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## **Integrated techno-economic assessment of a biorefinery process: the high-end valorization of the lignocellulosic fraction in wood streams**

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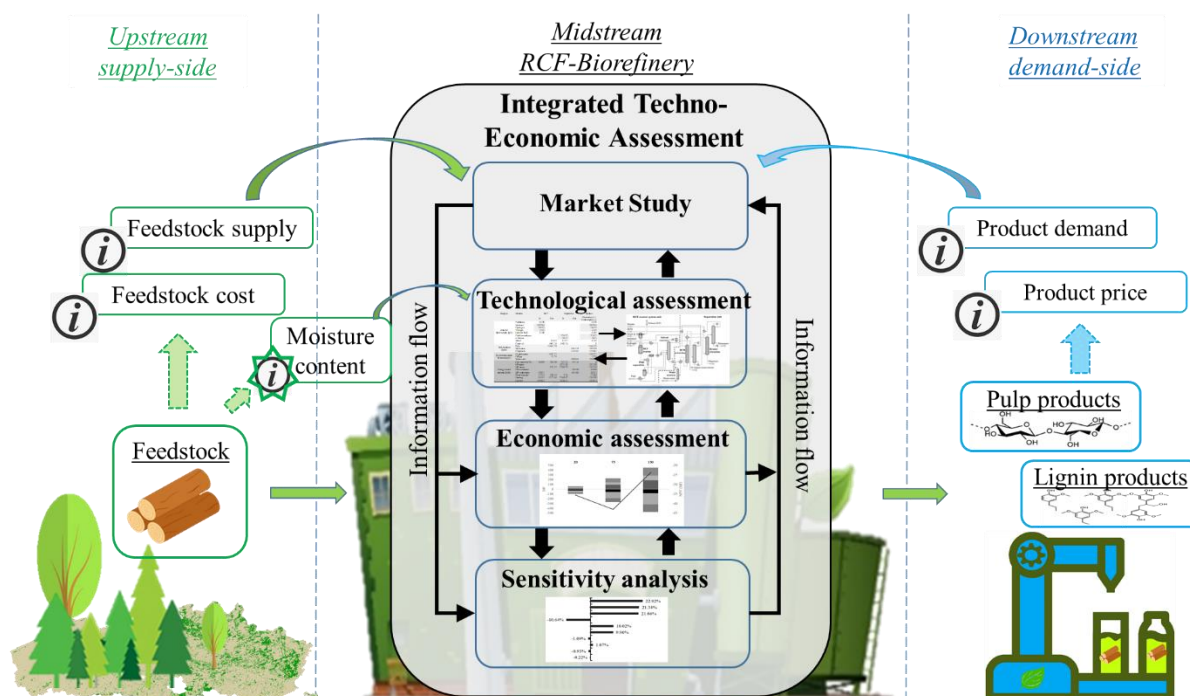
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## GRAPHICAL ABSTRACT



## ABSTRACT

A new *lignin-first* biorefinery with a reductive catalytic fractionation process, which targets the valorization of the lignin and the carbohydrate fraction into higher value end-products, is currently being designed. To identify the various R&D drivers for projects with a low technology readiness level (TRL), we developed an integrated techno-economic assessment (TEA) that directly integrates the results of lab studies with economic costs and benefits. Furthermore, different linkages are made to *upstream* wood availability and *downstream* demand to understand its fit into existing wood value chains. By making the relations across the wood value chain explicit within the integrated TEA, we find that the scale of the plant, the feedstock-specific output quantities, and output prices highly determine the economic feasibility. Furthermore, this detailed analysis reveals the importance of assessing different types of feedstock. If only virgin wood is available as feedstock, minimum capacity levels between 190 and 234 kilotons per year are needed for the investment to be profitable. Waste wood proves to be the most profitable feedstock with an NPV of M€ 59 and an IRR of 26%. Using only waste wood as feedstock makes the investment profitable at a lower capacity level of 80 kilotons per year and economic shocks can be absorbed. Based on these results we show that an integrated and detailed TEA is indispensable to define future development paths for early-stage, innovative technologies.

## KEYWORDS

Biomass conversion technology, biorefinery, lignocellulose, reductive catalytic fractionation, techno-economic assessment, wood valorization

## 1. INTRODUCTION

Due to the population growth rate and the associated increasing consumption, our world is transgressing its planetary boundaries (Rockström et al., 2009). Current fossil-based production processes are causing several environmental, social, and economic problems. To mitigate these destructive processes, our society must undergo substantial changes and find alternative, more sustainable production systems. The transition towards a bio-economy is part of these required changes and biorefineries can form the fundamentals upon which to build this bio-economy. To achieve this transition, the potential to produce bio-based energy, chemicals, and materials must be realized (Kamm et al., 2010), which means that new technologies need to be developed. The conversion of wood streams into high-value products holds the potential to support and accelerate the transition towards a sustainable bio-economy.

The industrial refining of wood started at the beginning of the 19<sup>th</sup> century with large-scale paper production and the emergence of related industries such as cardboard and pulp. Wood was also used for saccharification purposes (Kamm et al., 2010). The waste product resulting from this conversion process mainly consists of a black liquor that contains aqueous streams of lignin-derived products, hemicellulose, and alkaline chemicals. Mostly, this lignin comprising waste fraction is used for the production of energy. Hence, the current production processes do not valorize the woody biomass to its full extent (Calvo-Flores and Dobado, 2010). However, a new *lignin-first* biorefinery process, reductive catalytic fractionation (RCF), is being designed, which specifically targets the conversion of lignin into a valuable lignin oil that can be used to produce higher-value end-products such as lignin-derived (mono and oligo) phenolics (Renders et al., 2019). This process combines solvolytic action and catalysis to produce a depolymerized and stabilized lignin oil, with high chemical functionality, next to a solid (hemi) cellulose pulp (Renders et al., 2017). A comparison between several biorefinery technologies made by Schutyser et al. (2018) showed that RCF-technology has the most promising phenolic monomer yields, while the oligomer fraction is highly functionalized.

Even though the RCF-technology improves the current technological status, its implementation will not be successful if certain market conditions are not fulfilled. Therefore, the wood value chain needs to be assessed ensuring the availability of the feedstocks and the market for the targeted end-products. Verkerk et al. (2019) showed that Western Europe has a high unused wood biomass potential. However, it is not equally distributed within Western Europe. Certain areas have sub-optimal conditions for the location of a wood-based biorefinery. The minimal profitable capacity level of the biorefinery depends on the local feedstock supply, infrastructure, and market conditions. Looking at the *downstream* demand, these products have the potential to target a variety of consumer markets.

Despite the technological advancement of this innovative RCF-process, the key elements that determine its economic feasibility have never been defined in detail. Therefore, the first objective of this paper is to present the first fully-integrated techno-economic assessment of such RCF-process within the wood value chain.

Several techno-economic assessment (TEA) studies have been performed on wood-based biorefinery processes to determine the economic feasibility of single-feedstock wood, such as poplar (Cheali et al., 2016), red maple (Bond et al., 2014), and beech wood (Budzinski and Nitzsche, 2016). However, these TEA studies mainly limit their scope to the production of low-valued products and they do not analyze the potential of further valorization of wood. Another gap in traditional TEA's is the rigid structure and lack of focus on the multi-dimension aspects of the value chain. To face the long-run trend towards greater biodiversity in forests (Messier

et al., 2019) and feedstock supply uncertainties, underlines the need for flexible biorefineries considering several feedstocks rather than a single one. Failure to take these contingencies into account holds a risk of misleading results followed by sub-optimal investment decisions. Therefore, the second objective of this paper is to introduce an integrated TEA that can be adjusted to changing research and development (R&D) outcomes and to changes at different value chain stages – *upstream* feedstock’s availability and supply-side boundaries, *midstream* process-based technical and economic parameters, and *downstream* price and demand processes for the end-products – simultaneously. The adaptability of the TEA is highly relevant to assess R&D projects that are characterized by technical and market uncertainty. Taking a variety of different technical and economic parameters into account, this analysis can accelerate technological improvements as it reveals the crucial factors for early investments and the allocation of financial resources for the subsequent R&D steps.

## 2. METHOD

A TEA is often carried out on new technologies to improve the environmental and social impacts by its design and helps decision-makers make strategic investment decisions (Kuppens et al., 2015). The traditional TEA consists of four steps: (a) Market study, identifying market-related parameters potentially influencing the commercialization ability of the project; (b) a process flow diagram (PFD) and a mass and energy balance (MEB) providing a schematic overview of the main process units, inputs, and outputs of the process; (c) an economic assessment analyzing the economic feasibility based on technical and economic variables; and (d) a sensitivity analysis showing the most influential and/or critical variables affecting the economic performance of the biorefinery (Thomassen et al., 2019).

### 2.1 Integrated techno-economic assessment

The integrated TEA makes linkages between different variables of the technical and economic units. A change in one input variable directly affects multiple-linked intermediate variables, which in turn determine the different output variables, as shown in *Figure 1*. Input and intermediate variables are extended by newly introduced sub-variables which existing TEAs are lacking. A sub-variable makes it possible to modify certain variables on a deeper technical and economic level and enables the decision-makers to understand the variable-specific processes that affect the operating process of the technology. For instance, assessing the wood value chain, moisture content as a sub-variable affects drying and transportation cost on the supply-side and end-product output yields on the RCF-process side. This opens up a new possibility of a more in-depth techno-economic impacts assessment.

Most of the existing TEA papers evaluate commercialized technologies on a high technology readiness level (TRL) considering only one wood species. Bond et al. (2014), for instance, evaluate an  $n^{\text{th}}$ -commercial plant on a high TRL limiting its study on red maple as a feedstock. Our integrated TEA, on the other hand, uses RCF-based laboratory studies on a low TRL. It is tested for different types of feedstock revealing differences in species-specific feedstock cost and end-product yield compositions.

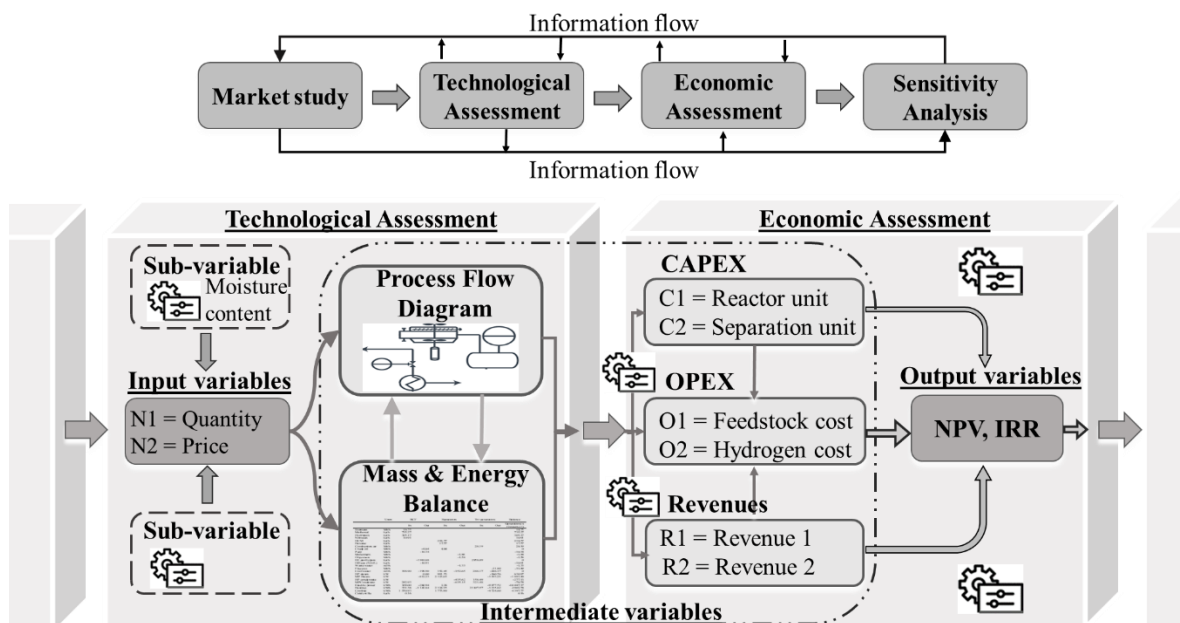


Figure 1. Integrated techno-economic assessment

All these modifications directly affect the PFD and the MEB, which in turn changes the economic-linked variables in capital expenditure (CAPEX), operational expenditure (OPEX), and revenues, resulting in the net present value (NPV) and internal rate of return (IRR). Next, a Monte-Carlo sensitivity analysis identifies the most influential variables and makes it possible to directly build a set of relevant research targets. Simultaneously, it allows decision-makers to link to the market study and to intensify R&D on the most influential variables. The integrated TEA is designed in a modular way such that it can be integrated with other disciplinary models (e.g. environmental impact models). Furthermore, it ties perfectly into Cooper's (1990) Stage-Gate process, which assesses every stage of an R&D project. The dynamic multi-variable dimension of the integrated TEA foresees adjusting the variables based on the stage-specific conditions of the project without rebuilding the model. This makes the integrated TEA indispensable for R&D projects.

## 2.2 Model assumptions

We developed an Excel-based model that incorporates all four stages of the integrated TEA. Information that is gathered during the market study is passed to the PFD and MEB, which is interlinked with the economic assessment and the sensitivity analysis.

### 2.2.1 Process flow diagram and mass & energy balance

The presented RCF-biorefinery is designed for the conversion of wood chips to carbohydrate pulp, lignin-derived monomers, and oligomers. The units used in this contribution is a scale-downed version using a reference process from a recent technical study, using an annual capacity of 2590 metric kilotons dry birch input per year (kt/y). Because this reference process includes further down-stream processing of lignin-monomers to phenol and propylene, submodules (hydro-processing and de-alkylation & distillation) are removed. Also, due to the smaller capacity modeled in this manuscript, the tri-generation unit, which produces energy by incinerating off-gas streams, is not realistic and therefore excluded. The main focus of this paper is the capacity level of 150 kt/y which is displayed in the PFD in *Figure 2*. A detailed MEB for the processing of birch wood with a moisture content of 5% is shown in *Table 1* (Liao et al., 2020).

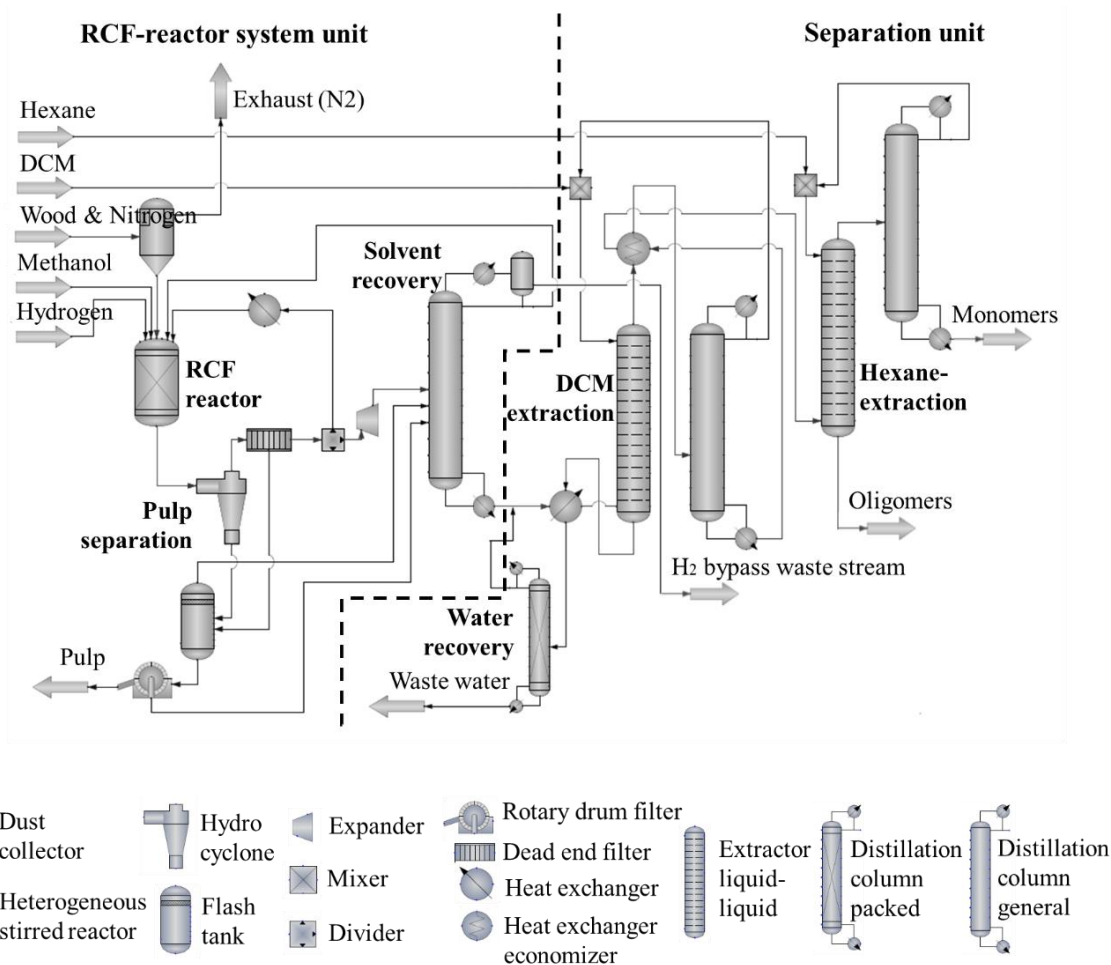


Figure 2. Process flow diagram (Modification of (Liao et al., 2020))

The first subunit is the RCF-reactor system. This reactor is continuously fed with 18.75 dry metric tons per hour (t/h) wood chips from which lignin is fractionated by extraction and catalytic depolymerization and chemically stabilized in presence of methanol, hydrogen gas and a solid catalyst (here: ruthenium on carbon, Ru/C). The retention time in this subunit is 1.5 hours. After the reaction, filtration of the solid carbohydrate pulp results in 11.6 t/h pulp. Next, the solvent (methanol) is removed via distillation and introduced back into the reactor leaving a liquid oily product mixture, consisting mostly of phenolic monomers and oligomers from lignin, next to some solubilized carbohydrates. In a partial condenser, most of the hydrogen is recuperated together with methyl acetate (from hemicellulose) and a very small amount of methanol. Because of the presence of the methanol/methyl acetate azeotrope, further separation of them is economically unacceptable. Therefore, this so-called H<sub>2</sub> gas bypass waste stream will be sent to an external-incinerator for heat recuperation. In the second subunit, the separation unit, crude lignin oil is washed with water to remove the carbohydrates, while the phenolic monomers and oligomers are extracted in dichloromethane. Purified lignin oil is obtained after the removal and recycling of dichloromethane. The aqueous sugar solution will be treated as wastewater. Finally, the purified lignin oil is treated by *n*-hexane to extract the light lignin monomers from the heavy lignin oligomers fraction leaving purified phenolic oligomers with a quantity output of 1.15 t/h. Removal and recuperation of *n*-hexane results in purified phenolic monomers with a quantity output of 1.89 t/h, respectively.

Table 1. Mass and energy balance for 150 kt/y birch wood (derived from (Liao et al., 2020))

Category	Streams	RCF		Separation		Balance
		In	Out	In	Out	Generation (+) Consumption (-)
Material input/output (kg/h)	Feedstock	18750				-18750
	Methanol	1092.85				-1092.85
	Hydrogen	181.32				-181.32
	Nitrogen	11.25				-11.25
	Ru/C-catalyst	0.165				-0.165
	Dichloromethane			225.27		-225.27
	n-Hexane			18.11		-18.11
	Water		0.332	0.471		-0.139
	Crude oil		5562.18	5562.18		0
	End-products (kg/h)	Pulp		11661.29		
Monomers					1894.10	1894.10
Oligomers					1149.61	1149.61
By-products/waste streams (kg/h)	H <sub>2</sub> gas bypass		1582.22			1582.22
	Off gas		11.25			11.25
	Wastewater				3980.63	3980.63
Energy-based streams (kWh)	Cool water (m <sup>3</sup> /h)	204.99	204.99	157.33	157.33	0
	HP steam			1021.90		-1021.90
	MP steam		837.11	2188.70		-1351.59
	HP condensate				448.96	448.96
	MP condensate	250.37			654.60	404.23
	Electric power	112.34	289.54	2.35		174.85
	Heating	341.53	1177.85	2189.42		-1353.10
	Cooling	1598.43		1830.31		-3428.74

### 2.2.2 Net present value

For a firm, the decision to invest in a new plant or new industrial processes depends on the profitability of such projects. In this paper, we used both, NPV and IRR, to assess the economic feasibility of the RCF-biorefinery process. *Equation 1* describes the NPV, which calculates the discounted current value of the future cash flows resulting from the initial capital investment (CAPEX). If the NPV is larger than zero, the investment is considered profitable and worthwhile to be undertaken. If the NPV is smaller than zero, the firm should forego investment in the project. The IRR is the internal discount rate for which the NPV is zero. If the IRR is greater than the discount rate, the project is considered profitable (*Eq.2*).

$$NPV = \sum_{t=1}^n \frac{CF_t}{(1+i)^t} - CAPEX, \quad (1)$$

$$0 = \sum_{t=1}^n \frac{CF_t}{(1+IRR)^t} - CAPEX \quad (2)$$

The net cash flow ( $CF_t$ ) in year  $t$  is the difference between annual discounted revenues and operational expenditures ( $OPEX$ ). The discount rate  $i$  is 15%. The CAPEX represents the initial capital investment in year 0. For the RCF-biorefinery, we consider a project lifetime of 20 years ( $n$ ).



### 2.2.3 CAPEX and OPEX

In determining the CAPEX, one of the main challenges in projects at a low TRL is the availability of precise cost data for a particular capacity or equipment size. For the RCF-biorefinery the precise scaling factor is unknown. Therefore, we use the 'six-tenth' rule to scale-down the total equipment cost of the RCF and separation unit based on the total equipment cost of the reference plant with a capacity of 2590 kt/y (Liao et al., 2020). The cost proportion of each submodule (i.e. RCF and a separation unit) is displayed in *Table 2*. Also, a storage facility (i.e. woodshed) is implemented that allows for a backup of seven days in case of interrupted feedstock supply. It is assumed that the end-products will be directly forwarded to the demand-side assuming no additional cost for storage facilities after the production process. For the base case scenario, we consider three capacity levels of an annual 20, 75, and 150 kt dry wood intake to cover various supply conditions of Western Europe. Following Peters et al. (2003), total delivered equipment cost (including 10% delivery allowance) is multiplied by a factor of 5.03 to calculate the CAPEX.

Table 2. CAPEX for capacity levels of 20, 75, and 150 kt/y in (M€)

Process unit	%	20 kt/y	75 kt/y	150 kt/y
RCF <sup>a</sup>		4.13	9.12	13.83
Separation <sup>a</sup>		0.30	0.67	1.01
Storage facility <sup>b</sup>		0.04	0.17	0.34
H <sub>2</sub> gas bypass pipelines <sup>c</sup>		0.11	0.27	0.44
Total equipment cost		4.58	10.23	15.62
Delivered equipment cost	100	5.05	11.25	17.17
<b>CAPEX</b>	<b>503</b>	<b>25.41</b>	<b>56.67</b>	<b>86.48</b>

<sup>a</sup>Derived from (Liao et al., 2020), <sup>b</sup>(Kühmaier et al., 2016), <sup>c</sup>(Sinnott and Towler, 2019)

The second major component of the economic assessment is the annual OPEX, which covers the costs of producing and selling the products listed in *Table 3*.

Table 3. Annual OPEX for capacity levels of 20, 75, and 150 kt/y in (M€/y)

Items	Cost in €/t	20 kt/y	75 kt/y	150 kt/y
<b>Material cost</b>				
Birch	171	3.42	12.83	25.65
Methanol <sup>a</sup>	393	0.46	1.72	3.43
Hydrogen <sup>b</sup>	2100	0.41	1.52	3.04
Nitrogen <sup>a</sup>	102	0.001	0.005	0.009
Dichloromethane <sup>a</sup>	313	0.08	0.28	0.56
Hexane <sup>a</sup>	712	0.01	0.05	0.10
Ru/C-catalyst <sup>a</sup>	418000	0.07	0.28	0.55
<b>Operating cost<sup>a,c,d</sup></b>		<b>5.22</b>	<b>10.51</b>	<b>17.51</b>
<b>General expenses<sup>d</sup></b>		<b>1.13</b>	<b>5.09</b>	<b>7.87</b>
R&D <sup>d</sup>	5 % of revenues	0.48	1.82	3.63
<b>Annual OPEX</b>		<b>11.28</b>	<b>34.00</b>	<b>62.35</b>

<sup>a</sup>(Liao et al., 2020), <sup>b</sup>(Thomas et al., 2016), <sup>c</sup>(Bridgwater et al., 2002), <sup>d</sup>(Peters et al., 2003).

### 2.2.4 Revenues

*Table 4* summarizes the three main revenue streams – pulp, monomers, and oligomers – for all three capacities. It is assumed that pulp is sold based on the sugar price. Note that the sugar price tends to be very volatile, it increased from 475 €/t in 2010, to almost 750 € in 2013, and then decreased to 320 €/t in November of 2018 (European Commission, 2019). Thus, we estimated a long-term sugar price of 404 €/t. It is to emphasize that only 79% of the 11.6 t/h pulp output (Section 2.2.1) is considered sugar-based pulp, resulting in lower revenues. For both lignin-based

end-products, monomers and oligomers, prices of 1750 €/t are assumed, reflecting the average phenol-formaldehyde resins market price within the range of 1500-2000 €/t (Van den Bosch et al., 2015).

Table 4. Annual revenues for capacity levels of 20, 75, and 150 kt/y in (M€/y)

End-products	€/t	20 kt/y	75 kt/y	150 kt/y
Pulp <sup>a</sup>	404	3.96	14.84	29.68
Monomers <sup>b</sup>	1750	2.14	8.04	16.08
Oligomers <sup>b</sup>	1750	3.53	13.25	26.50
<b>Annual revenues</b>		<b>9.68</b>	<b>36.31</b>	<b>72.61</b>

<sup>a</sup>(European Commission, 2019), <sup>b</sup>(Renders et al., 2018)

### 3. RESULTS AND DISCUSSION

We first analyze the profitability of the RCF-process and the importance of scale. Then, we perform a Monte-Carlo sensitivity analysis. In the next step, various feedstock species and their combinations are assessed, followed by break-even point (BEP) analysis on capacity levels, feedstock costs, end-product prices, and discount rates.

#### 3.1 The importance of capacity level

The scale is an important factor in the economic feasibility of the RCF-biorefinery. The NPV, corresponding to the three capacity levels with processing facilities of 20, 75, and 150 kt/y for birch, is outlined in *Figure 3*.

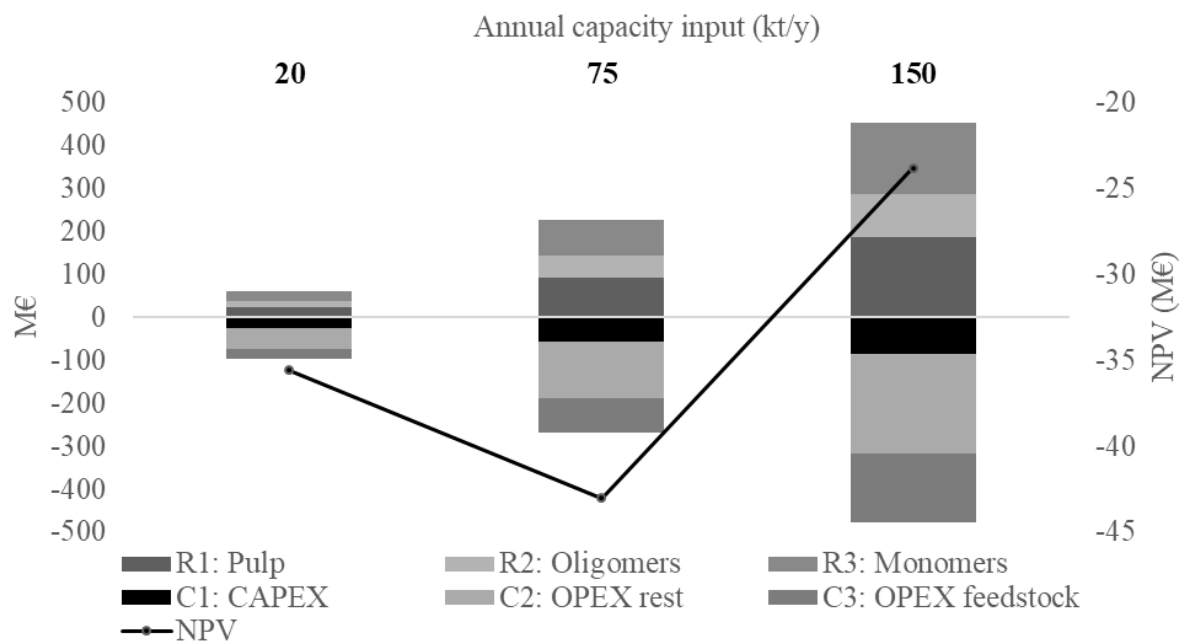


Figure 3. Cumulative discounted revenues (R, above), costs (C, below), and NPV for the base case capacity levels

Based on the current assumptions, a relatively small RCF-biorefinery with an annual capacity of 20 kt/y has an annual OPEX of 11.28 M€/y which is higher than the annual revenue of 9.68 M€/y, resulting in an annual net cash flow of -1.94 M€/y. Hence, total cost increases from M€ -25 (CAPEX) to M€ -35 (NPV). Surprisingly, a larger-scale facility which processes 75 kt/y results in an even lower NPV (M€ -42). Even though there is positive net cash flow of 2.3 M€/y

for a scale of 75 kt/y, the increase in total cumulated discounted net cash flow is lower than the increase in CAPEX. It shows that the benefits associated with economies of scale do not always outweigh the costs of the increase in scale and that there exists a minimum level of scale at which the NPV starts to increase. For 150 kt/y capacity, a positive cash flow of 10.25 M€/y leads to an increased NPV of M€ - 23.45.

### 3. 2 Monte-Carlo sensitivity analysis

To some degree, all variables incorporate uncertainties and variable values can change over time. Therefore, we performed the Monte-Carlo sensitivity analysis on an RCF-biorefinery with a capacity of 150 kt/y to indicate the variables with the highest impact on economics. In this case, 10 000 iterations per scenario are simulated. Each iteration selects a random value between a minimum and maximum for all project variables, under the selected distribution shape. All variables are following a triangular distribution pattern characterized by a most likely value with a variance of  $\pm 10\%$ . The tornado diagram in *Figure 4* illustrates ten sensitive variables that affect the NPV the most. The input bars to the left (right) represent a negative (positive) input correlation with the NPV.

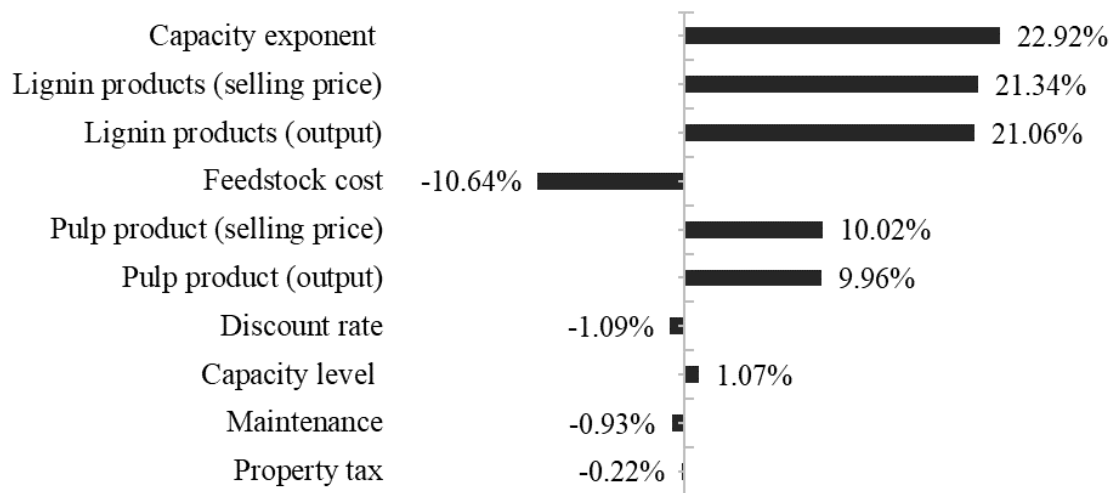


Figure 4. Tornado diagram: Most sensitive variables and their contributions to variance in NPV

The capacity exponent has the largest impact on the NPV representing the economies of scale (e.g. new technologies, productivity improvement, learning effects, etc.). The research focus should, therefore, be on improving and optimizing the plant facilities and its operations. Besides, capacity exponent directly affects the CAPEX of the capacity level which is ranked as the 8<sup>th</sup> most sensitive variable. At first appearance, the capacity level seems to be a variable with a relatively low impact. Note that capacity level change will not be limited to 10%. In Section 3.1., starting from a capacity level of 20 kt/y, a capacity increase of 375% and 750% was shown. Hence, the combination of both, capacity level and the capacity exponent, underlines the importance of scale and its effect on the profitability. Prices for pulp and lignin-based end-products are ranked as the 2<sup>nd</sup> and 5<sup>th</sup> most influential variables, respectively. Potential advice is to focus on R&D activities, aiming to improve the quality of the end-products with higher selling price potential. Looking at the demand-side, favorable advantages of the end-product must be communicated in an effective way to raise awareness and increase demand. Similarly sensitive are output yields of the end-products which have the 3<sup>rd</sup> and 6<sup>th</sup> largest impacts on the NPV, respectively. Potential further research can focus on feedstocks with higher output yield on the supply-side level or increased R&D effort for further

improvement of the RCF-process. The feedstock cost (supply-side) is ranked as the 4<sup>th</sup> most influential variable. Lower processed feedstocks with lower prices are the potential targets. When it comes to the discount rate (7<sup>th</sup>), the focus should be on resolving the project-related uncertainties. This is a long-term process that needs R&D investments to be resolved.

Looking for potential economic improvement, Monte-Carlo sensitivity analysis revealed the most influential input variables which will be the fundament for the next assessments in Section 3.3 and 3.4.

### 3.3 Different feedstock species and their combinations in dry wood condition

Feedstock output yields (pulp, monomers, and oligomers) are very sensitive variables that can be improved by increasing R&D in process efficiency in the long-run. In the short-run, research on alternative species with potentially higher output yields should be aimed to boost the output yields. Therefore, an additional assessment is performed that studies the impact of different wood species and its output yields on the economic feasibility of the RCF-biorefinery.

Birch, poplar, pine, waste wood (type B), and their combinations are considered. Both birch and poplar are hardwood species. Approximately half of the European forest area is populated usually by coniferous species (Michel et al., 2018). As a representative of coniferous species, pine is also considered. Waste wood with its promising output yields is examined as the only non-virgin wood feedstock. The capacity level of 150 kt/y remains the same. The methanol consumption and H<sub>2</sub> gas bypass generation changed to 531.94 kg/h and 285.27 kg/h, respectively. Other species-specific changes are illustrated in the mass balance, *Table 5*. CAPEX increases slightly to 88 M€ assuming a higher storage capacity of 8000 m<sup>3</sup> to handle all possible species-specific capacities.

Table 5: Mass balance changes for poplar, pine, and waste wood (kg/h)

Category	Streams	RCF		Separation		Balance
		In	Out	In	Out	Generation (+) Consumption (-)
Poplar <sup>a</sup>	Crude oil		5007.83	5007.83		0
	Pulp		12945.76			12945.76
	Monomers				1833.13	1833.13
	Oligomers				1560.03	1560.03
	Wastewater				3315.55	3643.66
Pine <sup>b</sup>	Crude oil		4156.30	4156.30		0
	Pulp		13797.28			13797.28
	Monomers				1081.24	1081.24
	Oligomers				1771.91	1771.91
	Wastewater				3021.47	3332.15
Waste wood	Crude oil		3668.97	3668.97		0
	Pulp		14284.61			14284.61
	Monomers				865.04	865.04
	Oligomers				1719.56	1719.56
	Wastewater				2779.29	3113.37

<sup>a</sup>(Renders et al., 2016), <sup>b</sup>(Van den Bosch et al., 2015)

Feedstock cost is an essential driver when it comes to the profitability of the RCF-biorefinery. It is composed of different sub-costs, as illustrated in *Table 6*. The first cost factor is the price of the stem. Next, wood is harvested and forwarded to a collection location following by the chipping and drying processes. The last step is the transportation to the RCF-biorefinery. The total average distance is assumed to be 100 kilometers for all species and 50 km for waste wood.

Table 6: Feedstock cost compositions for all species

		<b>Birch</b>	<b>Poplar</b>	<b>Pine</b>	<b>Waste wood</b>
Stem <sup>a</sup>	€/m <sup>3</sup>	46.70	34.90	34.30	40.59 <sup>c</sup>
Harvesting <sup>b</sup>	€/m <sup>3</sup>	10.47	16.28	9.85	
Forwarding <sup>b</sup>	€/m <sup>3</sup>	9.24	9.24	9.24	
Chipping <sup>c</sup>	€/m <sup>3</sup>	6.89	5.04	6.27	4.16
Drying <sup>d</sup>	€/m <sup>3</sup>	35.58	30.94	38.48	7.86
Transport <sup>c</sup>	€/m <sup>3</sup>	6.05	3.87	4.82	2.60
Feedstock price	€/m <sup>3</sup>	114.93	100.27	102.97	55.21
<b>Feedstock price</b>	<b>€/t</b>	<b>171.03</b>	<b>232.93</b>	<b>192.28</b>	<b>95.61</b>

<sup>a</sup>(Boosten et al., 2017), <sup>b</sup>(Wassink, 2017), <sup>c</sup>(Gybels et al., 2012), <sup>d</sup>estimated from (Francescato et al., 2008), <sup>e</sup>estimated from (Garcia and Hora, 2017).

Table 7 shows how different wood species and their combinations in a dry stage (5% moisture content) affect the profitability of the RCF-biorefinery. Note, the sugar fraction in pulp is used to calculate the pulp revenues. Birch has been already discussed in Section 3.2. NPV for birch decreases slightly due to the adapted storage capacity. For poplar, annual OPEX increases by 13.64% compared to birch. Even though the annual OPEX increases, this is compensated by higher monomers and oligomers output yields for poplar. Thus, net cash flow increases by 10% resulting in an NPV of -18.90 M€ and IRR of 11.24%. For pine, revenues remain the same and OPEX slightly increases compared to birch. This results in an NPV of M€ -33 and an IRR of 8.27%. The utilization of waste wood has a positive NPV of M€ 50 and an IRR of 26%. Compared to birch, feedstock cost decreased mainly by a lower drying process.

Next, different combinations of the above-mentioned species are taken into account. Depending on the region, the availability of one wood species might be insufficient to match the demands of the RCF-biorefinery and hence a variety of wood species will be required as intake. Equal proportions of birch and poplar (FC1) are considered, with an NPV of M€ -23 and an IRR of 10.43%. For the combination of birch, poplar, and pine (FC2), the NPV and IRR decreased further to M€ -26.54 and 9.7% due to the pine proportion. The combination of all four feedstocks (FC3) is considered as the best alternative to single-use feedstocks with an NPV of M€ -5.14 and an IRR of 14% close to the hurdle rate of 15%.

Table 7: Economic results for the capacity of 150 kt/y (Birch, poplar, pine, waste wood, and their combinations in dry wood condition)

Parameters	Unit	Birch	Poplar	Pine	Waste wood	FC1	FC2	FC3
Pulp	wt%/t	62.19	69.04	73.59	76.18	65.62	68.27	70.25
- Sugar in pulp	wt%/t	48.97	57.01	53.66	57.42	52.99	53.21	54.27
Monomers	wt%/t	10.10	9.69	5.66	4.51	9.89	8.48	7.49
Oligomers	wt%/t	6.12	8.31	9.47	9.17	7.14	7.97	8.27
<b>Revenue (total)</b>	<b>M€/y</b>	<b>72.36</b>	<b>81.91</b>	<b>72.32</b>	<b>70.84</b>	<b>77.14</b>	<b>75.52</b>	<b>74.36</b>
Pulp	M€/y	29.68	34.55	32.52	34.79	32.11	32.24	32.88
Monomers	M€/y	26.49	25.41	14.84	11.86	25.95	22.25	19.65
Oligomers	M€/y	16.08	21.84	24.85	24.08	18.96	20.92	21.71
<b>OPEX (total)</b>	<b>M€/y</b>	<b>62.66</b>	<b>71.18</b>	<b>63.86</b>	<b>47.65</b>	<b>66.93</b>	<b>65.91</b>	<b>61.35</b>
Feedstock cost	M€/y	25.65	34.94	28.84	14.34	30.30	29.81	25.94
<b>NPV</b>	<b>M€</b>	<b>-26.87</b>	<b>-18.90</b>	<b>-33.11</b>	<b>59.08</b>	<b>-23.09</b>	<b>-26.54</b>	<b>-5.14</b>
<b>IRR</b>	<b>%</b>	<b>9.70</b>	<b>11.24</b>	<b>8.27</b>	<b>26.08</b>	<b>10.43</b>	<b>9.70</b>	<b>14.00</b>

### 3.4 Break-even point - analysis on capacity levels, feedstock costs, end-product prices, and discount rates

The *midstream* capacity level and the *upstream* feedstock supply conditions were assessed in Sections 3.1 and 3.3, respectively. Next, we analyze for which combinations of capacity level and feedstock cost, the NPV is zero. The results are presented in *Figure 5*.

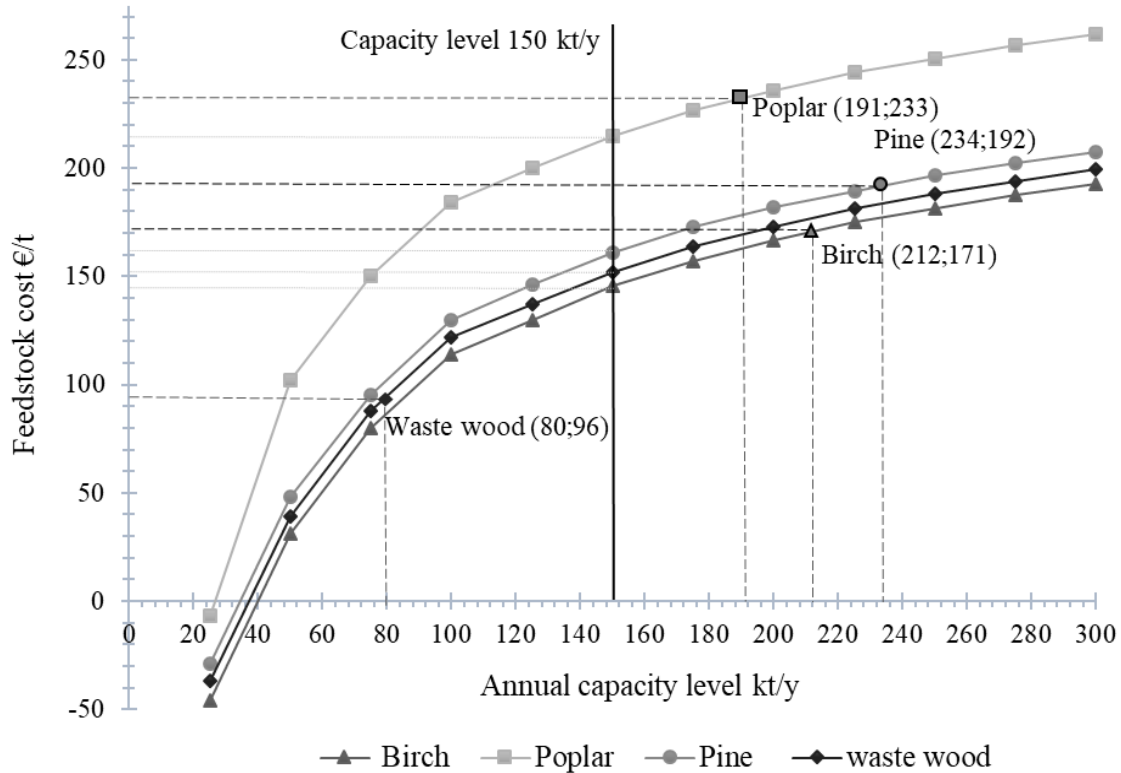


Figure 5: Break-even point - analysis on the capacity levels and feedstock costs (the labeled markers represent the base case values for the different types of feedstock)

For a capacity level of 150 kt/y to become profitable, birch, poplar, and pine feedstock costs need to decrease to 145 €/t (-15%), 214 €/t (-8%), and 161 €/t (-16%), respectively to reach the BEP. For waste wood, on the other hand, feedstock cost can increase to 152 €/t (59%).

Under the current birch feedstock cost of 171 €/t, a capacity level of 212 kt/y is necessary to be profitable. Poplar and pine need an annual capacity level of 191 and 234 kt/y, respectively, to surpass the BEP. For waste wood a capacity of 80 kt/y is sufficient. This implies that a waste wood-based RCF-biorefinery is resilient to supply shortages and can operate in locations where feedstock supply is limited. For FC1, FC2, and FC3 and their base case feedstock costs, BEP capacity levels are 202, 212, and 160 kt/y, respectively under the current feedstock costs.

Next, *downstream* demand is considered to assess the end-product price (2<sup>nd</sup> and 8<sup>th</sup> most influential variables) changes that are needed to reach the BEP, shown in *Table 8*. To reach the BEP, price increases between 6 % and 17% are required for birch, poplar, and pine. Waste wood, on the other hand, can absorb a price decrease of around 28% for both, the pulp and lignin-based products. Regarding the feedstock combinations, price increases between 2% and 15% are sufficient to reach the BEP. To achieve higher prices it is advised to intensify R&D efforts in RCF-technology to improve the quality of the end-products. From the demand-side perspective, competitiveness improvement of the end-products must be tackled by raising

awareness of its advantages (e.g. renewable feedstock, the substitution of fossil oil-based products, etc.)

Table 8. Break-even point – analysis of end-product prices

	Birch	Poplar	Pine	Waste wood	FC1	FC2	FC3
Pulp price	+15.4%	+9.4%	+17.3%	<b>-28.7%</b>	+12.4%	+15.3%	+2.7%
Lignin-based products	+10.7%	+6.8%	+14.1%	<b>-27.8%</b>	+8.7%	+10.6%	+2.1%

The profitability depends not only on the capacity level, feedstock cost, and the end-product price but also on how the decision-maker perceives the total risk of the project. Discount rates are chosen depending on the TRL of a project and its associated uncertainties. In our study, cost and price variables are considered to be constant which is a simplification of reality. Besides, learning effects, technological improvements, and policy uncertainties are difficult to capture and therefore hard to incorporate. To tackle these shortcomings, a risk premium is added to the risk-free discount rate to incorporate project-related uncertainties. However, some uncertainty will remain. Van Dael et al. (2015) stated that R&D projects are usually discounted by 15% to 20%. Following this advice, a discount rate of 15% was considered. However, for a very risk-averse decision-maker, a discount rate of 15% might be an optimistic value for an R&D project with a low TRL in that early stage. For a discount rate of 20%, only waste wood would be considered to be economically profitable (see IRR in *Table 7*). When technology reaches a certain maturity stage and the products prove to be competitive and have a solid market, it is possible to assume that the discount rate might have a lower value. For instance, biomass conversion technologies in the energy sector are discounted by 10% (Hern et al., 2015). Taking a discount rate of 10%, poplar, waste wood, FC1, and FC3 prove to be competitive. Birch and FC2, on the other hand, are close to the hurdle rate of 10% with an IRR of 9.7%. Pine as single-use feedstock is proved to be not competitive under the current assumptions.

### 3.5 Main implications and recommendations

#### 3.5.1 Valorization of wood

Our integrated TEA assessment reveals that the RCF-technology valorizes wood on a high economic and technical level (carbon efficiency). Nevertheless, in several aspects, a significant margin for improvement still exists. For instance, Renders et al. (2018) showed significant improvement in yield outcomes by using a different solvent – a mix of 50% of n-butanol and water – under milder reaction conditions. Therefore, further research to ameliorate the RCF-process (e.g. in terms of cost reduction or revenue increase per production unit) is needed accompanied by a periodic integrated TEA assessment.

#### 3.5.2 Waste wood as the best alternative

It is clearly shown that waste wood is the feedstock of choice. Lab stage-based results indicate that waste wood (type B) is technically suitable for the RCF-process. However, it is often neglected as a feedstock for high-value end-products due to the presence of contamination (Kutnar and Muthu, 2016). Further in-depth research is required to identify these contaminants (organic and inorganic) and quantitatively allocate their mass flow throughout the biorefinery and into the different product streams. From a cascading point of view, waste wood under the RCF-biorefinery creates more added value than in other sectors (e.g. energy). However, the waste wood market is almost fully saturated. Besides, new EU targets for 2030 to reduce greenhouse emission by using biomass, including waste wood, are limiting the utilization of waste wood (European Commission, 2017). Thus, RCF-biorefinery would face stronger

competition. On the other hand, the profit margin could be sufficient to absorb price shocks up to a price level of 152 €/t for a capacity level of 150 kt/y (*Figure 5*). Another point of attention is market acceptance. From the consumer perspective, waste wood-based end-products might face difficulties to be accepted due to the contamination issue. From the legal point of view, sensitive sectors (e.g. agriculture) have strict regulations. Therefore, policies are needed to lift barriers to use waste wood as a feedstock and increase market acceptance. Undoubtedly, such policies must be supported by studies, confirming limited environmental impact and toxicity for end-users, and if required specific waste wood quality standards must be implemented. Consequently, it would assure the safety of the end-products sending a positive signal to the consumers.

### 3.5.3 Value chain-specific integration

Depending on the capacity level and the associated wood supply, a market entry might disturb the market. Three scenarios are possible: (a) The feedstock supply-side absorbs the additional demand with *no-to-small* impact on future wood prices. (b) The market might be saturated and additional wood demand would cause scarcity and increasing feedstock costs leading to a non-profitable project. And even if the RCF-biorefinery can pay higher feedstock prices, certain species could not be available due to supply shortage (e.g. new regulations, policy changes, pesticide infection, geographical location, etc.). Näyhä (2019) stated that, for certain high-quality products, it is a challenge to find a specific type of wood. Building on that, the use of waste wood could minimize such species-specific supply constraints. Section 3.3 showed that a feedstock mix including waste wood brings significant economic improvement and that single-use waste wood is already profitable at a capacity level of 80 kt/y. (c) Additional wood demand could also act as a feedstock price stabilization mechanism. This mechanism is likely to become even more important in future climatic conditions were forest disturbances (storms, pathogens, insects, and drought), which can have the effect of temporal high feedstock oversupply and price drops, are expected to increase in activity (Seidl et al., 2017). Due to the feedstock flexibility of the RCF-biorefinery process, price shocks could be absorbed by switching to a different type of feedstock.

Another point associated with feedstock availability is the optimal location of the RCF-biorefinery. The location must be strategically chosen considering easy access to feedstock supply and wood value chain infrastructure. It needs to be assessed whether the infrastructure already exists, if additional extensions are needed, or if a new RCF-biorefinery-tailored infrastructure must be established. The optimal location also depends on other factors. The envisioned RCF-biorefinery does not incinerate H<sub>2</sub> gas bypass waste streams itself and therefore would allocate these streams to an external incinerator, thus limiting the location choice. Hydrogen prices are determined by accessibility and transportation cost. We used a price of 2100 €/t assuming access on a large industrial scale with *no-to-short* transportation distance. Lowering the accessibility to a small industrial scale with longer transportation distance could lead to a price increase of up to 6000 €/t (Thomas et al., 2016).

Hence, based on our assessment it is recommended to design the RCF-biorefinery and its infrastructure in a flexible way to tackle the above-mentioned supply-side based uncertainties. Because of RCF-technology flexibility, decision-makers should also consider different feedstocks or feedstock combinations to overcome supply-side challenges. Several constraints limit the location choice. Due to the hydrogen accessibility and H<sub>2</sub> gas bypass waste stream incineration, chemical- or Bio-hubs with access to hydrogen seems to be suitable for the RCF-biorefinery.



### 3.5.4 Use of wet wood due to reduced processing costs

Following up on the sensitivity analysis (Section 3.2), the use of wet feedstock, which requires less processing compared to dry wood, can decrease the cost and the environmental burden of the feedstock. One of the main cost drivers of feedstock is drying. It amounts between 31% to 37% of the total cost of virgin wood (*Table 6*). Reducing the drying cost would also lead to a decrease in greenhouse emissions. Schutyser et al. (2015) showed that wet wood is applicable for the RCF-process. However, due to the absorbed water in wet wood transportation cost increases. Therefore, further research is needed to conclusively show the advantage of wet wood as an alternative to dry wood.

## CONCLUSION

An integrated TEA was developed to solve the rigidity of traditional TEAs by mutual multi-linkage between input and intermediate variables, which eventually results in multiple chosen output variables. Besides, this integrated TEA introduces new parameters (e.g. moisture content) that are giving the decision-maker new insights and in-depth assessment possibilities between the technical and economic processes on a low TRL-based technology using laboratory studies. Furthermore, the TEA is designed as a modular system allowing to combine it with different disciplinary models. All of these features are making integrated TEA's indispensable for R&D projects. An economic feasibility study on the reductive catalytic fractionation-process was performed which targets the conversion of wood into higher-value end-products. A detailed process flow diagram and mass and energy balance for a capacity level of 150 kt/y wood feedstock input were displayed. First, different capacity levels (20, 75, 150 kt/y) were assessed showing that scale has a large impact on profitability advising to focus on optimizing the plant facilities and its operations. Second, a Monte-Carlo sensitivity analysis was carried out assessing the most influential parameters. Third, the economic feasibility of different feedstock species and its combinations were assessed revealing species-specific impacts on the different processing stages and associated product yields and illustrating the importance of species-specific cost and price structure. Our assessment revealed that waste wood is the feedstock of choice. The break-even point-analyses show the potential of waste wood to absorb several economic shocks such as; end-product price decrease (-28%) on the demand-side, feedstock cost increases (59%), and a feedstock availability decrease to 80 kt/y on the supply-side. Nevertheless, the results should be interpreted with caution due to potential wood value chain-specific constraints, such as supply availability, optimal location choice.

Conclusively, our integrated TEA shows to be an indispensable tool to not only assess the economic feasibility of a biorefinery but also to define a multi-dimensional strategy of choosing the appropriate scale with possible optimal feedstock combinations under the most promising wood value chain conditions.

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## **NOMENCLATURE**

### **Abbreviations**

CAPEX = Capital expenditure

€ = Euro

FC = Feedstock combination

IRR = Internal rate of return

MEB = Mass and energy balance

M€ = Million euro

NPV = Net present value

OPEX = Operational expenditure

PFD = Process flow diagram

R&D = Research and development

RCF = Reductive catalytic fractionation

TEA = Techno-economic assessment

TRL = Technology readiness level

### **Subscripts**

BEP = Break-even point

$CF_t$  = Net cash flows generated in year t

h = Hour

$H_2$  = Hydrogen

i = Discount rate

$I_0$  = Initial investment (CAPEX) in year 0

kWh = Kilowatt-hour

$m^3$  = Cubic meter

kg = Kilogram

kt = Metric kiloton

t = Metric ton

n = Project lifetime

Ru/C = Ruthenium on carbon

y = Year

wt% = Weight percent

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