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Market diffusion of biomass-to-end-use chains for solid sustainable energy carriers from biomass by means of torrefaction

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ABSTRACT: Increasing demand for biomass asks for innovative preparation and densification technologies for this commodity. Torrefaction can help to produce denser bioenergy carriers and therefore to promote the large-scale implementation of bioenergy. This paper addresses the question of how to simulate the market diffusion of this technology including possible impacts on several social and environmental aspects. A software tool will be developed to compute scenarios for the diffusion of torrefied biomass-to-end-use chains based on a comparative analysis of these chains which are generated by combining the results from different modules. These, partly interdependent modules operate with optimisations and uncertainty calculations to find best and most likely constellations for intra- and intercontinental biomass supply to different end users. Subsequent work will integrate knowledge and data from experimental research done within the SECTOR project funded by the EU FP7 Program and will be combined with socio-economic-, environmental assessments and LCA to derive conclusions and recommendations about environmental sound deployment strategies of torrefied biomass and torrefaction technologies. The first result will be a thorough assessment of a high number of representative theoretical biomass-to-end-use chains for solid energy carriers by means of torrefaction that could become relevant in the next decade.

1 INTRODUCTION

1.1 Objectives of this research

To investigate the possible market diffusion of the torrefaction technology under strict sustainability boundary conditions, the experimental work done within the FP7 SECTOR project[1] is accompanied by extensive desk studies and modelling work presented in this paper. This work has the objective i) to identify and define relevant biomass-to-end-use value chains for torrefaction-based bioenergy carriers, ii) to assess these chains in terms of socio-economic indicators and iii) to develop deployment strategies and scenarios based on these chains.

1.2 Key structure of this paper

To investigate the full potential of torrefied material, it is necessary to calculate biomass-to-end-use chains including different combinations of feedstocks, preparation technologies and end users. Chapter 2 starts with an insight into these biomass-to-end-use constellations, pointing out the need for a software tool and its requirements. The last part of the next chapter shows how the biomass-to-end-use chain simulation tool (BioChainS) will serve to finally derive deployment strategies and scenarios and will deliver a basis for a full sustainability assessment, including socio-economic- , life cycle- (in terms of energy and GHG balances) and full environmental assessment carried out by the project partner. After a short introduction into the structure of the documentation of the mentioned basis in chapter 3 the storylines for the market diffusion simulation will be explained in detail in chapter 4.

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1.3 System boundaries

Biomass-to-end-use chains start at the biomass feedstock production site. For the economic assessment a detailed investigation of biomass production and harvesting is beyond the scope of this work. Prices and properties for the biomass obtained in the forest, the plantation site or at the biomass processing industry will be sufficient for the calculation. As fuel properties can have an effect on the end-use, the system boundary at the other side of the biomass-to-end-use chain at least has to consider the combustion efficiency of those biofuels for the generation of heat and electricity, or the production efficiency of other end-user types and resulting retooling costs. Costs of providing the produced renewable heat and electricity or the produced bio-chemical to the consumers will not be included in this investigation, because it is not relevant for the objective of this research. Torrefaction technologies are assumed to be available commercially at the end of the current decade. Therefore the temporal horizon for the deployment scenario calculation will cover the time range beginning with 2020 and ending with the year 2030.

The different technological and logistical options considered for each step of the biomass-to-end-use chains are listed in detail in chapter 2.1.

The analytical approach described in this paper focuses on socio-economic assessment of biomass-to-end-use chains. This includes the costs over the whole biomass-to-end-use chain and the comparison with the reference systems, namely similar biomass-to-end-use chains without torrefaction.

The objective of this work is to derive conclusions for cost-efficient and environmentally sound deployment strategies for torrefied material in general. This means that biomass-to-end-use chains do not have to be specified in great detail. Although it is necessary to differentiate between world regions for provisioning feedstock and end user types for the final consumption, it will be out of scope of this work to suggest for example specific torrefaction plant sites more precisely than just recording the world region itself.

2 ASSESSMENT OF GENERIC BIOMASS-TO-END-USE CHAINS

The objective of this part of the research is twofold: 1) to calculate a great number of exemplary torrefaction based biomass-to-end-use chains and 2) to assess the generated chains socio-economically. The results will be analysed in order to develop deployment strategies and scenarios for torrefied material. Different exogenous assumptions (like energy prices, technology development, policy settings, see chapter 4) will furthermore lead to differing deployment scenarios.

The following paragraphs describe the main segments of a biomass-to-end-use chain and how their combinations lead to a high number of generic and still relevant constellations. Due to this comprehensiveness of combinations and especially because of its extension by different kind of uncertainties, a powerful modelling tool is required. 2.2 gives a short insight into the requirements for such a tool and 2.3 explains the theoretical background of the tool BioChainS.

2.1 Structure of generic biomass-to-end-use chain assessment

Biomass-to-end-use chains are defined as the entire biomass supply starting at the feedstock producer and finishing with its consumption at the end user. Travel distances can vary from several to a few thousand kilometers and are separated and delimited through the following segments:

- Origin and type of feedstock
- Solid fuel processing method
- Location and type of end user

Various feedstocks that could be interesting for torrefaction will be considered. The assortment reaches from forest, plantation and other virgin wood, by-products and residues from wood processing industry, used wood, herbaceous biomass from agriculture and horticulture, by-products and residues from herbaceous processing industry to by-products and residues from the fruit processing industry. The following feedstock origins are considered:

- 28 EU countries
- Eastern Europe and Ukraine
- North America
- Commonwealth of Independent States
- Africa
- Asia
- Latin America

Not all feedstocks are expected to be relevant in every considered world region and just the data of the most relevant feedstocks for every investigated country will be used. Decisive for the calculation of biomass-to-end-use chain deployment strategies is the sustainable yield, availability of the feedstock (Uslu et al, 2008) and its seasonal harvesting or production patterns. Furthermore, a biomass price paid to the producer and the feedstock quality has to be considered. Feedstock density, heating value and moisture content influence transportation costs and solid biofuel production (Hamelinck, 2005).

Biomass can be dried, grinded, torrefied and/or densified in order to produce a dense bioenergy carrier. To derive conclusions about torrefaction, different combinations of these preparation steps will be considered. A combined torrefaction and densification process will be compared to a conventional densification process (pelletisation or briquetting). Torrefaction without densification will be confronted with untreated biomass like chips for energetic use. Energy and mass balances have to be calculated for different torrefaction technologies namely rotary-drum, moving-bed, torbed, fluidised bed reactors and simple densification like pelletisation and briquetting to also establish a link and consistency to the LCA. Investment costs I_i of the different components (subscript i), their depreciation time τ_i and an origin dependent interest rate i will serve to calculate the capital expenditures C_i (CAPEX) of the preparation step[2]:

$$C_i = I_i * \frac{i(1+i)^{\tau_i}}{(1+i)^{\tau_i} - 1}$$

Maintenance costs as share of the CAPEX and operational costs calculated with time-, location- and feedstock dependent labour and energy costs sum up to the operational expenditures (OPEX):

$$O_i = C_i * M_i + F_i * C_{fossil} + L_{prep}^{a,b,c} * C_{labour}^{a,b,c}$$

A thorough assessment of OPEX will include re-investments, insurances, license fees, availability, contracted services and capital tied-up (Svanberg et al., 2013) which are assumed to be addressed by $C_i * M_i$. Depending on the selected origin, feedstock and solid biofuel processing technology, specific costs, efficiencies and working time for various solid biofuel products will be generated. Density, heating value and moisture content are used for further considerations.

For the last chain segment, different pre-defined end-uses will be taken into account:

- Co-firing in coal fired power plants,
- (Co)-gasification,
- Combustion in small scale pellet boilers and
- Processing to bio-chemicals

The requirements of these end-uses regarding the biomass fuel, seasonal demand patterns and

[2] A list of used abbreviations can be found in chapter 7.

efficiencies finally define the entire biomass-to-end-use constellation. Torrefied pellets for example are expected to have a higher grindability than normal pellets (Koppejan et al., 2012), thus extra treatment costs in coal fired power plants vary depending on the co-fired solid biofuel. Spreading production and demand patterns furthermore lead to the need of storage between the chain links.

The described segments and their options are visualised in table 1. The origin and feedstock segment will influence the biomass-to-end-use chain mainly by the availability and yields of biomass, labour and fuel costs, interest rates and energy taxation. Depending on the comprehensiveness of the input data, this segment has a high potential for the merging of options and thus for the reduction of generated biomass-to-end-use constellations.

Table 1: Segments and options to be combined to biomass-to-end-use constellations

Origin & Feedstock			
28 EU-Member States + 14 world regions			
Feedstock 1	Feedstock 2	Feedstock 3	Feedstock n
Preparation			
4 torrefaction technologies plus densification	densification	4 torrefaction technologies and no densification	no torrefaction, no densification
End User			
Co-firing	Co-gasification	Small scale pellet boiler	Material use

Transport between these segments (supply and distribution) will be addressed as uncertainties and will upgrade the biomass-to-end-use constellations to representative generic biomass-to-end-use chains. This approach will be discussed in part 2.3 of this paper.

2.2 Software tool and data requirements

By combining the main segments from 2.1 several thousand generic biomass-to-end-use constellations would result, depending on the profundity of the input data and thus on which constellations may be merged (see chapter 2.1). By upgrading these constellations with a biomass transportation model, representative generic biomass-to-end-use chains could be generated. However, only a smaller number of chains might be really relevant, thus, selected, most attractive and relevant chains will serve as a basis to calculate deployment scenarios up to 2030 for the socio-economic assessment. To this end a software tool is necessary. The developed tool for the biomass-to-end-use chain simulation (BioChainS) is described in 2.3. However this chapter gives an overview on the four main requirements for the realisation and utilisation of a software tool that should be capable of assessing deployment strategies and scenarios for biomass-to-end-use chains in general:

- Using high quality input data: Literature provides a wide range of data about transport routes (e.g. EC, 2012) as well as costs regarding the supply from the feedstock production site to the gate of the solid biofuel preparation plant (Suurs, 2002). On the other hand, information about costs and properties of torrefaction plants and differing transportation and handling needs for torrefied material are rather rare (Bergman, 2005),(Uslu et al., 2008), (Koppejan et al., 2012). Further utilisation in small scale pellet boilers, co-gasification and co-firing plants or for material use is not yet documented. This missing data will be gathered from the partners within the SECTOR-project by using standardised data questionnaires. However, most probably there will be gaps of data and partly high uncertainties. The software tool should be able to deal with this high level of uncertainties. Therefore many parameters like transportation distances, used vehicles and biofuel preparation plant sizes, carrying a high uncertainty, lead to an uncertainty calculation rather than the utilisation of simple mean values.
- Realistic representation of market behaviour: Biomass-to-end-use chains have to be described in a consistent way taking into account restrictions, linkages and dependencies between the single steps of the chain. Spreading of production and demand patterns for example leads to a need for extra storage steps that have to be addressed properly. Other examples are logistical restrictions which should be taken into account as far as possible.
- Generate information in the right resolution for further analysis: The output data has to be provided in a clear and transparent format to facilitate the description and illustration of supply chains including the assessment of costs and efficiencies over the whole chain. A clear description is not only the linkage to the socio-economic assessment but also to LCA and environmental assessment that will be executed by the project partners.
- Link to scenario calculation for relevant storylines: The modification of time dependent variables allows calculating scenarios based on different pathways regarding policy settings, energy prices and other framework conditions. Next to the price development of fossil fuels and labour costs, differing end user demands, technological learning and taxes should be considered in this simulation. In the next chapters scenario calculation and storylines will be further outlined.

2.3 BioChainS – theoretical background

In order to meet the objectives of biomass-to-end-use chain assessment and scenario development and in order to meet the requirements outlined above, the tool BioChainS has been developed. In this tool, the biomass-to-end-use constellations described in 2.1 are upgraded with a biomass transport model. Linkages, dependencies and restrictions are addressed as well as uncertain parameters to get a possibly realistic representation of the market diffusion of biomass-to-end-use chains.

The tool will integrate different software types for various sub questions of this research. While most calculation steps require statistical programing executed in R (RStudio, 2012), route optimisation and calculation is best done with a geographic information system tool like ArcGIS (Esri, 2012). In the next sections the actual steps of the biomass-to-end-use chain simulation tool BioChainS will be discussed in greater detail. The following flow diagram (Figure 1) starts with the main structure behind BioChainS. Parallelograms indicate data bases while squares stand for single programs executed with different software named in brackets.

The first step is to optimise sizes of preparation plants (e.g. torrefaction, densification) for different feedstocks in their origins. This will be done in the **plant size optimisation & solid biofuel production calculation** tool. The objective function for the optimisation is the equation for the specific biofuel production and preparation cost, c_{fuel}:

$$c_{fuel} = c_{prep} + c_{supp}$$

Specific preparation costs for biofuel processing as well as specific supply costs depend on plant sizes (Kumar et al., 2003). Torrefaction and/or densification plant costs have to be scaled from reference preparation data received from the **solid biofuel preparation** data base. Plant sizes are described as yearly biomass input m_{prep}^{in} thus implementing varying minimum supply distances for a circle service area depending on the sustainable biomass yield and availability which are documented in the **origins & feedstocks** data sheet.

$$d_{supp} = \sqrt{\frac{m_{prep}^{in}(scale)}{Y * a * \pi}}$$

For a small part of the investigated feedstocks it makes sense to discuss the chipping at the production site or in terminals. In these cases the univariate optimisation becomes multivariate to find the best constellation of biomass supply to the solid biofuel processing plant gate. The optimal sizes of torrefaction and/or pelletisation plants will be used as mean values and a probability function will serve for the uncertainty of plant size selection. The plant size selection will also determine the minimum supply distance. In case of chipping at the roadside or in terminals, probability functions for the supply and comminution structure, receive the most likely constellation from the optimisation. Specific supply costs include the biomass price paid to the biomass producer, fixed costs, labour-, time- and distance dependent transportation costs towards the biomass processing plant gate and in some cases chipping

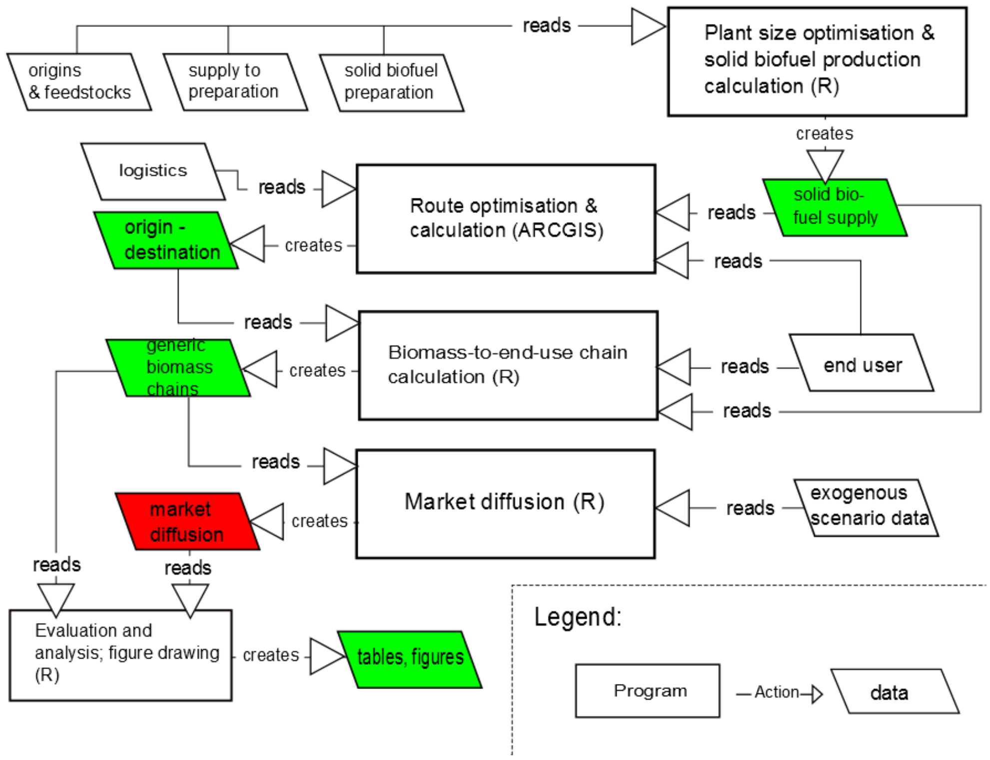

Figure 1: Main structure of BioChainS: Parallelograms indicate data bases while squares stand for single programs executed with different software named in brackets

costs (from the **supply to preparation** data base). Therefore labour- and fuel costs are received from the **origins & feedstock** data set.

$$c_{supp} = \frac{C_{chip}+C_{supp}+L_{supp}^{a,b,c}*c_{labour}^{a,b,c}+F_{supp}*C_{fossil}}{HV_{feed}} + p_{feed}$$

Preparation costs are calculated using CAPEX and OPEX (see 2.1) for the single solid biofuel production steps depending on local fossil fuel prices, labour costs, interest rates and scaling factors. This detailed calculation results furthermore in an energy balance. A mass balance of the preparation step has to be calculated to derive a mass ratio μ_m and thus specific preparation costs. Preparation costs C_{prep} of a torrefaction and/or densification plant with a reference size $m_{prep}^{in}(ref.)$ and a scaling factor sf are used for upscaling to a plant with size $m_{prep}^{out}(scale)$.

$$c_{prep} = \frac{C_{prep}(ref.) * \left(\frac{m_{prep}^{in}(scale)}{m_{prep}^{in}(ref.)}\right)^{sf}}{m_{prep}^{in}(scale) * HV_{fuel} * \mu_m}$$

$$with\ \mu_m = \frac{m_{prep}^{out}(scale)}{m_{prep}^{in}(scale)}$$

In the **route optimisation and calculation** tool transportation costs from the biofuel production sites described in the first result sheet (**solid biofuel supply**) to the different end users (addressed in the data sheet **end user**) including handling and storage are addressed. Therefore inter- and intracontinental transport chains have to be distinguished. The research objective in both cases is to find representative transport constellations of relevant producer and consumer settings. The major difficulty may relate to the fact that coordinates for future production plants are unknown. On the other hand the objective of this work is to derive conclusions for cost-efficient and environmentally sound deployment strategies for torrefied material in general. This means that biomass-to-end-use chains do not have to be specified in detail. Average distances and optimal constellations regarding the transport modes possibly used in the feedstock origins for the forwarding of solid biofuel to the origin main ports, from the origin main ports to the EU main ports and from these ports to the different end user types will be sufficient to derive conclusions. Still, these distances and constellations have to be implemented as probability functions, considering not only optimal average values but also upper and lower boundaries. Table 2 shows a list of such probability functions and their properties.

Using probability functions for uncertain parameters ask for an uncertainty calculation in form of Monte Carlo simulations. To give an example, results will not be single costs of solid biofuel deployment strategies but rather cost distributions. These costs are furthermore generated by separated labour- and fuel calculations to provide the right resolution not only for the socio-economic assessment but also for further LCA and environmental assessment carried out by the project partners. This linkage will also facilitate the calculation of selected deployment scenarios of torrefaction based biomass-to-end-use chains.

Locations from European coal fired power plants will be used as well as centroids of the NUTS-3 regions for the calculation of the delivery to small scale pellet boilers. Probability functions will be generated for the transport from the EU main ports to the end users in case of inter-continental solid biofuel supply as well as from the centroids of the feedstock origins to the end users where no ocean shipping is needed. To this end the TRANS-TOOLS software developed by the European Commission will be applied (EC, 2012). This software as well as the calculation for the forwarding from solid biofuel production plants to the main harbours of the origins will be executed with ArcTransport in ArcGIS (ESRI, 2012). An **origin-destination** matrix with cost distributions for the transport of different solid biomass types from all kind of feedstocks in different world regions to European end users is the output of this process.

In the **biomass-to-end-use chain calculation** tool, biomass production, supply, processing and distribution are extended with end user properties from the **end user** data sheet and storage calculations depending on demand and supply patterns to get the total specific costs for the utilisation of solid biofuels. The results are probability distributions for total specific costs, efficiencies and the corresponding percentages to the different chain links for every combination of feedstock, feedstock origin, preparation technology and end user type. This information will be computed and gathered in an easy to read output file (illustrated as **generic biomass-to-end-use chain** data base) for further evaluation and analysis of the biomass-to-end-use chains. This output file (see chapter 3) will also serve to address the most interesting biomass-to-end-use chains for the scenario calculation used for the socio-economic assessment and for the LCA and environmental assessment executed by the project partner in further research.

Generic biomass-to-end-use chains will be described through their specific costs and efficiencies. Deployment scenarios ask for the consideration of biomass potentials in different world regions as well as demand capacities and locations of the investigated end user types. Most promising biomass-to-end-use chains will be selected and scenarios up to 2030 calculated, assuming that most attractive biomass-to-end-use chains penetrate stronger into the market than others. This calculation will be carried out by the **market diffusion** tool using **exogenous scenario data** describing the storylines illustrated in chapter 4. Varying fossil fuel prices, labour costs, taxes, factors presenting technological learning, benefits, restrictions and end user demand will be determined in different storylines. The focus of the analysis will be on the competitiveness for torrefied material over fossil fuels and other solid biofuels. BioChainS will be expanded with a market simulation tool that is capable of calculating moved capacities. By using a Logit-approach, market decisions will be generated

Table 2: Probability functions and properties mainly for the transport model

Parameter	Uncertainty distribution	Abbreviation	Comments
Supply distance	triangular	$f_{supp}^{distance}(d\|d_1,d_2,d_3)$	$d_1 = d_{supp}$ minimum distance, d_2 average and d_3 maximum distance
Distribution distance to port	triangular	$f_{port}^{distance}(d\|d_1,d_2,d_3)$	d_2 average distance to main port deliverable from the entire region, d_1 and d_3 min. and max.
Ocean shipping distance	triangular	$f_{ocean}^{distance}(d\|d_1,d_2,d_3)$	d_2 average distance from main ports to EU-main ports
Distribution distance to end user	triangular	$f_{eu}^{distance}(d\|d_1,d_2,d_3)$	d_2 average distance from main EU-ports to end user
Supply mode	multidimensional discrete (or different correlated discrete)	$f_{supp}^{mode}(Q_T^{a,b},Q_R,Q_S)$	Q gives the share of distance mastered by transport mode (truck, train (rail), ship)
Ocean shipping mode	discrete	$f_{ocean}^{mode}(P_{S1,S2,S3,S4})$	Gives the probability of vessel selection (Supramax, Panamax, Capesize, Handysize)
Distribution modes to port	multidimensional discrete (or different correlated discrete)	$f_{port}^{mode}(Q_T,Q_R,Q_S)$	Q gives the share of distance mastered by transport mode
Distribution mode to end user	multidimensional discrete (or different correlated discrete)	$f_{e.u.}^{mode}(Q_T,Q_R,Q_S)$	Q gives the share of distance mastered by transport mode
Preparation plant size	triangular	$f_{prep}^{size}(k\|k_1,k_2,k_3)$	k_2 for optimal plant size, k_1 and k_3 for min. and max.

and memorised within the simulation tool. The scenario calculation tool will furthermore serve as a basis to be upgraded to a diffusion model. To investigate market diffusion of new technologies in the renewable energy sector, more parameters have to be considered. Decisions addressed as uncertain parameters could, for example, follow different probability distributions depending on the flow of information and thus on the fact if investors are private or public. Furthermore, prices and costs have to be differentiated to simulate profit margins. Only by taking the possible profit of a new technology into account, its diffusion potential can be computed. The output of this computational step will be a market diffusion data set including most important and relevant generic biomass-to-end-use chains and their possible development for different storylines.

3 DATA STRUCTURE AND RESULTS INSIGHT

First generic biomass-to-end-use chains have been computed to clarify questions about the data structure of the result sheets. Even though specific total costs in [€/$GJ_{solid\ fuel}$] include fuel costs and labour costs it appears to be beneficial that these costs are illustrated summarised for every chain link. To guarantee an easy link to the socio-economic assessment, LCA and environmental assessment, two additional result sheets have been generated. Specific total working hours for the supply, processing and distribution of the solid biofuel are gathered and listed as well as the specific fuel consumption in [MJ/$GJ_{solid\ fuel}$] over the entire biomass-to-end-use chain. For the beginning this leads to a clear description of the chain progress depending changes of costs and efficiencies.

Because BioChainS will execute uncertainty calculations, the discussed values and results represent only the mean values of subjacent distributions. These distributions will be investigated in detail to illustrate and distribute as much generated information as possible in an easy to understand format. The mentioned list of results will furthermore have a second dimension to address different preparation methods and end user combinations. A third dimension is necessary to differentiate origin, feedstock, storyline and year combinations. For a start this seems to be the simplest way to illustrate the fullness of generic biomass-to-end-use chains and thus to get the fastest access to analyse deployment strategies, scenarios and economic assessment of torrefied material.

Results will be illustrated as average values for costs [€/$GJ_{solid\ fuel}$], fuel consumption in [MJ/$GJ_{solid\ fuel}$] and working time for every chain link: Supply and handling with different transport modes, storage, preparation (torrefaction, torrefaction and/or densification), distribution and handling with different transport modes, end use and the cumulated results. One or two more data rows are necessary to address the uncertainty calculation with standard deviations and/or minimum and maximum values.

These data rows will be calculated for different preparation methods, torrefaction, torrefaction and densification, densification and no preparation, and different end users namely co-firing in coal fired power plants, (co)-gasification, combustion in small scale pellet boilers and processing to bio-chemicals and will be indicated as preparation-end user combinations.

The data-matrices are generated for every combination of feedstock, origin, year and storyline to complete the documentation of generic biomass-to-end-use chains.

Market simulation and diffusion calculation will result in different market trends for various biomass-to-end-use chains and biomass-to-end-use constellation cluster. It could be of special interest, for example, to observe the share of torrefied biomass for different end users or feedstocks.

4 STORYLINES

In this chapter, we develop storylines for the future relevance of torrefaction and torrefied material.

Storylines are a qualitative description of how the future could develop in terms of different dimensions and aspects. Storylines should be consistent, plausible and relevant for the overall objective of the project. The scenarios, which will be developed with the tool BioChainS as a next step in the project, will build on these storylines. Storylines show an overall qualitative picture of the future and leave enough space for interpretation, concrete quantification and variable settings. Scenarios are a concrete implementation of a certain storyline. So, storylines could be considered as something like the overall plot of a story: “Snow White and the seven dwarfs” has a clearly structured narrative. However, there are numerous movies, cartoons, books telling the story in slightly different ways and concrete details. How long does it take Snow White to come to the seven dwarfs? Which logistical problems does the queen have to overcome in order to find Snow White?

Summing up, the storylines describe the general plot of the story and the scenarios are like a concrete film script with clear and more quantitative details for each of the storylines.

There are several reasons and objectives for developing storylines within the project SECTOR:

The simulation of scenarios requires a set of general, exogenously given framework conditions like overall development of energy prices, technology development, policy settings, etc. The storylines provide a basis for defining these framework conditions in a plausible and consistent way.

The storylines serve as a guideline through the development of scenarios: They should ensure that scenarios take into account the most relevant future settings, which may influence the market diffusion of torrefied material.

The storylines can help to structure and cluster the different scenarios. In this way, they support the interpretation of scenarios and modelling results.

Last but not least, the qualitative considerations deliver insight how the different dimensions and aspects of future scenarios of torrefaction and market diffusion of torrefied materials are linked with each other. This may guarantee to take into account all relevant aspects and dimensions in the modelling work.

The overall questions behind the development of storylines and scenarios are:

- What is the possible future role of torrefied biomass-to-end-use chains under different framework conditions?
- What is the possible future role of torrefaction in the biomass sector under different framework conditions?

The different plots of our storylines should span the whole range of relevant developments starting from a future with quite adverse conditions for torrefied biomass up to very positive assumptions leading to a strong market development. So, what are the main impact variables which we consider as relevant for the future development of torrefaction? Based on the discussions during an expert workshop[3] held within the project SECTOR, we identified the following main aspects: Biomass availability, demand for (torrefied) biomass and technological development. All these dimensions may be strongly affected by policies, which therefore form a higher-level aspect to be discussed separately.

1) Biomass availability:

The availability of biomass resources is one of the key preconditions for each type of biomass-to-end-use chain. The availability of biomass for torrefaction does not only depend on biomass resource potentials but also on competing uses. In particular, the different regional scales and the

[3] Expert workshop with SECTOR partners from different disciplines and technology fields on 15 May 2013, Vienna.

different biomass feedstocks relevant for torrefaction have to be taken into account.

- Biomass resource potentials: On the one hand, there are uncertainties regarding the amount of biomass resource potentials for different feedstocks in different world regions. On the other hand, the values strongly depend on assumptions like land use, yields, climate change impact, competing uses, sustainability criteria etc.
- Competition with non-EU countries: Europe is part of the global trade with biomass resources. Thus, the demand for biomass in other world regions will affect the price and availability of biomass resources in Europe.
- Competition for domestic EU-biomass: The optimum future allocation of domestic European biomass resources is not straightforward. So, there are huge questions of how the competition for biomass resources within Europe will develop. This refers both to the competition between different sectors of energetic and non-energetic use as well as between regions.
- Efficient use of biomass resources: The more efficient the use of biomass for providing services (be it for food, materials, energy services), the lower the potential competition and the lower the price of biomass.
- (Import) logistics: Logistics play a crucial role when it comes to biomass availability, both with respect to imported and regionally accessible biomass. Thus, the future development of logistics may play a key role.
- Sustainability criteria: the future design of sustainability criteria might impact the actual availability of bioenergy resources, in particular when it comes to imports.

It is far beyond the scope of this work to deal with all these aspects in detail. So, there will be storylines with high and such with low biomass availability. They may be the results of different combinations of all the corresponding aspects listed above. At least some of the aspects listed above are also impacted by policies (e.g. agricultural policy, sustainability criteria, public support of building biomass logistics). These policy aspects will be discussed below.

2) Demand for (torrefied) biomass

For two reasons, the demand for biomass is highly relevant for our storylines. First, additional demand for biomass is in competition with biomass for torrefaction and thus reduces biomass availability. This aspect has already been discussed before under the bullet point “biomass availability” and we will not go into this aspect here again. Second, the demand for end uses which may be covered by torrefied biomass is one of the key prerequisites for any market development. The demand for (torrefied) biomass end uses is mainly driven by the following aspects:

- Overall demand for different end uses: The various end-use sectors may show very different development. E.g. the development of coal power plants as potential co-firing stations may strongly depend on the CO2-price, the price relation of electricity, coal and natural gas etc. Another example is the small scale heat demand which might be differently affected by building insulation in various storylines.
- Economic viability of applying (torrefied) biomass to provide different end uses: The economic viability of torrefied biomass in different end-uses depends basically on the economic comparison with the corresponding reference case. So, fossil fuel prices, biomass feedstock prices, biomass preparation costs, CO2-prices, fuel taxes, possible support policies for biomass are key drivers and should be considered in the storylines. With respect to torrefied biomass, also the relation between the economic viability between torrefied biomass and conventional solid biomass is a relevant issue to be taken into account.

Again, we won’t be able to model all these aspects in detail within this work. Rather, we want to derive reasonable assumptions for the development of the demand for various end-uses and we want to define consistent framework conditions based on existing energy scenarios and models (e.g. PRIMES, Green-X). The economic viability itself will not be given exogenously in the model BioChainS but will be simulated endogenously.

3) Technological development

Torrefaction is still under development. The technological reliability and economic performance will strongly depend on speed of technology development taking place in the coming years and decades. E.g. achievable energy densities of torrefied material or cost of torrefaction technologies belong to the crucial aspects of future development. Therefore, different paths will be considered. One path with a strong, ambitious progress in the reliability, technological performance, energetic efficiency and considerable cost reductions and another one with moderate progress concerning these aspects.

All these three variables listed above (biomass availability, demand for (torrefied) biomass and technological development) are depending on the policy framework:

- Biomass supply policies: A considerable set of policy fields affects biomass supply. This includes agricultural policies, global trade policies, sustainability criteria for solid biofuels, public support of biomass logistics etc. We will not go into details for these biomass supply policies. Those

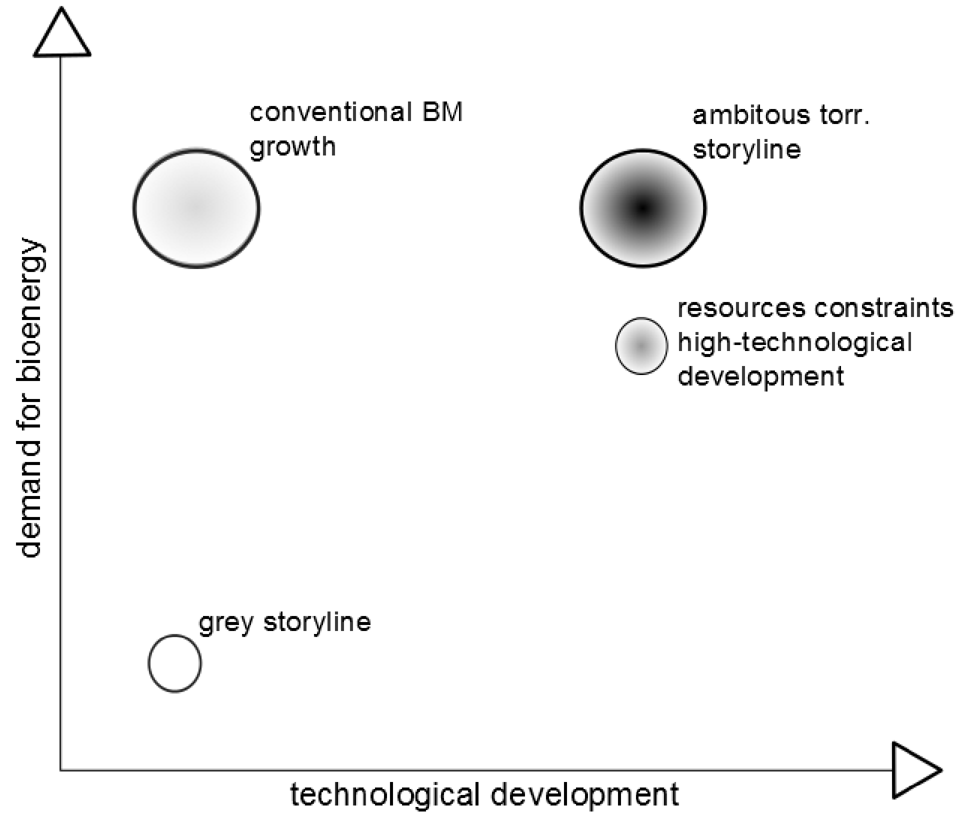

Figure 2: Key dimensions of torrefaction storylines: Biomass availability is indicated as third dimension: Smaller object size for storylines represent lower biomass availability. Furthermore the shading of the filling indicates the grade of market penetration of torrefied biomass in the bioenergy sector.

storylines with high biomass availability will assume a favourable policy framework in place regarding the listed policy fields.

- Biomass demand policies: Up to now, a high share of biomass use in Europe is driven by policies (at least those end-use sectors relevant for torrefied material). Therefore, the future development of this set of policies is crucial for the further demand of biomass. This includes in particular the support of electricity from biomass, e.g. via feed-in-tariffs, CO2-taxes, the European Emission Trading Scheme, biofuel blending quotas and subsidies for small scale biomass heating systems. Some of these policies, in particular CO2-taxes (and/or prices) will be modelled explicitly in the scenarios. For the storylines, we will assume that those storylines with high biomass demand might include highly ambitious policies (but may also be driven by high technology development and high fossil fuel prices). The biomass support policy settings will be distinguished between the sectors heat, electricity and transport fuels. Thus, an ambitious policy for transport biofuels could lead to a lower availability of biomass resources for the sectors heat and transport with corresponding impact of the uptake of torrefied biomass-to-end-use chains.
- R&TD policies: Partly, technology development also depends on corresponding policies supporting research and technology development. Thus, the paths with high vs. moderate technology development also imply related R&TD policies.

Figure 2 summarizes the key dimensions of torrefaction storylines along which we build our storylines.

1) Ambitious torrefaction growth
This storyline is driven by a strong EU policy for bioenergy. This includes the development of logistic infrastructure in order to increase the availability of biomass, also with respect to imports. Other world regions do not follow the EU in its ambition which leads to only moderate global competition for biomass resources. At the same time, the EU implements support policies for biomass in all end-use sectors. This leads to a high economic efficiency of biomass, supported by a favourable ratio of biomass prices to fossil fuel prices.
The EU policies include a strong support for technology development. Thus, high cost reductions for torrefaction occurs

combined with a high technological quality of the torrefaction process leading to high energy densities of torrefied products. A strong market growth of torrefied material is expected and leads to a significant share of torrefied biomass until 2030.
The role of biomass in different end-use sectors etc. will be investigated in terms of different scenarios within this storyline.

2) Resource constraints, High-Tech
Due to the global climate mitigation strategy (and/or strong increase in fossil fuel prices) the global and EU biomass demand strongly increases. Due to this strong competition for biomass (both for energetic and non-energetic purposes) the biomass price increases. However, the policies in place keep the demand in all end-use sectors high.
Due to the high global efforts in climate change mitigation, high technological progress is achieved. This results in high cost reductions for torrefaction combined with a high technological quality of the torrefaction process leading to high energy densities of torrefied products.
A moderate market growth of bioenergy and torrefied biomass is expected for the European Union. However, due to the global competition this growth is slower than for other renewables.
The role of biomass in different end-use sectors etc. will be investigated in terms of different scenarios within this storyline.

3) Conventional biomass growth
Due to the global climate mitigation strategy (and/or strong increase in fossil fuel prices) the global and EU biomass demand strongly increases. Due to this strong competition for biomass (both for energetic and non-energetic purposes) the biomass price increases. However, the policies still keep the demand in all end-use sectors high.
No real technological breakthrough is achieved in torrefaction. Costs are high and technological quality and reliability is low. Only moderate energy densities can be achieved by torrefaction.
The demand for bioenergy grows. However, due to the global competition this growth is slower than for other renewables. Torrefaction is expected to only cover small niches of the bioenergy sector. The scenarios will focus on the question how these niches could look like and what are most promising niches.

4) Grey storyline
No ambitious climate mitigation policies are implemented, neither at the global nor at the European scale. No strong effort is taken in mobilising additional biomass resources and no major investments in biomass logistics occur. Together with low competition for biomass resources, this results in medium availability of biomass. There is no major resource constraint of fossil fuels and therefore price levels for fossil and biomass resources remain moderate.
No real technological breakthrough is achieved in torrefaction. Costs are high and technological quality and reliability is low. Only moderate energy densities can be achieved by torrefaction.
Renewable energy and biomass in particular shows only very low growth. Torrefaction does only play a minor role in small niches of the bioenergy sector. The scenarios will focus on the question how these niches could look like and what are most promising niches.

5 CONCLUSIONS AND OUTLOOK

A computational approach is chosen to calculate deployment strategies and scenarios for the socio-economic assessment of biomass-to-end use chains based on torrefaction. Providing the possibility for further detailed analysis of the generic biomass-to-end-use chains, the calculation of LCA and environmental assessments should be facilitated in the other tasks of the project SECTOR. Figure 3 illustrates the schemata of the concept that will be used for this research. The next paragraphs will lead once more through this concept to highlight the next steps and open questions of each part starting with the biomass transport model:

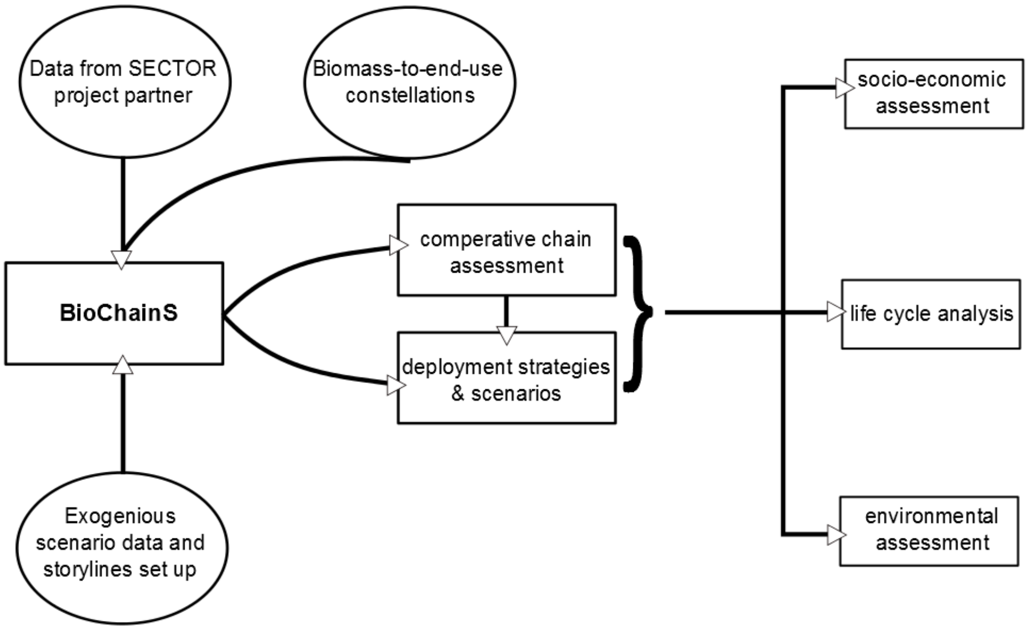

Figure 3: Concept used for this research and system boundaries of the calculation tool BioChainS: Ellipsoids and rectangles differentiate input and output of this research

Issues concerning train schedules and back-hauls possibly have to be considered separately. Furthermore, a method for optimising storage needs and costs for spreading demand and production patterns has to be developed, if realistic costs for biomass-to-end-use chains based on torrefaction should be computed. This optimisation as well as the average from the transport distance and vehicle selection optimisation will serve as most likely values in different probability functions mentioned in 2.3. Further work is necessary to calculate or estimate properties, functionalities and other parameters of these probability functions.

A similar issue can also be addressed for the optimisation of plant sizes and the creation of plant size-, supply distance- and comminution location probability distributions. The supply distance function of 2.3 calculates the minimum distance for feedstock supply for a circular deployment area (in this case without chipping). Assuming a triangular probability distribution for this distance, a maximum distance, for example for a preparation plant site at the port and an average supply distance are missing and have to be estimated properly. Another enhancement for the calculation of generic biomass-to-end-use chains comes with the information about the torrefaction technologies. An energy- and mass balance for the different preparation methods is vital for a realistic presentation of the market behaviour of torrefied biomass. This equally applies for all kind of restrictions and dependencies between the chain links and segments. Another example is the need to include retooling costs for coal fired power plants if costs and efficiencies for un-torrefied pellets or briquettes are computed. Furthermore open questions about the chemical use of torrefied material have to be discussed.

Necessary input data will be collected among the project partners and integrated in BioChainS. The first results will be a comparative assessment of biomass-to-end-use chains to be validated using the available exemplary chains. This will help to calibrate the model and to outline further necessary improvements.

The scenario development will be done by collaborating closely with the project partners to track all kind of perceptions how framework conditions for torrefied material could change until 2030. The entire approach including the storyline settings will be furthermore reviewed by external experts to guarantee a wide acceptance of the generated results.

7 ABBREVIATIONS

The following table 3 summarises the abbreviations used in this paper.

Parameter	Abbreviation	Units
Sustainable yield of feedstock	Y	t/ha*a
Feedstock availability	a	$\%_{area}$
Feedstock price	p_{feed}	€/GJ
Feedstock density	ρ_{feed}	kg/m^3
Feedstock heating value	HV_{feed}	GJ/t
Feedstock moisture content	MC_{feed}	$\%_{w.c.}$
Labour costs for qualifications a, b, c	$C_{labour}^{a,b,c}$	€/h
Fuel costs	C_{fossil}	€/kWh
Interest rates	i	%
Investment costs of components i	I_i	€
Chipping costs	c_{chip}	€
Maintenance costs of components	M_i	$\%_{CAPEX}$
Fuel consumption of components	F_i	kWh/a
Depreciation time of components	τ_i	Years
Capital expenditures of comp.	C_i	€/a
Operational expenditure of comp.	O_i	€/a
Labour need for the facility for qualifications a, b, c	$L_{prep}^{a,b,c}$	PM/a
Solid biofuel density after preparation	ρ_{fuel}	kg/m^3
Solid biofuel heating value	HV_{fuel}	GJ/t
Solid biofuel moisture content	MC_{fuel}	$\%_{w.c.}$
Solid biofuel grindability[4]	HGI_{fuel}	1
Solid biofuel specific prep. costs	c_{prep}	€/GJ
Overall specific facility efficiency	μ_{prep}	%
Specific expenditure of human labour	$C_{prep}^{a,b,c}$	€/a
Specific biofuel production and preparation costs	c_{fuel}	€/GJ
Biomass preparation plant mass input	m_{prep}^{in}	kt/a
Biomass preparation plant mass output	m_{prep}^{out}	kt/a
Biofuel processing mass ratio	μ_m	1
Scaling factor	sf	1
Efficiency of end user for different fuels	μ_{eu}^{fuel}	%
Chipping costs	C_{chip}	€/t
Specific supply costs	c_{supp}	€/GJ
End user demand	D	GWh/a
Supply distance	d_{supp}	km
Fuel consumption of supply	F_{supp}	kWh/t
Labour need for supply	$L_{supp}^{a,b,c}$	h/t
Other transportation costs for supply	C_{supp}	€/t
Preparation costs	C_{prep}	€/a

Table 3: Abbreviations used in this paper

[4] „Hardgrove Grindability Index (geology) -- Encyclopedia Britannica“. Access 23. June 2013. http://www.britannica.com/EBchecked/topic/255047/Hardgrove-Grindability-Index.

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