for different pellet plant sizes, torrefied and white pellets and the full list of feedstocks. The minimum supply distance depending on a circle service area around the pellet production site (Schipfer et al., 2013) is calculated depending on two feedstock yield, availability and accessibility combinations. With feedstock yield, availabilities and accessibilities of 0.04 t/ha*a and 0.14 t/ha*a the supply distances to a pellet plant with an input of 40 kt/a of 60km and 30km have to be considered respectively. In BioChainS however fixed pellet plant output sizes are used and the input/output ratios are used to calculate supply distances for comparable biomass-to-end-use chains.

To derive the input/output ratios of the generic biomass-to-end-use chains energy and mass balances of the preparation processes are used. For all cases (including the white pellet plants) the heat[5] necessary to dry the feedstock down to 10% moisture content is considered to be derived from fresh biomass thus increasing the necessary input for both preparation types compared to their exogenously given output sizes. Biomass is considered to be processed at 10 w-% (Obernberger and Thek, 2010) and (Arpiainen et al., 2014b) to produce white- and torrefied pellets with 10 w-% and 5 w-% respectively. Furthermore an average dry basis mass loss of 21 % (Lemus et al., 2014) is calculated for the torrefaction process. This mass is released into the torrefaction gas which is furthermore burned to produce the heat for the torrefaction process. Alternatively the torrefaction gas can be processed to produce biochemicals (Arpiainen et al., 2014a) to improve the economics of the torrefied pellets. This alternative is not considered in the generic biomass-to-end-use chain modelling, instead the gas is considered to be burned to derive heat for torrefaction. Furthermore the assumption is made that the processes can be further optimised and by using the heating content of the torrefaction gas a steady auto-thermal point[6] can be reached where no other fuel is needed for the torrefaction of the feedstock. The output mass specific electricity consumption for milling, feeding system, torrefaction, conditioning and pelletisation is assumed with 144 $kWh/t_{torr\_pellet\_out}$ which is 26% higher than the assumed electricity consumption for white pellets of 114 $kWh/t_{white\_pellet\_out}$ from (Obernberger and Thek, 2010) mainly due to a higher power consumption for the milling process[4].

Next to heat demand (covered by biomass feedstock) and electricity demand for the heat- and electricity cost calculation assumptions for the annual fixed costs and labour costs have to be made to derive levelled costs for the two pellet preparation processes (Schipfer et al., 2013). For both preparation processes the sum of annual capital charge factor of 11,75 % (10% interest rate over 20 depreciation years), of 21 % start-up costs split over 20 years and 4 % for maintenance and insurance is multiplied with the investment costs which is scaled according to a scaling factor of 0.7 ((Schipfer et al., 2013) and (Lemus et al., 2014)). Within the SECTOR project investment costs for a torrefaction plant with $100kt_{torr\_pellet\_out}/a$ size of 20-25 M€ have been communicated. According to (Arpiainen et al., 2014b) a 30% higher investment cost for the torrefaction of lower density feedstock (according to the examples straw versus beech) has to be assumed due to a more constricted annual throughput of the facility (simulated in BioChainS for SECTOR feedstock codes 3,4,5,8,13,14,15,16,17,19,20 and 21). Using the same scaling factor of 0.7 for the white pellet production investment costs for the white pellet counterpart of around 7 M€ can be assumed based on (Obernberger and Thek, 2010). For the consumption of labour the same number of workers for torrefied pellet production as for white pellet production can be assumed taking into consideration the production plant pellet output sizes[6]. For the different plant sizes labour employment in full

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[5] Drying biomass in a belt dryer with 4 $MJ/kg_{ev.water}$ (Arpiainen et al., 2014b)

[6] Personal communication, SECTOR Meeting, Berlin 29.01.2014

time equivalents have been estimated (see Table 6) for the lowest, average and highest salary class necessary to run the plants based on (Personal communication, DBFZ, Ingemar Olofsson and Javier Lemus), (Qian and McDow, 2013), (Svanberg et al., 2013).

Pellet output kt/year	Investment costs M€ torrefaction	Investment costs M€ white pellet	Labour use FTE/average salary class	Labour use FTE/lowest salary class	Labour use FTE/highest salary class
40	12	4	2	1	1
100	23	7	4	1	1
200	37	12	7	2	2
500	69	22	14	2	2
1000	113	36	22	3	3

Table 6: Investment costs for torrefaction of material with bulk density ≥ 300 kg/m³ and investment costs for white pellet production (Obernberger and Thek, 2010) scaled with a scaling factor of 0.7. Full time equivalents (FTE) for three salary classes (average for operation, lowest for administration and highest for management).

Feedstock and technology specific input/output ratios result in varying supply distances for the investigated cases. As already mentioned also the combination of feedstock yield, availabilities and accessibilities is determining for the supply distance and thus the supply costs. Two combinations of these parameters were assumed as outlined above resulting in a lower and a higher supply distance for each pellet production plant size, technology and feedstock. The supply distance is used to calculate country and fuel price specific supply costs (excluding feedstock and harvesting costs) for the feedstock to the pellet production plant. The sum of supply costs and process costs for the production of white and of torrefied pellets is illustrated in Figure 17 for the simulated production plant output sizes and the lower and higher distances respectively and the coniferous stem wood feedstock in Austria. Optimal preparation plant sizes can be expected for this example between 100-200 kt/a and 200-500 kt/a for the lower- and the higher feedstock yield, availability and accessibility combination respectively. For the white pellet production plant no advantages through scaling could be simulated for the specific cases in the year 2013. This result can vary for feedstock with different bulk densities, countries with different salaries for the transportation and pellet production and varying fuel costs.

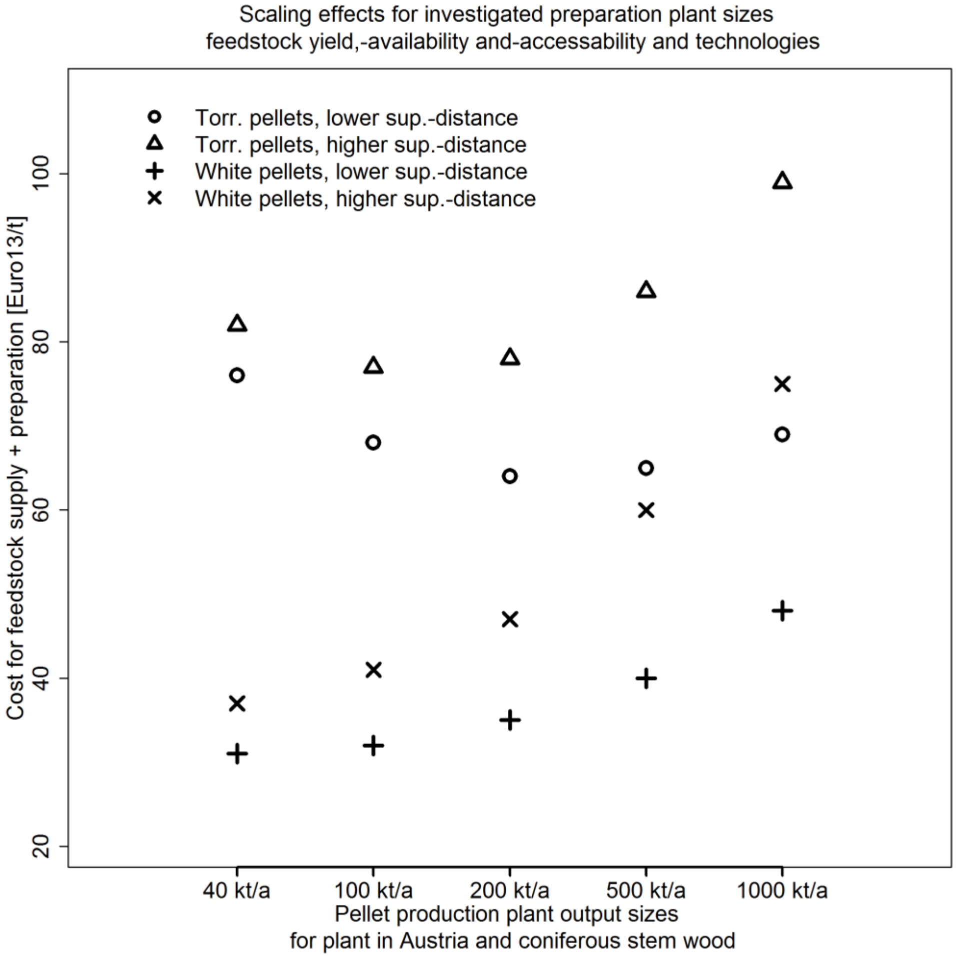

Figure 17: Example of scaling effects for torrefied- and white pellet production due to increasing transport distances and decreasing specific pellet production costs. The lower supply distances are calculated using a higher feedstock yield, availability and accessibility combination compared to the higher supply distance.

Torrefied and white pellets produced differ in characteristics including durability, fines and ash content, bulk density and calorific value. For the generic biomass-to-end-use chain simulation the difference in net calorific value was used exclusively to calculate advantages and disadvantages of torrefied to white pellets. For the full list of feedstock used in BioChainS only the simulation and implementation of the net calorific values was possible. Therefore the net calorific values are calculated using the gross calorific values (GCVs) of the feedstock (Table 3), the assumed moisture contents (M_C) of the produced pellets and the average dry basis mass loss ΔM_{DB} for the torrefaction process outlined above.

$$NCV_{pellet} = \frac{GCV_{feed}(100 - MC) - 2{,}44 * MC}{100} * (1 + \frac{\Delta M_{DB}}{100})$$

With a ΔM_{DB} of 0 as well as 10% moisture content for white pellets and a ΔM_{DB} of 21% and a moisture content of 5% for torrefied pellets and the gross calorific values outlined in (Table 3) net calorific values for white and torrefied pellets in the range of 12-17 MJ/kg and 15-22 MJ/kg are calculated (Table 7).

Pellet types	Minimum NCV MJ/kg	Average NCV MJ/kg	Maximum NCV MJ/kg
White	11,5	15,7	17,3
Torrefied	14,8	20,2	22,3

Table 7: Minimum, average and maximum for net calorific value of white and torrefied pellets according to the gross calorific values of the SECTOR-feedstock and the assumed moisture contents and dry basis mass losses in the torrefaction process.

9 Annex III: Distribution considerations

White- and torrefied pellets are considered to be produced at the origin of the used feedstock. The consumption of the pellets however is simulated to take place in the EU28-region, not specifying the respective end user`s member state. For pellets produced in Russia, Canada, USA or Tanzania transportation to the ports is calculated for three distances by the three modes truck, rail and inland waterway. A 100km transport distance from pellet production plant to the port is simulated for pellet plants close to the port, or 400km as a medium distance or 800km for the maximum distance to a hinterland pellet plant. In all cases a Panamax bulk carrier is used to overcome the average distance from Russia (St.Petersburg), USA (Brunswick), Canada (Halifax) and Tanzania (Chake Chake) to the European ports in Italy (Acitressa), UK (Aberdeen), Netherlands (Amsterdam) and Portugal (Avairao). The average shipping distances are listed in Table 8 and based on (SeaRates.com, 2014).

Port-EU-average	Russia	Canada	USA	Tanzania
km	3575	5306	7346	10496

Table 8:Average distance from Russia (St.Petersburg), USA (Brunswick), Canada (Halifax) and Tanzania (Chake Chake) to the European ports in Italy (Acitressa), UK (Aberdeen), Netherlands (Amsterdam) and Portugal (Avairao).

For the continental transport in the EU28 inclusively Switzerland, Ukraine and Norway another 100km, 400km or 800km are calculated using the three different transport modes truck, rail and inland waterway. These transports are simulated for all pellet chains, for pellets from another continent after shipping to an EU port for the transportation to a large scale end user in the EU28 or to a pellet retailer and for all pellets originated in the EU28, CH, UA and NO to a large scale end user in the EU28 or to a pellet retailer. For further transportation from the pellet retailer to small scale end users another 100km or 200km are calculated using mode specific parameters for a pellets truck (Obernberger and Thek, 2010).

For the calculation of transport costs the same approach outlined in (Annex II: Production plant sizes and supply distances for white and torrefied pellets) using mass specific variable- and fixed costs and fuel and labour consumption is used. Two simplifications have to be stressed which helped to keep the simulation in a computational frame. Torrefied and white pellets are not differentiated with regards to their bulk densities or to other parameters including hydrophobicity, durability and handling safety which will play a decisive role for large distance transportation. These parameters cannot be simulated for the pellets based on the large number of feedstock since there is insufficient literature about these parameters. However first results regarding these parameters can be found in (Pommer et al., 2014),(Nanou et al., 2014a), (Nanou et al., 2014b) and (Abelha et al., 2014). The second simplification to be mentioned is the calculated fuel for transportation. Truck transport (including pellet truck transport) is considered to use exclusively Diesel, transportation on rail electricity in every country and all shipping types heavy fuel oil (HFO).

In Table 9 the fuel types as well as the fixed and distance variable mass specific parameters are listed for the calculated transport modes. Values are derived from literature (Hoefnagels et al., 2013a), (ZSSK Cargo, 2014), (Rotter and Rohrhofer, 2014), (Obernberger and Thek, 2010), (Baltic, 2014) and (UNCTAD, 2013) and are related to the maximum payload in tonnes of the respective transport mode. Fixed equipment costs mostly refer to the hourly cost of the transport mode and the waiting time used for loading or unloading.

Transport mode	Equipment costs €/km*t	Fuel use kWh/km*t	Labour use h/km*t	Equipment costs fixed €/t	Fuel use fixed kWh/t	Labour use fixed h/t	Fuel type used
Truck	0,020811	0,133745	0,000699	0,572308	1,360202	0,019231	Diesel
Rail	0,000033	0,031593	0,000007	0,057600	1,300000	0,012000	Electricity
Waterway	0,001347	0,018441	0,000006	1,151549	1,300000	0,001447	HFO
Panamax	0,000425	0,007450	0,000001	1,151549	1,300000	0,001447	HFO
Pelletstruck	0,027622	0,159182	0,000808	0,828648	1,714263	0,024237	Diesel

Table 9: Mass specific fixed and distance dependent parameters for transportation based on (Hoefnagels et al., 2013a), (ZSSK Cargo, 2014), (Rotter and Rohrhofer, 2014), (Obernberger and Thek, 2010), (Baltic, 2014) and (UNCTAD, 2013).

In order to derive harmonised conclusions about the impact of transport distances on white and torrefied pellet deployment simulated costs for long distance continental transportation (on the European continent as well as in RU, CA, US and TZ) for the three transport modes truck, rail and inland waterway are averaged. To still have a meaningful expression about the cost of transportation over different distances the share of the transport modes for freight transport was used to calculate weighted averages. Share of transport modes used for freight transport are listed in Table 10 based on (EUROSTAT, 2014b), (TNO M&L, 2008), (Worldbank, 2014), (Padova, 2005) and (Brogan et al., 2013). Statistics for all countries for a harmonised time frame could not be acquired.

Region	Road	Rail	IWW	Reference
EU28	75	19	7	(EUROSTAT, 2014)
RU	98	2	0	(TNO M&L, 2008)
TZ	100	0	0	(Worldbank, 2014)
CA	7	93	0	(Padova, 2005)
US	82	13	6	(Brogan et al., 2013)

Table 10: Share of transport modes (in %) used for freight transport based on (EUROSTAT, 2014b), (TNO M&L, 2008), (Worldbank, 2014), (Padova, 2005) and (Brogan et al., 2013).

Summarizing the approach used for calculating the distribution of white- and torrefied pellets it should be mentioned one more time that mass specific costs for transportation are simulated similarly for both commodities resulting in the same costs per tonne white and torrefied pellets. Differences result subsequently by converting the mass specific transport costs into energy content specific transport costs. Furthermore all storage considerations have been neglected since cost shares are expected to be rather low within the entire biomass-to-end-use chain cost calculation as well as storage tests with torrefied pellets within the project are outstanding.

10 Annex IV: Costs for end users and reference fuels

Three different end users are considered. The consumption of white and torrefied pellets through co-firing in coal fired power plants, gasification for the production of synthetic natural gas which can further be used for heat and/or power or chemicals production and the combustion in small scale pellet boilers or stoves. For all end users a EU28-average tax of 11,9% is assumed based on the average percentage of tax on goods and services per GDP from (OECD, 2014a). Mass specific costs calculated for feedstock, supply, (torrefied or white) pellet production and distribution are cumulated and converted into energy content specific costs according to the net calorific values outlined in (Annex II: Production plant sizes and supply distances for white- and torrefied pellets).

Resulting costs for large scale end users are now directly compared with the EU28-average price for coal (see Annex VII – data tables). As already mentioned no capacity effect costs are included. These costs would emerge for advanced (and also poorer) storage, handling and milling properties for torrefied compared to white pellets depending on the co-firing share, the available infrastructure and the coal fired power plant capacity ("SECTOR D3.7 in press," 2015) and cannot be estimated for the generic biomass-to-end-use chain calculation in this study yet.

In the case of gasification, costs and efficiencies of the process have to be considered to produce synthesis gas out of torrefied pellets. A direct comparison between torrefied and white pellets is not possible at this stage of the research. For the entrained flow gasification technology advantages for torrefied pellets can be highlighted due to lower power consumption for milling (Nordin et al., 2013) and due to the shape of the particles; milled torrefied pellets form spherically shaped particles while white pellets form needle shaped particles[7]. This results in similar transportation properties of the torrefied biomass particles to coal particles while more carrier gas is needed for spherically shaped particles from milled non-torrefied pellets. The effect on the overall efficiency of the gasification in entrained flow gasifiers for white pellets could not be estimated but is expected to be significant and in favour of torrefied pellets. An upcoming Deliverable (D.4.7) within the SECTOR project will outline first comparisons for this end user.

For small scale combustion EU averages for heating systems are calculated using weighted averages from the exemplary countries Spain, Germany and Rumania using data from the ENTRANZE database (ENTRANZE, 2014). With estimated 1800 heating hours per year operation and maintenance and annuities are calculated for coal, oil, gas, district heating

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[7] Personal communication; Michiel Carbo, ECN, 15.01.2015

(simplified also with natural gas) and electricity and are averaged weighted by the country specific share of the respective heating system. These annual fixed costs as well as the country specific share of the used heating systems are further averaged weighted by the energy consumption for household heating of the exemplary countries to the EU consumption. This approach results in average weighted fixed costs for heating in Europe of around 45 €/MWh. The calculated weights of the different heating systems are around 54%, 20%, 11%, 9% and 6% for natural gas, fuel oil, natural gas in district heating, electricity and coal respectively. EU28 average prices for these fuels (Annex VII – data tables) are used to calculate an average fuel price for heating to be cumulated with the fixed costs of this reference system. For pellets the costs for pellets delivered by pellets trucks are considered, furthermore averaged annual costs for a pellet central heating system and a pellet stove of 70 €/MWh are used to derive comparable costs of torrefied, white pellet and reference fossil heating systems (Table 11.1 and Table 11.5 in Obernberger and Thek, 2010).

Reference fossil fuel prices are listed in (Annex VII – data tables). Energy prices in USD/toe NCV are acquired from (IEA, 2014) including all taxes and levies. By using yearly conversion rates for USD to € and 11,63 MWh/toe values are converted to €/MWh regarding to the year of query.

11 Annex V: GHG-model extension of BioChainS

The approach used for this study facilitates the extension of the cost calculation of the generic biomass-to-end-use chains with emission calculations for CO_2 emitted throughout the white- and torrefied pellet chains. Since costs of every biomass-to-end-use chain step are based among others on electricity or fossil fuels used, their emission factors are sufficient for the mentioned purpose. From the BioGrace II tool (Neeft and Ludwiczek, 2014) values for the European electricity mix (10-20kV), for hard coal, diesel, natural gas and fuel oil of 707 kg_{CO2_eq}/MWh, 404 kg_{CO2_eq}/MWh, 338 kg_{CO2_eq}/MWh, 258 kg_{CO2_eq}/MWh and 336 kg_{CO2_eq}/MWh are adopted. Only electricity is used for the pellet production process since the heat demand is covered with fresh biomass (Annex I: Biomass harvest for pellet production). The same emission value for electricity is also used for train transportation, while the diesel emission factor is used for truck, inland water way and ocean shipping. Diesel is furthermore used for harvesting and supply of the feedstock (Annex I: Biomass harvest for pellet production).

Emissions for biomass production are derived from (Ecoinvent, 2013) for Eucalyptus, Willow and Miscanthus and applied to the feedstock properties (Annex I: Biomass harvest for pellet production). Therefore it is assumed that the same emissions occur for the production of Bamboo, Paulownia, Poplar, broadleaved and coniferous stem wood as for Eucalyptus and its volume specific emission factor can be converted into mass specific emission factors using the bulk densities given in (Annex I: Biomass harvest for pellet production). Furthermore it is assumed that Reed canary grass emits the same CO_2 volume as Miscanthus. Similar to the production cost calculations in (Annex I: Biomass harvest for pellet production) no emissions are assumed for the production of harvest and other residues as well as saw dust. Especially for harvesting residues this approach represents a simplification since the additional fertiliser needed if the residues are not degrading on the field would account to additional emissions (Kühner, 2013). Emissions for the production of the feedstock used in BioChainS are listed in Table 11.

SECTOR code	Description used in WP2	Emissions for production kgCO2/t
1	Stem wood, conferous without bark	49,8
6	Broadleaves, stemwood with bark	45,7
10	Eucalyptus	48,4
11	Paulownia	48,4
12	Bamboo herbaceuos	54,8
16	Miscanthus	71,7
18	Willow	67,4
19	Reed canary grass	71,7

Table 11: Emissions integrated in BioChainS based on the SECTOR feedstock and (Ecoinvent, 2013). For SECTOR feedstock not listed no emissions are considered for this study.

12 Annex VI: Theoretical considerations

In this annex the already mentioned linear correlation between average deployment costs and deviations for torrefied and white pellets is further examined to identify its driving factors and to derive a relationship to make the breakeven point predictable for every single biomass-to-end-use chain pair.

First the data set was analysed using linear regression. Therefore the data was subset to find the expected perfect fits (vanishing p-value and $R^2=1$) for which every deviation from the average can be perfectly described by the average total deployment costs and vice versa. Next to the factors pellet output size and feedstock costs and type which contribute to different deviations independently from the average deployment costs, two further chain characteristics have to be used for sub setting in order to derive perfect correlations; the country in which the feedstock is produced and processed as well as the type of supply distance for which a long and short distance was calculated for each chain. The distribution, no matter how far and in which modes can be left aside. The correlation factor and in the same time the slope of the parallels observed in the dot plots is around 0.125 and statistically significant (p-value $<2*10^{-16}$) for all chains for which the described characteristics are held constant. In other words, increasing the average deployment costs for any biomass-to-end-use chain pair with the same feedstock, supply distance type, pellet production output size and country of origin by one unit (€/MWh, €/GJ ,€/t, or €/m³) decreases the deviation for the torrefied and increases the deviation for the white pellet chain counterparts per 0.125 units respectively. This is tantamount with a decrease of the difference between the pellet chain counterparts of around 0.25 units per one unit of average cost increase.

The difference or double of the absolute value of the cost deviations from the average cost for biomass-to-end-use chain pairs is illustrated as ΔC in Figure 18. The two plotted drawn-through lines illustrate the relationship between every extra cost in €/t added to the production costs and added energy deployment costs in €/MWh, no matter if these costs occur before (feedstock costs) or after (distribution costs) the pellet production step. The only requirement for these additional costs is that they can be expressed in costs per mass and are equal for torrefied and white pellets which is the case for most distribution modes and costs before the pellet production plant gate.

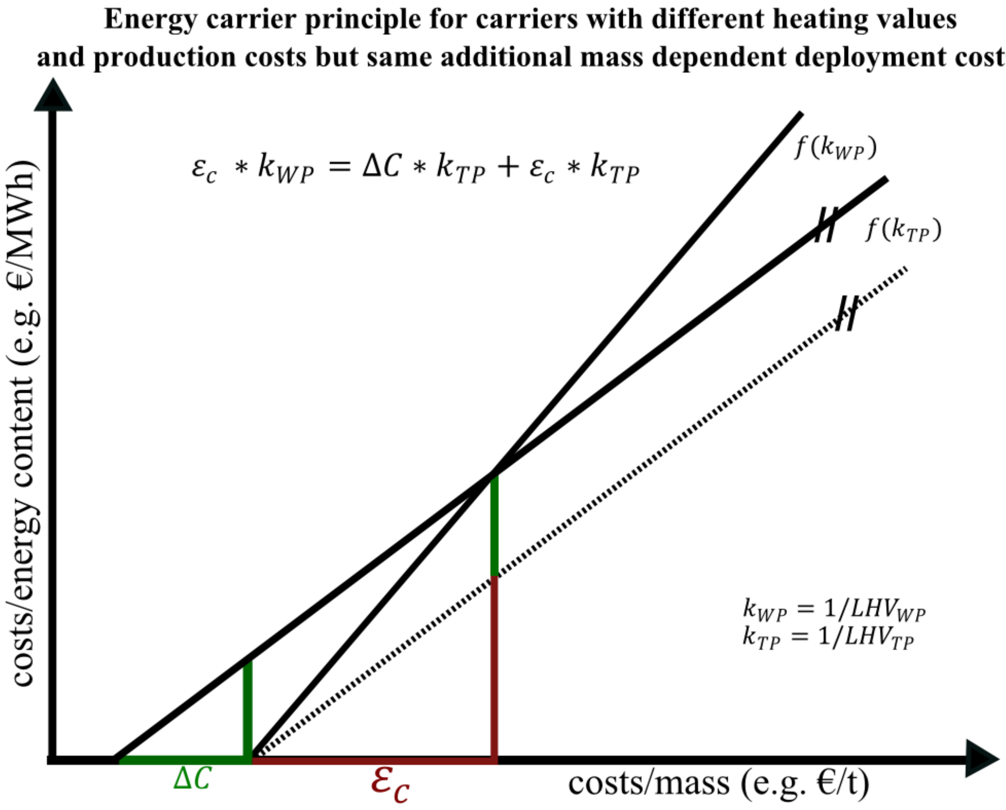

Figure 18: Relationship between break even costs for energy deployed by energy carriers with varying production costs and net calorific values.

Due to the different lower heating values for white pellets (LHV_{WP}) and torrefied pellets (LHV_{TP}) different slopes ($k_{WP}\ and\ k_{TP}$) result for the conversion to additional energy deployment costs. The added mass specific costs ε_c that is necessary to reach the breakeven point between energy deployment of white and torrefied pellets can now be derived geometrically.

The projection of ε_c can be expressed for both energy contents $k_{WP} = 1/LHV_{WP}$ and $k_{TP} = 1/LHV_{TP}$. This leads to a relation using the projection of ΔC as follows:

$$\varepsilon_c * k_{WP} = \Delta C * k_{TP} + \varepsilon_c * k_{TP}$$

The mass specific added costs can now be expressed using the production cost difference and the slopes for the conversion into costs per energy content:

$$\varepsilon_c = \Delta C * \frac{k_{TP}}{k_{WP} - k_{TP}}$$

The fraction containing the slopes can be reformulated using the lower heating values:

$$\varepsilon_c = \Delta C * \frac{LHV_{WP}}{LHV_{TP} - LHV_{WP}}$$

Therefore every biomass-to-end-use chain pair reaches its break even costs when the difference between the production costs equal the multiplication of similar added mass specific costs times the percentage difference between the torrefied and white pellet lower heating values.

The percentage difference between torrefied and white pellet lower heating values is the same throughout all biomass-to-end-use chain pairs in this study. This is due to the fact, that the same torrefaction degree was used for all feedstock as well as the same differences in moisture contents between torrefied and white pellets. This simplification is further explained in (Annex III: Distribution considerations) and leads to a constant elasticity of the cost differences between WP and TP concerning the deployment costs of 29 %. The same consideration holds for volume specific added costs when energy densities are used instead of lower heating values.

The difference between the theoretical value of 29% and the value calculated out of the linear regression of 25% are beside inaccuracies in the simulation also the increased biomass input for torrefaction leading to similar but not identical supply distances and feedstock costs for the white pellet counterparts. The input/output ratios are simulated for each feedstock and torrefied and white pellet processes individually according to the feedstock`s moisture content, heating value and dry basis mass loss due to torrefaction (0% for white pellet and 21% for all torrefied pellets). The varying feedstock characteristics result in varying slopes between 25.1% and 25.5%.

13 Annex VII – data tables

13.1 Energy prices

€2013/MWh	EU-average	Ukraine	Switzerland	Norway	Russia	Canada	USA	Tanzania
Electricty industry	104,7	36,7	99,8	51,7	36,7	67,9	51,4	16,1
Diesel	115,1	68,0	127,8	130,4	95,4	90,8	79,0	65,2
Coal industry	18,8							
Coal household	42,7							
Natural gas industry	40,4							
Electricty household	174,6							
Fuel oil industry	81,4							
Fuel oil household	103,7							

Table 12: 2013 energy prices including taxes and levies based on (IEA, 2014) and an average 2013 exchange rate of 0.75 US$/€ and a conversion factor of 11,63 MWh/toe.

13.2 Labour costs

For labour costs total labour costs from (EUROSTAT, 2014c) are acquired for the European member states and used directly for harvesting, supply and distribution as well as for the medium salary class in the pellet production calculation. For the lowest and highest salary class for the pellet production calculation Decile 5/ Decile1 and Decile 9/ Decile 5 gross earnings ratios (OECD, 2014b) for all genders are used to calculate the deviation from average labour costs. Average wages for non-EU countries are derived from the relation of gross national income of European countries and the respective countries based on (Fischer Weltalmanach, 2014). Gross earning decile ratios for non-OECD countries are borrowed from the US which represents the highest differences between lowest and highest salary class. Salaries for 2013 are listed in Table 13.

€2013/h	Lowest salary	Average salary	Highest salary
Austria	18,2	31,4	60,9
Belgium	20,6	38,0	67,9
Bulgaria	2,2	3,7	7,7
Czech Republic	5,5	10,3	19,0
Germany	17,0	31,3	55,9
Denmark	23,1	38,4	63,9
Estonia	4,6	9,0	18,4
Spain	12,6	21,1	42,1
Finland	21,4	31,4	55,0
France	23,0	34,3	68,2
Greece	8,5	13,6	27,1
Croatia	4,9	8,8	17,6
Hungary	4,3	7,4	17,6
Lithuania	3,6	6,2	12,8
Latvia	3,7	6,3	13,0
Italy	19,3	28,1	43,4
Netherlands	20,5	33,2	59,2
Poland	4,4	7,6	15,7
Portugal	6,2	11,6	21,4
Romania	2,7	4,6	9,5
Sweden	29,2	40,1	66,3
Slovenia	9,2	14,6	29,9
Slovakia	4,7	8,5	17,0
United Kingdom	11,6	20,9	41,5
Ukraine	1,4	2,4	4,9
Switzerland	36,0	53,0	97,1
Norway	30,9	48,5	71,4
Russia	3,9	8,3	19,8
Canada	16,9	33,2	62,8
USA	16,2	34,3	81,6
Tanzania	0,2	0,4	0,9
Brazil	3,6	7,6	18,1

Table 13: Hourly 2013 salaries including taxes for three salary classes based on (EUROSTAT, 2014c), (OECD, 2014b) and (Fischer Weltalmanach, 2014).

14 Abbreviations

Abb.	Description	Abb.	Description
EU	European Union	NCV	Net calorific value
AT	Austria	GCV	Gross calorific value
BE	Belgium	BD	Bulk density
CZ	Czech Republic	MC	Moisture content
DE	Germany	PJ	Peta Joule
DK	Denmark	MJ	Mega Joule
EE	Estonia	MWh	Mega Watt hours
ES	Spain	kWh	Kilo Watt hours
FI	Finland	E&M	Energy and mass
FR	France	Mt	Megatonnes
GR	Greece	Kt	Kilotonnes
HR	Croatia	a	Year
HU	Hungary	l	Litra
LT	Lithuania	m	meter
LV	Latvia	kg	Kilo gram
IT	Italy	GHG	Green house gas
NL	Netherlands	CO2	Carbon dioxide
PL	Poland	HFO	Heavy fuel oil
PT	Portugal	ha	Hectare
RO	Romania	CHP	Combined heat and power
SE	Sweden	db	Dry basis
SI	Slovenia	h	hours
SK	Slovakia	EN	European Norm
UK	United Kingdom	WP	White pellets
CH	Switzerland	TP	Torrefied pellets
RU	Russian Federation	LHV	Lower heating value
UA	Ukraine		
CA	Canada		
US	United States of America		
TZ	United Republic of Tanzania		