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Wood utilization scenarios and their sustainability impacts in Finland

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Academic dissertation

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ABSTRACT

Social, economic and environmental impacts vary in different wood utilization patterns, and national level strategies should consider possible trade-offs and regional needs. This thesis explored a variety of wood utilization scenarios in Finland and assessed their possible future benefits and trade-offs in environmental, economic and social sustainability, forming plausible pathways to actualize preferred outcomes reflecting different priorities in the goal setting. The research was conducted by using model-based sustainability assessment tools, material flow based Tool for Sustainability Impact Assessment (ToSIA) and Lifecycle Assessment (LCA), and explorative participatory scenario methods visualizing the targets quantitatively. The participatory methods utilized actor and researcher stakeholders from industry, policy, and multiple R&D fields. The results showed that cascading and shifting secondary wood flows e.g. industrial side streams and end-of-life wood-based products from energy uses to material uses, results in increased climate benefits and economic competitiveness. Energy use of wood had lower employment, value added, and substitution benefits as well as shorter carbon storing time compared with material uses of wood. Thus, modern wood-based construction, chemicals, textiles and composites need to increase their share in the product portfolios. National policy tools can support this development only to a limited extent, because the global markets set the market framework for wood uses. To change the global market environment, internationally renewed policies aiming at restricting fossil uses are needed to make wood-based material applications more competitive. European Union (EU) policies should also apply incentives to support factor integrates supporting renewable resource savings. Public financial support to develop new processing technologies and product design of wood-based modern applications are needed to boost cost-competitiveness. Industries and other private investors can contribute to sustainable development by focusing on improving existing processing technologies and making them more resource and energy efficient. However, international policy efforts are still needed to increase the mix of alternative clean energy forms in Finland.

Keywords: Cascading, impact assessment, Participatory methods, Plausible pathways, Product portfolios, Trade-offs

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Joensuu, 4th March 2020
Janni Kunttu

LIST OF ORIGINAL PUBLICATIONS

This thesis is based on data presented in the following articles, referred to by Roman Numerals I–IV. Articles are reprinted with the kind permission of the publishers.

I Suominen, T., Kunttu, J., Jasinevičius, G., Tuomasjukka, D., Lindner, M. (2017). Trade-offs in sustainability impacts of introducing cascade use of wood. Scandinavian Journal of Forest Research, 32(7): 588–597. https://doi.org/10.1080/02827581.2017.1342859

II Karvonen, J., Kunttu, J., Suominen, T., Kangas, J., Leskinen, P., Judl, J. (2018). Integrating fast pyrolysis reactor with combined heat and power plant improves environmental and energy efficiency in bio-oil production. Journal of Cleaner Production, 183: 143–152. https://doi.org/10.1016/j.jclepro.2018.02.143

III Kunttu, J., Hurmekoski, E., Heräjärvi, H., Hujala, T., Leskinen, P. (2020). Preferable utilisation patterns of wood product industries' by-products in Finland. Forest Policy and Economics, 110(2020). https://doi.org/10.1016/j.forpol.2019.101946

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AUTHOR'S CONTRIBUTION

In **Article I**, Tommi Suominen designed the research objectives, while Janni Kunttu collected the data and carried out the analysis and had the main responsibility of the interpretation of the results. Authors jointly contributed to the manuscript writing, but Suominen and Kunttu had the main responsibility of it. In **Article II,** Jaakko Karvonen developed the research objectives. Jaakko Karvonen, Janni Kunttu and Tommi Suominen jointly designed the methodology. The data collection was done in collaboration between Jaakko Karvonen and Janni Kunttu. Jaakko Karvonen had the main responsibility in manuscript writing, and all the authors contributed to result interpretation and in making conclusions. **In Article III,** Janni Kunttu designed the research objectives and the methodology was designed jointly with the co-authors. Janni Kunttu carried out the data collection and analysis and had the main responsibility of writing the manuscript and interpretation of the results. The co-authors contributed to the manuscript by editions and comments. In **Article IV**, Janni Kunttu and Elias Hurmekoski jointly designed the research objectives and methodology. Janni Kunttu collected the data and implemented the analysis with the help of co-authors. Janni Kunttu had the main responsibility of writing the manuscript, and the co-authors participated in finalizing the article by editing and commenting the structure and conclusions.

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1. INTRODUCTION

1.1 Background and motivation

Global demographical and industrial growth is expected to increase demand for materials and energy (Abas et al. 2015; World Energy Council 2019), which in total may triple the resource use by 2050 (Kok et al. 2013; Reh 2013). At the same time, the Paris Agreement on Climate Change stipulates that global emissions and removals be balanced in the second half of the 21st century. Nearly 86% of the global energy demand in the 2010s is still covered by fossil fuels (Abas et al. 2015). Therefore, the demand for renewable materials and fuels substituting fossil derived ones is increasing fast. The role of forests in climate change mitigation is two-fold: forests are sequestering and storing carbon, and harvested wood resources substitute fossil materials and fuels as well as store carbon in the technosystem (Geng et al., 2017). Political goals and actions aiming to increase the growing forest stock and area are rather clear compared with ones considering harvested wood utilization, because they include multiple contradicting sustainability targets and drivers. The European Union Bioeconomy Strategy aims at increasing resource efficiency, securing sustainable uses of renewable sources for industrial purposes and ensuring environmental protection (European Commission 2018). The strategy defines sustainability widely and the wood utilization patterns aiming at achieving maximal economic competitiveness may, for instance, vary from the patterns aiming at achieving maximal greenhouse gas (GHG) emission reductions. It is recognized that the lack of clear actions in relation to targets in policies is one of the main uncertainties in biomass use development in Europe (Hagemann et al. 2016). From this perspective, the European Union Action Plan for Circular Economy is clearer. It aims to improve resource efficiency by keeping the value of materials, products and resources in the technological ‘closed loop’ system as long as possible by e.g. reuse, recycling and product design (European Commission 2015).

Resource efficiency is one of the key components responding to increasing demand of renewable materials (World Energy Council 2019). The cascading principle applied to wood products, one of the circular economy tools, aims at prolonging the lifetime and creating more added value (Vis et al. 2016). The cascading principle has been hierarchized into priority use categories as follows: wood-based products, extending their service life, re-use, recycling, bio-energy and disposal (European Commission, EU Forest Strategy 2013). This implies that wood products should be reused and recycled as many times as possible before energy generation or landfilling. This is based on research evidences which indicate that prioritizing material uses over energy generation increases the carbon stock in harvested wood products (HWP), and creates more social and economic benefits such as employment and revenues through new business (Sathre & Gustavsson 2006; Kim & Song 2014; Vis et al. 2016). Yet, because wood is classified as a renewable source, its energy use may increase under global renewable energy targets (World Energy Council 2019).

The greatest potential to improve resource efficiency by cascading loops relies on secondary resources meaning industrial side streams and end-of-life wood and wood-based products (waste wood) (Vis et al. 2016). Industrial side streams, including for example sawmilling and panel production solid by-products, and black liqueur from pulp milling, formed 38.6% of the total wood flows in early 2010s in Europe (Mantau 2015). To date, side streams are still primarily combusted for energy in Europe (Mantau 2015; Hassan et al. 2018) despite the range of potential applications in the field of chemical, biofuel and modified wood industry with high GHG reduction and added value potential (Packalen et al. 2017). In some southern countries of the European Union, such as Spain and Italy, waste wood has been cascaded in particleboard production (Pirhonen et al. 2011). Using end-of-life waste resources in material production could help regions with scarce forest resources to increase their wood-based production volumes. For example, in the Netherlands this kind of material cascade use has received a lot of interest, because the wood industry is highly dependent on imported wood and cascade use could improve their self-sufficiency (Mantau 2012; Sokka et al. 2014).

However, the possibilities to favor material use over energy use do not only depend on policies, but country-specific circumstances, such as industry structure, available alternative energy sources to replace wood, and market forces. In some countries, such as Finland, a high export rate of wood products shows that cascade loops take place after export (Sokka et al. 2014). Thus, the energy recovery after material cascading might not be as efficient as elsewhere. It raises a question whether wood can be replaced with another clean energy form or may material cascading increase the demand for fossil fuels or virgin wood combustion in those cases, especially if there is a limited access to solar or wind power. Thus, it is not self-evident that altering wood-flows to increase material production would save forest resources or increase resource efficiency or create extra revenues for the industries. Therefore, the country-specific circumstances and possible outcomes of new practices should be carefully evaluated in advance to form plausible strategies for wood utilization in line with regional needs.

In Finland, studying the impacts of different wood utilization practices are especially important since Finnish forests are the main renewable source and therefore the basis for bioeconomy (Ministry of Employment and the Economy 2014). Forests cover 86% of the total land area of Finland (Vaahtera et al. 2018). Sawmilling and pulp milling industries are the biggest roundwood utilizers, using altogether around 70 million cubic meters annually (Vaahtera et al. 2018). The pulp and paper industry contributed to nearly 80% of the whole sector’s turnover in 2017 (Vaahtera et al. 2018). The Finnish bioeconomy is expected to contribute in total of €100 billion by 2025 (Ministry of Employment and the Economy 2014). The objective of the Finnish Bioeconomy Strategy is to ”generate economic growth and new jobs from an increase in the bioeconomy business and from high added value products and services while securing the operating conditions for the nature’s ecosystems” (Ministry of Employment and the Economy 2014). The strategy focuses on social and economic sustainability through diversification of wood-based products and new uses of wood. Achieving these benefits might require increasing the value of wood-based products but also increasing the use of wood. The net growth of Finnish forest resources was 13 million cubic meters in 2018, whereas in previous years it has been around 18 million cubic meters (Viitanen et al. 2019). The harvest level was nearly 80 million cubic meters in 2018 and, in order to reach the carbon sink target levels set by the EU in LULUCF regulation, Natural Resources Institute Finland has estimated that the maximum harvest level will be around 77 million cubic meters annually in the near future (Ministry of Agriculture and

Forestry & Natural Resources Institute Finland 2019). This level is based on a target so as to ensure an economically sustainable wood supply for industrial needs, and the selected interest rate (here 3.5%) highly affects the results. The harvest levels reflect the economic situation globally and thus in reality they fluctuate. Harvest levels are expected to decrease in turn after 2019 (Viitanen et al. 2019). Since harvest levels are driven by the market situation, it might be most beneficial, from the perspective of long-term sustainability, to explore ways to further improve resource efficiency and develop low-carbon solutions in the whole forest sector.

The impact of forest management on the carbon balance is relatively well studied in Finland. The forest growth and forest carbon sink can be increased with intensified forest management, including, for instance, forest fertilization, improved regeneration material and ditch network maintenance (Gustavsson et al. 2017; Heinonen et al. 2017; Heinonen et al. 2018). Less attention is paid to actions increasing the carbon sink in the technosystem in terms of increasing substitution benefits and carbon storage which, however, is needed to efficiently reach net negative emissions. To obtain net negative GHG emissions in the forest sector in a time scale of 100 years, the substitution benefits of increased harvesting should be higher than the loss of forest carbon stock in Finland (Seppälä et al. 2019). In case of a 17% increase in harvesting levels, Seppälä et al. (2019) concluded that a ton of harvested forest carbon should substitute on average two tons of fossil carbon in GHG emissions from non-wood products. This is referred as Required Displacement Factor (RDF = 2 tC/tC) which measures the required avoided emissions per unit of wood used when replacing non-wood products with equal functionality.

Each wood-based product has a different Displacement Factor (DF) depending on its end-use. In general, energy use of wood has in most cases lower DF compared with material uses (Soimakallio et al. 2016; Leskinen et al. 2018). The roundwood is mostly used for material applications and only small-sized wood or harvest residues, which are not suitable for material uses, are used for energy generation in Finland (Vaahtera et al. 2018). However, since over 90% of the industrial side streams and end-of-life wood-based products are used for energy (Mantau 2012; Hassan et al. 2018), the average DF over total annual wood-based production, and value added, could be further much increased by shifting side streams into material production. It is clear that wood plays an important role as a renewable energy source in Finland (Sokka et al. 2014) and the shift to material uses might require complex structural changes, for example increasing the shares of solar and wind power and increasing the energy efficiency of the industries. Solar and wind power still have growth potential in Finland, but it would require higher economic profitability for these technologies and sufficient raw material supply to manufacturing of the new plants (Hakkarainen et al. 2015; Sokka et al. 2016), and it is possible that other low-carbon solutions e.g. nuclear power would be needed as well to cover the energy demand. There are also differences in climate benefits between wood-based fuels. For example, modern liquid biofuels e.g. pyrolysis oil in substituting fossil fuel oil could result in significant climate benefits (Steele et al. 2012). However, the climate impacts of biofuels depend on the raw materials used as well as conversion and material efficiency (Zinoviev et al. 2010) and, thus, the results are not always net negative greenhouse gas emissions.

Another issue with wood-based substitution benefits is that the DF measure changes dynamically over time depending on emission development. Allwood et al. (2010), Muthu et al. (2012), and Wei et al. (2017) indicated significant fossil-based GHG reduction potential for fossil-based, metal and mineral industries towards 2050, meaning that wood-based products may substitute less emissions in the future. Considering the uncertainties of substitution impacts, decision making could benefit from utilizing assessment studies applying multiple indicators including the carbon stock in HWP or carbon residence (average time in years wood stores carbon in the technosystem). Also, economic and social dimensions should be part of the assessment in relation to country-specific needs.

Quantitative impact assessment tools can be applied to study these questions and, thus, they become suitable tools in decision making and future planning in the private and public sectors (Lloyd & Ries 2007). They aim at showing an impact of a particular system before it is applied (Lloyd & Ries 2007). These studies may include regional or country-specific data and, thus, they can give very detailed insight of the sustainability impacts. On the other hand, the quantitative impact assessment studies often ignore future development of the indicators used to measure the impacts, or completely new innovation systems, due to lack of suitable data (Lloyd & Ries 2007; Reap et al. 2008). To future related questions in decision making, foresight methods can be applicable as they aim at capturing the development directions of the operation environment (Cook et al. 2014). For example, the future of bioeconomy markets and diversification of forest-based have been studied by applying these methods (Hagemann et al. 2016; Hetemäki & Hurmekoski 2016). European studies after 2010 have focused on exploring possible, and probable, future development pathways to avoid pitfalls from the social and economic perspective (Hagemann et al. 2016; Giurca & Späth 2017). Scenario pathways mean a combination of actions eventually leading into actualization of the scenario and outlining the synergies between key influence factors (Hagemann et al. 2016). The benefit of the approach is that it considers all the dimensions of the operation environment. This includes important, yet not always visible, links between e.g. societal trends and policy prioritization (McCormick & Kautto 2013; Hagemann et al. 2016). Country-level studies of the key-influence factors affecting the wood-based product markets are implemented especially in countries planning biorefinery investments, such as Finland and Germany. They state that political actions are the most powerful influence factor affecting the future development of bio-based product portfolios, because the industries need to guarantee that the new investments and production are in line with the political strategies (Näyhä et al. 2014; Hagemann et al. 2016; Hetemäki & Hurmekoski 2016; Giurca & Späth 2017). The analysis of the key influence factors could be beneficial to combine with analysis of the sustainability impacts of changing wood utilization patterns. Optimally this could result in more insight of the future environment and indirect trade-offs in sustainability.

1.2 Objectives and research questions

The main objective of this thesis is to support political and industrial decision making and strategy formation towards sustainable future by exploring a variety of wood utilization scenarios in Finland and assessing their possible future benefits and trade-offs in environmental, economic, and social sustainability. This includes exploring pathways to actualize preferable outcomes reflecting different priorities in the goal setting. Therefore, the aim is to seek answers for this question setting by a set of different scenario methods, utilizing quantitative impact assessment and qualitative scenario tools. Varying methods are used to explore different aspects of the future evolvement and, based on those, to improve understanding of the direct and indirect impacts and development pathways towards goals.

The main research questions in this thesis are: i) what sustainability impacts may occur in the regional circumstances when wood flows are shifted from primary energy use to support material cascading and higher-added value biofuel production technologies, and ii) what are the key stakeholder motivations and priorities driving different wood utilization patterns and, finally, synthetizing iii) what structural changes in the operation environment would be needed, and how to implement them in a market viable way, to alter wood utilization patterns to increase positive climate impacts under increasing material demand.

The methodological premises are that i) quantitative impact assessment scenarios fail to offer clear conclusion of the 'best case scenario', if assessed impacts are not linked to country specific needs and priorities, ii) qualitative scenarios benefit from quantified data from the illustrative perspective, iii) scenario key influence factors and their synergies are not the same in Finland as in similar studies implemented in other countries, if the country-specific circumstances are different.

This thesis consists of four sub-study articles. Their objectives and research questions are defined in more detail below:

Article I: The environmental, social and economic sustainability impacts of end-of-life wood cascading into material uses are assessed in the regional circumstances (North Karelia, Finland). The research scope is to explore which benefits will occur and are there trade-offs when shifting end-of-life wood products (waste wood) from energy use to long-lifetime particleboard products. GHG emissions, carbon stock in HWP and energy use of production represent the environmental impacts, while employment and production costs represent the social and economic impacts. Tool for Sustainability Impact Assessment (ToSIA) program (Lindner et al. 2010) is used to capture consequences of altering the material flows.

Article II: This study compares the GHG emissions and air pollution of producing and using wood-based pyrolysis oil instead of fossil heavy fuel oil. It also assesses a standalone production system integrated in a Combined Heat and Power plant (CHP). The regional impacts are part of the interest and, thus, the production of pyrolysis oil in the modelled scenarios takes place in North Karelia, Finland. The study also addresses how the direct and indirect impacts vary within the value chains and, thus, both ToSIA (Lindner et al. 2010) and LCA (Jensen et al. 1997) are used in the assessment.

Article III: This study explores what kind of by-product utilization patterns of Finnish forest industries are considered preferable, what is the motivation behind them, and which actions are needed to attain those scenarios by 2030. The aim is to capture the visions of different stakeholders by using explorative scenario method based on a 'Q2 Scenario technique' (Varho & Tapio 2013), which visualizes the scenarios numerically and enables scenario formation without consensus seeking. A variety of scenarios and their strategical pathways are identified.

Article IV: The scope of this study is to seek strategic pathways for improving the substitution impacts of Finnish wood-based market structure to the level which could produce net negative emissions regardless of the harvest levels and including possible decrease in substitution impacts in the future. Therefore, the research questions include i) how product-specific DFs may change in the future, ii) what kind of product portfolios could set ‘net negative emission level’ achieve in 2050 in Finland and are there differences in their carbon residence over total production, and iii) which actions are required to enable market viability and implementation of those scenarios. The study uses mixed methods consisting of quantitative target scenario formation using literature, modified LCA assessment (Höjer et al. 2011), a substitution calculation framework (Hurmekoski et al. 2019), and qualitative pathway formation implemented by using a participatory backcasting method (Robinson 1990).

2. MATERIALS AND METHODS

2.1 Theoretical background of methods applied

This study applied quantitative impact assessment and foresight methods with the focus of future production systems in forest-based bioeconomy. The differences of the used methods have been summarized in Table 1. Quantitative impact assessment is an approach to support decision making related to future actions (Lloyd & Ries 2007; Linkov et al. 2009). Quantitative impact assessment may study e.g. economic or climate impacts of a new operational system, such as technology or business model. For example, it can be used for evaluating the sustainability of a new material processing technique or raw material before it is applied. Quantitative impact assessment outputs show the magnitude of the impact (Linkov et al. 2009). Thus, the results are clear in terms of interpretation, meaning that the numerical quantities have the same meaning for everyone, and can be easily compared with the baseline situation. However, there might be several indicators used for the evaluation in the social, economic, and environmental dimension, which hinders a clear “best case scenario” selection.

Multi-criteria analysis, meaning weighting the importance of indicators, can be applied to address this issue (Linkov et al. 2009), but this requires participatory approaches and clear goal definition. Nevertheless, the parameters used in quantitative assessment often rely on statistics and literature of existing systems. Therefore, the results include uncertainty when assessing completely new systems where data is not available (Lloyd & Ries 2007), or the studied system is planned in further future where the whole environment may have changed (Holmberg & Robert 2000). Pesonen (2000) suggested to address this problem by modifying quantitative parameters based on selected scenarios and assumptions of the future environment they could exist. Still, another related issue in quantitative impact assessment is called “scenario uncertainty” (Lloyd & Ries 2007). This means that the studied alternatives are based on historical or current trends and therefore do not fit long-term foresight scenarios, or they are subjectively self-defined by the researcher(s) and possibly leaving out a range of better justified scenarios (Lloyd & Ries 2007).

Foresight methods can be used to collect empirical data of non-existing systems (Cook et al. 2014), for example new innovations in wood-based products. A common aspect in foresight studies is that they all aim at foreseeing what is possible or probable (explorative approach, multiple choices) or preferable/unpreferable (Normative approach, certain goal) in the future (Bell 1996). The foresighting, part of future studies, has its roots in strategic military and economic planning, implemented already by the ancient Egyptians scheduling the harvests (Hawkins 2005). Foresighting has been widely used in corporate as well as national strategy planning already before the 20th century (Jemala 2010), but in the recent decades it has been applied to several research fields including environmental, social and economic sustainability studies (Holmberg & Robert 2000). Unlike quantitative assessments, and for example statistics studies, foresight scenarios – future visions and pathways – cannot have research hypotheses because no one knows what the future holds, and there is a countless amount of possible scenario variations. Instead of aiming at predicting, foresight studies mainly focus on clarifying complexity of the future evolvement and revealing path dependency (Tiberius 2011). In the path dependency theory, the actualization of any future scenario depends on the changes that eventually come through a complex network of influencing factors, and their indirect, direct and unexpected impacts form the scenario (Tiberius 2011).

Understanding the whole operational environment including e.g. societal, technological and environmental aspects is an important part of any strategy formation (Wade 2012). Since strategy formation is built on specific goals, foresight studies may include a normative aspect by defining the desirable scenario. It is argued that such goals should always be defined quantitatively when possible to clarify the interpretation (Robinson 1990). Integrating quantitative and qualitative data may also help to analyze the collected data when, for example, expert views are compared (Tapio et al. 2011).

Table 1. Description of different scenario approaches, their strengths and weaknesses

Approach	Quantitative model-based impact assessment	Qualitative scenario analysis (foresight)	Integrated scenario methods (foresight)
Data type	Quantitative	Qualitative	A mixture of qualitative and quantitative
Data source	Literature, statistics	Empirical: Stakeholder/expert inputs	Empirical/semi empirical: Literature, stakeholder/expert inputs
Basis for scenarios used for comparison	Often subjective "what if"	Depends on question setting normative or explorative: Possible/Probable/Preferable	Depends on question setting normative or explorative: Possible/Probable/Preferable
Strengths	Results are illustrative when quantified Provides most detailed results and serves as efficient tool for thinking May require less resources than full foresight exercise	Scenarios are well-justified when based on comprehensive stakeholder input Long-term timescale is possible as changing operational environment is considered	Scenarios are well-justified when based on comprehensive stakeholder input Results are illustrative when quantified Long-term time-scale is possible as changing operational environment is considered
Weaknesses	Poor justification of scenarios and model parameter assumptions: Based on current operational environment	Quality of data depends on comprehensiveness of stakeholder/expert i) representativeness and their backgrounds, ii) their understanding of time space and question setting	Techniques are complex and time consuming Quality of data depends on comprehensiveness of stakeholder/expert i) representativeness and their backgrounds, ii) their understanding of time space and question setting

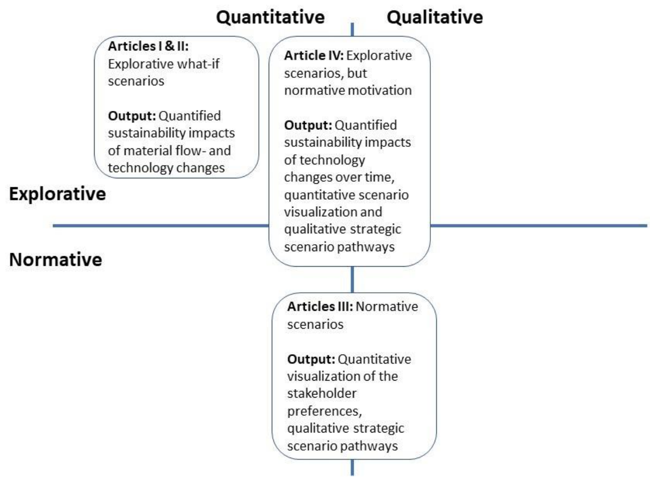

Figure 1. Illustration of the research approaches used in Articles I–IV and descriptions of the research outputs.

In this thesis, quantitative impact assessment using what-if scenarios was implemented in the first place (Articles I and II) to gain insight of the possible impacts of altering wood flows and applying new technologies. The scenarios were formed from an explorative perspective, and the parameters used in the models were based on the existing environment of today. Without setting a priority order for the measured indicators, the selection of the "best case scenario" can be challenging or unclear. Therefore, the next study (Article III) focused on exploring what is considered preferable, yet realistic, future vision of secondary (by-product) wood flow utilization and are there varying perspectives. To this question setting, scenarios were formed quantitatively to compare the visions stakeholders have, but scenario pathways and justifications were qualitative. In the final study in this thesis (Article IV), the aim was to take a different viewpoint in goal setting and select normatively the desired target future in advance. Here, quantitative impact assessment was applied to quantify, and indicate exploratively, a set of alternative scenarios possibly achieving this goal. Model parameters were also adjusted to fit the future visions literature presented of the technological development expectations related to the future, to address the "parameter uncertainty" issue. Since the structural changes needed to achieve these scenarios was of interest, strategic pathways were built by utilizing qualitative data collected by participatory approach. The phases of this thesis are illustrated in Figure 1.

2.2 Sustainability impact assessment with ToSIA and LCA (articles I & II)

2.2.1 Scenario overview and impact assessment tools applied

Articles I and II used explorative what-if scenarios to assess sustainability impacts of wood cascading practices and novel technologies to produce wood-based energy (combined heat and power) and fuels (pyrolysis oil). The scenarios were ‘from cradle-to-grave’ value chain variations of wood cascading and energy generation, where either material flow was altered or technologies changed. The geographical scope in both case studies was the region of North Karelia, Finland. As both case studies focused on assessing exploratively different ways to implement resource-efficiency affecting practices, market demand was out of the study scope.

In Article I, the effect of introducing material cascade use of end-of-life wood-products before energy use was modelled and assessed. This way, cascading scenarios either i) maintain or increase the production volume of particleboard, while ii) harvesting volumes decrease or remain the same (see 2.1.2). In the case study, untreated waste wood was utilized for particleboard production instead of established practice, energy generation. Material cascading was limited to untreated waste wood (end-of-life sawnwood) originating from construction or demolition sites in North Karelia. The particleboard made out from cascaded wood was assumed to be combusted for heat and electricity in the second lifetime loop, where it was not exported. The scenarios included the whole life cycle of selected wood products starting from forest harvesting and ending to end-of-life options.

In Article II, the environmental impacts of wood-based pyrolysis oil production chain were assessed in terms of energy-efficiency and emissions. The alternative scenarios evaluated a standalone plant and integrated (combined with heat and power production) factory, and compared those with fossil-based heavy fuel oil supply chain.

Tool for Sustainability Impact Assessment (ToSIA) (Lindner et al. 2010) and Life Cycle Analysis (LCA) (Jensen et al. 1997) were the tools chosen to quantify environmental as well as social and economic impacts of the selected variations of wood cascading (Article I) and modern energy technology (Article II) practices. Article I utilized only a ToSIA analysis, but included social and economic impacts in the assessment in addition of environmental impacts. Article II utilized both ToSIA and LCA analyses to capture direct and indirect emissions but did not include social or economic indicators in the assessment.

ToSIA is a tool to evaluate sustainability impacts occurring in different material-flow based production systems or value chains (Lindner et al. 2010). It is a process-based approach that compares material flows and environmental, economic, and social impacts based on them in alternative scenarios (Lindner et al. 2010). The value chain being analyzed can contain multiple end-products as well as raw material sources. The value chains in ToSIA are typically quantified as carbon flows (Suominen et al. 2012). Unlike LCA, ToSIA usually does not take into account indirect sustainability impacts such as emissions related to machine maintenance and production, etc. LCA is standardized in the ISO 14040 and 14044 standards (Ahlgren et al. 2015), which means that the calculation methods are unified to enable comparable analyses. EcoInvent 3 (Wernet et al. 2016) is used in Article II. While LCA allows indirect impacts to the assessment, material flow based ToSIA flexibly allows the user define freely the system boundaries and data used for the analysis. Both have their advantages and, therefore, it was beneficial to utilize both tools.

2.2.2 *Explorative what-if scenario definitions and data collection*

The baseline and the scenarios in Article I were made on a hypothetical basis, and material flows were simplified by excluding assumptions of material loss during the processes. The idea was not to model the practices in detail, but compare the difference between energy and material uses. Therefore, the assumptions are simplified to avoid erroneous conclusions. The baseline and scenario descriptions in Article I were the following (see also Figure 2):

Baseline: All the waste wood, which is collected from demolition and construction sites in North Karelia and further processed in North Karelia's waste management, is combusted for energy in Kainuu (transportation distance 230 km) and nothing is cascaded for materials. The by-products originating from sawmilling are used for particleboard production in North Karelia.

C-export: Available untreated waste wood is used for particleboard production instead of energy generation in Kainuu. The transportation distance from waste management in North Karelia to hypothetical particleboard factory is 68 km. As a result, the production volume of particleboard increases. The additional production of particleboard is exported. Thus, they are away from local energy uses in their second end-of-life. Consequently, the energy output generated from local resources decreases.

C-domestic: The same value chain assumptions as in C-export, but here the additional production of particleboard is used locally. Thus, this source will eventually (in the end of the second lifetime) enter the waste management as treated waste wood and contribute to local energy generation. The idea of this scenario is to assess a hypothetical situation where the second cascade loop, here "recovery for energy" does not happen outside of Finland and, therefore, does not decrease available resources in the energy generation. Thus, the amount of waste wood in energy generation is set the same as in the baseline, except all energy generation entering wood is treated particleboard now. No loss during use stages is assumed to have only the cascading impact in the scenario difference. The exception is that particleboard has here slightly higher energy content than untreated waste wood.

C-forest: Sawlog harvesting yield is decreased, which decreases the by-product volumes from sawmilling industry to the particleboard factory. Available untreated waste wood is substituting sawmilling by-products in particleboard production. Therefore, the particleboard production volume remains the same as in the baseline. Because less sawlogs are harvested, the amount of harvest residues, which would be used for energy, also decreases. The decrease is only 280 tons of carbon and therefore it has no visible effect on material inflows. However, the sawmill production decreases due to lower harvesting volumes and, therefore, the share of exported products is decreased in order to retain the baseline local use of construction wood.

C-energy: the same as alternative C-forest, except that the total harvesting volume equals the baseline. Less saw logs are harvested to reduce the total sawmilling production volume and therefore their by-products, and instead more forest energy biomass is harvested to reach the same harvesting volume as in the baseline. The total wood material used locally for energy generation is now 9.3 units. The share of exported products decreases in order to supply the same amount of wood products to local uses as in the baseline.

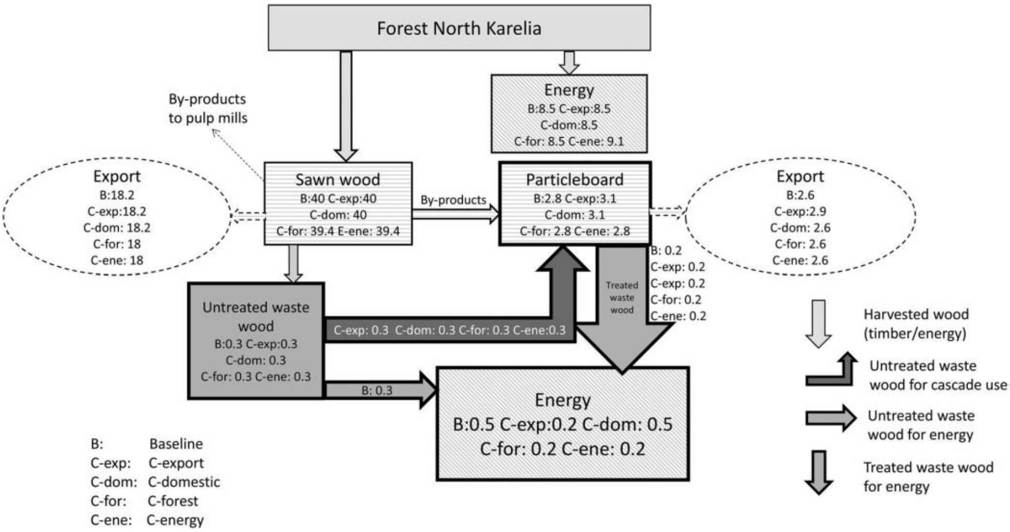

Figure 2. Visualization of the baseline and scenarios. The numerical values in the figure represent the wood flows in 1000 tons of carbon. Figure source: Suominen et al. 2017.

The data for by-product utilization in the particleboard production, and waste wood volumes and shares in the baseline were partly missing, and therefore were estimated by collecting anonymous information from industry, demolition and waste management companies operating in North Karelia and nearby regions. The specific process descriptions and well as their material inflows are presented in the supplemental material 3 of Article I (Suominen et al. 2017).

Scenario descriptions and assumptions (in each scenario the net energy output is the same) used in Article II are the following (see also Figure 3 and supplementary material in Karvonen et al. 2018):

CHP & HFO: CHP and the Heavy Fuel Oil (HFO) chains are used to produce the required total energy (1,028 GWh) and their emissions are summed. All the processes are in the annual basis. 305,000 tons of crude oil are drilled in Russia and ship transported to Porvoo in Finland (250 km one-way based on a map), where 6% of the crude oil is refined into HFO. Thus, approximately 305,000 tons of crude oil are altogether processed in the refinery to produce the 18,300 tons (208 GWh) of HFO. In the analysis, emissions from the other products (94% of the output products) are excluded in the analysis. HFO is transported 200 km from the oil refinery to an unspecified heat plant for heat production. CHP plant uses 137,100 tons of energy wood and equal amount of harvest residues, and additionally 81,000 tons of peat. The CHP output energy is 820 GWh.

CHP & Pyr: CHP and pyrolysis are standalone plants producing the required total energy. 50,000 tons of Pyrolysis oil (PO) are needed to substitute 18,300 tons of HFO (208 Gwh). Pyrolysis oil plant uses 75,000 tons of energy wood and equal amount of harvest residues, whereas CHP plant uses 137,100 tons of energy wood and equal amount of harvest residues, and additionally 81,000 tons of peat.

CHP-Pyr-integrate: Here, the CHP plant and the pyrolysis reactor are integrated and the by-products of the pyrolysis process are fed back to be utilized as extra energy. Because of extra energy, the roundwood and peat raw materials for CHP are reduced so that the total production of the CHP plant remains at 820 GWh. Thus, the integrated plant requires 205,400 tons of energy wood and equal amount of harvest residues, and peat use can be decreased to 76,980 tons. The produced 50,000 tons of bio-oil are transported 200 km to substitute for HFO.

The data for the integrated factory was gained from the literature (e.g. Onarheim et al. 2015; Steele et al. 2012), but a real-life example, a CHP-pyrolysis integrate existing and previously operating in Joensuu, Finland, also inspired the scenario planning. The fast pyrolysis liquifies the biomass by exposing it to 500 Celsius degrees for about 2 seconds (Onarheim et al. 2014). The fast pyrolysis process results in char and non-condensing gas fractions as by-products. The by-products can be used as extra fuel to produce internal heat when fed back to the pyrolysis process (Kohl et al. 2013). The fast pyrolysis uses 15% of the feedstock energy, but additional energy is needed before the process itself, as the roundwood-based feedstock needs to be dried and grinded (Onarheim et al. 2014). In the scenarios of Article II, the origin of the roundwood and harvest residues used for pyrolysis was assumed to be North Karelia. The conversion efficiency assumptions used were: 66% pyrolysis oil, 12% gases, and 22% char. In addition, the CHP plant is assumed to use peat in addition of roundwood. For processes outside the pyrolysis and CHP plants, such as forestry and transports, databases (VTT 2016) and technical reports were utilized. The specific process descriptions of the value chains in Article II, including e.g. forestry operations and transportation data, are presented in supplementary data (Appendix B in Karvonen et al. 2018).

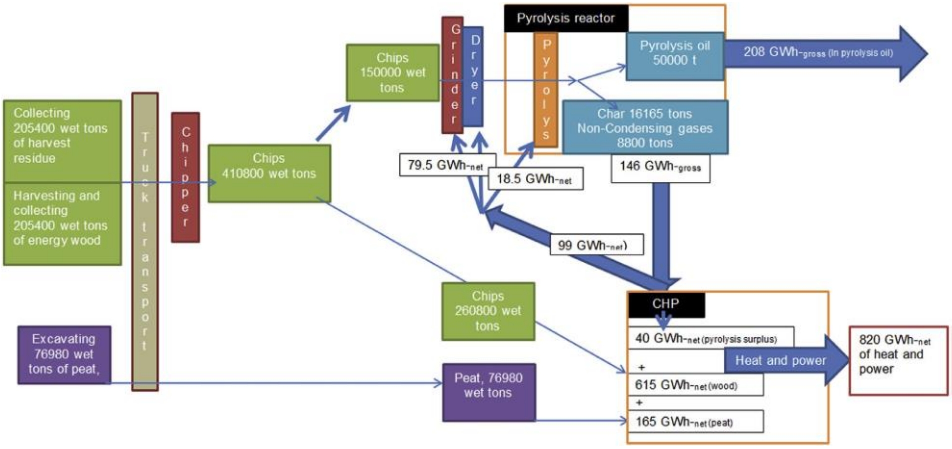

Figure 3. Wood-based value chains used in the assessment in Article II and illustration of the energy contents. Figure source: Karvonen et al., 2018.

2.2.3 Sustainability indicators and calculation methods used in the assessments

This chapter presents the selected sustainability indicators in Articles I and II, and the respective calculation methods. The indicators are described in Table 2. The social and economic sustainability indicators used in Article I were production costs per harvested ton of carbon (€/t of C) and employment in full-time equivalents per harvested ton of carbon (FTE/t of C). Energy output in megawatt-hours (MWh), energy use in kilowatt-hour per harvested ton of carbon (kWh/t of C), greenhouse gas emissions (kg of CO_2 equivalents/t of C) and carbon stock in HWP measured environmental sustainability. Energy output per harvested ton of carbon (kWh/t of C) was calculated to show trade-off effects between energy and material use of wood. The environmental indicators used to examine the environmental impacts in Article II were CO_2 equivalents, sulfur dioxide (SO_2), nitrogen oxides (NOx) and fine particle matter (PM, ∅< 10 mm).

In Article I, production costs, employment, energy use, and greenhouse gas emissions were assessed in ToSIA, whereas carbon stock in HWP and energy output were assessed separately. The total material flows and half-lives needed for carbon stock calculation are presented in the supplemental material 6 in Article I (Suominen et al. 2017). The ToSIA indicators were calculated for each process within the system boundaries. These processes included the steps from forest harvesting to end-of-life use and, thus, consisted of multiple transportation, processing and wood product production processes. The ToSIA indicators were calculated by accounting the absolute amount of indicator needed to process incoming material flow inside a process. Only wood material related processes were included to the assessment, and indirect processes e.g. machinery production were excluded. The included processes and calculation data e.g. transportation distances, hour productivities, machine and fuel specific emission factors and energy contents are more specifically presented in the supplemental material 3, 5 and 6 in Article I (Suominen et al. 2017). For the scenario comparison, the indicator results are presented per ton of carbon, which is a unit used to model the material flows.

The indicators in Article II were assessed in both, ToSIA and LCA, to assess also differences between direct and indirect emissions. Here, the direct emissions mean the emissions occurred from the processes, which are parts of the supply chains from natural resource harvesting (oil drilling or wood harvesting) to end use (energy generation). ToSIA included material processing based direct emissions and LCA included also indirect emissions, meaning e.g. machinery production. ToSIA analysis was carried out first, as it was the more case-specific method of the study and it enabled modelling of (local) resource use. Indirect emissions were applied next to the assessment by applying them on top of adjusted regional ToSIA data, in LCA. These indirect emissions were taken from the EcoInvent database. Therefore, process-based indicator data was applied to LCA assessment as well, but the difference was that in LCA the indirect emissions were included on top of them. The only exceptions in using ToSIA data in LCA were the processes for crude oil drilling and production and refinery operations: In ToSIA, emissions given in Wihersaari (1996) were used, while the LCA calculations relied on the EcoInvent data. These exceptions were made because these processes were more complex in LCA and inputting the values gained from Wihersaari (1996) might have resulted in double counting some emissions. In LCA, SimaPro 8 (PRé Consultants 2019) was used to characterize the climate impacts as CO2 equivalents. The process-based indicator factors and their process related data including e.g. transportation distances and hour productivities are presented in detail in supplementary material of Article II (Karvonen et al. 2018).

Table 2. Indicators used in the assessments in Article I & II and their descriptions.

Indicator	Description	Article I	Article II
Production costs (€)	Sum of material costs, labor costs, energy costs, other productive costs (e.g. maintenance and depreciation) and non-productive costs (e.g. taxes) per process unit (m^3, kWh, etc.) The calculation applies to each process (export excluded).	Included	Excluded
Employment (FTE)	Number of person-years (full-time equivalents, FTE) per process unit. One FTE is assumed to equal 1,732 h/year in Finland. The calculation applies to each process (export excluded).	Included	Excluded
Energy use (kWh)	Sum of energy use (machinery, electricity from the grid, non-renewable and renewable energy use). The calculation applies to each process (export excluded).	Included, biogenic and fossil energy.	Excluded
Greenhouse gas emissions (kg of CO_2 eq.)	Total CO_2, CH_4 and N_2O emissions presented in CO_2 equivalents. Emissions are transformed to CO_2 equivalents by using GWP (Global Warming Potential) factors. The factor for CO_2 is 1, for CH_4 is 25, and for N_2O is 298 (Lindroos et al. 2012). The calculation applies to each process (export excluded and emissions from the growing forest).	Included, biogenic and fossil emissions.	Included, biogenic emissions are applied to PO and CHP.
Sulfur dioxide (SO_2)	Total SO_2 emissions occurred in the value chains.	Excluded	Included
Nitrogen oxides (NOx)	Total NOx emissions occurred in the value chains. PM emissions were excluded from the combustion processes.	Excluded	Included
Fine PM, ø< 10 mm)	Total PM emissions occurred. PM emissions were excluded from the combustion processes.	Excluded	Included
Carbon stock in HWP	Total carbon stock in the pool of HWP. The factors here influencing carbon stock are annual carbon inflow into the pool and half-life values of the products (IPCC 2006).	Included	Excluded
Energy output	The total generated net energy output inside the system boundaries. The generation type is CHP and energy efficiency 82% (Hytönen 2010).	Included	Energy output is used to make the scenarios comparable
Energy efficiency	The energy efficiencies were assessed by comparing process-required input material and net output energy converted into GWh. The calculation applies to PO production and CHP plant processes.	Excluded	Included

2.3 Scenario analysis approach combining quantitative and qualitative data (Article III)

2.3.1 Overview of methodological approaches and study phases

Article III aimed at gathering views on preferable but realistic futures of by-product utilization patterns in 2030 in Finland and at forming normative scenarios from a set of quantitative ratings. The preferable allocation of by-products in the scenarios was presented with quantitative values to support analysis and interpretation. A set of future scenarios were formed based on different opinions. This study utilized as a basis the ‘Q2 Scenario technique’, originally developed by Varho and Tapio (2013). The idea was to combine quantitative and qualitative data, which were gathered by sending a short questionnaire for the experts and completing the qualitative scenario storylines by using face-to-face interviews (Varho and Tapio 2013). The Q2 scenario approach has similarities with the Delphi technique, which utilizes iterative expert assessments (Gupta & Clarke 1996). Delphi is especially suitable for exploring long-term scenarios, when there is no future-related information available for the analysis (Linstone & Turoff 1975; Bell 1996). Traditional Delphi studies aim at attaining consensus among the experts, but there are also variations which allow different opinions. The Q2 scenario technique is similar to Disaggregative Policy Delphi that allows diverging views (Tapio 2003), and uses quantitative cluster analysis to group and classify the similar opinions.

In Article III, a rather close timeline (2030) was selected for the scenarios. The reason for it was that the scenarios were meant to be realistic at least in a theory. The definition of “preferable” was exclusively defined by the experts, because the aim was to explore different viewpoints. The market demand forecasts are, therefore, outside the scope of this study. Experts were selected from a comprehensive coverage of stakeholder groups: experts in the field of research, industry, policy, and interest groups meaning Non-Governmental Organizations (NGOs) such as federations and associations. The experts in those four main groups were divided further into representing forestry, energy, primary wood products, and refining industries (e.g. chemistry). Following the principle of Argument Delphi studies, expert coverage was more important than the number of participants (Rikkonen & Tapio 2009). A total of 17 experts participated in the study, two of whom were unable to participate in the interview phase.

The study consisted of two phases. In the first phase, an Excel-based questionnaire was sent to experts, where they had to illustrate by numerical allocation shares the preferable uses of by-products in Finland in 2030. Experts expressed the preferable use rate and use in percentages for sawdust, wood chips, and bark. The pre-defined possible uses were heat and power, pulp and pulp-based biorefinery products, liquid biofuel production, wood composites, particleboard and fiberboard, and additionally they were able to define some other use not mentioned. Experts provided a short justification for their preferred future view and gave the main drivers for it.

Quantitative allocation shares illustrating the preferable scenarios were grouped by their similarities by applying hierarchical cluster analysis (see Section 2.3.2) to form pre-scenarios for the second phase i.e. interviews. Face-to-face interviews were implemented during December 2017 and February 2018. Before these interviews, clustering results (compiled scenarios, their justifications and drivers) were sent to each expert. After seeing the scenarios and their justifications, the experts were given a chance of modifying their own original answers. If any changes were made, the cluster analysis was performed again to see if the quantitative scenarios changed. In the interview phase, the experts evaluated the benefits and probability of the scenario representing their own view. They also evaluated how the most probable future development might differ from the one they prefer. Next, they evaluated the concluded drivers and were asked to rank the main drivers and the main barriers for the scenario implementation. In the final phase, they evaluated the advantages, possible disadvantages, and the likelihood of the other scenarios. The qualitative data were extracted to a transcription and, by applying a futures table, the results were compiled into scenario pathways.

2.3.2 Data analysis: quantitative and qualitative scenario compilation

The preferred use rates (%) and uses of by-products were combined into scenarios based on their similarity. A hierarchical clustering method (Bridges 1966) was used as a simple classification tool to group similar type of answers. The quantitative similarities were measured based on squared Euclidean distance of average linkage (between groups) by using the SPSS® statistical software. Since there was a relatively small number of variables and expert answer, it was possible to select the number of final clusters based on group distances without further statistical analysis.

The cluster analysis showed which answers could be combined into a same group (=cluster). The groups translated into scenario figures after calculating group averages. The drivers, descriptions and evaluations of the scenarios were compiled to scenario stories by using a compilation table, called the futures table approach in the foresight studies (e.g. Leppimäki and Laitinen 2007). For this, the drivers were classified by the identified theme: political, research and development, cooperation and information provision, and mixed.

2.4 Quantitative target scenarios combined with participatory approach (article IV)

2.4.1 Overview of study phases

Article IV defined exploratively market scenarios for wood-based products in 2050, which would on an annual basis achieve net negative emissions in the short-term through wood substitution in Finland. The study identified also strategic pathways to these scenarios consisting of structural changes in the operational environment. The study was implemented in multiple phases, starting from the quantitative scenario modelling which utilized life-cycle analysis parameter estimations based on literature, and a substitution calculation framework presented by Hurmekoski et al. (2019). The participatory backcasting approach was used to explore qualitative pathways for the scenarios.

The backcasting method (Robinson 1990) requires a vision of the future and defines stepwise, from the vision to today, what kind of structural changes are needed to reach this future. Backcasting has been widely used as a planning tool for environmentally sustainable business and market development (Holmberg & Robert 2000). Quantitative scenarios can clarify the future vision and differences (Tapio et al. 2011). Robinson (1990) suggested that goals or constrains in backcasting should be expressed quantitatively when possible for better illustration.

Thus, we have used LCA, whose parameters are adjusted to fit future expectations, so as to assess the future climate benefits of wood and use these estimations in the ad-hoc model to expose alternative market scenarios to reach the DF=2 tC/tC. LCA is a quantitative tool used for comparing environmental impacts of alternative production technologies and value chains based on e.g., fossil resources used and their emissions. Höjer et al. (2011) and Robertson (2016), for example, have used it to quantify and illustrate impacts of future scenarios.

This mixed method study consisted of three stages: i) estimating the wood end-use based DFs in 2050 by using LCA framework, ii) target scenario modelling by wood flow modification in ad-hoc model and estimating the wood product carbon stocks in the scenarios, and iii) strategic scenario pathway formation using participatory backcasting. To allow major enough changes as necessitated and considering typically slow transformation of forest industries, a timeframe of 2050 was adopted.

2.4.2 Data collection and quantitative target scenario formation

The quantitatively defined goal in the scenarios was that the volume weighted wood-product portfolio in 2050 results in DF of 2tC/tC through their entire lifetime in the technosystem. For this, estimations of the DF values in different product categories in 2050 had to be made. Since it is not possible to foresee substitution impacts of wood-based product in the future, the DFs in several product categories should only be considered as rough approximations used in scenario formation. That is to say, the main purpose of quantitative component in the scenarios was to illustrate for the workshop participants the possible magnitude of required changes to reach the target of DF=2, while the main results are the scenario pathways based on the semi-quantitative descriptions. Since the DF approximations are used as an illustration tool, the following uncertainties are less important in the conclusions, scenario pathway formation meaning e.g. the required actions in the technological or political field. The DFs were based on literature evaluating production emissions (Table 3). The DF estimations do not consider for example end-use country and export emissions, which naturally would affect the factors. Also, the production emission data of new products such as bio-based chemicals were mostly missing/unavailable, and mainly based on the study of Aryapratama & Janssen (2017). In this case, exceptionally high DF product group was needed in any case to illustrate “lower required changes scenario”. This product group could have been as well something else than biochemicals.

The new wood-based products such as chemicals and mixed material composites were assumed to be based on by-products originating from primary production. This excludes the roundwood processing based emissions and increases the DF values. Even the product category specific DFs vary depending on multiple factors, the general decline of DFs towards future is a logical assumption when fossil-based industry reduces emissions due to technological development.

The DFs were determined considering the current substitution impact in 2016 and the potential impact in 2050. The DFs account only for fossil emissions, since the DF=2 scenario target is based on the article by Seppälä et al. (2019), where the DF refers to fossil emissions. DFs were calculated on an annual basis according to Equation 1

$$DF = \frac{GHG_{alternative} - GHG_{wood}}{WU_{wood} - WU_{alternative}} \qquad \text{(Equation 1)}$$

Where

GHG*alternative* and **GHG*wood*** are the GHG emissions resulting from the use of the non-wood and the wood alternatives expressed in mass units of carbon (C) corresponding to the CO_2 equivalent of the emissions

WU*wood* and **WU*alternative*** are the amounts of wood used in the wood and non-wood alternatives, expressed in mass units of C contained in the wood.

To estimate the 2050 DFs, the impact of future decarbonization of energy sector on carbon footprints of wood and alternative products was included. Thus, the emissions were modified to be lower in 2050. The assumption simply was that GHG emissions of energy production would decrease gradually by 80% of their 2016 level by 2050 (Haller et al. 2012). Also, the emission decreasing effect of fossil and mineral material recycling was taken into account in DF 2050 calculations based on recycling rate assumptions in 2050 (See also Appendix A in Kunttu et al. 2020 (unpublished)).

Cascade use of end-of-life wood products was taken into account when formulating the target scenarios, which created extra substitution benefits. Cascade use was assumed to increase the life cycles of wood products from 1- to 3-fold (Loops 1–3). We assumed that solid wood products will mainly be *reused* (Loop 1) first in the end of their lifetime. Secondly, untreated sawnwood was *recycled* (Loop 2) for mixed-material wood composites. This includes the sawnwood, which was *reused* first in Loop 1. Finally, all the solid wood product material was *combusted for energy* (Loop 3). According to average use times and half-lives of solid wood products, it was assumed that 50% of total production will be available for cascading in 2050 (IPCC 2006; Viitanen 2011). Because it was overly optimistic to assume that all of this 50% can be reused first, the following assumptions of the use categories were made: only 80% of the end-of-life sawnwood was reused, 15% recycled, and 5% combusted for energy. In the second life cycle, 100% was recycled and in the third lifecycle, 100% combusted finally for energy. This means that only a certain share of original sawnwood production can proceed to the three cascading loops.

Similar assumptions were made for textiles. It was assumed that 85% of total production of textiles will be available for cascading in 2050 (Ellen MacArthur Foundation 2017), while the rest was assumed to be lost in production or processing. The lost share of textiles did not therefore create extra substitution benefits. In the first life cycle, 45% of the end-of-life textiles proceeded to reuse, 45% were recycled back to textiles, and 10% was combusted for energy. In the second lifecycle, 100% was combusted for energy. Therefore, textiles received the maximum of only two cascading loops.

The DF factors were different for cascading loops, because recycling decreases fossil-based emissions (see also Appendix B in Kunttu et al. 2020 (unpublished)). Combustion for energy (any wood-based material) was assumed to have DF of 0.27 tC/tC, where wood-based material does not have processing emissions and is replacing fossil-based energy source. Reuse of solid wood products was simply assumed to have DF of 1, which is average for multiple construction end-uses in 2050. Construction, where wood product substitutes e.g. steel and cement, was assumed to be the main end-use for reused wood products, because there the risks of harmful additives might be lower than in in-house (e.g. in-walls, decoration, furniture) uses. The DF for recycling of solid wood products (mixed material composites) was based on assumption that both wood and plastic have decreased emissions to 20% due to energy technologies and recycling. The DF for recycled textiles (1.03) is based on the assumption that the recycling rate (20%, processing of fibers) applies to both, non-wood and wood-based textile fibers, since textiles are often mixture of different fibers.

The quantitative target scenarios were formed by reallocating wood flows in an iterative manner on high-DF end-uses, until the DF average over the production in 2050 equaled 2 tC/tC (within an accuracy of two decimal places). It is important to notice that the scenarios account only for the production in the year 2050. This study did not account for wood flows from previous nor up-coming years. The process started from reallocating (baseline) side streams, then end-uses, and finally roundwood if necessary. The ad-hoc model (Excel) included all the domestic wood flows in Finland from harvesting to end-products and end-uses. The wood flows were presented as allocation shares and estimated future DFs (Table 3) were applied to end-uses. The model consisted of three parts: i) virgin wood flow allocation to primary industries, ii) by-product allocation to energy and material applications, iii) wood-based end-product allocations to different end-uses.

The carbon residence was calculated for each scenario to evaluate how long (in years) the wood-based product portfolios store carbon (C) on average (volume weighted) in the technosystem. The residence of carbon in HWP was calculated according to the IPCC's stock change model (IPCC 2006). The residence time of carbon is referred here as the 'volume weighted average length of time a ton of carbon remains in the technosystem'. The annual average carbon stock over 100 years was divided by the annual average stock change (carbon releasing to the atmosphere in tons of C), to get the C residences of the scenarios. The initial flow from forest was assumed to be approximately 16 million tons of C. The outflow, 'release' of the wood product carbon stock is calculated by using product-specific default half-times (IPCC 2006). The cascade use was included to the C residence estimation by using "equilibrium" assumption. This means that even though the newly introduced cascade loops increase the carbon storage in certain product categories due to new lifetime loops, the carbon inflows and outflows in the product categories would remain the same annually after reaching the "equilibrium" stage. This equilibrium will be reached when the production and cascading volumes are the same over the years in a long enough time period.

The baseline scenario (Figure 4), which is used as the scenario analysis starting point, is based on official statistics presented by Natural Resources Institute Finland (2017). The primary energy in terms of CHP production and mill energy dominates the production. By applying a DF estimation in 2050 to the baseline production structure, the production volume weighted DF would be 0.23. For the same reason, the carbon residence time is only 14 years. The end-uses of final product groups are generalized by using a data compilation presented in Hurmekoski et al. (2019).

Table 3. Displacement factor estimations in 2016 and 2050 for different wood-based products. Table source: Kunttu et al. (2020, unpublished). See also Appendix A in Kunttu et al. (2020, unpublished) for more data details.

Intermediate product	End-use	DF 2016	DF 2050
	Construction	1.1	0.82
	Packaging (pallets)	1.1	-0.02
	Furniture	0.9	0.12
Sawnwood	Other	0	0
	Construction	1.1	0.74
Panels	Other (furniture etc.)	0	0
Mechanical pulp	Newsprint	0	0
	Graphic papers	0	0
	Packaging (carton boards)	1.40	0.30
Semi-chemical pulp	Packaging (carton boards, sack paper)	1.4	0.30
Kraft pulp	Graphic papers	0	0
	Hygienic papers (tissue, toilet etc.)	0	0
	Packaging (carton boards, sack paper)	1.4	0.30
Dissolving pulp	Textiles	3.96	1.2
	Other	0	0
Energy	CHP	0.7	0.14
	Mill energy	0	0
Diesel	Transport fuel	0.63	0.16
Ethanol	Transport fuel	0.7	0.52
Ethylene	Packaging	1.3	0.82
Pyrolysis oil	Replacing HFO	0.33	0.08
Wood-PP plastic composites *mixed wood and fossil-based plastic, emissions based on material shares	Replacing full PP plastic in construction/furniture/car components	7.38	3.2
Wood-concrete hybrids *solid components of wood and concrete, emissions based on material shares	Replacing concrete in construction	1.18	0.90
Biochemicals	Adipic acid (multiple end-uses such as fabrics, tire cords, plasticizers)	46.96	11.52

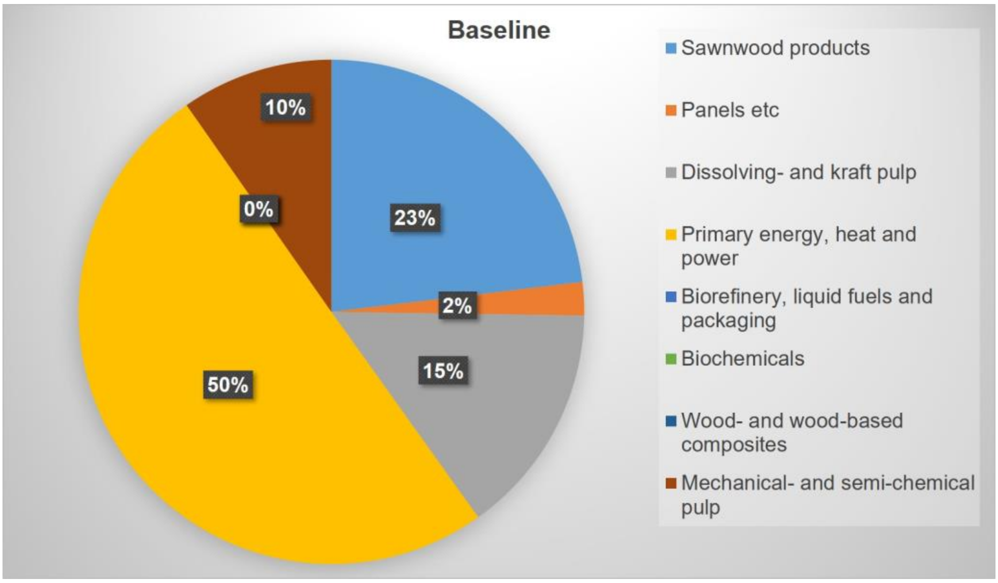

Figure 4. Finnish forest-based product portfolio with product shares of the total wood-based production. The shares are calculated based on wood material flow allocation in mass unit. Wood flows include domestic roundwood and secondary wood flows (side streams and waste wood). The allocation is based on 2017–2019 data, collected from multiple sources (e.g. Hassan et al. 2018; Natural Resources Institute Finland 2017). Figure source: Kunttu et al. (2020, unpublished).

2.4.3 Scenario pathway formation: Participatory approach

To ensure a comprehensive range of expertise and backgrounds (Rikkonen and Tapio 2009) among stakeholder participants, a PESTE classification (Political, Economic, Social, Technological, Environmental) (Gupta 2013) was used. In addition, the stakeholders were also divided into "bioeconomy actors" and "researchers/other specialists". Each of the categories – political, economic, societal/social, technological and environmental – included at least one actor and one researcher. There were 16 participants in the workshop. A half-day workshop was organized in Helsinki on April 25, 2019. The workshop was divided into three steps: i) introduction of wood substitution and forest carbon sink topics, and generated target scenarios in the technosystem, ii) identifying restrictions, and their opposite situations called as "scenario enablers", and their driving actions, and iii) placing the enablers on timeline for each scenario and voting the most important enablers. The main idea was that the stakeholders consider the political, economic, social, and environmental, operating environment when visioning structural changes towards market structures in the scenarios. We used Ketso workshop toolkit (www.ketso.com), developed in 1995 by Dr. Joanne Tippett.

The outcomes were compiled into a uniform storyline for each scenario. We clarified the themes by defining their meanings. "Political" or "political control" theme includes laws, regulations, goals and strategies, "Economic", or preferably "Industrial transformation”, includes commercial supply chains converting the natural resources into products and services for the society, “Social”, or preferably “societal needs”, includes consumers, public opinions and general well-being, and “Technical”, in this case called “R&D&I”, includes the great variety of research and development areas including technical development as well as market research. The “environment” means natural conditions and limitations in natural resources. The enablers were also scored in the workshop by asking the stakeholders individually to vote for the most important one.

3. RESULTS

3.1 Article I: sustainability impacts of cascade use of wood

3.1.1 Environmental impacts of wood cascading in North Karelia

The local energy output inside the system boundaries consisted of a CHP plant utilizing virgin wood, and a heating plant utilizing waste wood as a source of energy. It should be noticed that the energy output here does not account for energy use, which is assessed separately as an indicator. When the end-of-life untreated waste wood was cascaded, meaning use for particleboard production instead of direct combustion for energy, the local energy output decreased by 5.3–5.7% in cases where i) the additional particleboard did not enter local waste management (C-export), or ii) there was no additional energy harvesting included (C-forest) (Table 4). In cases where cascade use i) led to extra energy wood harvesting to maintain the same harvest level as in the baseline (C-energy), or ii) resulted in additional particleboard production and use locally, the energy output increased by 0.05–0.6% compared with the baseline. However, when comparing the energy use between the value chains, cascade use increased the energy use per unit of harvested wood by 0.3–1.4% in the scenarios C-export and C-domestic due to additional production of particleboard.

In the C-forest scenario the energy use decreased by 1.5% because of the indirect impact on wood flows, which decreased sawmilling activity. Although in the C-energy in total more virgin wood was harvested due to extra energy wood harvesting, energy use decreased by 1.1%. This is a logical result because the value chain from forest to direct energy combustion is shorter than the one where sawlogs are processed into multiple products, which eventually arrive to energy generation in their end-of-life. Thus, the latter value chain uses more energy over the total lifetime. The assumptions of the transportation distances are important impact factors here as well, since the end-of-life waste wood was assumed to be combusted for energy in Kainuu (one-way distance 230 km) whereas in the cascading option and virgin wood combustion the particleboard factory and CHP plant were located in the case study region (North Karelia).

GHG emissions were accounted only inside the system boundaries (locally). Thus, the emissions were 1.9% lower in the C-export scenario compared with the baseline (Table 4). The GHG emissions from wood combustion are higher than from particleboard production, because in the energy generation the carbon content of wood is released to the atmosphere. Therefore C-energy increased the GHG emissions by 0.5%, although the transportation emissions were lower in this scenario due to shorter transportation distances, similarly as in the energy use indicator. The C-domestic increased the emissions by 0.6% as the cascaded material increased the total lifetime and thus created more length to the value chain inside the system boundaries. The C-forest resulted in slightly lower GHG emissions (0.3%) compared with the baseline, as the sawmilling activity was decreased and the long value chain wood products decreased in volume.

Cascade use increased the lifetime loops for wood products resulting in more wood products in use in short-term and, therefore, higher C stock in HWP at a time when material use is favored over energy use. The carbon inflows from the forest were equal in the C-export, C-domestic and the baseline, and carbon stock in HWP increased by 0.9% in the cascading scenarios (Table 4). However, as the carbon inflow was lower in C-forest compared with the baseline and long-lifetime sawmilling products were decreased, carbon stock in HWP decreased by 1%. In the C-energy, carbon inflow was the same as in the baseline, but carbon stock decreased by 1% due to increased energy use of virgin wood resources. This results from the shorter lifetimes.

Table 4. Sustainability indicator results in the scenarios

Indicator	Baseline	C-export	C-domestic	C-forest	C-energy
Energy output (MWh)	76,379	72,296	76,421	72,057	76,885
Production costs (EUR/t of C)	478	479	485	475	474
Employment (FTE/1000t of C)	3.32	3.33	3.34	3.30	3.31
Energy use (kWh/t of C)	1,748	1,753	1,772	1,721	1,728
GHG emissions (kg of CO_2 eq/t of C)	1,286	1,261	1,294	1,256	1,293
Carbon stock (Mt of C)	10.8	10.9	10.9	10.7	10.7

3.1.2 Social and economic impacts of wood cascading in North Karelia

The production costs per harvested ton of C increased by 0.2% in the C-export, as the production of particleboard is more expensive compared with the direct combustion in the baseline (Table 4). C-domestic increased the production costs by 1.5%, as the additional particleboard production was used locally, meaning that the 'second cascade loop' in terms of combustion of end-of-life particle board was added on top in value chain costs. C-forest and C-energy decreased the production costs by 0.6–0.8% due to decreased sawmilling activity (C-forest) and increased relatively cheap energy use of virgin wood (C-energy). Material uses of wood had higher employment benefits compared with energy use of wood. Thus, employment increased in the scenarios C-export and C-domestic by 0.3–0.6% compared with the baseline due to additional particleboard production resulting from cascade use (Table 4). For the same reason employment decreased by 0.6–0.3% in C-forest and C-energy.

3.2 Article II: Environmental impacts of Integrating fast pyrolysis reactor with combined heat and power plant

The value chain emissions and energy efficiencies were assessed by using two methods: including only direct process-based impacts (ToSIA) and including also indirect impacts (LCA). Therefore, the results from LCA show typically higher emissions than ToSIA. The only exception was NOx emissions, where the LCA showed lower emissions for crude oil processing (Table 6). This is explained by the data exception, where ToSIA data were not used in the LCA for direct process emissions in the crude oil processing.

The CHP+HFO scenario, considered as the business as usual case, had the highest energy efficiency of 90% (Table 5). The CHP+Pyr alternative consisting of stand-alone plants had the lowest energy efficiency of 83%. Integrating the pyrolysis conversion with CHP plant (CHP-Pyr integrate) increased the energy efficiency up to 86%, because the additional energy reduced the need for peat as input fuel in the CHP. Despite of the high energy efficiency, fossil emissions in CO_2 equivalents, and air pollution emissions, NOx, SO_2, and PM, were the highest in the CHP+HFO scenario. The CHP+Pyr and CHP-Pyr integrate decreased the fossil emissions (CO_2 equiv.) by 44–49% depending on the assessment method (Table 6). Similarly, the air pollution decreased in the scenarios including pyrolysis oil production and use. The lowest fossil emissions and air pollution emission occurred in the CHP-Pyr integrate scenario.

Table 5. Energy efficiencies in the scenarios based on material input (in GWh) and gained energy.

	Input, GWh	Output, GWh	Efficiency %
CHP+HFO	1,149	1,028	90%
CHP+Pyr	1,244	1,028	83%
CHP-Pyr integrate	1,201	1,028	86%

Table 6. The differences in assessed emissions between scenarios “CHP+Pyr” and “CHP-Pyr integrate”, and between assessment methods “LVA” and “ToSIA”. Table source: Karvonen et al. (2018).

Relative change to CHP+HFO	CHP+Pyr		CHP-Pyr integrate	
	ToSIA	LCA	ToSIA	LCA
Fossil CO_2 eq	-44%	-47%	-47%	-49%
Biog. CO_2 eq	43%	43%	38%	38%
Sum of CO_2 eq	8%	6%	4%	2%
NOx	-67%	-55%	-68%	-56%
SO2	-61%	-65%	-62%	-66%
PM	-76%	-78%	-77%	-78%

To compare the total emissions, biogenic GHG emissions in CO2 equivalents were also assessed. When summed up with fossil GHG emissions, the CHP+Pyr increased the total emissions by 8–6% and CHP-Pyr integrate by 4–2%, respectively. The CHP+HFO value chain includes fossil fuel utilization, whereas pyrolysis oil is based on renewable source. Therefore, the comparison between those scenarios cannot be made, without adjusting the impacts of biogenic emissions to be comparable with fossil emissions. These adjustments would require accounting e.g. the forest rotation time and growing forest radiative forcing effect, which then would be included to the climate impact analysis in a certain time horizon. This was excluded in this analysis. However, the biogenic emissions can be compared between the pyrolysis oil scenarios: the standalone plant (CHP+Pyr) and the integrated plant (CHP-Pyr integrate). The CHP-Pyr integrate obviously results in less emissions, since less raw material is required to produce the same amount of energy compared with a standalone plant. This is a direct result of higher energy efficiency.

3.3 Article III: Preferable utilization patterns of wood product industries' by-products in Finland

3.3.1 *Pulp and bioenergy -scenario*

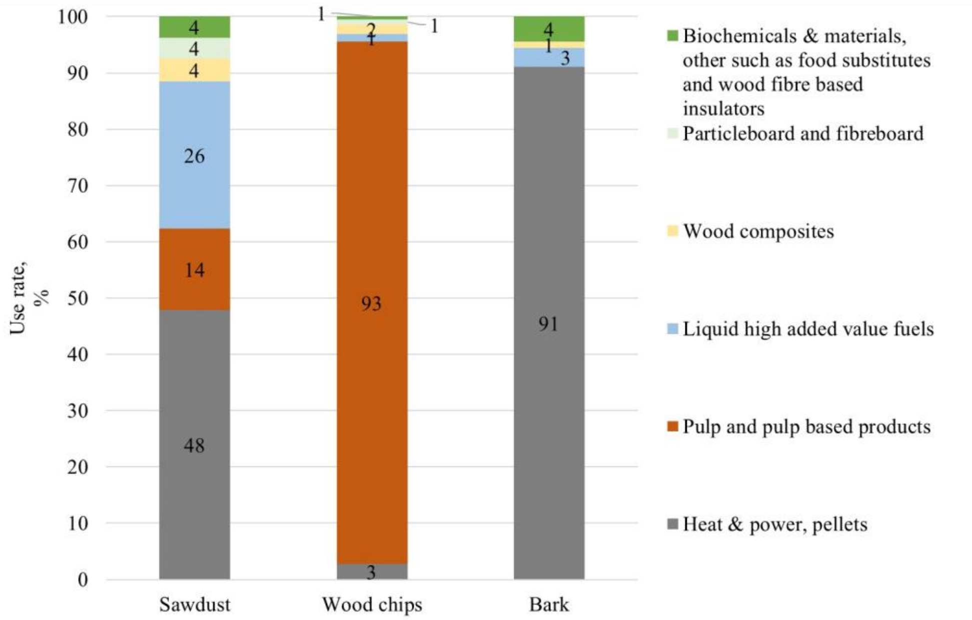

Figure 5. The preferable by-product utilization pattern in the *Pulp and bioenergy* scenario. The use rates are averages of all given answers inside the cluster (scenario). Figure source: Kunttu et al. (2020).

The Pulp and bioenergy -scenario gathered the views which highlighted established practices and realism, meaning that major changes may not be possible to achieve in the near-future (Figure 5). These answers were from the experts from industry (all industry experts), research, and interest group (NGOs). Altogether 53% of the respondents shared this vision. The scenario did not present any major changes to current by-product uses in Finland. In the scenario, a major share (93%) of wood chips was allocated for chemical pulping/biorefinery, whereas bark (91%) was allocated mainly only for energy. The uses for sawdust were more divergent and included bioethanol, pulp, and energy. According to the experts, sawdust has the biggest availability compared with other by-products, because its quality and moisture content limits its possibilities of use and profitable transportation.

The experts justified bioethanol uses for sawdust (average 26%) by existing investment plans, which would easily support this direction. Also, chemical industries could benefit from intermediate bioethanol-derived products. The experts also allocated a moderate share of 14% of sawdust for chemical pulp, but pointed out that more advanced sawdust boilers would be needed to actualize this. Heat and power including pellets dominated the preferable use of sawdust with a 48% allocation share, due to their low prices. Other experts considered this scenario realistic, but risky in case of market failure, less beneficial in terms of creating new business or employment, and stated that it includes too much short-lifetime products. Thus, it is not in line with the climate change mitigation targets.

The scenario was considered very realistic, and biggest uncertainty was only related to sawdust markets, as there is not enough piloting enabling new innovations. The stakeholders argued that competitiveness of fossil-based products hinders market uptake of new high added value products. The regulation and legislation represented another barrier for this scenario. The experts stated that a stable policy environment is needed to support investments. The experts highlighted that integrated systems in processes, factories, and cities are necessary to ensure the versatile and circular utilization of materials.

3.3.2 Versatile uses -scenario

The versatile uses -scenario consisted of answers highlighting diverse use for by-products and new innovations (Figure 6). The experts sharing this view represented research, policy, and interest group stakeholders, forming altogether 41% of the experts in the study setting. They argued that a great variety of products increases substitution potential and minimizes the risk of market failure. They believed versatile uses could be reachable by 2030, because there is still only a moderate amount of new uses included. The other experts instead argued that the actualization of the scenario requires major technical and political changes, and it may be possible that some of the multiple production lines would eventually start to dominate the markets. However, the other experts also agreed that, when successful, multiple production lines would indeed decrease the risk of market failure. The experts sharing the vision of the Pulp and Bioenergy scenario also agreed that it would be beneficial diversify uses for sawdust. Still, some criticism was received about a great variety of short-lifetime products.

Sawdust was allocated to liquid biofuels such as ethanol (39%), particleboards and fiberboards (11%), wood-based composites (20%), and high added value biochemicals such as nanocellulose or proteins (Figure 6). Experts stated that wood chips are the most homogeneous, high-quality by-product group, and preferred to use it for chemical pulping (44%). The experts stated that bark could be used as a renewable fuel source for the pulp mills, but it would be a valuable source for dedicated bio-based chemicals as well. Integrated utilization in that sense would be preferable.

In general, this scenario favored decreasing the share of energy use. The experts believed that increasing energy efficiency, competition between renewable energy forms, and assumed declining of district heating could drive this development. The need to increase the energy efficiency would however apply to existing processes and systems as well, and the number of integrated factories should be increased for this. To this, commercial piloting, including its public funding, is needed to prove the functionality of the technologies. The R&D actions should be preferably implemented in cooperation of research institutes and the industries. Again, unstable policy environment and subsidies supporting one-sided production was ranked the most important barrier. Thus, according to the experts, selecting a common policy path and focusing on restrictive regulation would be needed to force companies to make changes.

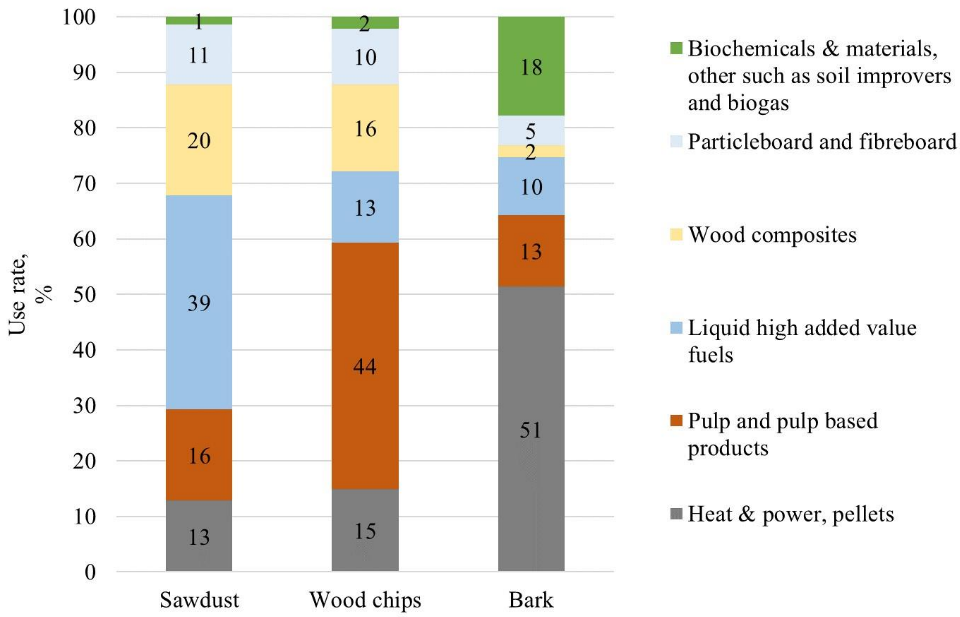

Figure 6. The preferable by-product utilization pattern in the Versatile uses -scenario. The use rates are averages for all given answers inside the cluster (scenario). Figure source: Kunttu et al. (2020).

3.3.3 Long lifetime-products -scenario

The long-lifetime products -scenario was a vision of only one expert (research field). The answer was so different from other expert answers that it formed its own cluster. The justifications of the scenario relied on environmental aspects; minimize the release of carbon. Here, sawdust, wood chips and bark were only allocated to long-lifetime products: panels (allocation share 50%) and composites (allocation share 50%). The main barriers found were in the EU regulation focusing too much on supporting liquid biofuel and wood-based heat and electricity production, and research and development as the technical properties of by-products may hinder the usage on long-lifetime products. To implement the scenario, political actions should support the wood industries to contribute to the goals of the Paris Agreement through e.g. carbon balance trading. The other experts considered it reasonable to favor long-lifetime products because of their climate benefits and high market price, but considered the Finnish market too narrow for this scenario. However, the main problem pointed out was that scenario did not include any pulp milling or energy uses. All the experts believed that this scenario would require major changes in policy and research fields, and especially alternative energy generation systems developed at a global level would be needed. Some experts suggested this scenario to be more feasible in a country with fewer pulp factories and more panel production.

3.4 Article IV: Targeting net climate benefits by wood utilization in Finland: Participatory backcasting combined with quantitative scenario exploration

3.4.1 Biochemicals & biofuels -scenario

Biochemicals & Biofuels -scenario weighted production of bio-based chemicals and fuels (Figure 7) and reached the DF of 2tC/TC by reallocating mainly side streams and end-uses and, thus, being the closest to baseline production. Yet, the carbon residence time did not notably increase neither compared with baseline (from 14 years to 16 years). More cascading loops (re-use, then recycling, and finally combustion for energy) were applied for textiles and solid wood products, but the cascading volumes were on the same level with the baseline. The biggest difference compared with the baseline was that side stream utilization on primary energy (mill and CHP) was reduced by over 70%. The stakeholders assumed that diverging opinions of the political goal prioritization and lack of willingness, among the political “zero-emission” calculation for wood fuels, would hinder the shift from the energy use to refining uses. Relatedly, the lack of alternative energy forms and techniques would be a restriction.

From the technical perspective, the stakeholders stated that the wood-based chemical yields are too small and there is not enough piloting evidence of their functionality. Also, the strong position of the “traditional products” in the markets, and low fossil oil price and high production costs of wood-based chemicals and fuels are not tempting the industries to shift their production to refineries. The competitiveness might be low from the perspective of consumers as well.

The stakeholders considered the political actions the most important enabler and, thus, the transition toward this scenario should start from compensating the potential decline of the forest carbon sink in the international climate strategy through focusing on sustainable forest management and reducing fossil fuel use by tightened taxation. Similarly, tax reliefs on renewables and wood-based liquid biofuels are needed. At national level, policy support should focus on research and development, and investments. This composes the direct impacts of the new wood-based products e.g., better health impacts on the consumers. Next, by 2040, financial support should be allocated also to increase expertise in production. This enables renewing the business ecosystems and allows smaller companies to step in. Green and ecolabels are created to further support market growth. As a milestone in 2035, liquid biofuels would have consequently taken over market leadership, as their prices have reached closer equality with fossil fuels. By 2050, the market share of biofuels has stabilized and production is self-sufficient. The demand of wood-based heat and power has reduced remarkably.

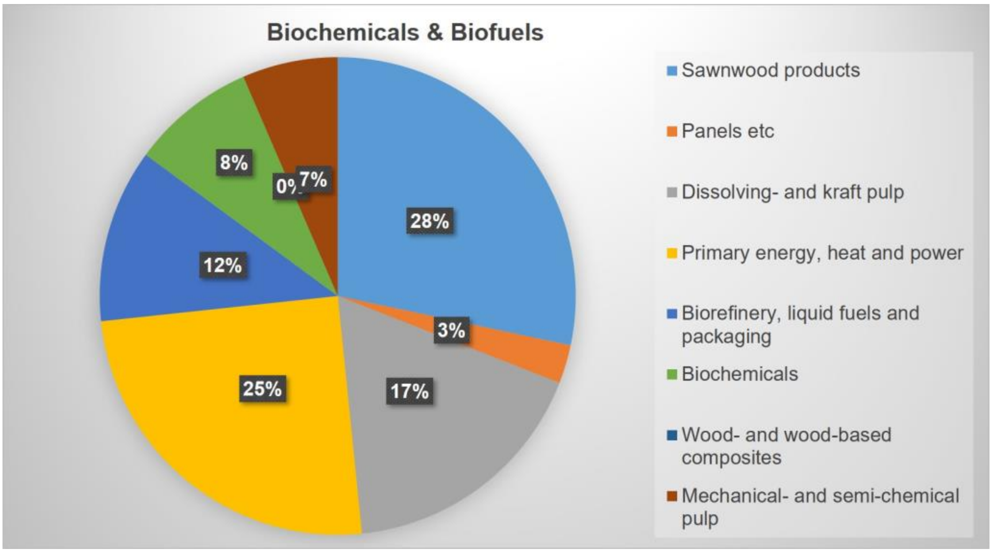

Figure 7. Finnish forest-based product portfolio with product shares of the total wood-based production in the Biochemicals & biofuels -scenario. The shares are calculated based on wood material flow allocation in mass unit. Wood flows include domestic roundwood and secondary wood flows (side streams and waste wood). Figure source: Kunttu et al., (2020, unpublished).

3.4.2 Composites & textiles -scenario

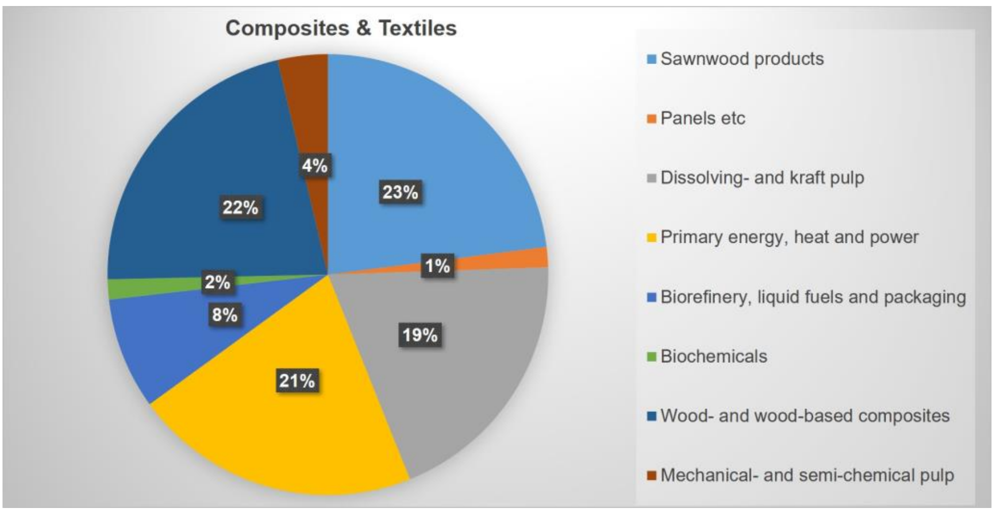

Figure 8. Finnish forest-based product portfolio with product shares of the total wood-based production in the Composites & textiles -scenario. The shares are calculated based on wood

material flow allocation in mass unit. Wood flows include domestic roundwood and secondary wood flows (side streams and waste wood). Figure source: Kunttu et al., (2020, unpublished).

In the Composites & textiles scenario, the roundwood use on traditional sawnwood was reduced by around 30% and allocated instead for composites and hybrids (Figure 8). The side stream utilization on primary energy was reduced by 70%, and increasingly used for mixed composite products. In the end-uses, the biggest difference compared with the baseline was that dissolving pulp was increasingly used for textiles instead of graphic paper. These differences increased the shares of solid wood products and cascading potential, resulting in carbon residence of 24. However, diverging opinions again in the political goal prioritization was stated as a restriction to shift towards this scenario. The material cascading was seen to be problematic as well, as the energy use of is still dominating and politically there are no supporting systems to prioritize material uses, and there are not enough alternative energy forms to replace wood. The technical immaturity of the wood-based composite and textile products may also hinder the market competitiveness in the first place: The composites were seen too energy intensive, final products not high-quality, and textile production questionable in terms of environmental sustainability. This affects the consumers' opinion. It is challenging for small companies to enter to the markets too, as the position of traditional wood products is strong as well as the position of conventional cotton and synthetic textile markets.

Affecting consumer perceptions was considered the most important enabler. This is connected to research and development lowering the price and improving other qualities of wood textiles and composites. The actions start from increasing the public and company innovation funding, meaning that policies drive replacing the fossils. The end-users and the brand owners are needed to be engaged to the R&D processes. By 2025, the environmental responsibility could be already a trend among consumers. At this point, especially the negative impacts of cotton are brought up and restrictions are set for its production: taxation, emission trading, and smart regulation. Proven health and environmental benefits of the wood-based textiles and composites boost the markets. Next, the funding should be allocated to construct "returning system" for textiles and a clear binding system for recycling and waste management. By 2050, demand of wood in the CHP plants has decreased through renewable use regulation and new energy technologies, and the recycling rate is 100%.

3.4.3 Circular construction -scenario

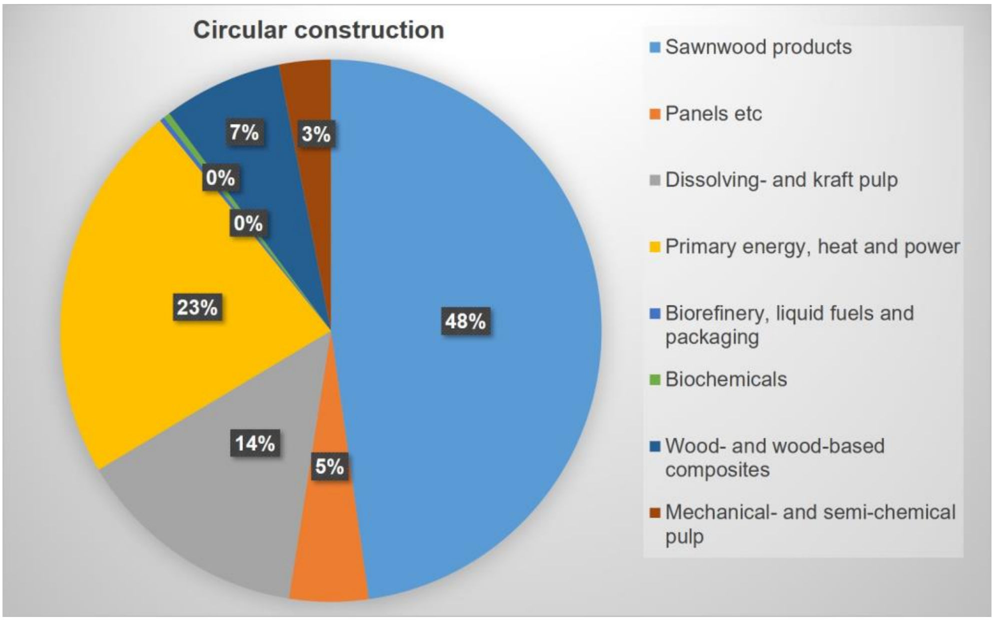

Figure 9. Finnish forest-based product portfolio with product shares of the total wood-based production in the Circular construction -scenario. The shares are calculated based on wood material flow allocation in mass unit. Wood flows include domestic roundwood and secondary wood flows (side streams and waste wood). Figure source: Kunttu et al., (2020, unpublished).

In the Circular Construction scenario, 70% of the harvested roundwood was allocated to sawmilling industries to reach DF of 2 tC/tC target by wood-based construction products (Figure 9). This also increased the wood cascading volumes and resulted in carbon residence time of 31 years. The side stream use on energy generation was decreased by 60%. As in the other scenarios, the stakeholders stated that political restrictions rely in the political goal prioritization, and lack of incentives to support wood construction as well as material recycling. From the technical perspective, the sawing yields are too low to increase the sawmilling production on this scale and decreasing the energy use of wood is challenging due to the lack of alternative energy sources. The stakeholders also evaluated that the current forest management does not support this scenario. From the market perspective, the sawnwood price was considered is too high to increase the demand, and the lack of expertise and education in modern wood construction and architecture.

In order to shift wood use from energy use to long-term material uses, a common international renewable energy policy is needed for regulating stricter taxation on fossils. Next, the national education in wood construction must be branded flexible and attractive. Perceived as the most important enabler, carbon footprint should be fast included to the construction regulations and re-use of materials boosted through restrictions on disposal of demolition wood. In addition to this, the wood construction needs to be standardized and ecolabels and cascading labels developed, and public wood construction boosted through city planning.

Actions in the coming years need to consider also forest management and aim at increasing the resilience and sawlog yields by e.g. thinnings from above. By 2040, the construction sector actively uses wood as a raw material and responsible, climate smart construction is a trend. The availability of wood for long-lifetime uses has increased as funding for new energy innovations has resulted in decreased wood demand for heat and power production. By 2050, new business models for wood cascading and recycling are in use. The market growth of wood-based construction products has decreased the production. Forest resource sufficiency is guaranteed, and large clear cuttings are restricted. 100% of the waste wood is recycled.

4. DISCUSSION

The aim of this thesis was to explore a variety of wood utilization scenarios in Finland and assess their possible future impacts in environmental, economic, and social sustainability, and form pathways to actualize the preferable outcomes reflecting different priorities in the setting of goals. This was conducted by applying i) quantitative impact assessment tools ToSIA and LCA and ii) explorative future scenario studies visualizing the implementation quantitatively and utilizing participatory approaches.

Articles I and II explored by what-if scenario setting in ToSIA and LCA, which environmental, social and economic sustainability impacts may occur in the regional circumstances in North Karelia, Finland, when wood flows are shifted from primary energy use to support material cascading, and when integrated factor technology is applied to higher-added value biofuel production and heavy fuel oil substitution.

Article III analyzed the key stakeholder motivations and priorities driving different industrial side stream utilization patterns. This study applied a method A Q2 scenario technique (Varho and Tapio 2013) to construct scenarios and quantitatively analyze the differences in stakeholder visions.

Article IV synthetized quantitative impact assessment and future scenario analysis to explore what structural changes would be needed to alter wood utilization patterns in a market-viable way to increase positive climate impacts under increasing material demand. This study applied mixed methodology combining quantitative impact assessment, target-oriented scenario modelling, and participatory backcasting.

The hypothetical scenarios in Article I were designed to aim at either increasing particleboard production volumes or at saving forest resources due to material cascading. These scenarios introduced waste wood utilization in particleboard production with varying impact assumptions in material flows. The material flow changes were constructed based on the literature suggestions, e.g. cascade use should aim at increasing the land-use efficiency or decreasing the pressure of forest harvesting (Sathre & Gustavsson 2006; Höglmeier et al. 2014). Since available waste wood was shifted from energy use to particleboard production, locally either (i) the total wood-based energy output decreased, when the possible end-of-life combustion for energy was implemented after export, or (ii) the energy output remained the same when local particleboard volumes increased and additional particleboard production was not exported, but used in the production region and returned to energy recovery, or (iii) available wood for energy was increased in other wood flows, side streams or virgin forest resources, to cover lack of waste wood in energy generation caused by cascade use.

There is a clear trade-off in material cascade use, because decreasing the available waste wood for energy might result in increased use of less sustainable energy sources. If the cascaded waste wood will not be exported but used inside the region, it returns in the local waste management and theoretically the waste wood resources available for energy would not decrease. However, in reality there is always loss of production and not all of the original production return in waste management nor energy recovery. In addition, a major increment in particleboard production and consumption in Finland is unlikely since the main European markets are in the Central and Eastern countries, and particleboard is mainly imported from nearby countries (UNECE/FAO 2017).

The GHG emissions from the value chain increased when cascade use was applied and the total harvest level remained the same, because it increased the lifetime loops for a unit of harvested resource and therefore prolonged the value chains. It is important to notice that the transportation distance was shorter for material cascading than for end-of-life energy generation. If the transportation distances were assumed to be the same, material cascading would have increased the emissions even more. The results are generally in line with studies suggesting that the net climate impact of cascading depends on the resource it is substituting, additional carbon stock benefits, and possible indirect impacts on virgin resource use (Sathre & O'Connor 2010; Sikkema et al. 2013; Kim & Song 2014; Suter et al. 2016). Here, substitution impacts were excluded and only the material flow related impacts were assessed. These results show that the location, meaning production, end-use and cascade use process locations, are important factors affecting the total sustainability performance. Therefore, excluding GHG emissions from the export onwards is distorting the real image of the climate impacts. The scenario where cascade use increased particleboard production and additional production was exported, the results showed less GHG emissions misleadingly. Thus, the result depended on calculation system boundaries and not cascade use itself.

From the social and economic perspective, material cascade use created more added value than energy use, as the assessed material uses generally had higher employment impact and multiple lifetimes for harvested unit of wood increase the total economic value, even though the production costs during total service life increase. However, the magnitude of impacts of introducing cascade use of wood entirely depends on the volume that is available for material cascading. In this regional case study, the sustainability impacts remained very marginal (under 1–2% compared with the baseline) due to relatively small share of untreated waste wood, which was selected for the cascading resource. Greater impacts would require increase in end-of-life wood volumes. New waste separation techniques, such as near infrared technique (NIR) (Sommerhuber et al. 2015) and the restrictive regulations on wood treatments (Winder & Bobar 2016), could improve the availability of suitable waste wood for material cascading, and could provide easy solution to improve resource efficiency in low-consumption regions.

Previous studies have implied that saving virgin wood resources would be one of the most important results of cascade use (Sathre & Gustavsson 2006). From the technosystem perspective, the scenarios where the cascade use of waste wood decreased harvest levels indirectly, did not create social nor economic benefits since the production volumes did not increase. The hypothetical scenario where cascade use would this way reduce harvest levels in Finland seems unlikely in reality, as the particleboard production is not depended on round wood but by-products in Finland.

Therefore, the scenarios in this study assuming impacts on virgin wood utilization are very unlikely. In fact, also increasing particleboard production volumes in Finland seem unlikely, as the statistics have shown decreasing trend for its production (Natural Resources Institute Finland 2017). More realistic use for waste wood from the future market perspective could be wood-based composites such as mixed wood-plastic applications (Sommerhuber et al. 2015).

The highest climate impacts are gained when the available resources for cascading are used to increase the total carbon stock in long-lifetime products to prolong the total C storing time. This requires adding more lifetime loops for the harvested wood resources. Therefore, releasing secondary resources, such as side streams, for energy use by applying waste wood to substitute them in material uses, does not result in C stock or residence benefits, because in total the lifetime loops will not increase. Releasing round wood or by-products for energy uses does not necessarily mean no climate benefits at all. In some cases, GHG emissions might be lower for by-product or round wood energy uses than for waste wood, depending on transportation and treatment costs (Höglmeier et al. 2014). The scenarios would have benefitted from expert evaluation to consider more likely future applications and scenarios for cascade use and indirect impacts on material flows including e.g. impacts on export. However, this study gave insight of the secondary wood resource potential in the regional basis, and quantified the impact of increasing the total lifetime of harvested wood resources.

Article II studied impacts of introducing high added value wood-based pyrolysis oil production and a modern factor integrate that could save energy. Instead of completely hypothetical scenarios, these regional what-if scenarios had their roots in real life applications, making the assessed scenarios more realistic and justified. The results of Article II showed that integrated system in pyrolysis oil production can indeed increase energy-efficiency and therefore save virgin material resources, and consequently result in higher climate benefits compared with standalone pyrolysis oil and CHP systems.

Similar conclusions are presented in the study of Kohl et al. (2013), where integrated system compared with stand-alone resulted in 45% CO_2 emission reductions. Furthermore, the results here showed that biofuels can substitute fossil emissions up to 49%. Steele et al. (2012) found higher a CO_2 eq emission reductions of 70% when stand-alone pyrolysis production and use was compared with residual fuel oil. However, the previous studies are not directly comparable with these scenarios of pyrolysis integration, as the regional circumstances such as transportation distances, available raw materials technologies, and end-products to be substituted, set various basis for the net impacts. Therefore, region-wise adjusted assessments of the sustainability including material selections and flows are crucial to make decision of the most favorable system.

In Article II, important aspect of the study was not only to compare emissions between fossil-based heavy fuel oil and wood-based pyrolysis oil scenarios, but to compare different wood-based production technologies as well (integrated and standalone plant). To date, wood-based biogenic CO_2 emissions from energy generation are excluded in the GHG accounting in European climate policies (European Commission 2013). Therefore, policies may treat integrated wood-based systems unfairly since they are not able to capture the biogenic carbon emission reductions. This study revealed that if biogenic carbon was accounted, integrated system resulted in 4% less GHG emissions compared with the standalone option. Still, this study did not account social or economic impacts. Therefore, the benefits of integrated systems discovered can only be generalized to environmental sustainability. This study could have benefited from extra assessment including more sustainability aspects. In general, the increased energy and material efficiency may decrease the production costs, for example in raw material costs. One of the premises of this thesis was that quantitative impact assessment scenarios fail to offer clear conclusion of the ”best case scenario”, if assessed impacts are not linked to country specific needs and priorities. In case of this study, the assessment of social and economic impacts could have indeed supported decision making in corporation level and Finnish policies related to integrated technologies.

The ”most optimal” wood utilization pattern depends on which impacts are desired to be achieved. Article III compiled three different preferable futures for the utilization of wood product industries' by-products in Finland by 2030, based on ”most preferable” visions of the stakeholders. In the Pulp and bioenergy -scenario, the stakeholders implied that by-products were mainly used for pulp and energy production. This was mostly a vision of the industrial experts and the motivation was to respond to the existing needs by staying in line with the current Finnish forest industry structure.

The Versatile uses -scenario was mainly a vision of the research and policy experts, and highlighted a great variety of uses for by-products including new bioproducts such as wood-based composites and chemicals. The motivation behind the scenario was to diversify the production to increase fossil substitution potential and decrease market failure risk. The Long-lifetime products -scenario was a vision of one research expert and suggested using half of the by-products for wood-based composites and another half for particleboard and fiberboard. Achieving the goals of the Paris Agreement and increasing the carbon stock in the technosystem was the justification for this.

It is understandable that industrial experts prefer patterns close to ‘business as usual’, because for example wood chips are important raw material for pulp industry in Finland (Hassan et al. 2018). The Pulp and bioenergy -scenario clearly included careful consideration of the current and planned investments, their reliability, and political atmosphere, which thus made the scenario very realistic. In this vision, developing existing technologies and systems was seen more important than completely new innovations. The reason for this might be avoiding risky investments in completely new business environments and production, when the market share of new bioproducts is not stabilized. From the R&D perspective, commercial piloting of new innovations and adopting new production is often funded by industry’s old production (Hansen et al. 2015). It is recognized that private investors require proof of commercial functionality before financing e.g. new technologies (Mazzucato & Semieniuk 2018). There cannot be large-scale piloting without financial support and, thus, a vicious circle is created. Zindler & Locklin (2010) refer to the problem with the term “the Valley of Death”. To avoid this problem, experts hoped more public funding for new innovations, which would be implemented in cooperation with industry and research ”sectors”.

Other experts criticized Pulp and bioenergy on being a vision too short-term and unambitious, and relying on too few production lines which might be economically risky. The policy and research experts visioning the Versatile uses -scenario as the favorable development were more willing to focus on new innovations creating new wood-based products with higher substitution potential, and increase material circulation through integrated systems in line with recommended cascading principle and multi-product factories (D'Amato et al. 2017; Mair & Stern 2017; Packalen et al. 2017). In general, Versatile uses -scenario was seen as a possible next step scenario for Pulp and bioenergy, which seems likely since their drivers were in line, too. The Long-lifetime products -scenario was considered to be very far from the realistic development as it would require major changes in the political prioritization as well as industrial structure.

The experts agreed that from the carbon stock perspective as well as economic value creation point of view, this scenario could be beneficial. Wood-based construction products are long-lifetime as well as high in their market value, and they have relatively good substitution potential (Sathre & O'Connor 2010; Leskinen et al. 2018). While the scenario supports widely accepted cascading principle ”material use before incineration”, the increment in mixed material wood products might be challenging from the end-of-life recycling perspective, which calls for product design (Korhonen et al. 2018).

One of the main barriers for Long-lifetime products -scenario was the lack of particleboard production in Finland. Wood and wood-based composites were again seen as more realistic option than particleboard, considering their market growth. However, to release by-products for material uses in the first place, there needs to be alternative energy forms and techniques developed. Experts stated that this is possible if the biggest production countries globally agree to prioritize the development of clean energy forms. According to global energy scenarios, prioritizing renewable energy and adopting strict carbon pricing could also lead to other direction, meaning increased use of biomass in the energy generation (World Energy Council 2019). The reason for this is that most likely the renewable energy forms would depend on regional circumstances and resources available.

Although the experts' visions of preferable development varied, they achieved consensus of the main factors affecting by-product uses in Finland. These included an international policy environment; secondly, national strategies implementing international goals, research and development funding allocation and cooperation between research and different industries, and finally competitiveness of fossil products. The third premise of this thesis was that scenario key influence factors and their synergies are not the same in Finland as in similar studies implemented in other countries, if the country-specific circumstances are different. However, the results from German case studies found very similar influence factors (Hagemann et al. 2016; Giurca and Späth 2017) with the exception that they included consumer perceptions, and experts in Article III highlighted cooperation possibilities between different sectors rather than competition. The second premise, however, which was that qualitative scenarios benefit from quantified data from the illustrative perspective, is supported by the results of this study. Also, the analysis benefit from quantitative data, since grouping similar answers would have been a complex task without it and it could have been impossible to see the crucial differences between scenarios. Especially, the difference between the Pulp and bioenergy- and the Versatile uses -scenarios would have been difficult to see based on qualitative descriptions.

Most of the stakeholders favored future visions with many similarities with the current by-product utilization system. Thus, the scenario formation could have benefit from different question setting approach. In this study (Article III), the stakeholders defined preferable future scenarios first by altering numerically allocation shares of by-products on different applications and then justified, why their choices were preferable. This way, the process of creating scenarios was more ”action-oriented” relying on realistic and possible changes and perceptions of what can be achieved with by-product allocation, rather than based on ultimate goals and hopes the stakeholders wish from the future. Stakeholders might mix the preferred goals with strategic actions in foresight studies, and this way favor patterns that are familiar, or easy, to them (Godet et al. 2009). Thus, more target-oriented scenarios could have been achieved by first asking the ultimate goals, and then asking stakeholders to quantitatively define the by-product utilization pattern that could achieve these goals in their opinion. However, since in this study the time-frame was rather short (scenarios by 2030), the scenarios could have become too unlikely with this approach.

In Article IV, the scenarios took longer timeframe (2050) to enable visioning of major changes, and were based on a specific target: net climate beneficial wood utilization under increasing material demand. The quantified target was that the volume weighted DF is 2 tC/tC, accounting the total lifecycles of the wood-based product portfolios produced in 2050. Because the target was set in advance, it was possible to exploratively define three quantitative scenarios that could achieve this target technically. The scenarios accounted possible declining of wood substitution benefits in the future by using quantitative impact assessment (LCA). In reality, there is a greater variety of scenarios implementing the target 2tC/tC, but here different production lines were highlighted on purpose to see the differences in scenario pathways. There are many uncertainties in future DF calculation and, thus, these scenarios are only approximate illustrations of the changes that might be needed to implement the DF target. This was needed to set a common vision of the magnitude of changes that would be necessary to implement each scenario, which was the main objective of this study. If the scenarios were presented as qualitative descriptions highlighting potentially high DF products, the stakeholders' images of the required changes might have been too modest. However, the indicative DF calculations gave important information of the effects of low-carbon technologies and fossil material recycling on wood product substitution potential in the future.

In the Biochemicals & biofuels -scenario a major share of side streams was allocated for chemical extraction and advanced biofuel production. In the Composites & textiles -scenario, roundwood was used for wood hybrid and composite production, and pulp was increasingly used for wood textiles instead of graphic paper. In the Circular construction -scenario, sawmilling industries dominated the roundwood utilization and high share of sawnwood products increased the material cascading potential of waste wood. Despite the fact that all the scenarios resulted in the same average DF, the carbon residences within the scenarios highly varied setting them to very different positions in their total climate impacts. Especially the impact of cascade use could be seen in this, as for example Circular construction increased the cascading potential and resulted in total C residence of 31 years. In the baseline and Biochemical & biofuels the residence was notably lower (14 and 16 years) due to short life-time products. These results are only indicative, since there is not yet enough data available of the real lifetimes of relatively new wood-based products.

In all the scenarios of Article IV the direct wood combustion for energy (CHP, mill energy) had to be reduced by half to reach the DF=2 goal. This was not surprising, as studies have shown lower substitution benefits for energy use compared with material uses (Rüter et al. 2016). As stated in Article III as well, to release wood for material purposes, country-level actions were not considered sufficient. Instead, a globally agreed climate policy and actions would be needed. Here the stakeholders highlighted the need for common price for fossil fuels based on GHG emissions, and tax relieves and incentives for advanced biofuel and renewable energy technology development. According to the stakeholders, Circular construction -scenario requires also massive changes in the Finnish forest management aiming at increasing the wood production and support the resilience. In the technosystem side, it was highlighted that increasing the wood-based construction in Finland requires renewing the regulation and including wood in the public planning. The stakeholders also implied that wood-based construction should be seen ”trendy” in the global level too, which might be more challenging than convincing consumers in Finland. According to the stakeholders, the other scenarios require even more actions in the international level to increase the market demand.

The stakeholders were concerned that the consumers globally are not convinced of the sustainability and quality of wood-based textile production, nor safety of the wood-based chemicals in e.g. cosmetics. Thus, evidence of positive health and environmental impacts along technical development would be the most important action to achieve Composites & Textiles as well as Biochemicals & Biofuels by 2050. This point is highlighted also in the recent studies (Meeusen et al. 2015; Pfau et al. 2017; Stern & Ranacher 2018). Also, political restrictions would be needed in cotton production. Cotton is likely competing the most with wood-based textiles, because its quality properties are very similar (Hurmekoski et al. 2018). Otherwise, the Composites & textiles -scenario could be easier to achieve than other scenarios due to expected market increment of wood composites (Sommerhuber et al. 2015). Market increment can be expected in case the technical development decreases the production costs, and therefore lowers market prices. Production technology and end-product development was important aspect in all the scenarios. Especially some biochemical conversion technologies, including e.g. adipic and acrylic acid, iso-butene and isoprene, are suffering from “the Valley of Death” loop and have not reached large scale commercial piloting stage (Taylor et al. 2015).

The research approach and well introduced scenarios in Article IV in the workshop clearly helped the stakeholders to understand the problem setting and its goal. A careful introduction to the background and problem setting in the scenario motivation is a crucial point in participatory approaches (Godet et al. 2009). The barriers in the scenarios were well recognized and considered the whole operational environment. However, the invented actions to overcome the barriers remained mostly in a general level, and especially their timing and causal reactions seemed unclear. The time dimensions tend to be difficult in participatory approaches, because people easily underestimate the impact of actions in a long-term (Ratcliffe 2015). The benefit of this approach is that the participatory approach is also a learning process for the stakeholders, and these kind of scenario methods may help to start the process towards target scenario implementation (Höjer et al. 2011). Still, in both (Articles III and IV) the stakeholders highlighted the importance of international policy actions. Therefore, further analysis of the global influence factors could have proven useful.

The research scope in this thesis focuses on Finland, but the findings can have more general importance and partly applicable in decision making in other similar countries. Sweden has many similarities with Finland in the industrial structure and country specific needs (Swedish Trade and Invest Council 2016). There, the country has already set major national research piloting programs for biorefining (Swedish Trade and Invest Council 2016), and therefore shifting secondary wood flows, such as by-products, to advanced biochemical production and biofuels through integrated production systems, could be reached even faster than in Finland due to existing financing programs.

Possible upscaling targets can also be found from Central Europe. For example, in Germany nearly half of the harvested roundwood is processed into sawnwood products, resulting in high volumes of by-products (Eurostat 2017). There, the interest in material circulation is high and the country could benefit from integrating wood-based composite and hybrid production on side of sawmilling industries. Similarly, Poland uses only 12% of the roundwood for energy generation (Eurostat 2017). Therefore, investing in mixed material production could be implemented without high trade-offs in availability of wood-based energy sources.

5. CONCLUSIONS

It has been estimated that the demand for harvested timber is increasing in Europe from 20% up to 70% in the near future due to general global population growth and the renewable energy targets (Bringezu et al. 2011). Social and economic goals in terms of revenues and employment play a major role in the Finnish strategy among major international goals, such as the climate change mitigation. Research literature, along with the findings of this thesis, show a clear need to focus on technosystem development in terms of wood utilization patterns and production systems, since it highly affects the total sustainability impacts. These results show that it is not self-evident that wood utilization is sustainable regardless of the end-use.

Forest management practices increasing the wood production or improving carbon balances are generally well advanced in Finland, but the practices in the technosystem after harvesting have received less attention. The results of this thesis show that the energy uses of wood potentially need to be reduced in favor of emerging uses in e.g. chemical markets to gain net positive impacts in climate change mitigation as well as higher social and economic sustainability benefits, if the wood demand increases in the future and substitution impacts decrease due to emission technology development. Patterns favoring material uses over energetic uses, including integrated energy efficient systems and material cascade use, are in the core actions to balance climate change mitigation and reach higher social and economic sustainability benefits.

In the Finnish context, energy use of wood is mainly based on secondary wood flows (industrial side streams and end-of-life wood), which is already a form of cascade use (Mantau 2015; Vis et al. 2016) and ensures minimizing the landfilling. Still, the findings show lower social and economic as well as climate benefits for energy uses of secondary wood flows compared with material uses. From the climate perspective, the meaning of carbon residence may significantly increase due to the indicated decrease in wood substitution potential in the future. Therefore, releasing approximately half of the side stream volumes for material uses, especially long-lifetime applications such as wood-based construction products, and following cascading principle in waste wood utilization is highly suggested.

End-of-life wood product utilization could also create new business models and, therefore, more employment and revenues. In terms of volumes, the material cascading potential of end-of-life wood products is relatively low compared with side streams and, according to previous studies, such as Sokka et al. (2014), high export rate is hindering the in-country end-of-life utilization benefits. This means that the energy recovery of already cascaded wood products would happen elsewhere, and locally these resources would not contribute to the sustainable energy generation anymore. This is the greatest challenge in transiting Finnish secondary wood flows from energy to material uses: replacing the wood as the main renewable energy source. The results of this thesis suggest that diversifying the energy source mix in Finland and focusing on decreasing the energy demand by integrated technologies might be the most feasible solutions. This way the market disruption risks and risk to increase fossil fuel utilization can be minimized in comparison to a situation where only few energy sources are dominating (Pilpola & Lund 2018). The energy mix could include more solar, wind and nuclear power as well as possibly modern carbon capture and storage (CCS) technologies (Pilpola & Lund 2018). However, the results of this thesis do not suggest ending wood-based energy generation completely, but to add more material cascading loops before energy recovery. Also, liquid modern wood-based fuels such as pyrolysis oil and ethanol increase the climate change mitigation potential in integrated production systems.

The material cascading of waste wood resources in Finland needs actions as well. The national re-use and recycling potential could be increased by applying more advanced product design. Also, literature suggest e.g. restrictive legislation on wood preservative uses which hinder cascading options (Winder & Bobar 2016). Increase in wood-based construction and untreated wood products would further help to increase cascading potential. Bigger market share of wood-based construction would require less restrictive regulation, standardized modern construction practices, but also renewed education programs related to wood-based product utilization that are appealing to future professionals.

The Finnish sawmilling industries plays a major role in this transition producing long-lifetime, untreated, sawnwood products. Their production systems could benefit from research funding allocated to improve the efficiency in sawing techniques. Also, funding allocated to diversify the market environment for by-products could help to increase the revenues of the industries and therefore increase the R&D activity. If the production volumes of sawmilling industries increase and the markets of by-products are not divergent, it may lead to increased energy use, as indicated in a Norwegian backcasting study (Sjølie et al. 2016). The findings of this thesis and previous studies show that wood-based composites, such as wood-plastic mixtures, and biochemicals may have high substitution potential especially when secondary resources such as by-products are utilized as a raw material (Sommerhuber et al. 2015; Aryapratama & Janssen 2017).

Other potential high added value and high DF uses for by-products are chemical pulp milling products, which already use efficiently wood chips as raw material (Hassan et al. 2018) as well as liquid biofuels such as ethanol and pyrolysis oil. Chemical pulp derived textiles are more favorable from the climate perspective than graphical paper for instance. Thus, textiles should radically increase their market share compared with paper products, but also increasingly substitute cotton and synthetic textiles.

National level market share increment may not be sufficient to boost private investing in these identified promising new products and their technologies. To appeal private investors, the market pull should radically increase globally, which is possible through technological development improving cost competitiveness and quality to meet the consumer expectations. Here, public financial support is crucial to boost technological development. The value chain efficiency in terms of applying 3D technology in wood-based composite production, and integrated multi-product factories producing e.g. biochemicals and liquid biofuels, or utilizing chemical pulp milling side streams in modern biofuel production, are needed to boost material cascading. The new production systems are considered high-risk, since most of the technologies are missing commercial piloting stage and end-products are relatively new in the markets, and considered less competitive compared with fossil equivalents.

Thus, the results of this thesis as well as previous studies highlight the need for public funding for these innovations (Mazzucato & Semieniuk 2018). International policies also may help to balance the price competition by applying restrictive regulation, or higher taxation, on fossil-derived products and energy intensive equivalents. On the national level, actions including national funding and R&D in cooperation of research institutes and industries, may take the first step by focusing on developing the current production systems and their integrations, and recycling technologies. In Finland, industrial processes are already mainly utilizing renewable bioenergy and as stated in this thesis, factor integrates may show their benefits only in biogenic GHG emission reductions. Therefore, EU policies should aim at supporting production technologies that decrease biogenic emissions, or alternatively decrease the virgin wood resource utilization through higher production efficiency. This could be implemented e.g. by lower taxation.

The scenario stories of this thesis state that the main driving force for the energy transitions would rely on global policies, which should consistently set targets for adopting renewable energy technologies and set a common GHG emission based taxation on fossil fuels to boost alternative energy source development and markets. However, the transition pathways in this thesis are based on visions of the Finnish stakeholders. Thus, international perspectives could complement the analysis. International foresight studies indicate that including renewable energy targets in global policies may in fact increase the utilization of biomass in energy generation (World Energy Council 2019). Therefore, the next steps in research should aim at clarifying plausible outcomes on international policy making and their interlinkages with influence factors affecting national wood utilization patterns.

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