Norwegian University of Life Sciences
Faculty of Environmental Sciences and
Natural Resource Management

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Forest-based biofuels in the Nordic countries: Potentials and interactions with the forest industries and the energy sector

Skogsbasert biodrivstoff i Norden: Potensialer og samspill med skogindustrien og energisektoren

Walid Fayez Mustapha

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Walid Fayez Mustapha

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PhD supervisors

Professor Erik Trømborg
Faculty of Environmental Sciences and Natural Resource Management
Norwegian University of Life Sciences
Postbox 5003, 1432 Ås, Norway

Professor Torjus Folsland Bolkesjø
Faculty of Environmental Sciences and Natural Resource Management
Norwegian University of Life Sciences
Postbox 5003, 1432 Ås, Norway

Dr. Maarit Kallio
Natural Resources Institute Finland (Luke)
Latokartanonkaari 9, 00790 Helsinki, Finland

Evaluation committee

Professor Anne Toppinen
Department of Forest Sciences
University of Helsinki
P.O. Box 27, 00014 University of Helsinki, Finland

Professor Martin Junginger
Copernicus Institute of Sustainable Development
Utrecht University
Heidelberglaan 2, 3584 CS Utrecht, The Netherlands

Professor Hans Fredrik Hoen
Faculty of Environmental Sciences and Natural Resource Management
Norwegian University of Life Sciences
Postbox 5003, 1432 Ås, Norway

Preface

They say a PhD teaches you how to think.
It turns out they were right.
Only now, in retrospect, am I able to appreciate their saying.
Because up until this very moment,
I was busy thinking about my PhD.

This project has been one of the most challenging endeavors I have undertaken in my adult life and I appreciate every moment of it. From the initial naive optimism, the subsequent dismantling realization of the sheer magnitude of the project, to the hard work and determination driven by a blend of stubbornness and motivation, leading to victories, both big and small, along a long and winding path.

I would like to thank my supervisors, Prof. Erik Trømborg, Prof. Torjus F. Bolkesjø and Dr. Maarit Kallio. Thank you, Erik, for always finding time for fruitful discussions and your unwavering guidance and mentorship throughout my time at NMBU. You always allowed me to pursue my ideas and knew when to step back and when to push. Thank you, Torjus, for helping me bring the essence out of my papers. The quality of the work would surely have fallen short of its' potential without your guidance. Thank you, Maarit, for giving me a great overview of the Finnish forest sector and for the workshop in Vantaa.

Thank you, Gustav, for bringing out the best in me during ping-pong matches. Thank you, Eli, for great talks when things were rough. Thank you, Franz, for being a true friend and teaching me how to counter-rotate my hands. Thank you, Åsa, for being at the forefront of GAMS modelling and thank you, Eirik, being a great office mate. Thank you to the administration staff who made this entire process run smoothly and thank you to everyone else at Sørhellinga who made my time here great.

A special thank you to my mother, Sabah Ghalayini, for always believing in me and to my brothers Ahmad, Mohammad and Khaled, and my sister Mayssa, for paving the way for me. Thank you to my lifelong friends in Denmark and my new friends in Norway. Finally, thank you, Ingrid, for tolerating my absent-mindedness, for your loving support and for your unwavering encouragements.

Ås, October 2017
Walid Fayez Mustapha

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List of papers

Paper I

Taeroe, A., Mustapha, W. F., Stupak, I. & Raulund-Rasmussen, K. (2017). Do forests best mitigate CO_2 emissions to the atmosphere by setting them aside for maximization of carbon storage or by management for fossil fuel substitution? *Journal of Environmental Management*, 197: 117-129. doi: 10.1016/j.jenvman.2017.03.051

Paper II

Mustapha, W. F., Bolkesjø, T. F., Martinsen, T. & Trømborg, E. (2017). Techno-economic comparison of promising biofuel conversion pathways in a Nordic context – Effects of feedstock costs and technology learning. *Energy Conversion and Management*, 149 (Supplement C): 368-380. doi: 10.1016/j.enconman.2017.07.004

Paper III

Mustapha, W. F., Trømborg, E. & Bolkesjø, T. F. Forest-Based Biofuel Production in the Nordic Countries: Modelling of Optimal Allocation. *Forest Policy and Economics*: In press, available online. doi: 10.1016/j.forpol.2017.07.004

Paper IV

Mustapha, W. F., Kirkerud, J. G., Trømborg, E. & Bolkesjø, T. F. Hard-Linking of a Forest Sector Model to an Energy Systems Model - Effects of Large-Scale Forest-Based Biofuel Facility Deployment and Carbon Prices on the Technology Mix in the Nordic Energy Sector. Submitted to *Energy*.

Abstract

The climate change mitigation discourse and national energy supply security is encouraging the abatement of fossil-based energy use. Biofuels have been deemed one of few alternatives for fossil fuel replacement in transportation and forest-based biofuels are currently promoted in the Nordic countries as a promising path for a climate friendly transportation sector. However, biofuels from forest feedstocks have recently come under scrutiny due to the questionable climate change benefits gained from forest biomass and the high production costs associated with the conversion pathways. In addition, large-scale deployment of biofuel facilities will change the feedstock market thereby potentially altering the cost-competitiveness of the existing forest-dependent industries.

In Paper I, a carbon flux modelling framework covering three forest management alternatives was formulated to determine the climate change mitigation potential of using forest biomass for energy generation and substitution of carbon intensive materials, rather than leaving forests unmanaged for carbon accumulation. We found that biomass extraction for energy generation generally provides mitigation benefits in the short-term. Results were sensitive to parameters such as the reference fossil fuel, material alternatives to wood, production chain emissions and energy conversion efficiencies but less sensitive to the development of carbon pools in the unmanaged forest.

In Paper II, we reviewed the techno-economic literature on lignocellulosic biofuels to determine the cost-competitiveness of the most promising conversion pathways with fossil-based and current biofuel alternatives. We applied the techno-economic data in the Nordic Forest Sector Model, which includes a biofuel investment module and endogenous feedstock prices. We found that hydrothermal liquefaction and pyrolysis are the most cost-competitive of the conversion pathways we addressed in the study, but that they are not cost-competitive with fossil-alternatives. They may, however, become cost-competitive with current biofuel alternatives, given technology learning associated with large-scale deployment of facilities. Elevated feedstock costs from large-scale deployment may counteract the cost reductions from learning.

In Paper III, we addresses how conversion pathway features may affect regional allocation in the Nordic countries using the Nordic Forest Sector Model and techno-economic data representing a large-scale Fischer–Tropsch biofuel plant. We quantified regional allocation in the model and altered the particularities of the Fischer–Tropsch technology to reflect the range

of variation expected from current lignocellulosic conversion pathways in a scenario analysis approach. We found feedstock agnostic conversion pathways to, in general, be allocated in regions with access to side-stream feedstock from sawmilling activity. The expense/revenue associated with electricity had very little effect on the allocation, while heat as a side-stream revenue provided Swedish regions with a comparative advantage. Labor costs were a hindrance for allocation in Norway, but depended on the labor intensity of the conversion pathway. Industrial sawmilling activity was found to increase as a result of biofuel facility allocation.

In Paper IV, we hard-linked the Nordic Forest Sector Model with an energy systems model, Balmorel, to understand how elevated demand for forest-based feedstock, associated with the proliferation of a Nordic biofuel sector, may affect use of biomass from forests in power and heat generation. We also addressed how CO_2 prices will affect use of forest biomass for heat and power. We found that current forest-based power and heat generators would be used to a lower extent with increasing biofuel facility deployment. Heat and power generation investments would also redirect to other renewable technologies. Elevating CO_2 prices was found to lead to abatement of existing fossil-based generators and promote new investments. A combination of low to moderate CO2 prices and large-scale biofuel investments favored investments in heat pumps over forest-based alternatives.

Synopsis

1 Introduction

1.1 Biomass from forests for climate change mitigation

As an extension of climate change mitigation discourse and energy supply security, abatement of fossil-based energy technology is eminent. In conjunction with a prioritization of emissions mitigation by the global community, fossil fuel emissions in 2015 remained unchanged compared to the preceding year and a notable slowdown in the most recent decade (2006-2015) to 1.8% compared to 3.6% in the 2000s occurred (Le Quéré et al. 2016). A high share of renewable energy characterizes the Nordic energy system. Gross inland renewable energy consumption accounted for 24%, 31%, 61%, and 50% in Denmark, Finland, Norway and Sweden, respectively in 2012 (Helmisaari et al. 2014), a large share of which is forest-based, especially in Finland and Sweden. The climate change mitigation properties of forest biomass are, however, heavily debated. In national greenhouse gas (GHG) accounting to the UNFCCC, forest biomass is considered carbon neutral (IPCC 2012) as carbon released through combustion for energy is recaptured by subsequent forest regrowth. In addition, forest biomass replaces fossil alternatives in energy generation. However, the carbon neutrality assumption has met resistance in the literature. Many studies have established that forest biomass is not immediately carbon neutral due to the time needed for forests to regrow and sequester carbon lost from harvest and subsequent combustion for energy (e.g. Cherubini et al. 2011; Holtsmark 2012; Lamers & Junginger 2013). This payback time span depends on the forest growth rate, the recovery rate and conversion efficiency in energy generation (Taeroe et al. 2017). A related concept, the parity time, includes the added accounting of a fossil-based reference case, where the alternative accounting of fossil carbon emissions are compared with the biomass case. Thus, the parity time also depends on, among other things, the energy density and conversion efficiency of the replaced fossil fuel, process chain emissions for the fossil and bio-based pathways and the replacement of fossil intensive materials in addition to the payback time variables. Given the complexity of carbon flux modelling, it is not surprising that parity times have been found to range between 0 and 400 years (Lamers & Junginger 2013). Regardless of potential drawbacks, recent Nordic projections foresee a significant increase in the utilization of biomass for energy, especially for biofuels (IEA 2016).

1.2 Biomass from forests for biofuels

While many options exist for stationary energy applications, only a few alternatives exist for replacement of fossil fuels in transportation. Biofuels are deemed the only practical low-carbon alternative for aviation, marine transport and heavy freight (IRENA 2016) and IEA (2016) predict that biofuels in 2050 will comprise nearly two-thirds of total energy used for transportation in their carbon neutral scenario.

The food vs. fuel tradeoff (Araujo et al. 2017) and risk of indirect land-use change has resulted in EU placing a cap on the use of food crops (i.e. first-generation feedstocks) for biofuels at 7 % for countries that have ratified the Renewable Energy Directive (European parlament 2015). Thus, the remaining 3 % of renewables in transportation must be based on other renewable sources, including second-generation biofuels. Given the provisioning of lower net CO_2 emissions in comparison to first-generation biofuels (Davis et al. 2012) and because they have no compatibility issues with the current vehicle fleet or distribution infrastructure due to being chemically/structurally similar to fossil-derived fuels (Araujo et al. 2017), production of second-generation biofuels may be a more promising avenue. The compositional complexity and variability of biomass from forests does pose considerable challenges and the technological development currently falls short of commercialization and large-scale deployment. Indeed, lignocellulosic biofuels will require technology learning and associated facility deployment to become more cost-competitive (Morrison et al. 2016). While the future of biofuels from forests is uncertain, investment in second-generation biofuel production facilities is an exciting prospect. If successful, a surge of biofuels will reduce dependence on fossil-derived fuels and ensure that the Nordic countries meet national and international blending mandate obligations and mitigate climate change. Thus, second-generation biofuel production in the Nordic countries may be a viable and enticing option, especially because of forest biomass availability, existence of a forest-industrial infrastructure and the prevalence of forest biomass conversion expertize.

1.3 Biofuel synergies and tradeoffs with the forest industries

Biomass from forests are widely employed in the Nordic countries in product manufacturing. In 2016, total use of biomass from forests exceeded 100 million m^3 according to FAOSTAT (2017) (see Fig. 1), of which a large majority is locally sourced. Industrial manufacturing of sawnwood and engineered wood products provisions material for a host of consumer products and in construction and pulpwood in an essential feedstock in pulp and paper manufacturing. Fig. 1 shows a general production increase from 1970 until the middle of the last decade. However, from 2005 – 2016 production appears to have stagnated. s

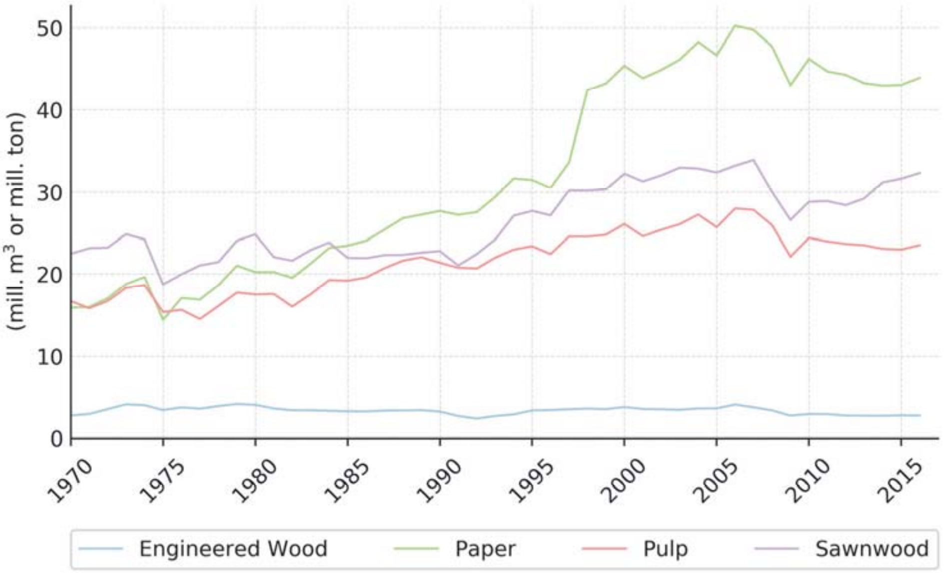

Fig 1. Forest-based feedstock use in the Nordic forest industries.

Future forest-based biofuel production will be inherently connected with the existing forest industries which may lead to synergies and trade-offs. Direct competition between forest-based biofuel technologies and existing industries for pulpwood will elevate pulpwood prices, thereby decreasing the cost-competitiveness of both industries. This will potentially be especially significant for the pulp and paper industry, which is, in general, characterized by low profit margins. However, synergies between the two industries, such as the production of biofuel from excess tall oil from pulp production may increase overall profitability of existing pulp and paper production units. By-products such as bark, dust and chips from sawmilling may provision feedstock for biofuel production and provide an additional source of side-stream sawmill revenue but current side-stream designation currently includes internal heating and deliveries to pulp and paper, pellets or board producers. Thus, an introduction of large-scale biofuel facilities may upset the side-stream flow balance and decrease profitability of existing producers. A potential synergic effect of increased demand for by-products may be elevated sawnwood production. Thus, the potential synergies and trade-offs between the forest industries and the future biofuel production facilities remain unclear.

1.4 Biofuel synergies and tradeoffs with the energy sector

The application of forest biomass for energy production in the Nordic countries is pervasive. Total Nordic utilization of forest biomass for heat and power equaled roughly 250 TWh in 2013 (Danish Energy Agency 2017; SSB 2017a; SSB 2017b; Statistics Finland 2016; Swedish Energy Agency 2017) (see Fig. 2), but annual fluctuations because of feedstock costs, temperature variability and production capacity changes cause forest-based feedstock use variation. For domestic applications, forest biomass is used in residential heating which ranges from in-house woodstoves to district heating systems. Stationary energy generation based on biomass (excluding peat) and waste accounted for over 300 TWh in the Nordics in 2013 (IEA 2016), a large share of which is forest-based. As shown in Fig. 2, the utilization of biomass from forests for energy production is different between the Nordic countries, where Finland and Sweden utilized roughly 100 TWh each in 2013, which is considerably higher than utilization in Denmark and Norway. Projections for heat and power generation using biomass imply a continued biomass utilization rate. IEA (2016) predict a stable utilization of forest biomass for heat and power towards 2050 in their carbon neutral scenario.

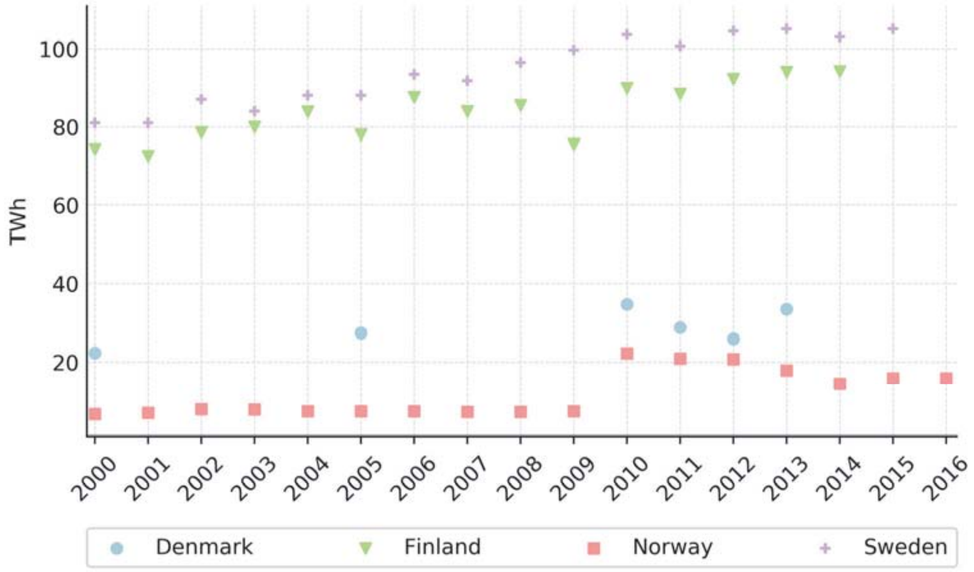

Fig. 2. Danish, Finish, Norwegian and Swedish forest-based feedstock use for energy generation in the Nordic countries. In Norway, only firewood is accounted for up until 2010 while the data includes all biomass for energy from 2010 and onwards.

Competition for forest biomass between the conventional energy sector and biofuel producers is a natural extension of biofuel facility deployment and proliferation. Depending on the feedstock agnosticism level of the conversion pathways, feedstocks with an expected demand increase and associated competition may include pulpwood of various species and harvest residues. Demand for sawmill feedstock traditionally used for production of pellets as well as sawmill chips may also increase as a result of the elevated demand. Thus, conventional energy producers using forest biomass may experience decreased cost-competitiveness. This will potentially deter ramping of forest biomass facilities in power and heat generation and may reduce the attractiveness of forest biomass conversion facilities compared to alternatives for heat and power generation. In addition, biofuel facilities, which provide side-stream heat for increasing profitability, may replace conventional heat producing technology.

2 Aim and scope of the PhD project

International climate change mitigation obligations have motivated interest in forest-based biofuel production in the Nordic countries. As a consequence, the forest-based feedstock market is bound to change which may result in potential synergies and trade-offs with existing industry. Thus, the broad research objective of this thesis was to determine the potential future role of forest-based feedstock in the Nordic countries and how deployment of large-scale biofuel facilities may affect the existing forest dependent industries.

The overarching objective of the thesis as defined above was answered via the following research questions:

1. *Is it best to store biomass in the biosphere or substitute fossil fuels and fossil intensive materials for climate change mitigation in the short and long-term?*

   While forest biomass for energy generation has been highlighted as a necessary and paramount way forward for a renewable shift, the CO_2 mitigation properties of forest biomass is, as mentioned in the introduction, currently the subject of avid discussion in the literature but also in the Nordic political sphere. The political sentiment may affect the future use of forest biomass and shift the Nordic biofuel policy landscape, potentially reverting the interest in forest-based biofuels.

2. *Are future forest-based conversion pathways for biofuel production cost-competitive?*

   Understanding the cost-competitiveness of biofuel conversion pathways is essential for determining the potential proliferation of biofuels. Forest-based biofuel technologies compete not only with current fossil-based options but also with other biofuel options. In addition, determining which technologies are most promising provides added clarity.

3. *Which Nordic countries and regions are most attractive for large-scale forest-based biofuel facility deployment and how does regional deployment change with changing technologies?*

   The attractiveness of individual Nordic countries in catering for biofuel production will determine the localization of large-scale biofuel facilities. This provides insight into the potential comparative advantages between the Nordic countries and reveals how techno-economic differences between forest-based conversion pathways may affect the overall biofuel facility localization. Localization changes because of techno-economic feature differences also indicates particular regional allocation prerequisites. Individual Nordic countries may thus favor different conversion pathways.

4. *How will biofuel facilities interact with the existing forest dependent industries given large-scale deployment?*

   As a consequence of changes to the forest biomass market associated with deployment of large-scale biofuel facilities, synergies and trade-offs with the existing forest-industries can be expected.

5. *How will large-scale biofuel facility deployment affect the heat and power technology mix?*

   Elevated forest biomass prices associated with deployment of large-scale biofuel facilities will result in a decrease in the cost-competitiveness of existing forest-based heat and power facilities and reduce the comparative attractiveness of investment in forest-based technologies for heat and power in the future Nordic energy system.

The research questions were answered in four research papers. Paper I addresses *question one*. Paper II addresses *question two* and party *question four*. Paper III addresses *question three* and partly *question four*, while Paper IV addresses *question five*.

3 Methodology

3.1 Overview

To answer the research questions, a mix of modelling frameworks, scenario analysis and partial equilibrium modelling was applied. In Paper I, we defined a carbon flux modelling framework to identify the climate change mitigation properties of forest biomass. The framework approach is covered in 3.2. In Papers II, III and IV, we applied the Nordic Forest Sector Model (NFSM). A short methodological justification for the structure and scope of NFSM in presented in 3.3. In Paper II, we conducted a literature review to identify techno-economic costs of promising forest-based biofuel conversion pathways and applied these in NFSM to see how feedstock cost elevation associated with large-scale deployment of forest-based biofuel facilities changed the overall cost-competitiveness of the conversion pathways through elevated feedstock costs associated with elevated demand. We also addressed how technology may lessen the cost increase effect from feedstock cost elevation. Paper III focus was directed to the allocation of biofuel facilities taking into account the technology related input ranges of forest-based biofuel conversion pathways to determine the regional and national competitiveness in catering for biofuel facilities. The effects on the sawmilling industry was also addressed in this paper. In Paper IV, we hard-linked NFSM with a Nordic version of a partial equilibrium energy systems model, to understand the role of forest biomass in heat and power given large-scale forest-based biofuel facility deployment. We addressed both forest biomass use in existing capacity and the future technology mix given numerous levels of Nordic forest-based biofuel production volumes and CO_2 price levels. A methodological overview of hard-linking between the models, as we applied it in Paper IV, is presented 3.4.

3.2 Carbon flux modelling framework

As mentioned in the introduction, the climate change mitigation potential of forest biomass has, in recent literature, been addressed using carbon pool and flux accounting of entire forest biomass value chains to estimate the parity times (e.g. Gustavsson et al. 2017; Lamers & Junginger 2013; Zanchi et al. 2012). The materials and methods in a conventional forest biomass carbon parity study, as those applied in Paper I, contain carbon flux tracking and biomass modelling and may contain management alternatives, fossil substitution and addressing uncertainty to calculate the parity times. The modelling framework we applied is displayed in Fig. 3.

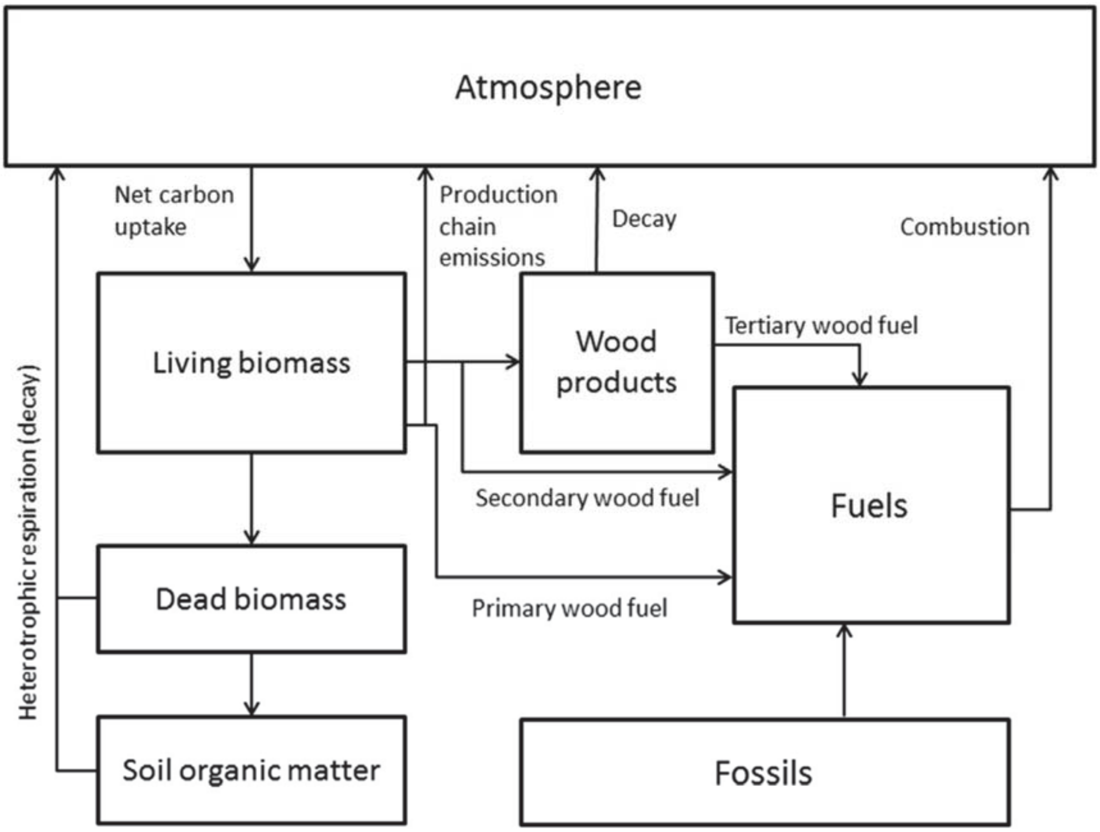

Fig. 3. Carbon pool and flux modelling framework (Taeroe et al. 2017)

Accurately representing carbon fluxes over time requires biomass modelling in the biosphere carbon pools and is especially important for the evaluation of climate change mitigation properties of forest biomass. This includes above- and belowground biomass as both may affect the atmospheric carbon balance. We addressed aboveground biomass by site-specific stand level biomass functions and biomass expansion factors to capture below-ground biomass, but stand level functions may also be applied. We represented belowground biomass and litter decay rates by exponential functions which is the convention in such studies (Gustavsson et al. 2015). Since the trade-off between forest biomass substitution of fossil intensive fuels and fossil intensive materials and carbon buildup is heavily debated (e.g. Duncker et al. 2012), we defined management alternatives with different levels of forest biomass extraction (see Gustavsson et al. 2017 for such an approach) to compare the comparative mitigation benefit of each option. Since parity times have been found to be greatly affected by the carbon intensities of substituted fossil fuels (Haus et al. 2014) and materials (Sathre & O'Connor 2010) we included two fossil fuels with potential for substitution. We used the parity time as one evaluation metric to determine the carbon benefits as others have done (e.g. Holtsmark 2012; Mitchell et al. 2012). Finally, to gain insight into the robustness of results we applied sensitivity analysis to uncertain parameters.

3.3 Modelling forest-based biofuels and the forest industries

An apparent approach to answering the research questions 2-5 posed in section 2.5 was the development of a Nordic forest sector partial equilibrium model. Partial equilibrium models are especially suited to address competitive markets and capture profit maximizing behavior of producers and utility maximizing behavior of consumers by finding region- and product-specific equilibrium prices. They are often used to project future sectoral development and policy and economic impacts (Sjølie 2011) but are best suited to address consequences of market shocks (Latta et al. 2013). The principles underpinning partial equilibrium models is the maximization of welfare or "net social payoff" which is the sum of consumers' surplus and the producers' surplus minus the transportation costs as shown by Samuelson (1952). A historical overview of early forest sector partial equilibrium models is provided by Buongiorno (1996), Toppinen and Kuuluvainen (2010) provides an overview of dominant themes in the literature while Latta et al. (2013) provides an overview of forest sector partial equilibrium models and recent applications.

The scope and magnitude of model development depends on availability of resources and data in addition to the designated application. The designated application of the model was to determine whether forest-based biofuel conversion pathways are cost-competitive in a feedstock competitive market, which Nordic locations are most attractive for facility allocation and how large-scale forest-based biofuel facility deployment may affect existing forest biomass dependent industry. Given these objectives, NFSM was developed and includes forest growth modelling and forestry, forest industrial production, the forest-based heating sector and regional/international product and feedstock trade. To model the cost-competitiveness of forest-based biofuel conversion pathways an investment module was included in NFSM. Fig. 4 shows a schematic representation of the model. Thus, an evaluation of novel forest-based biofuel conversion pathways and a representation of potential market shocks of forest-based biofuels on the existing forest industries was feasible. We applied different versions of NFSM in Papers II to IV and paper-specific NFSM versions are presented in their respective papers.

However, a more complete presentation of the NFSM structure, as it is was developed for the PhD project, is presented in the appendix.

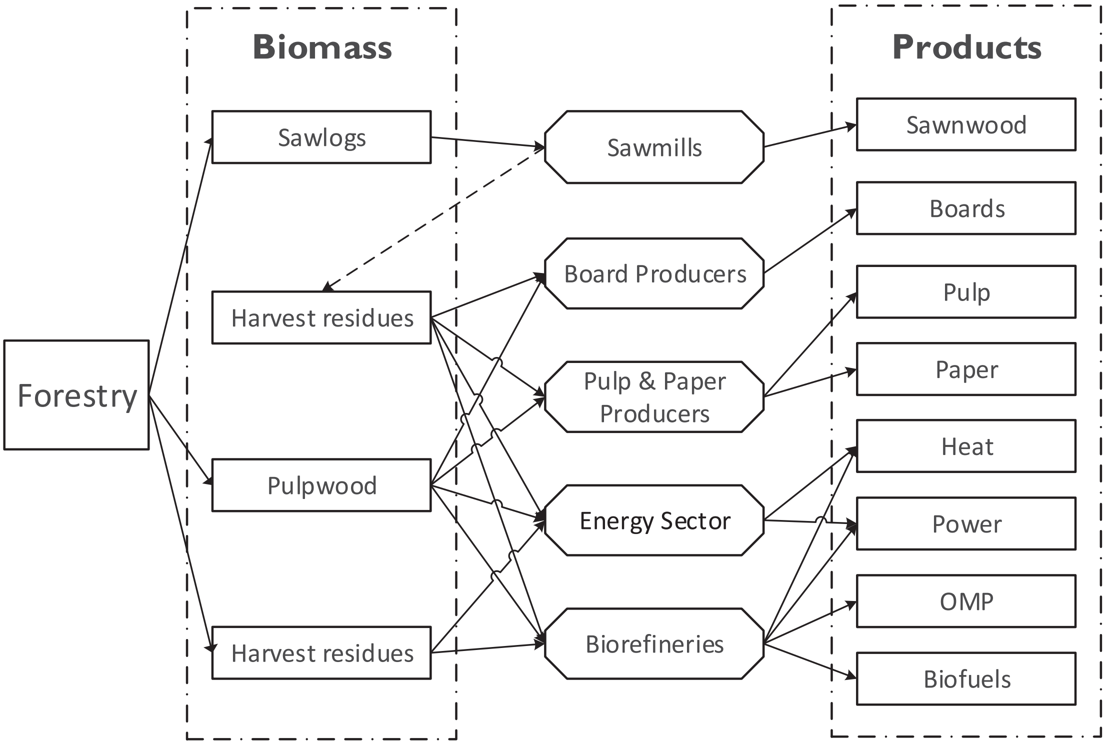

Fig. 4. Material flow from feedstock to product in NFSM. OMP is other market products.

NFSM shares many similarities with NTMIII (Trømborg & Solberg 1995; Trømborg & Solberg 2010; Trømborg & Sjølie 2011), which it is based on. At a methodological level, both models are deterministic, partial and spatial equilibrium models. Timber and harvest residue supply, industrial production, product demand and transportation and trade is modelled identically. Unlike NTMIII, which is formulated as a non-linear programming (NLP) problem NFSM is formulated as a mixed integer linear programming (MILP) problem, since this permits the addition of binary investment variables to allow for biofuel facility deployment with minimum capacity definition. An additional novel introduction to the objective function was an investment module, which permits the setting of various technology learning rates. Given the original non-linear objective function from NTMIII, non-linear technology learning and binary investment, piece-wise linear approximation was deemed necessary. The description in the appendix details the linearization and investment module thoroughly and formally. The NFSM also cover different regional areas and industry segments than NTMIII.

NFSM covers the Nordic countries and forest-based biofuel investment while NTMIII "only" represents the Norwegian forest industries and forest-based heat sector. However, NTMIII was used to model the impact of forest-based biofuel on heat production and the forest products market (Trømborg et al. 2013). Forest industry related Norwegian data applied in NFSM is in large based on NTMIII data. The rest of the forest industry data (i.e. Danish, Finish and Swedish data) was collected as part of the PhD work. All data applied in NFSM, besides forest-based biofuel data, is presented in a comprehensive data report (Mustapha 2016), while forest-based biofuel conversion pathway data defined in NFSM is based on a literature review documented in Paper II.

3.4 Linking the Nordic energy markets with the Nordic forest sector

In order to determine how large-scale Nordic biofuel facility allocation affects the Nordic heat and power sectors through forest-based feedstock price elevation, we hard-linked NFSM with an energy systems model covering the Nordic countries. We did this because NFSM only partially represents the energy sector (i.e. only forest-based energy generation). Hence, a sole application of NFSM would limit the interpretability of the results, since the relative attractiveness of forest biomass technologies compared to other energy generation technologies would not be captured. Thus, how the relative price increase of forest-based feedstock costs associated with large-scale facility deployment affects the utilization of forest-based feedstocks in heat and power requires the presence of all significant feedstocks and technology alternatives for meaningful interpretability. We therefore defined a formal hard-linking procedure with a Nordic version of Balmorel. A specification of the Balmorel structure is given in Ravn et al. (2001), the power systems data and the Nordic modelling approach is provided in Tveten (2015) while a description of the district heating data is provided in Kirkerud (2017). Balmorel was selected because it has hourly time resolution and thus better captures fluctuation in variable renewable energy generation, which permits a more realistic cost-comparison with forest-based feedstocks and technologies. It covers the same regions as NFSM, albeit the regionalization borders are somewhat different and it has a very elaborate representation of district heating and the district heating connection with the power market, which better permits the evaluation of forest-based heat and power generation technologies. From a practical perspective, Balmorel was also selected because it is an immediately available tool applied extensively in my research environment.

Hard-linking is defined as the automated data transfer between optimization models without informal user judgement (i.e. the link is formalized) (Glynn et al. 2015; Wene 1996). While Glynn et al. (2015) state that a hard-linking procedure tend to provide convergence and solution uniqueness, the definition by Wene (1996) is stricter by requiring solution uniqueness. Hard-linking of energy-economic models started with the MARKAL-MACRO linking (Manne & Wene 1992) but has since been applied between numerous models (e.g. de Maere et al. 2014; Messner & Schrattenholzer 2000; Wene 1996). To my knowledge, the proposed hard-linking formulation in Paper IV, is the first linking of a forest sector model with an energy systems model. A schematic representation of the hard-linking procedure applied in Paper IV is given in Fig. 5.

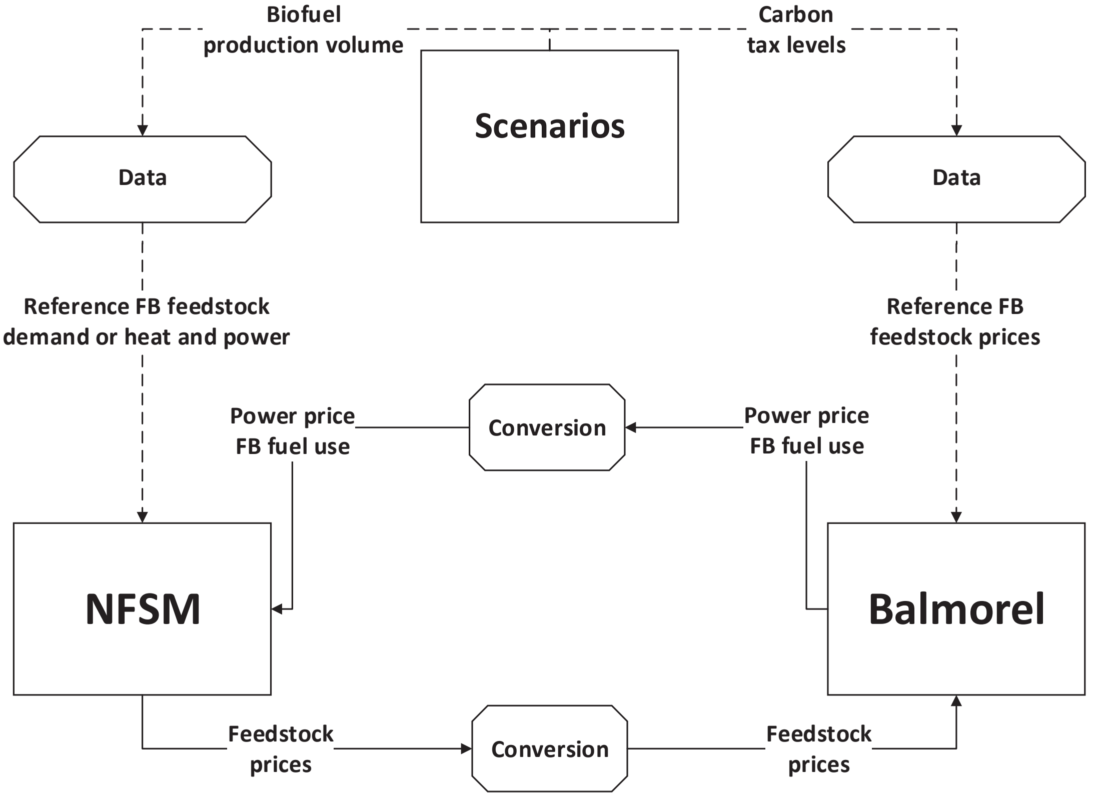

Fig. 5. Schematic overview of the hard-linking procedure. Solid arrows symbolize hard-linking iterations while stippled lines represent the initiation. The first step is the solution of Balmorel with the initiation data. Conversion steps negotiate differences in regionalization and feedstock categories between the models (Mustapha et al.).

The fulfillment of optimality conditions depends on the individual objective functions and constraint formulations and whether the models converge at one unique solution. If a hard-linking procedure provisions a unique solution and global optima is guaranteed in the individual models then the hard-linking procedure results in a global optimal solution. Balmorel is solved as an LP problem while NFSM is solved as MILP problem with 0% gap tolerance. Thus, both models provision global or near-global optima. However, since both investment modules are active in the iterations, neither a unique hard-linking solution nor convergence can be guaranteed. One option is to deactivate the investment module in one of the models, but we wanted both active for the Paper IV study. Another option is to define a relaxed convergence criterion, where the evaluated parameter change does not exceed a set threshold and ensure non-directional change by a formal t-test to identify whether steady state was obtained subsequent to each iteration between the models. While this does not guarantee global optima, a unique solution or convergence, it was deemed appropriate for Paper IV.

4 Main results and discussions

4.1 Forest biomass for climate change mitigation and implications for biofuels

The mitigation benefits of forest biomass was addressed in Paper I. We formulated three forest management alternatives for a mature European beech (Fagus sylvatica) stand: 1) continued beech monoculture management for sawlogs and wood fuels (BAU), 2) clearcutting and establishment of a hybrid poplar clone (*P. maximowiczii* x *P. trichocarpa* or OP42) energy plantation (ENERGY) or 3) designation of the stand as unmanaged for carbon storage (STORE). We calculated the cumulative net carbon emissions (CCE) of all management alternatives and the carbon parity times (CPT) of BAU and ENERGY relative to STORE. Results showed that ENERGY led to the lowest CCE with bituminous coal as the reference fossil fuel but also BAU performed better than STORE. Using natural gas as the reference fossil fuel, ENERGY and BAU produced almost equal CCE results while STORE provisioned the lowest CCE until the 41st year. CPT times ranged from 0–59 and 0–13 for BAU and ENERGY, respectively when the replaced fossil fuel was bituminous coal but increased to 0–56 and 0–156, respectively with natural gas being replaced. Besides the reference fossil fuel, the CPT ranges were especially sensitive to the substitution factor (i.e. life-cycle net greenhouse gas emissions factor from producing alternative products) and the wood product utilization ratio (i.e. ratio of forest biomass used in forest industrial wood products). CPT was also sensitive to changes in production chain emissions, biomass heating value and the relative growth rate of the stands.

Paper I revealed results that indirectly hold implications for forest-based biofuels. The main carbon emitting differences between liquid biofuel production and utilizing conventional biomass for heat and power is the process chain emissions associated with biofuel production, the difference in energy conversion efficiencies and the replaced fuel. Converting biomass to biofuel will inevitably result in added process chain emissions since energy must be expended in the conversion process. Hence, greenhouse gas (GHG) emissions from combined heat and power (CHP) plants have been found to be lower than lignocellulosic biofuel conversion pathways (Elsayed et al. 2003) and differences between biofuel facility process design and technology also result in different process chain emission (Menten et al. 2013). A conversion energy loss is also associated with biofuel production in comparison to CHP plants (Gustavsson & Le Truong 2016; Zhu et al. 2011). Thus, in isolation, a comparative postponement of carbon benefits can be expected from liquid biofuel utilization when compared to solid biomass utilization in CHP plants (Gustavsson & Le Truong 2016). While biomass for heat and power may substitute bituminous coal or natural gas, biofuels may substitute fossil-derived fuels or, alternatively, first-generation biofuels. This has a large impact on the potential climate change mitigation potential of forest-based biofuels. Given the large range of CCE and CPT reported in Paper I, the carbon flux modelling approach reveals great parameter uncertainty. Adding the uncertainty of which forest-based feedstocks to utilize in production of forest-based biofuels (e.g. harvest residues, pulpwood or sawmill residues) and the system boundaries (e.g. should substitution of carbon-intensive materials be taken into account? Should the substitution be considered replacement or displacement?) complicates the assessments and will surely lead to larger ranges for CCE and CPT. Overall, this may reduce the immediate value of such approaches.

4.2 Modelling biofuels and forest industry interactions

The cost-competitiveness of forest-based biofuels was explored in Paper II. We reviewed the techno-economic literature and applied conversion pathway specific data in NFSM to determine the production costs in a forest-based feedstock competitive environment. We found that fast pyrolysis and hydrothermal liquefaction are the most cost-competitive options of the reviewed pathways, but they were not cost-competitive with current fossil-based alternatives. Feedstock costs will increase as a result of changes to forest-based feedstock demand associated with large-scale facility deployment. Depending on the conversion efficiencies of the conversion pathways, a feedstock cost increase of 12.0–35.2% was found with biofuel production volume corresponding to 20% of annual fossil-based demand for road transportation fuels. The feedstock cost increase will lead to an increase between 9.9 to 26.2% on the total cost, depending on the conversion pathway. The increase in cost may be outweighed by the technology learning effect associated with facility deployment.

The utilization of reviewed techno-economic data comes with uncertainty. The lack of commercial-scale production facilities limits the techno-economic estimates to data from process modelling tools and pilot-scale facilities. As an extension, uncertain costs for manufacturing and installation can be expected. For instance, (Brown 2015) found a $300 million net present value (NPV) estimate range for thermochemical cellulosic facilities, depending on the level of optimisms applied in the estimation methodology. The scalability and scaling factor applied of the technologies is also questionable. Given the novelty of the conversion pathways and their current technology readiness level (TRL), upscaling as a straightforward endeavor is not ensured and we cannot know whether the process designs will perform as designated. In addition, the scaling factor applied is associated with uncertainty because process plant scaling factors have been shown to vary greatly (Remer & Chai 1993) and been shown to underestimate actual costs due to reliability problems in scaling (Merrow et al. 1981). Given the uncertainty associated with the methods for obtaining techno-economic costs, it is questionable whether these will be representative of future installation and production costs of the conversion pathways. As a means to mitigate the uncertainty, we defined cost ranges for the individual conversion pathways, which we believe was the most appropriate measure available given the study scope.

Two additional limitations underpin the methods definition. 1) We did not differentiate between lignocellulose utilized in the techno-economic studies and forest-based lignocellulose. Given the differences in compositional complexity and variability of lignocellulosic feedstocks (Yaman 2004) assuming the process designs will yield the same biofuel volume and product mix with different lignocellulosic feedstocks is a simplification. Given the lack of techno-economic estimates detailing forest biomass as feedstock, the applied approach was a necessity. Similarly, a lack of techno-economic estimates limited the study scope to the application of stand-alone facility data and ignoring the potential of side-stream revenue from high-value products. The implications of the study limitations is that defining the future costs of forest-based biofuels is non-trivial and will require large-scale facility deployment before more confidence can be installed in the estimates. Thus, it is difficult to determine whether forest-based biofuels will be able to compete with first-generation biofuels, fossil-based alternatives and other renewable options for transportation.

In Paper III, we explored the optimal allocation of biofuel facilities in Nordic regions with changing conversion pathway configurations. With a reference technology selected, we altered the techno-economic features of the technology to mimic techno-economic variation in the conversion pathways to see how certain techno-economic features may change the Nordic localization patterns. We exogenously specified two Nordic biofuel production volumes levels and permitted the regional allocation of facilities in NFSM subject to objective function maximization. We found that allocation is affected by type of feedstock utilized for production, whether side-stream heat is sold at market and the labor intensity. Electricity, which is a relatively small revenue/expense stream, was found to have little effect on allocation. Moreover, we found biofuel facility allocation affects generally increases the production volume of sawnwood as an indirect consequence of elevated chips demand for biofuel production leading to higher feedstock prices, which increases the cost-competitiveness of sawnwood producers.

The reality of investment decisions is associated with much more complexity than implied in this study. Thus, the approach in Paper III is highly simplified which is an unavoidable consequence of utilizing partial equilibrium models with investment modules for such evaluations. Besides this limitation, we further delimited the approach scope. Among the most important simplifications we delimited is non-explicit regional allocation and direct co-location and integration benefits. Given the current and planned localization of forest-based biofuel facilities, a general commonality is the close vicinity to, or integration with, existing pulp and paper manufacturers or sawmills to reduce costs by, for instance, sharing of supply chain infrastructure or workforce (Osaki & Seleghim 2017). The biofuel facility allocation module in NFSM is regionally explicit, in that biofuel capacity is allocated regionally, but implicit within regions. Thus, co-location and integration benefits, such as side-stream feedstock supply from existing industries, is only captured implicitly from the regional availability of side-stream feedstock. In contrast to our study, and in line with most planned forest-based biofuel facility deployment, explicit definition of biorefinery locations with options for co-location and integration with exiting industry, as the study conducted by Pettersson et al. (2015), permits a more realistic profile of optimal localization. Hence, our approach in Paper III may have better represented regional allocation with explicit localization modelling but was, in practice, limited by availability of data.

We did not differentiate between regional and national investment costs in our definition of the costs of facility installation. While the Nordic countries can be characterized as homogenous, facility investment costs may be different between countries and thus may have affected allocation results significantly. We also ignored regional and national policy support schemes in the investment. The policy framework and especially the political sentiment is cornerstone for investor security and confidence and is especially important for large-scale investments with a relatively long life cycle. Thus, much uncertainty is associated with the approach we applied in Paper III, but the study is more directed towards defining how the variables addressed in the sensitivity analysis may affect localization, rather than a firm declaration localization declaration.

4.3 Biofuel interactions with the Nordic heat and power sectors

In Paper IV, we explored the effects of large-scale biofuel investments and CO_2 prices on biomass usage in heat and power production in 2030. By defining various biofuel production volumes and CO_2 prices in a scenario analysis approach, we permitted regional allocation of biofuel capacity in NFSM and regional use of forest biomass in Balmorel in existing and new facilities. The hard-link between the two models provided endogenous biomass prices subject to CO_2 price and biofuel production volumes and determined the quantity of biomass used in current and future heat and power facilities. We found that deployment of large-scale biofuel facilities based on biomass from forests would substantially alter biomass used in existing heat and power facilities and affect the investment mix in heat and power. Large biofuel investments and low to moderate CO_2 prices decrease the relative attractiveness of heat and power facilities based on biomass in comparison to heat pumps. Elevating CO_2 prices results in added investment in heat and power generation, some of which will be based on biomass depending on biofuel production volumes, leading to higher abatement of existing facilities and increases in average power prices.

A central limitation to the study scope is the assumption of steady state development in the forest industries from reference year to 2030. Global decline in printing paper demand, may result in a decrease in Nordic printing paper production, which may free pulpwood for other designation. Assuming steady-state development of the pulp and paper industries limits the confidence in the general price development of pulpwood prices given large-scale biofuel investment, since the feedstock needed for biofuel may come from this release. Similarly, other effects such as GDP growth and GDP elasticity are ignored but may be important for the overall price results. The results of Paper IV should thus be seen more as results pertaining to the current forest industries than projected ones. The benefit of this approach is that it is free of assumptions about the future development of Nordic printed paper development. In addition, a decrease in the production of printed paper may not necessarily result in a decline in overall pulp and paper production (leading to a decrease in pulpwood utilization), since the industry might, for instance, pivot to packaging paper or other paper production. Thus, defining a general decline in Nordic printing paper production in NFSM without addressing the industry's ability to pivot and maintain the current biomass utilization is associated with much uncertainty and pessimism. We therefore avoided the inclusion of such projections in the study. Projections of forest growth are, however, associated with some certainty due to the biophysical properties of trees. However, we did not project forest growth into 2030, because this would imply implicit assumptions about the harvest regime. Thus, the forest industry and forest resource modelling in Paper IV may not capture the state of forests in 2030, but we believe the biggest value lies in capturing the market shocks rather than accurately projecting the future state of the forests.

4.4 Limitations of NFSM

Partial equilibrium models are simplified representations of more complex markets and market interactions. Thus, the representativeness of such models will be associated with limitations and pitfalls. Including several countries at high spatial scale in one model has proven challenging due to the between-country variation in data availability and quality. While NFSM has proven very useful for Papers II-IV, there are some limitations, which may hold significant implications for the results and future applications of the model.

The employed method for modelling timber supply in NFSM is associated with uncertainty and presupposes an accurate representation of biomass availability, prices and supplier response with changing demand. Depending on country, some regional price elasticities applied in NFSM, which determine the supply of roundwood, are perhaps outdated due to the structural changes in the forest sectors. The model may benefit by using updated elasticities of timber supply. Another option is to apply scenario analysis to timber supply elasticities in applications of the model to mitigate the uncertainty. Supply of timber may also have improved by applying cross-price elasticities. The availability of good empirical estimates of cross-price elasticities differs greatly between the Nordic countries, to my knowledge. Hence, to maintain homogeneity between the countries in the model, cross-price elasticities were not included.

The data covering the forest industries is associated with much uncertainty due to necessary assumptions, lack of data and simplifications. The application of incorrect input and output coefficients in production may drastically affect the supply and demand balance in the model and may misrepresent the actual values. The solution of the model’s objective function will not fully represent reality, which is why calibrating the model’s uncertain parameters to produce outputs better matching the reference year data is common practice (Paris et al. 2011). However, some unavoidable simplifications, such as the aggregation of pulp and paper products to a few categories, will misrepresent the complexity of price and product dynamics, but compromises are necessary when the actual market covers several thousand unique pulp and paper products.

Selecting a reference year, and associated data, for the modelling approach may have shortcomings. The reference data determines supply and demand curves for the model but also important parameters such as heat and power prices, labor costs and exchange rates between countries. The choice of reference year to parameterize the model may thus misrepresent the industry if a non-representative reference year is selected. Since the Nordic forest industries have been undergoing structural changes, selecting a representative year becomes a cumbersome endeavor. Thus, 2013 was selected at model development initiation because it was, at the time, the most recently available data. Other options for parameterizing NFSM could have been to use average estimates over a predetermined period or probabilistic approaches to cover the historical uncertainty.

A central limitation in NFSM is the regionalization of forest resources and transportation costs. Assumptions about transportation costs within regions were made assuming one central point of activity. In practice, many activity hotspots exist within one region in NFSM due to the size of the regions. Because of this simplification, the proximity to market and resources for industrial actors is altered and potentially misrepresented. Between-region transportation costs, which are assumed constant for forest resources, have a similar misrepresentation effect. Thus, regionalization limits the representativeness of NFSM, but is necessary given the framework of the model. A future improvement of NFSM could entail a finer spatial resolution but presupposes data access.

Given the comprehensiveness of NFSM and the magnitude of data needed to parameterize it, the development of the model has been time-consuming. Additional dedication to data collection is required to elevate the representativeness of the model, where especially the quality of input and output coefficients in the forest industries could be improved. This will require the support of industrial actors across the Nordic countries. Regardless of the shortcomings of the model, the functional form, data and assumptions have been presented and detailed, which makes the approach transparent. The studies addressed in Papers II – IV would not have been possible without the application of NFSM, despite the limitations.

5 Conclusions

The aim of this PhD project was to determine the potential future role of forest-based feedstocks and how deployment of large-scale biofuel facilities may affect the forest industries and the heat and power sectors. A carbon flux modelling framework was developed to address the climate change mitigation potential of forest biomass. NFSM was developed with an endogenous biofuel investment module to 1) determine the cost-competitiveness of forest-based biofuels and 2) regional allocation of facilities in the Nordic countries and 3) effects on existing forest industries. Finally, NFSM was hard-linked with Balmorel to determine the interactions between the forest biomass market and the energy market, to determine the future of forest biomass in heat and power generation, given scenario-specific deployment of forest-based biofuel facilities and CO_2 prices.

We found that climate change mitigation is best served by managing forests for biomass extraction, rather than leaving biomass to accumulate in unmanaged forests. We found that CPT results were very sensitive to the reference fossil fuel, material alternatives to wood, production chain emissions and energy conversion efficiencies, but not very sensitive to assumptions about the development of carbon pools in the unmanaged forest. The CPT was found to be useful, but should only be used when comprehensive knowledge of the evaluated systems is present and can be addressed transparently.

Feedstock and capital costs generally dominate the costs of the biofuel conversion pathways. Among the five reviewed alternatives, we found hydrothermal liquefaction and fast pyrolysis to provision the best economic performance, but feedstock costs will increase as a consequence of large-scale biofuel deployment leading to high conversion pathway costs. Technology learning may, however, counteract this but this will depend on the learning rate and the conversion pathway. None of the conversion pathways were found to be cost-competitive with fossil fuels, even with large-scale deployment and associated learning, but some may become cost-competitive with current biofuel alternatives.

In general, most of the biofuel facility occurred in Sweden, followed by Finland, Norway and Denmark, but changed with scenario-specific conversion pathways. Feedstock was central to allocation of facilities. Feedstock agnostic conversion pathways (i.e. able to use pulpwood, harvest residues and sawmilling residues) were especially allocated in regions with access to large volumes of side-stream feedstock from sawmilling activity, while less flexible conversion pathways were more limited in regional allocation. Electricity had a small contribution as a revenue/expense to the overall conversion pathways and had comparable market cost/price in the most attractive countries and therefore affected allocation to a very small extent. Heat was found to provide Sweden with a comparative advantage, while allocation in Norway increased with decreasing labor input. Industrial sawmilling activity can expect to increase as a result of biofuel facility allocation.

The competition for biomass from forests associated with large-scale biofuel facility deployment will substantially alter forest-biomass use for heat and power generation, because of elevated feedstock costs. Current heat and power generators will be used to a lower extent and investments in new heat and power generation capacity will redirect to other renewable technologies. Large-scale biofuel investments combined with low to moderate carbon prices lead to higher cost-competitiveness of heat pumps in comparison to forest-based heat generating capacity. Increasing CO_2 prices will lead to abatement of existing fossil-based generator, which encourages investments in new capacity. Forest-based technologies were less favored as candidates with increasing forest-based biofuel facility deployment.

This PhD thesis has adressed the potential of forest biomass utilization by addressing climate change mitigation properties, the potential future cost-competitiveness of forest-based biofuels and potential synergies and trade-offs with segments of the forest industries and the heat and power sectors. While this thesis has revealed that forest biomass may mitigate climate change, it has also revealed that biomass, as a feedstock, is limited in availability. Acquisition and utilization costs entail that stand-alone biofuel-oriented forest-based conversion pathways are not cost-competitive with fossil alternatives irrespective of moderate technological learning. If forest-based biofuel proliferation is realized, it will alter the forest-based feedstock market learning to both synergies and trade-offs as shown for sawmills and for the heat and power sectors. However, this may depend more on developments outside of the scope of this project.

6 Future research

Accurately modelling future biofuels from forests conversion pathways is a difficult endeavor. It requires not only the joint efforts across disciplines, but also more maturation of the conversion pathways, since the current techno-economic data is still somewhat ambiguous. Identifying biofuel facility co-location, integration and co-generation potential with existing facilities, I believe, will be cornerstone for the proliferation of biofuel from forests. Thus, the application of generic stand-alone techno-economic data should, over time, be replaced in the literature by case-specific integrative process designs as the realization that the one-size-fits-all facility, regardless of conversion pathway, will not be realized.

Forest biomass and associated price modelling needs additional improvements in NFSM to ensure better modelling of timber and harvest residue supply. A reconsideration of applying conventional timber supply elasticities and harvest residue bottom-up studies could be warranted. Perhaps agent based models, which take forest landowner decision-making processes into account, may better represent responses to demand shifts. Regardless, a joint effort between Nordic researchers is needed to address national and regional forest-resource particularities that are often tacit in national forest inventories and studies, but are central to accurately representing forest resources.

Considering the usage of biomass from forests in heat and power production, hard-linking NFSM with Balmorel was a fruitful effort and the approach will likely be used in future studies. A further step, which ensures global optima, is integrating NFSM with Balmorel as an add-on module. This will permit realistic evaluations of biofuel investment with emphasis on the potential for biofuel process designs to deliver side-stream heat and power to the market, which will allow endogenous competition with conventional heat and power generation technology. Integration of the models would ensure a complete framework to evaluate the role of Nordic forest biomass.

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Appendix

NFSM is a spatial partial equilibrium model covering the Nordic forest-based value chain, which ranges from forest growth to consumption of forest-based products. Agents are assumed price takers as they are relatively small in the international products market and because the Nordic countries are relatively open economies with few trade restriction. The model contains 32 regions – 10 regions in Finland, Norway and Sweden, respectively, 1 in Denmark and one representing the rest of the world to permit international trade outside of the Nordics. It is *spatial* in that the equilibrium solution is found for each region and each period and *partial* because it only includes forestry, forest industries and forest-based bioenergy and accounts for other industries indirectly through exogenously specified parameters. NFSM includes forest stock and growth, forest biomass supply, traditional forest industries, the forest-based heat sector and contains an investment module for forest-based biorefineries. Regional and product specific market equilibrium is obtained at an annual interval based on market product demand, supply of forest-biomass, production costs and revenue, maintenance and transportation costs.

Feedstock supply

Supply of forest biomass is modelled in two different ways depending on the feedstock. It is assumed that markets are perfectly competitive and suppliers of biomass will maximize their income in each period, disregarding potential future revenue. Roundwood is distinguished by species category (spruce, pine and deciduous) and designation (sawlog and pulpwood) for a total of six categories. Supply of roundwood is modelled as follows:

$$WP_{reg,wood} = \gamma_{reg,wood} HW_{reg,wood}^{\zeta_{reg,wood}} \qquad (A.1)$$

$WP_{reg,wood}$ is the price of roundwood category $wood$ in region reg. $\gamma_{reg,wood}$ is an estimated parameter detailed in $(A.2)$ and in $(A.3)$. $HW_{reg,wood}^{\zeta_{reg,wood}}$ is the roundwood harvest variable and finally, $\zeta_{reg,wood}$ is the inverse timber supply elasticity. Since $HW_{reg,wood}^{\zeta_{reg,wood}}$ is not given when time, $t = 0$, roundwood harvest is initiated as $\widehat{HW}_{reg,wood}^{\zeta_{reg,wood}}$ at definition but is estimated as a endogenous model variable at $t > 0$. $\gamma_{reg,wood}$ is estimated either by $(A.2)$ or $(A.3)$:

$$\gamma_{reg,wood} = \frac{\widehat{WP}_{reg,wood}}{\widehat{HW}_{reg,wood}^{\zeta_{reg,wood}}} \qquad (A.2)$$

$$\gamma_{reg,wood} = \frac{\gamma_{reg,wood}^{t-1}}{\left(\frac{GS_{reg,wood}}{GS_{reg,wood}^{t-1}}\right)^{\zeta_{reg,wood}}} \qquad (A.3)$$

At $t = 0$, $(A.2)$ determines $\gamma_{reg,wood}$ based on the reference roundwood price, $\widehat{WP}_{reg,wood}$, and the reference roundwood harvest, $\widehat{HW}_{reg,wood}^{\zeta_{reg,wood}}$, subject to the roundwood supply elasticity, $\zeta_{reg,wood}$. At $t > 0$, $\gamma_{reg,wood}$ is estimated based on $\gamma_{reg,wood}^{t-1}$, which is $\gamma_{reg,wood}$ in the preceding time period, and the ratio between the current and preceding growing stock, $\left(\frac{GS_{reg,wood}}{GS_{reg,wood}^{t-1}}\right)$, subject to the supply elasticity, $\zeta_{reg,wood}$. The growing stock, $GS_{reg,wood}$, is initiated as $\widehat{GS}_{reg,wood}$ based on reference values, but is updated at $t > 0$ based on $(A.4)$:

$$GS_{reg,wood} = \left(1 + GR_{reg,wood}\right) GS_{reg,wood}^{t-1} - HW_{reg,wood}^{t-1} \qquad (A.4)$$

The growing stock, $GS_{reg,wood}$ depends on the growing stock growth rate parameter $GR_{reg,wood}$ the growing stock in the previous period $GS_{reg,wood}^{t-1}$ as well as the harvest level in the preceding period , $HW_{reg,wood}^{t-1}$. $(A.5)$ produces a linearized approximation of the area under the roundwood supply curve of $(A.1)$:

$$\sum_{n=1}^{N} HARVW_{reg,wood,n} \approx \int_{0}^{HW_{reg,wood}} WP_{reg,wood} \, dHW_{reg,wood} \qquad (A.5)$$

The integral of the function returns the area under the roundwood curve, while $\sum_{n=1}^{N} HARVW_{reg,wood,n}$ produces N linear line segments of the integral. This permits the application of algorithms to solve discrete and combinatorial optimization problems. The justification of the piecewise linearization routine is that the model's objective function contains both nonlinear terms and binary variables. A linear function expresses the harvest residue price where the function parameters are based on engineering bottom-up studies (Carlsson 2012; Rørstad et al. 2010; Routa et al. 2013). Below, the harvest residue price is specified:

$$HRP_{reg,rdue} = \eta_{reg,rdue} + \theta_{reg,rdue} HR_{reg,rdue} \qquad (A.6)$$

$HRP_{reg,rdue}$ is the harvest residue price in region reg for residue $rdue$. $\eta_{reg,rdue}$ and $\theta_{reg,rdue}$ are the slope and intercept, respectively and are based on the aforementioned studies. $HR_{reg,rdue}$ is the harvest residue variable. Similar to $(A.1)$, a linearization approach is applied:

$$\sum_{n=1}^{N} HARVR_{reg,rdue,n} \approx \int_{o}^{HR_{reg,rdue}} HRP_{reg,rdue} dHR_{reg,rdue} \qquad (A.7)$$

The integral of the function on the right hand side returns the area under the harvest residue curve, while $\sum_{n=1}^{N} HARVR_{reg,rdue,n}$ is an approximation with N linear line segments.

Industrial production

A set of production technologies, $tech$, are given in each region, reg, based on reference capacity. Pulp and paper production units as well as board producers are modelled at unit level, while sawmill producers are aggregated according to mill size. Bioenergy producers are aggregated in each region. Input-output coefficients are given exogenously for each production unit/aggregate where a given set of inputs produce one unit of output of the principle product, but may also result in additional side-stream output depending on the unit/aggregate. Inputs include forest biomass, energy, intermediate products, labor and recycled paper, while principle products include four pulp and four paper grades, three sawnwood categories, three composite wood products, three bioenergy feedstocks, two categories of forest-based heating and three biofuels.

Reference capacity is given in NFSM for a majority of manufacturing units/aggregates based on observed production volume and/or known unit capacities. Pulp and paper production unit capacities are given. Due to the large number of sawmills production units are aggregated into three sizes. This permits the evaluation of potential economies of scale benefits. The reference production volumes determine the capacity of the aggregates. Composite wood manufacturing unit reference capacities are generally given by reference production volume since capacity specification was unavailable for most of these. No total reference use of bioenergy feedstocks is provided in NFSM. Instead, the model selects the volume and mix of bioenergy feedstocks depending on other production activities. Forest-based heating capacities are given by an identified reference production. Finally, forest-based biofuel production requires investment where investment volume, depending on the study, can be endogenously or exogenously given. Industrial production is subject to various constraints as detailed later in this section. Industrial production cost is modelled as follows:

$$PCOST_{reg,tech} = C_{reg,tech} PR_{reg,tech} \qquad (A.8)$$

Where $C_{reg,tech}$ is the marginal production cost of using technology $tech$ in region reg. $PR_{reg,tech}$ is the production output variable and $PCOST_{reg,tech}$ is the total cost. $(A.8)$ excludes labor costs in solid wood manufacturing, which is handled differently in the model.

Production flexibility typically characterizes solid wood mill operation due to varying demand and low ramping costs. However, labor cost elevation is a likely consequence of production volume ramping because employees will work outside of conventional working hours and/or additional employees must be sourced at potentially higher cost. Therefore, it is assumed marginal labor costs increase linearly at production exceeding the reference for solid wood units/aggregates. Solid wood labor manufacturing costs are modelled as follows:

$$WL_{reg,wtech} = \begin{cases} PR_{reg,wtech}\left(\left(PP_{reg,wtech} - 1\right)LC_{reg,wtech} + LC_{reg,wtech}\right), if\ PP_{reg,wtech} > 1 \\ PR_{reg,wtech} LC_{reg,wtech}, otherwise \end{cases}$$

$$(A.9)$$

$WL_{reg,wtech}$ is the cost of labor in solid wood manufacturing in region reg for wood technology $wtech$, $PR_{reg,tech}$ is, as detailed before, the production variable. $LC_{reg,wtech}$ is the unit labor cost of labor while $PP_{reg,wtech}$ is a fraction of 1, where 1 represents the reference production volume. A similar approach is applied for pulp and paper production units but is, in practice, not very relevant due to production capacity constraints as displayed in $(A.22)$.

Biofuel investment

NFSM includes an endogenous biofuel investment module to assess the feasibility of novel forest-based biofuel conversion pathways. The techno-economic data, the technologies and the biofuels differ depending on the scope of the studies, but share the general form of the investment module. Ensuring the competitiveness of biofuel facilities requires, in general, large-scale facilities. Hence, a modelling approach must take into account minimum facility capacity to avoid unrealistically small investments, which requires the application of binary variables. $(A.10)$ below displays how minimum facility capacity is ensured in the module.

$$BIOPRD_{reg,bio} = \begin{cases} BR_{reg,bio}, if\ BR_{reg,bio} \geq BC_{bio} \\ 0, otherwise \end{cases} \qquad (A.10)$$

$BIOPRD_{reg,bio}$ is the capacity (given as production volume) of investment in region reg for biofuel technology bio. $BR_{reg,bio}$ is an investment variable, which represents the production capacity, but is not included explicitly in the objective function. It is included implicitly as detailed later. BC_{bio} is the defined minimum capacity (in production volume) of the biofuel technologies. Hence, when $BR_{reg,bio} \geq BC_{bio}$, $BIOPRD_{reg,bio}$ inherits its value from $BR_{reg,bio}$. In cases where $BR_{reg,bio} < BC_{bio}$, $BIOPRD_{reg,bio} = 0$. In addition, $BR_{reg,bio} = 0$ in these cases as well since $BR_{reg,bio}$ will certainly reduce the objective function when $BR_{reg,bio} < 0$.

Endogenous technological learning with Nordic system boundaries is embedded in the model. This permits an evaluation of the potential effects of technology learning on the total investment costs of biofuel technologies. The investment costs can be expressed as a learning curve (Wright 1936) as detailed below:

$$\sum_{n=1}^{N} BIOINV_{bio,n} \approx CAP_{bio}\left(\sum_{reg} BIOPRD_{reg,bio}\right)^{-E} \qquad (A.11)$$

$\sum_{n=1}^{N} BIOINV_{bio,n}$ is the piecewise linear approximation of the total investment cost, CAP_{bio} is the capital cost and $-E$ is the learning parameter. The relative cost reduction for each doubling of capacity is the learning rate, LR, where $LR = 1 - 2^{-E}$.

Product demand

Demand is modelled conventionally with demand variation subject to exogenous elasticities and reference demand to determine the consumer response to price changes. Products for consumption include four paper grades, three sawnwood categories, three composite wood products, two categories of forest-based heating and potentially three forest-based biofuel products. Biofuel reference demand is set to be either equal to, or a given proportion of, the demand for the fossil alternatives. Near-perfect elasticity for biofuel is embedded in NFSM as it is assumed fossil and biofuels are perfect substitutes. Hence, demand for biofuels is modelled using horizontal demand curves. Below, the demand curve is given:

$$\sum_{n=1}^{N} CON_{reg,fin,n} \approx \int_{0}^{Q_{reg,fin}} (\alpha_{reg,fin} - \beta_{reg,fin} Q_{reg,fin}) dQ_{reg,fin} \qquad (A.12)$$

$\sum_{n=1}^{N} CON_{reg,fin,n}$ is the piecewise linear approximation of the demand function for region reg and final product fin. $Q_{reg,fin}$ is the demand variable. $\alpha_{reg,fin}$ and $\beta_{reg,fin}$ are the slope and intercept parameters, respectively and are detailed below:

$$\alpha_{reg,fin} = \widehat{PP}_{reg,fin} - \frac{\widehat{PP}_{reg,fin}}{\mu_{reg,fin}} \qquad (A.13)$$

$$\beta_{reg,fin} = \frac{-\widehat{PP}_{reg,fin}}{(\hat{Q}_{reg,fin}\mu_{reg,fin})} \qquad (A.14)$$

$\widehat{PP}_{reg,fin}$ is the reference product price, $\mu_{reg,fin}$ is the reference demand elasticity and $\hat{Q}_{reg,fin}$is the quantity demanded in the reference year.

Transportation and trade

Transportation and trade of feedstocks and intermediates between regions is modelled with a fixed loading cost in addition to a distance dependent variable cost based on either truck, train or shipping. Distance between regions is defined by region centers and road/rail/sea distance. Conventional forest-based transportation costs for final products is set as a calibration measure to reflect product price difference between countries, since these will differ depending on the difference in average quality and constitution of the product category aggregate. Transportation cost of biofuels is based on Cazzola et al. (2013).

$$TOTTC_{reg,jeg,all} = TC_{reg,jeg,all}TQ_{reg,jeg,all} \qquad (A.15)$$

$TOTTC_{reg,jeg,all}$ is the total cost of transportation from region reg to region jeg for all model products, $TC_{reg,jeg,all}$ is the fixed and variable transportation cost, while $TQ_{reg,jeg,all}$ is the transportation variable.

Objective function and constraints

The objective function and constraints provide the spatial equilibrium in competitive markets as shown by Samuelson (1952), where market equilibrium is the sum of producer and consumer surpluses given transportations costs, trade and constraints. Given the components mentioned above, the objective function to maximize for one period becomes:

$$Max \left(\begin{array}{c} \sum_{reg,fin} \sum_{n=1}^{N} CON_{reg,fin,n} - \sum_{reg,wood} \sum_{n=1}^{N} HARVW_{reg,wood,n} \\ - \sum_{reg,rdue} \sum_{n=1}^{N} HARVR_{reg,rdue,n} - \sum_{reg,tech} PCOST_{reg,tech} \\ - \sum_{reg,wtech} WL_{reg,wtech} - AN \sum_{bio} \sum_{n=1}^{N} BIOINV_{bio,n} \\ - \sum_{reg,jeg,all} TOTTC_{reg,jeg,all} \end{array} \right) \qquad (A.16)$$

AN is the annuity factor. The objective function is subject to the following constraints, which together with the objective function provides the model solution.

$$\begin{aligned} Q_{reg,fin} - \sum_{tech} CF_{fin,tech} PR_{reg,tech} \\ + \sum_{jeg} \left(TQ_{reg,jeg,fin} - TQ_{jeg,reg,fin} \right) = 0 \; \forall fin, reg \end{aligned} \qquad (A.17)$$

$$\begin{aligned} - \sum_{tech} CF_{int,tech} PR_{reg,tech} \\ + \sum_{jeg} \left(TQ_{reg,jeg,int} - TQ_{jeg,reg,int} \right) = 0 \; \forall int, reg \end{aligned} \qquad (A.18)$$

$(A.17)$ ensures that the consumption of final products, fin, in region, reg, is equal to the net available final products taking into account the regional production and the net regional export, while $(A.18)$ balances use of intermediate products int. $CF_{all,tech}$ is a technology input-output coefficient for all technologies (fin, int, $wood$, $rdue$). It holds that $CF_{all,tech} \leq 0$ for inputs, $CF_{all,tech} \geq 0$ for by-products, and $CF_{main,tech} = 1$ for the main product, $main$ (Kallio et al. 2004).

$$\begin{gathered} -HW_{reg,wood} - \sum_{tech} CF_{wood,tech} PR_{reg,tech} \\ + \sum_{jeg} \left(TQ_{reg,jeg,wood} - TQ_{jeg,reg,wood} \right) = 0 \ \forall wood, reg \end{gathered} \qquad (A.19)$$

$$\begin{gathered} -HR_{reg,rdue} - \sum_{tech} CF_{rdue,tech} PR_{reg,tech} \\ + \sum_{jeg} \left(TQ_{reg,jeg,rdue} - TQ_{jeg,reg,rdue} \right) = 0 \quad \forall rdue, reg \end{gathered} \qquad (A.20)$$

$$HR_{reg,rdue} \leq RMAX_{reg,rdue} \sum_{wood} HW_{reg,wood} \quad \forall reg, rdue \qquad (A.21)$$

$(A.19)$ and $(A.20)$ balance the regional use of roundwood and harvest residues, respectively, while $(A.21)$ limits the collection of harvest residue to a theoretical harvest level-dependent maximum, where $RMAX_{reg,rdue}$ is the theoretical maximum collection factor for harvest residue, $rdue$, in region, reg, based on the reference harvest level.

$$PR_{reg,px} \leq CAPA_{reg,px} \quad \forall reg, px \qquad (A.22)$$

$$\sum_{reg,tech} CF_{re,tech} PR_{reg,tech} \leq \sum_{reg,fin} \left(\nu_{reg,fin} Q_{reg,fin} \right) \qquad (A.23)$$

$CAPA_{reg,px}$ is either an observed reference production level or capacity for technology px in region reg. Production is constrained to the observed reference for various technologies depending on the study. In practice, constraint $(A.22)$ has been applied to forest-based heating and pulp and paper manufacturing. The constraint has been set to 10% above the capacity or observed production volume for pulp and paper mills to permit some production volume deviation from the reference. $(A.23)$ limits the use of recycled paper re to a predetermined rate corresponding to the paper consumption level. Finally, $(A.17)$ imposes a non-negativity constraint:

$$Q_{reg,fin}, HW_{reg,wood}, HR_{reg,rdue}, \\ PR_{reg,tech}, BR_{reg,bio}, TQ_{reg,jeg,all} \geq 0 \; \forall reg, jeg, all \qquad (A.24)$$

While nonlinear, the original problem is a convex optimization problem. Any solution thus fulfills the Karush-Kuhn-Tucker conditions. Therefore, a transformation to a MILP problem using separable programming as displayed above maintains a global solution in approximate terms. The model is solved using the General Algebraic Modelling System (GAMS) (GAMS Development Corporation 2016) IDE using the CPLEX solver.

Paper I
Taeroe, A., Mustapha, W.F., Stupak, I. & Raulund-Rasmussen, K. 2017. Do forests best mitigate CO_2 emissions to the atmosphere by setting them aside for maximization of carbon storage or by management for fossil fuel substitution? - Journal of Environmental Management 197: 117-129.
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Paper II
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Norwegian University
of Life Sciences

Postboks 5003
NO-1432 Ås, Norway
+47 67 23 00 00
www.nmbu.no