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

Deliverable No. D9.1

Description of the relevant biomass-to-end-use chains, including torrefied biofuels

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1 Introduction

1.1 Objective and content of this deliverable

The objective of this deliverable is to describe our approach and examples for biomass-to-end-use chains including torrefaction. So, the objective is twofold: First, we want to discuss methodological aspects of defining and describing biomass-to-end-use chains on different levels of detail. Second, we suggest concrete examples for biomass-to-end-use chains to be investigated in more detail during the further work in SECTOR. D9.2 describes the approaches and different aspects under which this more detailed investigation will take place in task 9.2 (socio-economic assessment), 9.3 (LCA) and 9.4 (environmental assessment). The description of biomass-to-end-use chains in this deliverable will serve as a basis for the further comparative investigations in this work package on the level of the biomass-to-end-use chains and for the development of torrefaction scenarios in Europe up to 2030.

The assessment of the different biomass-to-end-use chains will take place on different levels: (1) Generic chains will be described on a more aggregate level. This will provide the ground for a high number of different chains to be investigated without going in too much detail of regional transportation structures, logistical requirements etc.

(2) For three case studies of feedstock supply a detailed environmental and social impact assessment will be carried out. For related biomass-to-end-use chains, socio-economic investigations and LCA will be done.

(3) In addition, it is planned to investigate three exemplary biomass-to-end-use chains for a more detailed investigation of the economics and logistic requirements.

After the introduction (section 1) section 2 discusses our approach of describing biomass-to-end-use chains. In section 3 we document the data requirement for our analysis. Section 4 describes the structure for deriving generic biomass-to-end-use chains and additional exemplary biomass-to-end-use chains. Finally, section 5 presents the feedstock case studies.

1.2 System boundary

Work package 9 addresses the whole biomass-to-end-use chain and different types of this chain. In general, the system boundary includes the overall biomass-to-end-use chain from the feedstock to the end-use. However, various aspects will be investigated for the different chains: Socio-economic aspects (task 9.2), LCA (9.3) and environmental aspects for selected case studies (9.4). According to the relevance of different aspects in the overall chain, each task puts a slightly different focus on the elements in the biomass-to-end-use chains. Figure 1 shows the focus of the tasks 9.2, 9.3 and 9.4. For tasks 9.2 and 9.4, which focus on certain elements of the whole chain, a properly defined interface to the other remaining elements of the chain is set up.

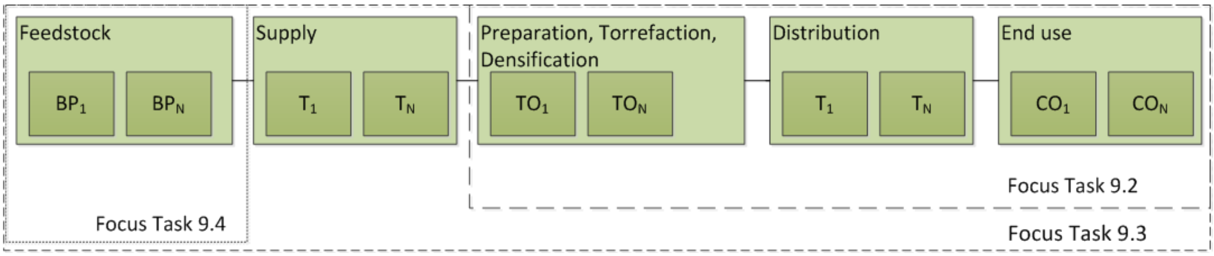

Figure 1. Biomass-to-end-use chain and system boundaries of different tasks in WP9 of the project SECTOR

1.3 Next steps and link to other activities and work steps in the project

The biomass-to-end-use chains defined in Task 9.1 are an important input for the assessment carried out in WP9. Since the defined pathways will be, at least to some extent, based on results produced within the SECTOR project, the results from the economic and environmental assessment in WP9 can be used to discuss optimisation potentials and possible advantages and disadvantages of different torrefaction technologies and torrefaction-based biomass-to-end-use chains.

To increase the quality of the WP9 results, input and actual data from SECTOR WPs 3 (data from torrefaction processes), 6 (logistics) and 7 (end-use) will be used. For this purpose, a data questionnaire (see chapter 3) will be sent to the different project partners. Furthermore, the results of tasks 9.2, 9.3 and 9.4 will be discussed with the different project partners. In this way the results and recommendations derived from WP9 can be used to investigate possible optimisation potentials within the specific SECTOR WPs (3, 6, 7). Furthermore, the results of task 9.4 might contribute to the general discussion on the sustainability of solid biomass for bioenergy and corresponding sustainability criteria and certification systems.

1.4 Literature review

There are currently very few scientific publications available concerning the impact of torrefaction on the biomass-to-end-use chains. In a seminal work Uslu (2008) showed a significant influence of pre-treatment steps on the performance of bioenergy chains, especially on logistics. Torrefied pellets were calculated to have the lowest overall costs in producing Fischer-Tropsch Diesel, compared to pyrolysis and conventional pellets in long-distance transport. Similar, in an earlier work Bergmann (2005) found that the profitability of a biomass to electricity chain based on co-firing of wood pellets in existing coal-fired power stations is expected to increase dramatically when using torrefaction technology instead of conventional pelletisation.

However, a range of publications is available on the logistics of “non-torrefied” (conventional white) wood pellets (Suurs, 2002; Sikkema et al., 2010; Pelletsatlas, 2012) as well as on a wider range of bioenergy carriers comparing or focusing mainly on pellets, wood chips or liquid biomass. (Energidata and Consulting, 2005; Hamelinck et al., 2005; McKeough et al., 2005; van Dam et al., 2009). Further a range of recent studies is dealing with supply and demand on bioenergy markets or aspects thereof, relevant in the context of biomass-to-end-use chains of torrefied biomass. (Hogan Michael, 2010; IPCC, 2011; Sikkema et al., 2011; Uasuf and Becker, 2011; Thek and Obernberger, 2012)

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2 Approach to describe biomass-to-end-use chains

There is a vast number of different types of feedstock that can be used for torrefaction e.g. Eucalyptus, Salix, sawdust etc. (for full list considered in the SECTOR project, see deliverable 2.1). Similarly, there are several different end-uses tor torrefied biomass such as co-firing boilers, (co-)gasification, small scale pellet boilers, bio-chemicals and bio-materials. In between these, a biomass-to-end-use chain must be established to deliver the biomass in a cost-efficient and sustainable way. Rather than describing every possible combination, the approach taken in this report is to identify different segments and different characteristics of the stages of a biomass-to-end-use chain containing a torrefaction process. This will serve as input for development of the torrefaction biomass-to-end-use chain calculation tool to be developed in this work package. Hence, some of the key characteristics of the following stages in the biomass-to-end-use chains will be described:

1. Feedstock
2. Supply
3. Preparation, torrefaction & densification
4. Distribution
5. End-Use

The following different characteristics have implications for biomass supply cost: (1) type of biomass and (2) cost of biomass. The types represent the source of raw material, whether it's agricultural, primary forest fuel or secondary (by-products). Rather than assessing every possible machine for harvesting and forwarding, representative machines will be based e.g. whether biomass is sourced directly from forest, fields or from industry. Furthermore, the cost of biomass differs significantly over the world (Heinimö and Junginger, 2009).

Different characteristics of the biomass-to-end-use chain include (1) type of vehicles used for handling and transportation (2) network design (3) and storage design. Different vehicles are suitable under different conditions. E.g. for forest biomass, it can be cost-efficient to supply loose forest residues when distances are short (Ranta and Rinne, 2006) and at longer distances it can be cost-efficient to transport in bundles (Kärhä and Vartiamäki, 2006). Hence, transport efficiency is dependent on the vehicle chosen and on transportation distance. Biomass-to-end-use chains also differ in the structure, e.g. where in the chain biomass is comminuted. Terminal chipping or crushing is often more efficient than roadside chipping (Kanzian, 2009), but requires an extra handling step which often renders higher system costs (Hall et al., 2001). Biomass can be stored differently with regards to type and design of storage, place, shapes which all has effects for how cost-efficient storage is (Gold and Seuring, 2011). These choices will be incorporated into the biomass-to-end use chain tool.

Production (preparation, torrefaction and densification) can differ on a number of aspects that include (1) technology selection, (2) size and location of plant, (3) torrefaction decisions and (4) densification type, that will have implication for torrefaction and biomass-to-end-use costs. There are principally a number of different technologies, which will be available to choose from e.g. rotary-drum, moving-bed, torbed and fluidised-bed. Torrefaction plants reap advantages from economies of scale (Uslu et al., 2008), but the larger a plant is, the larger the required procurement area becomes, and there is hence a trade-off between production cost and supply cost. Within production there are a number of decisions that have effects on torrefaction cost, e.g. temperature and duration time (Ciolkosz and Wallace, 2011, van der Stelt et al., 2011). Furthermore, different types of processes are available for densification, e.g. either pelletizing or briquetting, which will come at different costs rendering torrefied densified biomass with different product properties that will have implications for the subsequent distribution costs to customers. Costs for different torrefaction set-ups will be supplied by Work package 3 and incorporated into the biomass-to-end-use chain tool.

The distribution of torrefied densified biomass can differ on (1) type and (2) size of vehicle, (3) network structure. Torrefied biomass can be transported by truck, train and different kind of ships. It's often argued that transportation benefits from size, e.g. it's cheaper to transport by Panamax ship (60 000 to 100 000 dwt) compared to Handysize (20 000 to 35 000 dwt). The distribution to customers can be done differently depending on the customer size and location. Some large coal-firing customers with sea access have the possibility to invest in dedicated receiving facilities for pellets, e.g. Essen (Junginger et al., 2008). Other customers might need transhipment to smaller vessels, trains or trucks. Hence, depending on customer situation, there might be the need to tranship torrefied pellets in large ports, e.g. ARA. This will require torrefied pellets with good storage and handling properties.

End-users differ on aspects such as (1) quality demands and (2) demand pattern. Wolf et al. (2006) noted that household users cannot use pellets made from low quality feedstock. In comparison, large-scale users have often made large investments in boilers, accepting a wider range of quality. Furthermore, different end-users are going to have different demand patterns. In the biomass-to-liquid-fuels chain, the demand is likely to be levelled given that the demand on fuels is levelled over the year. From small-scale boilers, there will be a seasonal demand, depending on seasons and climate. Hence, different end users have different demand, which requires different biomass-to-end-use chains, which will be incorporated into the tool.

Figure 2 shows the systematic structure of biomass-to-end-use chains. As explained above, the focus of the tasks within this WP is slightly different: task 9.2 (socio-economic assessment) focuses on the last three steps in the chain (preparation, torrefaction, densification; distribution; end-use), task 9.3 (LCA) takes into account the whole chain and task 9.4 (environmental assessment) concentrates on the feedstock supply.

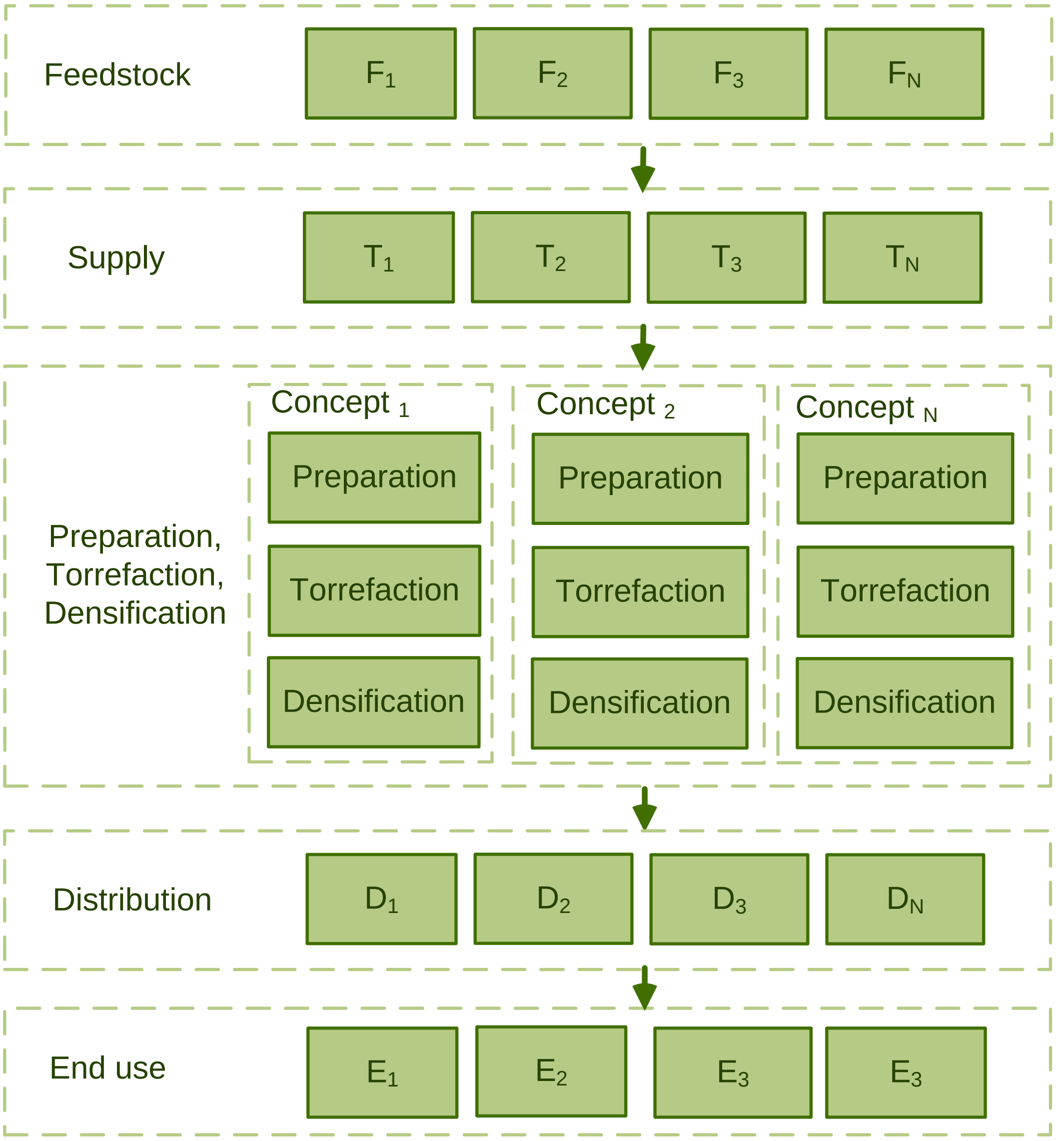

Figure 2. Biomass-to-end-use chain systematic

Figure 2 starts with the feedstock and finishes with the end-use, according to the physical biomass flow in the biomass-to-end-use chain. However, it should be taken into account that in reality the flow of requirements on the product actually goes just the other way round. Essential parts of the whole biomass-to-end-use chain are defined by the requirements and demand of the end-user. The characteristics, plant size, demand pattern and specific requirements of the end-use determine the distribution of torrefied biomass to the end-use. The requirement regarding the fuel quality may determine the specification or selection of torrefaction technologies, densification and preparation aspects which again may have an impact on the supply logistics and the selection of the feedstock. E.g. some customers might be willing to pay for high quality torrefied biomass with excellent storage properties (e.g. small pellet boilers) whereas others only base their purchase on the price (e.g. large coal-fired plants). Hence, there are a number of relevant restrictions, dependencies and interactions along the whole chain which have to be considered in the description of the relevant cases in this project.

These links and interactions are considered in the **biomass-to-end-use chain tool** developed in task 9.1 of SECTOR. The key objectives of this tool are:

- Clear, transparent, consistent and comprehensive description of biomass-to-end-use chains (of torrefied biomass and reference non-torrefied biomass)
- Assessment of costs over the whole biomass-to-end-use chain

For this purpose, the tool will describe biomass-to-end-use chains taking into account restrictions, linkages and dependencies between the single steps of the chains. Moreover, logistical requirements, storage, demand and supply patterns etc. will be considered.

The tool provides an interface to the socio-economic assessment (task 9.2), LCA (9.3) and the environmental assessment (task 9.4) by a clear description of biomass-to-end-use chains. Moreover, the scenario development for the role and future development of torrefaction (task 9.1) will also build on the description of chains within this tool: the scenarios will include the uptake and diffusion of different biomass-to-end-use chains.

Table 1 shows the structure of the tool. For each step in the chain, options will be selected (depending on the remaining parts of the biomass-to-end-use chain which define the overall chain):

- As a first step, the selection of the feedstock takes place. This will be done based on the feedstock list developed in WP2. The process function of this step is to provide the feedstock to a truck accessible road. Cost-calculation is done as a function of feedstock, region and possible additional specifications.
- The supply of the feedstock to the torrefaction plant is split up into three parts:
    - Storage and drying will be defined in terms of the storage type and duration of storage and drying. This selection depends on the transport mode before and afterwards and – as a crucial aspect – on the seasonal supply pattern of the feedstock and the seasonal demand pattern of the end-use. The process function of this step is to change the moisture content, energy density and other feedstock characteristics.
    - For the transport of the feedstock the transport mode including variants such as size of vessels and transport distance may be selected. This selection is done based on the overall setting of the whole chain (i.e. origin of feedstock vs. region of end-use) and degree of scale and centralization.
    - Before and after each transport step loading and unloading is required.
    - The whole step of storage and drying, transport and loading/unloading may be repeated several times with different transport modes, distances etc.
- At the torrefaction plant, three steps may take place: preparation, torrefaction and densification. For each of these steps different options may be selected from a list of

technologies, depending on the specification of the biomass feedstock. As a process function, each of these steps changes the fuel characteristics (energy density, bulk density, moisture content etc.). Between the different processing steps, storage might be required as well.

- During the distribution step, the torrefied biomass is transported to the point of end-use. The general description of the distribution is identical to the supply: i.e. storage, transport and loading/unloading are conducted depending on the seasonal supply/demand patterns, the logistical requirements etc.

- For the end-use, different pre-defined end-uses will be taken into account. The requirements of these end-uses regarding the biomass fuel, seasonal demand patterns etc. finally define the whole biomass-to-end-use chain. In the biomass-to-end-use tool, after the selection of all the pre-steps in the chain, only those end-uses may be selected with corresponding demand characteristics. I.e. the other parts of the chain have to be selected in a way to ensure the corresponding characteristics of the torrefied biomass.

Since the characterisation of each step differs depending on the region where it takes place (due to staff costs, electricity mix, energy taxation etc.), for each step a selection of the regional setting may be provided. Since a very detailed regional investigation is beyond the scope of this project, this will be done by a rough clustering of different world regions, e.g. developing countries, newly industrialised countries, industrialised countries.

Table 1. Basic structure of the biomass-to-end-use chain tool

		Select options	Dependencies / restrictions	Process function	Cost calculation as a function of …
Feedstock	Feedstock material + type of region of origin	Selection based on the list of feedstock provided by work package 2		provides feedstock to truck accessible road	f (feedstock type, region)
Supply	Storage, drying 1-n	Storage type and duration	transport mode (before and) after; seasonal patterns of the feedstock supply and end-use demand	provides storage and / or drying; may change moisture content, energy density etc.	f(feedstock characteristics, storage type, duration, logistical requirements)
	Transport 1-n	Select: R (Road), T (Train), S (Ship) + variants + distance (km)	Origin of feedstock, general type of biomass-to-end-use chain	transports feedstock from A to B	f(transport mode, distance, feedstock characteristics)
	Loading / unloading 1-n	Default selection by the tool depending on: transport mode before and after; characteristics and requirements of the feedstock		unloads/ loads feedstock to other transport mode or storage;	f(feedstock characteristics, storage type, duration, logistical requirements)
Preparation, torrefaction, densification	Preparation	Select from pre-defined preparation processes, specification of scale	characteristics of the feedstock	changes feedstock characteristics (e.g. bulk density)	f(feedstock characteristics, preparation process (and specification))
	Torrefaction	Select from pre-defined torrefaction processes (rotary-drum, moving-bed, torbed, fluidised-bed), specification of scale	characteristics of the feedstock after preparation	changes fuel characteristics	f(characteristics of prepared biomass feedstock, torrefaction process (and specification/ mode/output characteristics)
	Densification	Select from pre-defined densification processes	restricted by the characteristics of the torrefied biomass	changes fuel characteristics (e.g. bulk density, storage requirements …)	f(characteristics of torrefied biomass, densification process and specification)
Distribution		see above: „Supply“			
End-Use		select: (co-)firing, (co-) gasification, pellet boilers, bio-chemicals	restricted by the characteristics of torrefied biomass fuel	converts torrefied biomass into end-use (electricity, heat, bio-materials, …)	depends on system boundary => to be defined for each type of end-use

The biomass-to-end-use chains described in this tool will be input both to the socio-economic assessment in task 9.2 and the environmental assessment via LCA in task 9.3. The results of the LCA will be imported back to the biomass-to-end-use chain tool. This ensures an overall comprehensive assessment of defined systems.

3 Data requirements

In this section, we will describe the data requirements for the analysis of biomass-to-end-use chains and the characterisation of various steps. This will be split into the elements of the chain. We follow the structure of the questionnaire set up in order to collect the required data. The information generated with the help of the questionnaire will be used for i) the definition of different biomass-to-end-use chains in task 9.1, ii) partly for the assessment of socio-economic parameters in task 9.2 and iii) as an important factor in the assessment of environmental impacts from a large scale use of torrefaction technologies in WP9 tasks 9.3 & 9.4.

General settings that hold for each step in the chain are:

- Cost data and prices refer to Euro 2012.
- We distinguish between costs and prices: Costs reflect the expenses for producing a certain product or service. Prices reflect the intersection of supply and demand on a market. We are aware that data of costs and prices in some cases are not easy to be separated. We will try to document clearly the type of cost or price data.

Since the characterisation of each step differs from the region where it takes place (due to staff costs, electricity mix, energy taxation etc.), for each step a selection of the regional setting should be provided.

3.1 Feedstock

The data demand for the part of feedstock production/characterisation comprises several parameters related to feedstock production systems under consideration of specific regional aspects as well as cost parameters and a general characterisation of the feedstock. The questionnaire(s) for the data collection of the feedstock production and characterisation will be sent to WP2. Furthermore, it will be used in the case studies in task 9.4 to collect information for the production of suitable feedstock in different regions.

The data demand is structured into six categories. These categories include:

i) general information about feedstock & production system,
ii) information about the soil quality,
iii) water use and efficiency, water quality,
iv) information for the assessment of biodiversity issues,
v) information for the assessment of impacts from land use and land-use change,
vi) information for the assessment of economic parameters.

As an example, the parameters for the data category “general information about feedstock & production system” are shown in the following Table 2.

Table 2 data demand for feedstock production/characterisation

General Information about feedstock & production system		
Parameter	Unit	Comments
Name of the Feedstock		if residue or waste
Location of the feedstock plantation	admin unit (district or municipality	
Total study area	ha	
Total area of bioenergy feedstock production	ha	
Soil type	If possible according FAO soil classes	e.g. soil fertility in forests; soil types, etc.
Productivity of bioenergy feedstock	t/(ha*a) or m^3/(ha*a)	
Net biomass growth	t/(ha*a) or m^3/(ha*a)	applicable to forest resources; e.g. plantation interval (crop rotation), climate and irrigation specific yield, intercropping or coupled with livestock production; to be combined with the total wood resources harvested/collected or direct capture of ratio
Sustained yield	t/(ha*a) or m^3/(ha*a)	Only applicable to forest resources
Amount of deadwood used	m^3/(ha*a)	Only applicable to forest resources; large share of deadwood is likely to increase forest invertebrate biodiversity, target values depending on case study
Diesel use for cultivation+harvesting	l/(ha·a)	
N-fertilizer	kg N /(ha*a)	
P-fertilizer	kg P /(ha*a)	
K-fertilizer	kg K /(ha*a)	
Lime	kg CaO /(ha*a)	
Pesticides	kg/(ha*a)	
amount of used seed	kg/(ha*a)	
irrigation	m^3/(ha*a)	
Herbicides	kg/(ha*a)	
Amount of organic fertilizer	kg/(ha*a)	
Electricity for drying	kWh/(ha*a)	
Fuel oil (if others pls. specify) for drying	MJ/(ha*a)	
moisture/water content of the produced feedstock	%	
Bulk density	kg/m^3	
Lower heating value	MJ/kg	

3.2 Supply

The transportation, storage and logistics of the feedstock to the plant for the preparation, torrefaction and densification of biomass are summarized under the category supply. It is the sum of several subsets of transportation modes (truck, railway, ship) including storage and drying systems after each transportation step. Table 3 shows the data requirement for each of these subsets. The data is structured according to the following categories:

i) Means of transport

ii) Transport distance

iii) Costs of transport

iv) Jobs for transportation

v) Storage and drying

Table 3 data demand for each subset in the supply

General Information on each subset of the supply system Parameter	Unit
amount and type of biomass transported	t feedstock/a
used means of transport for providing subset 1 (e.g. truck, train, barge)	
payload of the used transport mode	t
used transport energy (e.g. diesel, electricity)	
specific energy used loaded	l fuel/km or kWh el/km
specific energy used unloaded	l fuel/km or kWh el/km
transport distance (loaded) of subset 1	km
transport distance (unloaded) after provision of subset 1	km
provided subset 1 per mean of transport and truckload	t feedstock/(transport and truckload)
Total transport costs for the amount and distance indicated above	€2012
Staff costs for the used means of transport	€2012/km
Costs for loading	€2012/t
Costs for unloading	€2012/t
Vessel/Truck/train costs excluding staff and fuel/energy costs (please specify whether this value refers to cost of equipment or market prices)	€2012/t/km
Jobs related to transportation	Full Time Equivalent (FTE)
amount and type of biomass transported	t feedstock/a
Storage / drying	
Type of storage/drying	
Duration of storage	days
Costs for storage	€2012/t

3.3 Preparation, torrefaction, densification

Data for the sections of torrefaction and densification in the overall value chain are separated into the categories:

i) specification of the plant concept

ii) economic data and

iii) social data.

Data related to the plant concept includes the general feedstock requirements, plant availability and location and figures related to the mass and energy balance of the torrefaction or densification processes. Economic data include the investment costs for the different plant components, capital costs (branch-typical depreciation time and interest rate), costs for operation and maintenance (incl. energy and staff costs), operating hours and simultaneity factor for electric or heat installations as well as costs for the biomass feedstock or respectively torrefied material and revenues for by-products. The social data requested includes the number of Full Time Equivalent (FTE) staff required for different positions in a torrefaction or pelletisation plant.

The data will be requested from the partners of WP3 for the torrefaction part and WP4 for the densification part.

3.4 Distribution

The distribution of torrefied biomass to the end-use is the sum of different transportation subsets. Thus, although the structure of the transportation and logistics in the distribution (transportation of torrefied/densified biomass) might be very different to the supply-step (transportation of raw biomass), the structure of data requirement is similar to the supply-step. Whereas the supply to torrefaction plant is likely to be done by truck, distribution of torrefied biomass is likely to be done in different kind of ships or train to utilize the potential transportation benefits of torrefied densified biomass. Given cost of ocean transport varies significantly throughout the year and between years, it will be specified what type of contract that is used for setting transportation price (long-term versus spot purchases of transports).

3.5 End-Use

The following end-uses will be taken into account: Co-firing boilers, (Co-)gasification, small scale pellet boilers and bio-chemicals and bio-materials.

In contrast to the elements of the chain explained above, for the end-use, the system-boundary for the socio-economic assessment has to be defined case by case. Three general approaches are possible:

1. End-use-gate: In this approach, the system boundary would be the gate of the end-user, e.g. the co-firing plant. So, for the economic assessment the price of torrefied biomass delivered to end-use would be relevant, i.e.: which price does the market allow the end-user to pay for the torrefied biomass. However, this approach would neglect the different end-use specifications of the torrefied and the reference end-use case and thus also the different cost-structure of the two cases.
2. Difference in the end-use cost structure: In this approach, for the economic analysis the key starting point would be the price of non-torrefied biomass (or other energy carrier as a reference case) delivered to end-use, i.e. which price does the market allow the end-user to pay for the biomass. As a second step, the additional (positive or negative) investment and operation and maintenance costs for torrefaction end-use compared to using non-torrefied biomass (or other energy carrier) in the end-use would be taken into account. Using this approach there would be no full assessment of the end-use as the system boundary is going directly through the end-use.

3. Full end-use socio-economic assessment: This would require a complete data set (e.g. investment costs, O&M, fuel costs, revenues of (by-)products etc.) of all end-uses and the corresponding reference cases.

The choice among these three approaches depends on the data availability for the end-use systems and will probably also differ among the different categories of end-uses.

So, also the data requirement differs for each of these system boundaries.

In any case, the following data are required:

i) Seasonal demand patterns: Energy production pattern over the year (monthly): Which is the amount of pellets/torrefied material consumed per month over a year?

ii) Location: Which locations of end-uses are relevant? Is it directly accessible by train, inland ship, oversea ship? Can they receive Panamax or smaller barge? What is the distance to larger ports (e.g. ARA)?

iii) Storage: What are typical storage amounts for these end-uses during the year?

iv) Technical data for conversion processes, in particular conversion efficiency

v) Economic data for conversion processes, (same as in 3.3 for preparation, torrefaction, densification technology) in particular:

   a. Investment costs
   b. Operation and maintenance costs, including auxiliary energy demand and material input
   c. Revenues of by-products

4 Overview on biomass-to-end-use chains to be investigated

In this section we provide an overview on biomass-to-end-use chains to be investigated in WP9 of SECTOR. We distinguish three levels of our investigation: On the first level we take into account a number of generic biomass-to-end-use chains without clear reference to a certain region and transport route (section 4.1) to be created with the tool mentioned in section 2. On this level, we are able to compare a large number of generic systems. On the second level, we document a smaller number of exemplary biomass-to-end-use chains, which we will investigate on a higher level of detail (section 4.2), in particular with respect to techno-economic and logistical aspects. These examples serve as illustration of the generic cases and are based on currently relevant biomass-to-end-use chains. The third level refers to the case studies described in section 5. For these case studies a comprehensive environmental assessment (task 9.4) will be carried out. Also socio-economic aspects will be investigated as far as required data is available from the case study investigations.

The three levels of our investigation support each other. The detailed investigation of concrete cases provides the basis and validation for the generic supply chains. On the other hand, the generic supply chains based on literature values may serve as default in case that for some detailed aspects of the concrete biomass-to-end-use chains data is missing.

4.1 Generic development of biomass-to-end-use chains

According to Table 4 we distinguish 8 principle clusters of generic biomass-to-end-use chains: Four types of regional origin of feedstock combined with two levels of centralisation. These levels of centralisation are associated with the scale of torrefaction plants: (1) small/medium scale torrefaction plants are typically located relatively close to the region of biomass supply and thus there is a short transport distance to the torrefaction plant; (2) the large scale torrefaction requires biomass resources from a larger region; the torrefaction plant is typically located near the port or other long-distance transport logistics with longer transport distances from the biomass supply region to the torrefaction plant. Not each of the 8 generic clusters will be as relevant as the others. E.g. large scale torrefaction is probably less relevant for an Intra-European torrefaction-based biomass-to-end-use chain than for an oversea feedstock origin. The transport distances shown in the table below are indicative and may change in the final generic biomass-to-end-use chains.

The selection of the feedstock will be done depending on the region of origin. The selection of the preparation, torrefaction and densification technology will be done based on the feedstock characteristics and the scale availability of the specific technologies.

End-use will be assigned according to the specific requirements of the end-use regarding fuel specification. Moreover, the seasonal demand pattern of the end-use combined with the seasonal supply pattern of the feedstock determines the required storage facilities. The combination of large scale torrefaction with large scale end-uses seems more likely but is not necessarily the only relevant combination.

From this combination of 8 clusters with a number of feedstocks, preparation, torrefaction and densification technologies as well as end-uses, a large number of possible combinations results. This range of combination sets up the frame from which a selection of most relevant biomass-to-end-use chains will be done. The tool developed in task 9.1 will allow to select and describe the relevant chains in a consistent manner and assess the economic viability of those chains.

Table 4. Structure for setting up generic biomass-to-end-use chains

		Small/medium scale torrefaction (near biomass supply)	**Large scale torrefaction** (near port/long distance transport logistics/end-use)
		Selection of preparation/ torrefaction/densification depending on feedstock-requirement and scale-availability	
Oversea developing or newly industrialised country	Selection of feedstock depending on regional availability	R50 – TORR – R100 - S+9500 - T200	R50 – R+100 – TORR - S+9500 - T200
Oversea industrialised country		R50 – TORR – T100 - S+7500 - T200	R50 – T100 - TORR – S+7500 - T200
Long distance continental		R100 – TORR – R200 T1000 – R100	R100 –R+200 – TORR - T1000– R100
Intra-Europe		R50 – TORR – R+300	R200 – TORR – T500

4.2 Exemplary biomass-to-end-use chains

The analysis of exemplary biomass-to-end-use chains are based on currently or recently operated conventional biomass chains, which serve as a basis for modelling a corresponding chain including torrefaction consisting of the same patterns. These exemplary biomass-to-end-use chains demonstrate the detailed economics of specific biomass products from the raw material in producing and exporting countries up to end-use in the destination conversion plant in the EU. In this way, they serve as exemplary investigations to concretise generic supply clusters described in 4.1. The process and logistic chain follows the general steps illustrated in Table 5 and outlined specifically in Figure 3.

The following examples are described in terms of their specific process and operating parameters:

- Industrial wood pellets produced in Northern America, in a 120 000 t/a pellet plant. Transport to export harbour via railcars. Shipping by handysize or panamax vessel to Rotterdam harbour. Delivery to and end-use in co-firing coal power plants located in different inland distances from Rotterdam harbour. (corresponds to large-scale production and supply case)

- Quality wood pellets produced in Central Europe from regional raw material. Pellet supply is around 100 km with intermediate storage at biofuel traders. End-use in small pellet boilers for generating space heat and warm water (corresponds to Intra-European small-scale production and supply case).

- Industrial wood pellets produced in Northwest Russia in a 40 000 t/a pellet plant, transported by rail to St. Petersburg and further on to Rotterdam harbour by small vessels. Delivery to and end-use in co-firing coal power plants located in different inland distances from Rotterdam harbour. (corresponds to medium-scale production and supply case)

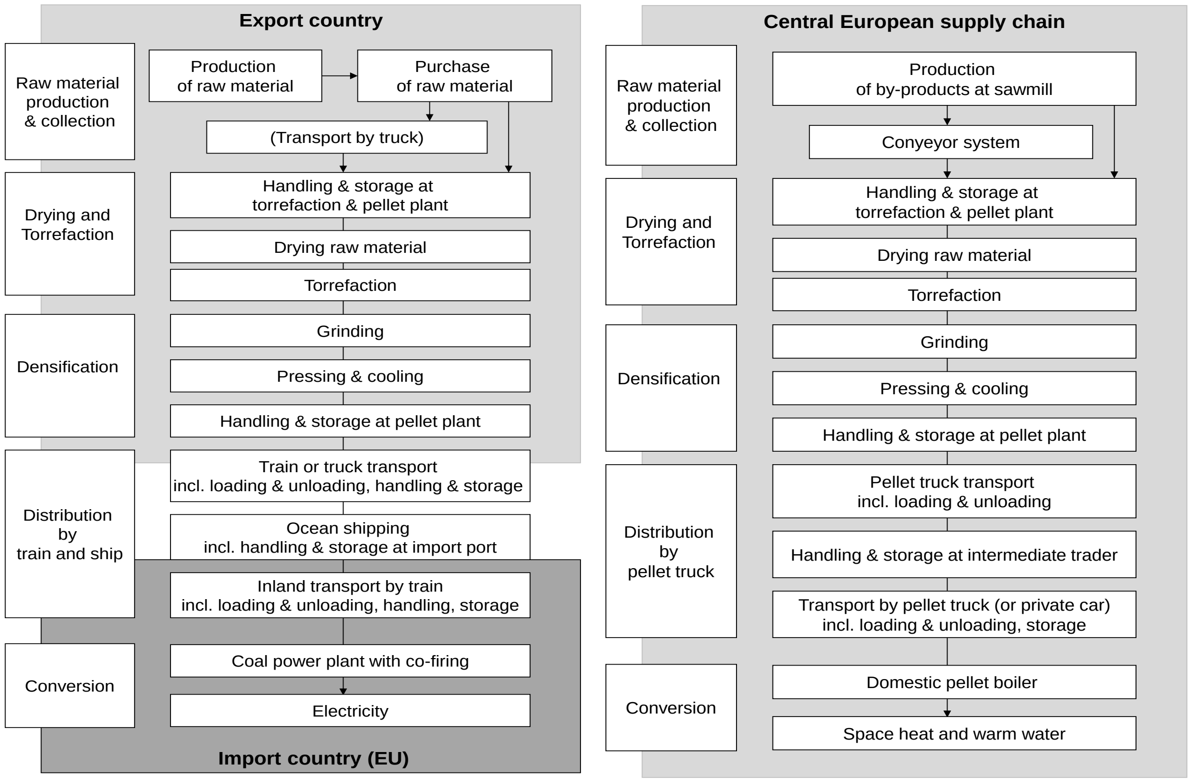

Figure 3: Exemplary biomass-to-end-use chains: pellets imported to Europe (left), domestic pellets (right).

4.2.1 Exemplary biomass-to-end-use chain 1: North American pellets to Europe

Industrial pellets produced in Northern America are mainly destined for export, particularly to co-firing power plants in Western Europe.

The raw material considered for the pellet production is sawdust and shavings from spruce, which are transported from sawmills or harvesting sites to the pellet plant at an average of 100 km (Sikkema, 2010; Urbanowski, 2005). For the drying operation a rotary drum dryer usually used in North America is modelled with 1 000 kWh/$t_{evaporated\ water}$ heat demand for drying (Urbanowski, 2005; Magelli, 2009).

The transport of bulk pellets to the export port is operated with railcars and is assumed to be 500 km to the harbour according to typical pellet plant locations. After storage in silos and loading with conveyor belts at a dedicated pellet terminal the pellets are shipped with a handymax (up to 50 000 deadweight tons capacity) or panamax vessel (up to 80 000 deadweight tons capacity) with latter one partially loaded with pellets to Rotterdam.

From Rotterdam harbour, several delivery options for the transportation to the destination conversion plant exist. For power plants located in Belgium or the Netherlands and accessible by waterways, the pellets are often transhipped to river barges with around 4 000 t capacity and directly shipped to the conversion plant´s port. For conversion plants not accessible by waterway, the delivery of pellets via trucks (short distances up to approximate 100 km) or train is suitable. For the considered biomass-to-end-use chain the delivery of pellets is modelled for 75 km, 400 km and 1500 km distance from ARA port to end-use conversion plant.

The current end-use of industrial pellets is usually the co-firing in coal power plants with steam turbine. This option has been destined for the present example. The technology and economic data are based on an 800 MW_{el} power plant (BMU, 2010).

4.2.2 Exemplary biomass-to-end-use chain 2: Central European pellets for domestic use

Many pellet production plants in Central Europe are co-located to sawmills using synergies like the direct supply of by-products (sawdust, shavings) and heat from converted bark from integrated biomass heat (and power) plants. The produced pellets in this example are destined for domestic use in small-scale pellet boilers and thus are produced in A1 quality according to ENplus. The pellet chain described is based on the detailed assessments in Obernberger, Thek (2010), the pellet chain evaluation in the master thesis of Maderthaner (2012) and from expert interviews (Lugner, 2012; Pichler, 2012).

The typical raw material used for pellet production is softwood residues from the wood industry. Usually, the roundwood is transported 50-100 km to the saw mill. Other distances can be considered for cross-boarder roundwood supply. The sawdust and shavings resulting from the cut roundwood are directly supplied to the co-located pellet plant. For the calculations a 40 000 t/a pellet plant based on Obernberger, Thek (2010) is modeled.

The produced pellets are directly loaded into a dedicated pellet truck and transported over a distance of 50 km on average to an intermediate storage or trader. Here pellets are stored in a silo. After sieving, the pellets are loaded to the delivery truck and transported approximately 50 km by pellet truck to the end-user (domestic household). These distances and transhipment can be adapted in distance and transportation mode for assessing other Intra-European biomass-to-end-use chains.

At the end-user the pellets are filled into the storage facility and used in a 15 kW pellets boiler for generating warm water and space heat.

4.2.3 Exemplary biomass-to-end-use chain 3: Russian pellets to Western Europe

The assessed region of Northwest Russia has vast wood reserves and a strong wood processing industry (e.g. Karjalainen, 2010; Rakitova, 2009; Raitila et al., 2009) and has direct access to the Baltic Sea. The biomass market is still in its infancy, but the number of pellet production plants is constantly growing. By 2009, about 800 000 t/a production capacity have been identified in Northwest Russia (Rakitova, 2009). The bulk part of produced pellets is exported with most pellets destined for the EU.

The raw material assumed is sawdust from soft wood with a moisture content of 55 %. For the considered supply case no or minor transport due to co-located sawmill or a close distance from the raw material supplying site to the pellet plant is assumed.

Following the current pellet plant capacities (Rakitova, 2009) for the Russian case a smaller pellet plant size with 40 000 t/a capacity is taken into account based on Obernberger, Thek (2010). The pellets produced are assumed to be B quality according to ENplus and handled in bulk.

The distance from pellet plant to the export harbour St. Petersburg is set 400 km according to the actual pellet plant locations (Karjalainen, 2010; Rakitova, 2009) and is assumed to be operated by train. The transport across the Baltic Sea takes place with smaller vessels and a load capacity of about 4 000 t (Hamelinck, 2005). The distance to Rotterdam is around 1 600 km (Marine, 2012).

The delivery to end-use conversion plant is similar to the exemplary chain 1 described above.

Table 5: Basic elements of exemplary biomass-to-end-use chains for torrefied biomass

		Example 1 (medium-to-large-scale torrefaction oversea)	Example 2 (small to medium scale torrefaction EU)	Example 3 (small-to medium scale torrefaction non-EU)
Feedstock	Feedstock material + type of region of origin	sawmill and forest residues, North America	sawmill residues, Central Europe, EU	sawdust, Russia
Supply	Storage			
	Transport 1	T.100	T.50	T.30
	Loading/unloading facilities, storage			
Preparation, torrefaction, densification	Preparation	Medium scale	Small- to medium scale	Small-to-medium scale
	Torrefaction			
	Densification			
Distribution	Storage			
	Transport 1	T.500	T.50	T.400
	Loading/unloading facilities, storage			
	Transport 2	S.16500	T.50	S.1600
	Loading/unloading facilities, storage			
	Transport 3	T.75 - 1500		T.75-1500
	Unloading facilities, storage			
End-Use		large scale co-firing	domestic use in small pellet boiler	large scale co-firing

5 Case studies of feedstock supply

The different feedstocks suitable for the torrefaction process are likely to originate from different regions of the world. Therefore, case studies are defined to represent different socio-environmental conditions under which relevant feedstocks already are or may be produced in the near future.

The following three major case studies will be conducted:

- Developed country with enforced legislation concerning the sustainability of biofuels, binding for biofuels and bioliquids, but supposed to be applied to solid biofuels by national solutions (legislation, schemes, standards) in the EU member states – e.g. from Central Europe (Austria; Saxony, Germany; etc.) (EC, 2010)
- Developed country with a differing/minimum legislation on the sustainability of biofuels, but with voluntary schemes applied to ensure broader sustainability of biofuels – e.g. North America (Georgia, USA) (Van Dam, Junginger et al., 2010; Chum, Faaij et al., 2011)
- Developing country without a binding or with a weakly enforced legislation and without largely applied standards and schemes on the sustainability of biofuels – e.g. sub-Saharan Africa (Tanzania) (Maltsoglou and Khwaja 2010)

In addition to the listed regulatory differences, the case studies also represent different climates and feedstocks (temperate - Saxony, subtropical - Georgia and tropical - Tanzania). It is planned to analyse at least one identical feedstock (such as sorghum or maize straw) across all case studies to allow for a better comparison of sustainability indicators.

Regarding the agricultural practices, conventional rainfed tillage agriculture with high fertilizer input is dominating. Organic agriculture is practised on <4 % (2011) of the agriculture land in Saxony (SMUL, 2012) and <1 % in Georgia (2007) (Vilsack and Clark, 2009). Conservational agriculture practices (i.e. no-till) are applied on 34 % of the agricultural land in Saxony (2011) (SMUL, 2012). In Georgia e.g. 29 % of corn production land (2010) (USDA, 2012) and 34 % of the cotton production land (2007) (Horowitz, Ebel et al., 2010) are managed under no-till regimes. Other aspects influencing land management and thus sustainability are e.g. farm size, ranging from medium to large scale farms with on average 86 ha in Georgia (2007) (Vilsack and Clark, 2009) to 150 ha in Saxony (2010) (StLa, 2011) for the developed countries. Contrastingly, in Tanzania – representing developing countries –, smallholder farms with sizes between 0.2 and 2 ha are dominating on 85 % of the arable land and no or minimal fertilizer use has been reported (Janssen, 2005; Maltsoglou and Khwaja, 2010). Additionally, Tanzania is a good example for tropical and especially sub-Saharan countries with weak energy access on the one hand and a large additional feedstock potential due to the expected increase in crop yields and the use of additional agricultural land on the other hand (Wiskerke, Dornburg et al., 2010).

Furthermore, the choice of different case studies provides the opportunity to assess different regional priorities regarding sustainability e.g. social or environmental or distinct categories of environmental sustainability. Van Dam et al. (2010) and Stupak et al. (2011) argued, for example, that developing countries emphasize social and economic sustainability such as providing sufficient energy, whereas developed countries concentrate on environmental sustainability as the former criterion is ensured for the short-term.

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