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*Article*

# Sustainability Impact Assessment on the Production and Use of Different Wood and Fossil Fuels Employed for Energy Production in North Karelia, Finland

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**Abstract:** The utilization rate of woody biomass in eastern Finland is high and expected to increase further in the near future as set out in several regional, national and European policies and strategies. The aim of this study was to assess the sustainability impacts of changes in fuel consumption patterns. We investigated fossil and woody biomass-based energy production chains in the region of North Karelia, focusing on some economic, environmental and social indicators. Indicators were selected based on stakeholder preferences and evaluated using the Tool for Sustainability Impact Assessment (ToSIA). The analysis was based on representative values from National Forest Inventory data, scientific publications, national and regional statistics, databases, published policy targets and expert opinion. From the results it became evident that shifting from fossil to wood-based energy production implies some trade-offs. Replacing oil with woody biomass in energy production would increase the local value added remaining in the region, create employment opportunities and would reduce total GHG emissions. However, firewood, wood chips from small-diameter trees from early thinning and wood pellets have high production costs. Moreover, large greenhouse gas emission resulted from wood pellet production. The case study generated valuable reference data for future sustainability assessments and demonstrated the usefulness of ToSIA as a tool presenting existing knowledge on sustainability impacts of alternative energy supply chains to inform decision making.

**Keywords:** heavy fuel oil; light heating oil; woody biomass; energy production; sustainability indicators; decision support systems; regional decision making; social; economic and environmental indicators

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## 1. Introduction

In Finland, about 28% of the total energy consumption comes from renewable sources of which woody biomass (with 21% of the total energy consumption) is currently the most important source of renewable energy [1]. The share of woody biomass in the region of North Karelia in eastern Finland is even higher than the national average, and has, with 34%, one of the highest utilization rates of woody biomass in heat and power generation in Europe [2]. Moreover, utilization of woody biomass is expected to increase in the future as set out in the Finnish Long-term Climate and Energy Strategy [3] and by local policy [4]. The main drivers to this development are increasing prices of heating oil and the political will to base regional development on regional natural resources [5].

In the North Karelian Forest Programme and the Climate and Energy Programme of North Karelia a large potential increase in the use of wood chips in energy generation is envisioned, where the use of wood chips will about triple [4,6]. The most significant increase in energy wood harvest is expected to come for a large part from small-diameter trees harvested by thinning of young stands. Harvest residues (tops and branches) and stumps are also increasingly utilized in wood chip production. Small-diameter trees, harvest residues and stumps are renewable resources. However, this does not necessarily mean that their use is sustainable.

During the past decades, Life Cycle Analysis (LCA) has been developed and has been the most widely applied approach for studying environmental impacts of a broad range of production chains [7,8]. However, LCA studies are usually restricted to the environmental impacts of production chains and do not necessarily take into account the social and economic dimensions of sustainability. Sustainability impact assessment (SIA) evaluates how changes like different policies, land-use management or alternative scenarios for future economic development affect the sustainability of a sector and provides information for decision makers on which decisions can be based [9–11]. A review of existing assessment methods was presented by Päivinen *et al.* [11] and this study also presented a new approach to assess sustainability impacts of alternative production chains of the forest sector. The approach describes the forest sector as a set of processes by which forest resources are used to produce biomass which is then converted to products, while at the same time delivering other ecosystem services. In their approach [11], each process is characterized by a set of indicators, describing the environmental, social and economic dimensions of sustainable development. In this paper we investigate fossil and wood-based energy production chains in North Karelia, focusing on some economic, environmental and social indicators. This is important since in the near future, the use of forest biomass for energy production is expected to gain an even greater share compared to today and the use of oil is expected to decrease. The Climate Change North Karelia project proposed for the region a 2020 target situation, where the transition from fossil fuels to renewable energy in heating and electricity production has taken place, with municipalities and cities leading the way. Greenhouse gas emissions have been reduced by 20% from the 1990-level, with 20% of the traffic fuels coming from a renewable origin [12].

The overall aim of this case study is to inform land management and policy decision makers on sustainability impacts of changes in fuel consumption patterns. In order to get a broad picture of the implications of changing from fossil to renewable fuel sources, we have made an analysis of several heat and energy production chains. To get an idea where the biggest changes are about to take place and where the biggest benefits can be obtained, we have studied these production chains at the process level. In that way, similar processes in different production chains can be compared. In this particular study we focus on utilization of forests resources in North Karelia with special emphasis on the use of firewood, wood chips and pellets in heat and power generation. An oil production chain was constructed focusing on the production and use of heavy fuel oil and light heating oil in order to compare different processes related to energy production from fossil and renewable sources. Different economic, social and ecological indicators were selected through stakeholder involvement during the Northern ToSIA project [13] and evaluated using ToSIA, the Tool for Sustainability Impact Assessment [14,15].

## 2. Material and Methods

### *2.1. Forest Wood and Oil Production Chain*

Three forest wood chains and two oil production chains were compared in this study (Figure 1), representing a sequence of processes taking place during bioenergy and oil production and its use for energy generation.

Energy Wood Chain: This chain includes thinning of small-diameter trees and extracting of harvest residues and stumps from final felling for the production of wood chips which are used for heat and electricity production at district heating and power plants.

Firewood Chain: This chain includes thinning of small diameter trees which are processed and sold by local forest entrepreneurs as commercial firewood which is used for heating of small-sized dwellings (e.g., farms, private apartments). A large part of the firewood is collected and processed by private-forest owners themselves.

Pellet chain: Pellet production from sawdust and cutter shavings from the sawmilling process. Pellets are used for heating residential homes and other small private and public buildings.

Oil Chain: This chain includes extraction, transportation and refining of crude oil to heavy fuel oil and light heating oil. Heavy fuel oil is used for heat and electricity production in district heating and power plants and light heating oil is generally used to heat residential homes, farms, schools and other private and public buildings which are not connected to a district heating network.

**Figure 1.** Topologies of the pellet, firewood, wood chip from energy wood, harvest residues and stumps and the heavy fuel oil (HFO) and light heating oil (LHO) production chains. Processes are represented by rectangle shapes. The products (oval shapes) pulpwood and wood products leave the chain. Please note that some processes are identical in several production chains. For instance, the process crude oil extraction belongs to the heavy fuel oil and the light heating oil production chain. The processes of the production chain are numbered and refer to the assumptions which are described in more detail in Table 1.

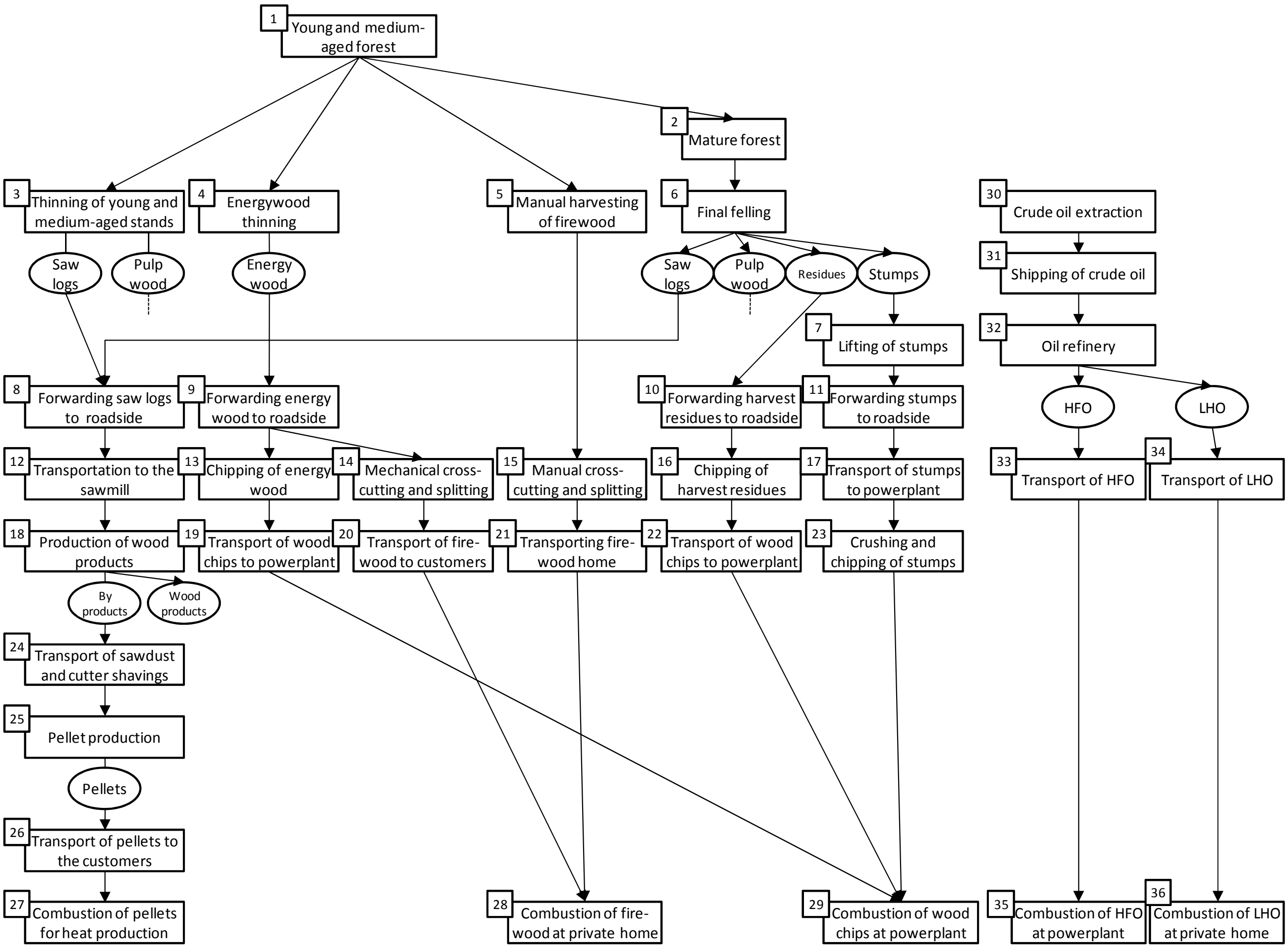



Table 1 describes the assumptions for all processes of the production chains in more detail. The results presented in this paper only consider the resources used for energy production and exclude the impact of e.g., sawlog and pulpwood production. Some forest management processes are similar in several production chains (Figure 1). For instance, the process "energy wood thinning" (process 4, Figure 1) is similar in the commercial firewood chain and the wood chip chain. The process "final fellings" (process 6, Figure 1) produces saw logs, pulpwood, harvest residues and stumps. In the following processes the sawdust originating from processing the saw logs is used in pellet production while the harvest residues and stumps are used in wood chip production.

**Table 1.** Assumption for all processes of the bioenergy and oil production chains.

| Processes | Assumptions |
|---|---|
| 1 | Young- and medium-aged forest includes open regeneration areas, young seedling stands, advanced seedling stands, young thinning stands and advanced thinning stands. In 2005, the area of young- and medium-aged forest was 1,271,000 ha [16] with a standing volume of 127 million $m^3$. |
| 2 | Mature forest is defined here as mature forest and also includes the categories seed tree stands and shelterwood stands as mature trees are the main component of these stands. In 2005, the area of mature forest was 144,000 ha [16] with a standing volume of 33.6 million $m^3$. |
| 3 | Includes 1st, 2nd and 3rd thinning by machine. Harvested trees are used as pulpwood (±90%) or sawlogs (±10%). In 2005, 1.536 million $m^3$ of roundwood were harvested during thinning [6]. |
| 4 | Whole trees are harvested as energy wood by machine. In 2005, 296,000 $m^3$ were harvested as energy wood [16]. |
| 5 | Motor-manual harvesting of firewood with a chainsaw by private-forest owner. |
| 6 | Clear-cut harvesting of mature stands. In 2005, 3.121 million $m^3$ of roundwood were harvested in final fellings [6]. |
| 7 | Stumps are lifted by excavator about one year after clear-cutting. In 2005, about 21,250 $m^3$ of stumps were extracted [17]. |
| 8 | Saw logs are forwarded to the roadside. |
| 9 | Whole trees are forwarded to the roadside. Average forwarding distance is 220 m. Data based on national averages from Kariniemi *et al.* [18]. |
| 10 | Harvest residues are collected and forwarded to the roadside. Average forwarding distance is 250 m. Data based on national averages from Kariniemi *et al.* [18]. |
| 11 | Forwarding of stumps to the roadside. Average forwarding distance was 250 m and about 60 $m^3$/ha of stumps were harvested [19]. |
| 12 | Transportation of saw logs to the saw mill by 60 t timber truck. |
| 13 | Road-side chipping of small-diameter trees from thinnings. Trees are chipped by a tractor-driven or truck-mounted chipper and blown into 110 $m^3$ trailer-truck. Forest chip suppliers can apply for KEMERA-chipping subsidy. Data based on national averages from Kariniemi *et al.* [18]. |
| 14 | Mechanical cross-cutting and splitting of firewood using a Palax Combi (Ylistaron terästakomo Oy, Ylistaro, Finland) firewood-processor by a forest entrepreneur. Data based on average productivity [20]. |
| 15 | Motor-manual cross-cutting with a chainsaw and splitting of firewood with an axe by private forest-owner. |
| 16 | Road-side chipping of harvest residues. Trees are chipped by a tractor-driven or truck-mounted chipper and blown into 110 $m^3$ trailer-truck. Data based on national averages from Kariniemi *et al.* [18]. |
| 17 | Stumps are transported to the power plant by a 110 $m^3$ trailer-truck. Data based on national averages from Kariniemi *et al.* [18]. |
| 18 | The production of wood products includes the sawmilling and the production of plywood. It is assumed that the conversion of 2.3 $m^3$ of timber produces 1 $m^3$ of solid wood products and 1.3 $m^3$ of solid by-products such as sawdust and cutter-shavings. |
| 19 | Transport of woodchips to the power plant by 110 $m^3$ trailer-truck. Average distance to the power plant is 40 km. The moisture content of wood chips is on average 38% for small plants and 48% for large plants [21]. Data based on national averages from Kariniemi *et al.* [18]. |
| 20 | Delivery of firewood sold by forest entrepreneur to private households. Generally firewood is transported to private houses by small truck or farm tractor/pick-up truck trailer combination. Average distance is set at 14 km and the average load is 10 $m^3$ loose. |

**Table 1.** *Cont.*

| Processes | Assumptions |
|---|---|
| 21 | Firewood is transported home by private-person by private car with a trailer. Average distance is 14 km and the average load is 1.4 $m^3$ loose. |
| 22 | Wood chips from harvest residues are transported to the power plant by a 110 $m^3$ trailer truck. Average distance to the power plant is 40 km. The moisture content of wood chips is on average 38% for small plants and 48% for large plants [22]. Data based on national averages from Kariniemi *et al.* [18]. |
| 23 | Stumps and roots are transported to a terminal or directly to the power plant were they are crushed or chipped by large movable or stationary crushers/chippers. Annual productivity of a terminal chipper for stumps is set at 80,800 $m^3$/year [23]. |
| 24 | Sawdust and cutter shavings are transported from the saw mill to the pellet mill in North Karelia. Average transport distance is 75 km. |
| 25 | Pellet production includes many processes such as dying the raw material, grinding the raw material, compressing pellets and screening and cooling of the wood pellets. The moisture content of the sawdust is reduced from approximately 50% to 10% [24]. |
| 26 | Pellets are transported from the pellet mill to the customers. Average transport distance is 50 km and average load is 5 t [25]. |
| 27 | Pellets are combusted for heat production in private houses or public buildings. |
| 28 | Firewood is combusted in private houses for heat production. |
| 29 | Wood chips are combusted at the power plant for heat production. |
| 30 | Overseas extraction of crude oil. |
| 31 | Transportation of crude oil by large tanker ship. About 95% of the crude oil imported to Finland comes from Russia and about 5% from Norway [26]. Transportation distance from Norway is set at 2000 km and the transportation distance from Russia at 200 km. |
| 32 | Crude oil is processed at an industrial process plant and refined into more useful petroleum products, such as gasoline, diesel fuel, asphalt base, heating oil, kerosene and liquefied petroleum gas. Only emissions and costs related to the production of light heating oil and heavy fuel oil are taken into account. |
| 33 | Heavy fuel oil is transported by 60 t tanker-truck from the refinery to the power plant. Transportation distance is set at 320 km. |
| 34 | Light heating oil is transported by 60 t tanker-truck from the refinery to the oil deposit and from there distributed to the customers. Total transportation distance is set at 347 km. |
| 35 | Heavy fuel oil is combusted at the power plant for energy generation. |
| 36 | Light heating oil is combusted at private houses and other private and public buildings. |

### *2.2. ToSIA Tool Description*

In our assessment we used the Tool for Sustainability Impact Assessment (ToSIA version 2.0) which was developed for the EFORWOOD project [27] and later expanded in the Northern ToSIA project [13]. In our assessment the whole value chain of different products of an Energy Wood, Firewood and Oil Chain in North Karelia was evaluated, from planting trees and extracting oil to the end use of products. ToSIA assesses sustainability impact by quantifying changes in the material flow which are linked to the processes of a production chain. In this way, comparisons can be made of changes inside production chains, between different chains and to future scenarios. A more detailed description of the ToSIA tool, the methodology and its possible applications has been given by Lindner *et al.* [15]. Each process of a production chain has an input and an output product. For instance, in the Energy Wood Chain the process "chipping of harvest residues" has "harvest residues" as input product and "wood chips from harvest residues" as an output product. In a process, an area, a material, substance or product changes its appearance or moves to another location. Processes of a simple Energy Wood Chain might for example include planting trees, tree growth, harvesting, forwarding, chipping, transportation and heat production. The start of the Energy Wood, Firewood and Pellet Chain was set to young and medium aged forest and the Oil Chain started with oil extraction. All three chains end with energy consumption in private households. ToSIA calculates the material flow through the processes of the production chains and combines these calculated material flows process-by-process with sustainability indicators reported per unit of material flow, e.g., production costs in €/$m^3$. Conversion factors are used when the unit of the material flow changes, for instance from cubic meters of wood chips to kWh in the combustion process at the power plant. In the production chains presented in this paper, ToSIA tracks the (organic) carbon in products, and as such each product should at least have a conversion factor to tons of carbon. In the Heavy Fuel Oil Chain fossil carbon is used instead. Water may evaporate, other materials may be appended to a wood-based product, but all additions or removals of carbon from products must be accounted for. Conversion factors for wood, wood-based biofuel and heavy fuel oil were obtained from Alakangas [28].

### *2.3. Data Collection*

The data on forest resources, harvested round-wood volumes, wood chip and firewood consumption for the year 2005 were taken from the Finnish Statistical Yearbooks of Forestry [16,17] (Table 2).

**Table 2.** General data on forest resources, wood products and wood-based energy and oil consumption in North Karelia in 2005.

| **Process** | **Amount** | **Unit** |
|---|---:|---|
| Forest resources | | |
| Area of young- and medium-aged forest | 1,271,000 | ha |
| Area of mature forest | 144,000 | ha |
| Standing volume young and medium-aged forest | 130,508,000 | $m^3$ |
| Standing volume mature forest | 34,596,000 | $m^3$ |
| Fellings | | |
| Intermediate fellings | 1,536,009 | $m^3$ |
| Regeneration fellings | 3,205,998 | $m^3$ |
| Products | | |
| Sawlogs | 1,991,999 | $m^3$ |
| Pulpwood | 2,369,006 | $m^3$ |
| Energy wood (small-diameter trees) | 296,000 | $m^3$ |
| Woodchips | 170,968 | $m^3$ |
| Wood pellets | 36,373 | t |
| Firewood | 294,000 | $m^3$ |
| Energy generation | | |
| Wood chips | 376 | GWh |
| Wood pellets | 173 | GWh |
| Firewood | 544 | GWh |
| Heavy fuel oil | 708 | GWh |
| Light heating oil | 365 | GWh |

It is estimated that about 294,000 $m^3$ of traditional firewood were used in North Karelia in 2005 [17]. Since the amount of energy wood, stumps and harvest residues removed from the forest was much larger than what was actually used by the power plants, we assumed that a large proportion of small-sized trees harvested as energy wood during thinning operations was apparently sold as firewood (±210,000 $m^3$) by forest entrepreneurs. The remainder (84,000 $m^3$), was estimated to be collected by private forest owners themselves. Data on heavy fuel oil and light heating oil consumption were taken from the North Karelian Bio-energy Programme [4] (Table 2).

### *2.4. Sustainability Indicators*

In this study, indicators were selected from the indicator framework which was developed in the EFORWOOD project [29,30] and in one case, an adaptation of these indicators was requested to suit the stakeholders' regional interest (instead of GVA, only the economic impact remaining in the region was of particular interest as "local value added"). Economic, social and environmental indicators were selected through stakeholder involvement during working group meetings which were arranged for the North Karelian Climate and Energy Programme [12]. In this way the stakeholder's interests and potential problems could be identified. During meetings with the North Karelian Climate and Energy programme working group it became clear that the stakeholders, who represented research and education, regional authorities, NGOs, energy production business, state-run enterprise and corporation of expert services, were most interested in the following indicators: production costs, local value added, employment and greenhouse gas emissions (Table 3).

**Table 3.** Indicators used in the study, their units and definitions.

| **Indicator** | **Unit** | **Definition** |
|---|---|---|
| *Economic* | | |
| Production costs | Euro | Labor costs (costs incurred by the employer), energy costs (e.g., fuel costs), other productive costs (maintenance, general industrial costs, administrative costs, sales expenditures, *etc*.) and non-productive costs (corporate taxes, capital charges, VAT and other taxes and charges) |
| Local Value Added | Euro | Local Value Added is defined the Gross Value Added remaining in North Karelia (imports, exports, product and value which stay in the region). It is calculated as: Local Value Added = consumer price of the finished product − production costs + subsidies |
| *Social* | | |
| Employment | Person-years | Absolute number (in full-time equivalents per year) which can be allocated to the particular process |
| *Environmental* | | |
| Greenhouse gas emissions from machinery | Kilograms of $CO_2$ equivalent | Emissions from machinery used in energy production calculated as Global Warming Potential (GWP) for 100 years according to the IPCC [31] guidelines. |
| Greenhouse gas emissions from fuel combustion | Kilograms of $CO_2$ equivalent | Emissions from combustion of fossil and wood-based fuel calculated as Global Warming Potential (GWP) for 100 years according to the IPCC [31] guidelines. |

The analysis was mainly based on collection of representative average values from literature. The indicator data collected in this paper were mainly from three sources: Scientific publications, regional and national statistics, databases, published policy targets and expert opinion. A list of the indicators with references to the source material is presented in Appendix Table A1.

System boundaries for the different chosen indicators were defined individually, because of the geographical scope of this study. Greenhouse gas emissions are included for all processes of the studied chains since their effect on climate is on a global scale and not bound to national or regional borders. Other indicators such as employment or local value added are given a more narrow spatial definition, and focus in particular on the region of North Karelia. This focus on local impacts of employment and local value added was one of the stakeholders' main wishes. Unlike in LCA, we do not cover production of machinery used in processes, such as harvesting equipment, oil drilling equipment, the manufacture of trucks or ships or building and maintaining infrastructure such as roads or shipping lanes, as this is not in the nature of SIA. SIA has clearly defined system boundaries and only direct impacts of the modeled processes are expressed as indicators reflecting economic, environmental and social aspects of sustainability. This principle is applied through-out the data collection and unless otherwise indicated, the indicators collected for the chains will express only the direct impacts of the process itself.

#### 2.4.1. Production Costs

Production costs are calculated by summing the costs of all processes needed to manufacture the finished product. Production costs include the price of the raw material, labor, energy, other productive costs (maintenance, administrative costs) and non-productive costs (e.g., VAT and any other taxes or charges). Production costs data were obtained from many different sources and more detailed source information is presented in Appendix Table A1.

#### *2.4.2. Local Value Added*

During the preparation of the North Karelian Climate and Energy Programme the work group participants were interested in the added value which remains in North Karelia, because regional development is an important aspect in the program. Therefore we used the term "local value added". Local value added can in this case be defined as Gross Value Added remaining in North Karelia. For locally produced fuels such as wood chips, firewood and pellets local value added is calculated as:

$$\text{Local Value Added} = \text{Consumer Price of the Finished Product} - \text{Production Costs} + \text{Subsidies} \quad (1)$$

For oil products, similarly, local added value was calculated as the value which stays in the area. Since all oil products in North Karelia are imported from abroad, no production costs are added inside North Karelia. Therefore, the local added value of oil is the same as the consumer price. The local added value of oil products can be expressed by a negative value since all oil products are bought from outside the area and the entire sum paid will leave the area. More detailed source information on the local value added indicator is presented in Appendix Table A1.

### 2.4.3. Local Employment

The social indicator employment represents the employment effect (number of person-years) that is created in the processes along the production chains. Employment figures related to wood chip production of small-diameter trees and harvest residues were taken from Ahonen [32] and Paananen [33], which are case studies from central and western Finland but which presumably give a good indicator for the employment situation in eastern Finland as well. There were no statistics available on the employment of crosscutting and splitting and home delivery of commercial firewood by local firewood entrepreneurs. Therefore we made our own estimation based on the average productivity of a tractor-driven firewood processor (5 $m^3$ loose/h) [20]. One person-year of work was set at 1732 h/year. Average distance for firewood transportation was set at 14 km and the average speed was set at 54 km/h.

Oil extraction, overseas transportation and the refinery process take place outside the region of North Karelia and were thus outside the system boundaries and are therefore not examined any further. Employment figures of domestic transportation by truck were estimated with the EFORWOOD FCBA transport tool [34]. Employment at the heating and power plants related to the combustion of heavy fuel oil are assumed to be similar to employment created by combustion of wood chips.

### 2.4.4. Greenhouse Gas Emissions

The environmental indicator greenhouse gas (GHG) emission quantifies carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$) released during the processes of the wood chip, pellet, firewood and oil production chain. The indicator is divided into two sub-indicators: GHG emissions from production processes and emissions from fuel combustion. The GHG calculations from combustion follow the Intergovernmental Panel on Climate Change regulations [31] and are calculated as Global Warming Potential (GWP) for 100 years. However, $CO_2$ emitted through woodchip, pellet and firewood combustion is highlighted differently in the results than $CO_2$ from oil combustion since emissions from woody biomass are sequestered again in vegetation re-growth.

Greenhouse gas emissions from machinery used in wood chip production from small-diameter trees, harvest residues and stumps were obtained from Kariniemi *et al.* [18]. GHG emissions for all processes in this study are based on national averages for Finland which are also representative for North Karelia. There were very few data available in the literature on GHG emissions from mechanical crosscutting and splitting of commercially sold firewood. Therefore, we made our own estimate based on the average productivity of a tractor-driven firewood processor (5 $m^3$ loose/h)[20], average fuel consumption (8.9 L/h) and average GHG emissions of farm tractors (2686 g $CO_2$ eq./L)[35], which is a similar approach which was used in an LCA study on domestic firewood production in Australia [36]. Commercial firewood is generally delivered to private homes by farm tractor or a small truck while firewood collected by private forest owners is normally transported by a private car with trailer. The average travelling distance (one way, loaded) for transporting firewood was set at 14 km. Emission factors for private cars and small trucks were taken from the Technical Research Centre of Finland [35] and added were greenhouse gas emissions from the unloaded return trip.

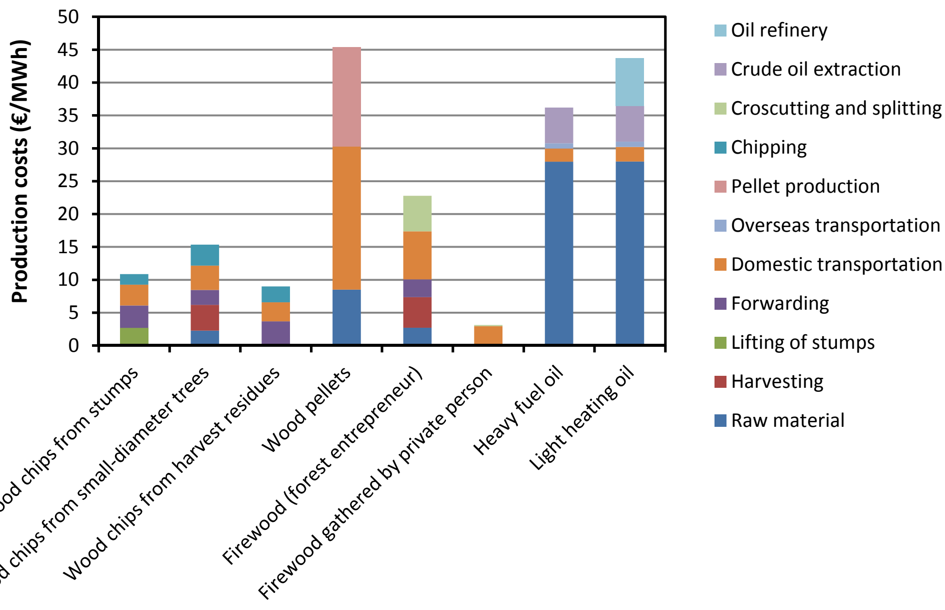
GHG emissions from the oil extraction and refinery process were taken from Wihersaari [37]. Most of the crude oil comes from Primorsk in Russia (±200 km) or Stavanger in Norway (±2,000 km) and enters Finland in the harbor of Skoldvik near Porvoo where the crude oil is refined to more useful products [38]. From there it is transported by ship to Naantali (±300 km) where the components of heavy fuel oil are blended. The refined products are then transported by ship to the terminal in Hamina (±400 km) from where they are distributed mostly by 60 t tanker trucks (max. load 40 t) to the heating and power plants in Finland (Hamina-Joensuu 320 km). Emissions from tanker ships and tanker trucks were obtained from the Technical Research Centre of Finland [35]. For tanker trucks we assumed a 100% empty back haulage. For tanker ships we calculated only the emissions from a one-way trip since in some cases they transport other cargo and as far as we know no information is publicly available if tanker ships usually return to the same port from where they departed. In general, shipping logistics are optimized and sailing unloaded is avoided.

## 3. Results

### *3.1. Production Costs*

Wood pellets, light heating oil and heavy fuel oil have the highest production costs (Figure 2). Sold firewood has relatively high production costs compared to wood chips which are the cheapest to produce. Wood pellets have high transportation costs and also the processes required in making pellets are expensive. Oil is relatively cheap to produce. However, the price of the raw material (crude oil) is high and makes up more than half of the production costs of heavy fuel oil and light heating oil.

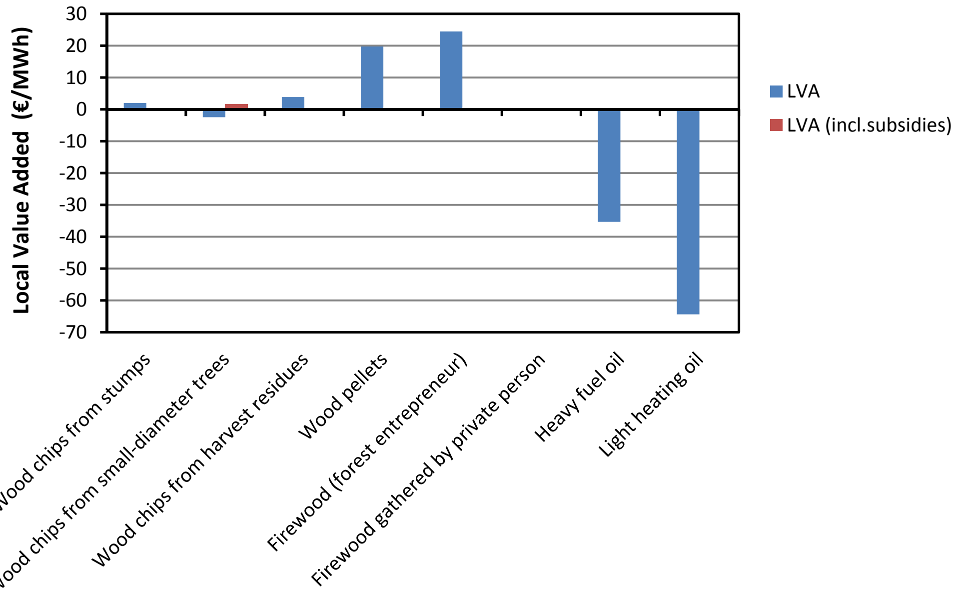
**Figure 2.** Production costs (€/MWh) of wood chips, pellets, firewood and oil in 2005. Note that the production costs for oil procurement occur outside North Karelia.



*3.2. Local Added Value*

Local added value (the value remaining in the region of North Karelia) is the lowest for oil; all oil products are imported and thus the total amount spent on oil procurement leaves the region (Figure 3). Wood chips have a positive although small local added value. Wood pellets and sold firewood have the highest local added value.

**Figure 3.** Local added value (€/MWh) of different wood-based and fossil fuels for energy production in North Karelia. The Local added value is defined here as the gross added value remaining in the region of North Karelia. Oil is imported from outside the region and therefore the entire amount which is spent on the procurement of oil is represented by a negative value.




*3.3. Employment*

Production of firewood and wood chips from small-diameter trees is relatively labor intensive and need a high input of labor (Figure 4) and thus offer good employment opportunities. Especially harvesting of small-diameter trees requires much labor input which is similar for wood chips from small trees as for firewood. Oil requires very little labor as most of the production takes place outside North Karelia and thus adds very little benefits to regional employment.

*3.4. GHG Emissions*

Greenhouse gas emissions per unit of energy produced from oil production were remarkably higher compared to most wood-based fuels (Figure 5). However, pellet production caused relatively more greenhouse gas emissions compared to oil. Of the other wood-based fuels, woodchips from stumps and firewood sold by a forest entrepreneur (Figure 5) had relatively high emissions from machinery. Wood chips from harvest residues and self-gathered firewood had the lowest emissions per unit of energy produced.

**Figure 4.** Relative employment (man years/GWh) related to wood chip, wood pellet, firewood and oil production and its use in North Karelia.

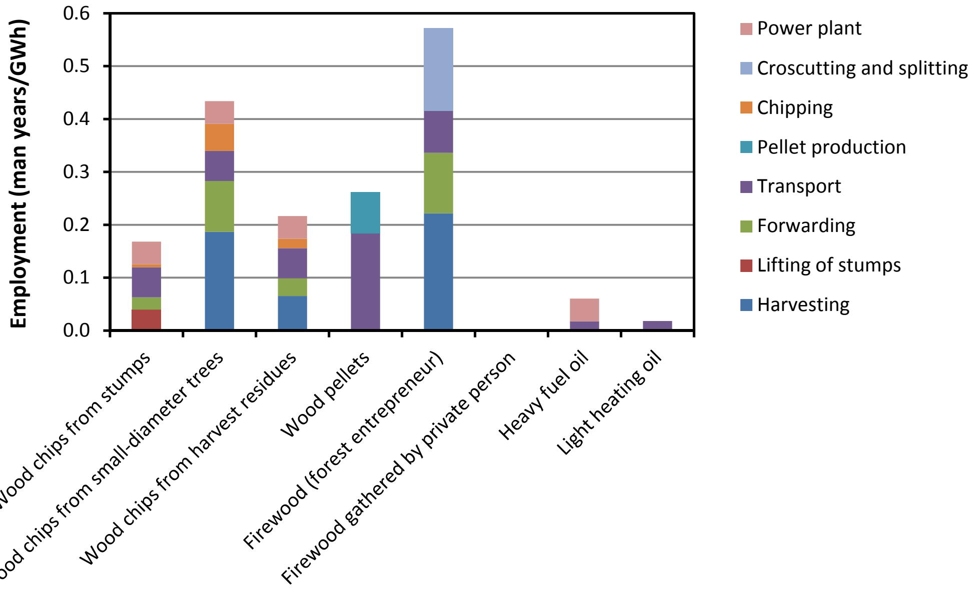
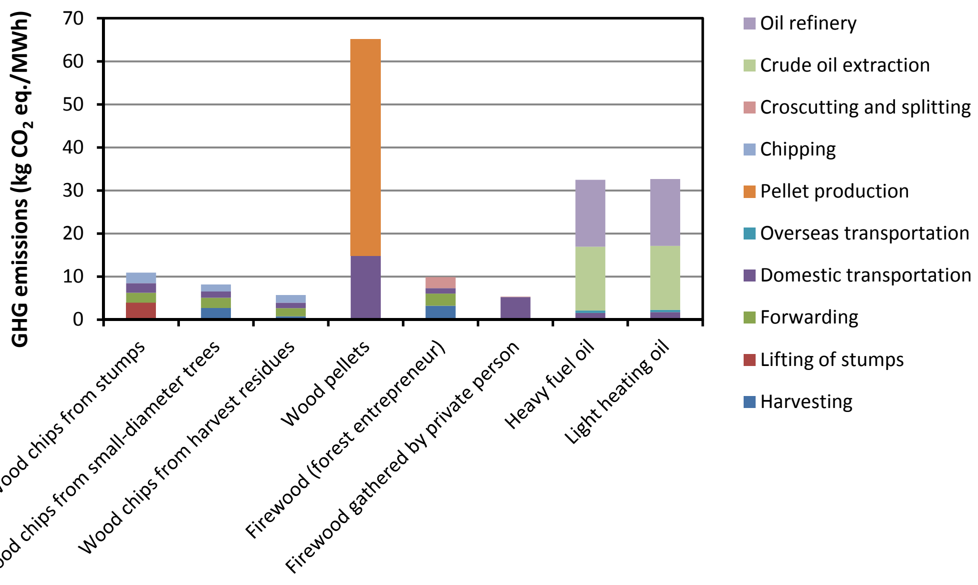
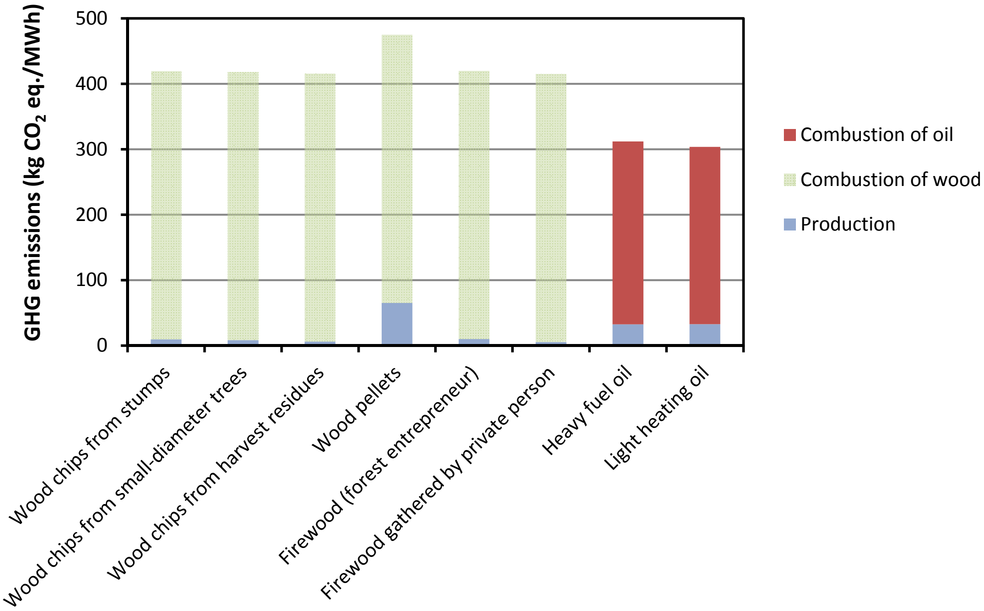



**Figure 5.** Greenhouse gas emissions (kg $CO_2$ eq./MWh) from machinery used in wood chip, wood pellet, firewood and oil production.




Most emissions, however, come from fuel combustion and emissions from machinery are actually only a very small part of the total emissions (Figure 6). Wood-based fuels and especially wood pellets have higher total emissions compared to oil. Nevertheless, it must be noted that the emissions caused by wood-based fuels are from renewable sources and taken up again by re-growth of the vegetation during a ±100-year period [39,40].

**Figure 6.** Greenhouse gas emissions (kg $CO_2$ eq./MWh) from production and combustion of wood chips, wood pellets, firewood and oil. Note: the stacked-bars highlighted in transparent green indicate combustion of renewable energy sources.




## 4. Discussion

### *4.1. Production Costs*

Wood chips have relatively low production costs and are therefore a very attractive alternative for replacing oil, which has relatively high production costs when we take the price of the raw material (crude oil) also into consideration. In 2005, the price of crude oil was about 54 USD/barrel (about 319 €/t) which makes up most of the production costs of for example heavy fuel oil.

In our assessment, wood pellets had the highest production costs. It must be noted however, that we took the Vapo Ilomantsi pellet mill as our example since our assessment focused on North Karelia and at the time of the investigation this was the largest operating plant in the area. The plant used a mixture of wet and dry sawdust. From our assessment it became obvious that a large part of the production costs originated from drying wet sawdust. In order to make pellets, the moisture content of the sawdust had to be reduced from 50% to 10% which required a lot of energy and thus high costs. High costs were also related to the transportation process. The Ilomantsi pellet mill imported raw material from Russia and transporting sawdust over long distances is costly. Furthermore, home delivery of pellets in small quantities is also costly. In our assessment we took as a baseline year 2005 and at that time the price of the raw material (sawdust) was only 8.5 €/MWh. If we would make the same assessment with data for the year 2011, the price of the raw material would be about half of the total production costs (18–20 €/MWh).

The oil price has increased considerably since 2005, which was the baseline year of our study, and this has an impact on the production costs. With increasing oil prices, not only the raw material prices for the production of heavy fuel oil and light heating oil increased, but this affected the production costs of wood-based energy sources as well since their production requires oil. It can indeed be noted that the price of oil and wood-based energy has more or less increased in parallel and the price of both oil and wood chips has about doubled since 2005 [41]. Both wood chips and oil are subjected to similar price fluctuations, however, wood chips are a cheaper alternative compared to oil. Future price fluctuations might, however, change the preference for one energy source over the other and how this will affect the preference for fossil or wood-based energy is hard to predict.

### *4.2. Local Added Value*

From our assessment it became obvious that oil has the lowest local added value. This is not surprising since all oil has to be imported and thus the total value of oil is leaving the region of North Karelia. From this point of view it would be a good alternative of replacing oil with wood chips, which have a considerably higher local added value. However, the local added value of woodchips is just a few €/MWh and for thinning of young stands it would hardly be profitable without KEMERA subsidy [42] (Figure 3). Nevertheless, woodchips have at least a positive local added value and thinning of young stands is mostly not done for making profit but more for improving growth of the remaining trees in order to optimize future income from the sales of pulpwood and saw logs.

Wood pellets and firewood have the highest local added value. Both have high production costs but they also have a high consumer price. Variation in production costs and consumer prices are critical for the profitability of a product and the viability of a sector or industry. The price of firewood has been steadily increasing over the recent years. Still it is hard to make a profitable firewood business due to the high labor input needed. Profitability of pellet production is even harder since the price of the raw material has increased considerably over the last couple of years but the consumer price of pellets has come down due to an increasing availability of pellets on the markets.

### *4.3. Employment*

There are statistics on firewood consumption in Finland but it is rather unclear how much firewood is actually sold by forest entrepreneurs and how much is collected by the private forest owners themselves for their own use. Therefore it is hard to give a precise estimate on the employment in the firewood business in North Karelia. Our indicator does however give a realistic estimate on the amount of work needed per unit of energy and thus on the employment opportunity that would be created if our estimated amount of firewood would be sold by entrepreneurs annually. The use of firewood is expected to increase in the future. For instance, the Bioenergy Programme for eastern Finland has set as a target to increase the use of firewood from the current 3,160 GWh to 4,000 GWh in 2020 [43]. Therefore, there are good opportunities to increase employment and promote entrepreneurship in the firewood business.

Wood chips from small-diameter trees require also a relatively large amount of labor input per unit of energy produced and thus provide good employment opportunities. Most labor is needed in energy wood harvesting and forwarding. Energy wood is harvested for a large part by thinning of young or neglected stands. Employment in energy wood harvesting is expected to increase in the future as the use of wood chips in heating- and power plants is expected to increase from 2,293 GWh in 2008 to 7,500 GWh in 2020 as set out in the strategies of the Bioenergy Programme for eastern Finland [43].

Pellet production also requires a relatively large labor input and seems to offer good employment opportunities. However, recently it was decided to make an end to the activities of the Vapo pellet mill in Ilomantsi [44]. About 15 persons were employed by this mill and its closure had an impact on local employment which is especially important for rural and remote areas.

### *4.4. GHG Emissions*

In our assessment, the production of pellets had the highest GHG emission per unit of energy produced. However, these high emissions do not necessarily give a representative picture of the impacts of pellet production in general. In our assessment, we used the Vapo pellet plant in Ilomantsi as an example which required large amount of energy to dry wet sawdust that was used in mixture with dry sawdust as pellet raw material [25]. GHG emissions were also high as long as energy was generated from non-renewable sources. Another reason for the relatively high emission resulting from pellet production was caused by the long transportation distance of the raw material mainly from Russia (±75 km). Additionally, the home delivery to the customers in relatively small loads (±5 t on average) was another source of emissions. GHG emissions and production costs for pellet production would be improved considerably if the pellet plant would use mainly dry sawdust as raw material. Moreover, synergies can be created by locating a pellet plant next to a sawmill. This would reduce emissions and production costs even further.

Heavy fuel oil and light heating oil had relatively high GHG emissions per unit of energy produced (Figure 5). This is mainly caused by the extraction (drilling) and refinery process which requires a lot of energy. Long distance overseas and domestic road transportation almost had no influence on GHG emissions per unit of energy produced and seems to be even more efficient in terms of emissions compared to wood chip transportation. Combustion of oil results in high emission values if we would consider the emissions from wood-based fuels to be zero as it comes from a renewable resource. The same amount of $CO_2$ which is released during combustion of woody biomass will be taken up again as new trees regenerate in the same place where they were harvested.

Firewood from local forest entrepreneurs had slightly higher emissions per unit of energy produced than self-gathered firewood since it requires processes such as mechanical harvesting, forwarding, crosscutting and splitting which are done by hand or chainsaw by the private-forest owner.

Almost all GHG emissions from self-gathered firewood came from the transportation process. Firewood collected by private persons is normally transported by a private car with a trailer which can carry about 1.4 $m^3$ loose. These are very small amounts compared to what is normally transported by a forest chip truck (about 100–115 $m^3$) to the heating and power plants in North Karelia. Thus, even though small cars consume quite little compared to large trucks, the small transportation load makes them very inefficient.

## 5. Conclusions

The aim of this study was not to give recommendations on which energy source is the most sustainable but more to provide information to decision makers on which they could base decisions. This study focused in more detail on the different processes in energy supply chains with the aim of better understanding the impacts of each specific process. Moreover, we compared similar processes in different production chains. In this case study, targets to reduce oil consumption, to increase the share of woodchips in energy generation and to replace oil with renewable sources had already been set [4,6]. Nevertheless, a sustainability impact assessment can also be used to verify a decision. Considering the indicators assessed in this study, we can pose the question if it was indeed a sensible choice to make a shift from fossil fuel based energy to wood-based energy? To answer this question, one has to keep in mind the local perspective of this study. In regional strategies and by regional decision makers [43], local employment is ranked highly. Some of the indicators indicated low efficiency and high costs, for instance in the pellet chain and the wood chips from small diameter trees. It is quite evident that favoring local employment and local added value results in some negative trade-offs. For instance, pellet production creates local employment but the production costs and GHG emission are high. If the assessment would have been carried out in a different region, preferences of local stakeholders may have been very different. For instance, labor intensive supply chains would not be very viable in a region with very high labor costs or shortage of work force. Finally, to answer the question if it was a sensible choice to make a shift from fossil to wood based energy, we can take the fossil fuel chain as a "baseline" that was there before the use of biomass increased. Based on the indicator results for the different value chains, it can be concluded that a shift from oil to wood-based energy had a positive impact on all of the investigated economic, social and environmental indicators.

However, only four indicators were assessed in our case study. In future assessments, it would be good to include more indicators, for instance a biodiversity indicator would add another dimension to the environmental sustainability assessment. There is still little evidence on the effect of biomass removal on forest biodiversity. Some recent studies indicate that biodiversity may be negatively affected by more intense biomass extraction [21,45]. Considering the rapidly growing use of woody biomass for energy, knowledge on the effects on decreasing amounts of dead wood left in the forest on biodiversity would be very important. In the most recent assessment of red listed species in Finland, forest management and decreasing amounts of dead and decaying wood were identified as the most important threats to species living in forested habitats [46]. Increased harvesting of woody forest-biomass for energy is unlike to improve this situation.

In future assessments, it would also be important to include other social, economic and environmental indicators such as for instance impacts on berries and mushrooms, recreational value, timber products, soil carbon balance and soil protection and fertility. This study included the choice of most preferred indicators of some regional stakeholders who were directly involved in the study. However, the stakeholder consultation could have been broader with more diverse interest groups, including the general public like ordinary citizens of North Karelia without business or political interests. Moreover, if we would consider a broader geographical scope in a study without a regional focus, it would be quite likely that decisions would have been made differently. Still, the study demonstrated that ToSIA was a useful tool to present the existing knowledge on sustainability impacts of alternative energy supply chains to decision makers, to facilitate quantified and better informed decision-making, in this case on the local to regional level.

## Acknowledgments

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## Appendix

**Table A1.** Input data for the calculation of the indicators with references to the original sources (databases, scientific literature, official statistics, branch statistics or expert opinion). Indicator data are given per process unit, e.g., in process number 4 "energy wood thinning" production costs are 8.62 €/m$^3$.

| Process by number | Indicator | Forest and other wooded land area (Hectare) | Production costs (Euro) | Local Added Value (Euro) | Employment (Person-years) | Greenhouse gas emissions (kg of $CO_2$ equivalent) | Reference |
|---|---|---|---|---|---|---|---|
| 1 | ha | 1,271,000 | | | | | [16] |
| 2 | ha | 144,000 | | | | | [16] |
| 3 | m$^3$ | | 8.62 | | $4.1 \times 10^{-4}$ | | [17,32,33] |
| 4 | m$^3$ | | 8.62 | | $4.1 \times 10^{-4}$ | 6 | [12,17,18,33] |
| 5 | m$^3$ | | 0.33 | | | 0.25 | [35] |
| 6 | m$^3$ | | 4.11 | | | 0.56 | [17,18] |
| 7 | m$^3$ | | 5.9 | | $8.7 \times 10^{-5}$ | 8.1 | [18,23,47] |
| 8 | m$^3$ | | 4.14 | | | | [17] |
| 9 | m$^3$ | | 10 | | $2.1 \times 10^{-4}$ | 5.2 | [18,32,33,48] |
| 10 | m$^3$ | | 8.1 | | $7.4 \times 10^{-5}$ | 4.2 | [18,32,33,48] |
| 11 | m$^3$ | | 7.5 | | $5.1 \times 10^{-5}$ | 5.13 | [18,19,23] |
| 12 | m$^3$ | | 5.68 | | $8.4 \times 10^{-5}$ | 13.2 | [17,34] |
| 13 | m$^3$ | | 7 | | $1.1 \times 10^{-4}$ | 3.6 | [18,32,33,48] |
| 14 | m$^3$ | | 10 | | $2.9 \times 10^{-4}$ | 4.79 | [20,35] |
| 15 | m$^3$ | | 0.33 | | | 0.25 | [35] |
| 16 | m$^3$ | | 5.3 | | $3.9 \times 10^{-5}$ | 3.92 | [18,32,33,47] |
| 17 | m$^3$ | | 6.99 | | $1.3 \times 10^{-4}$ | 4.86 | [18,19,32,33] |
| 18 | m$^3$ | | Outside system boundaries | | | | |
| 19 | m$^3$ | | 8.15 | −5.43(3.78)* | $1.3 \times 10^{-4}$ | 3.2 | [18,32,33,48] |
| 20 | m$^3$ | | 13.55 | 45.33 | $1.5 \times 10^{-4}$ | 2.32 | [34,35] |
| 21 | m$^3$ | | 5.14 | | | 9.43 | [35] |
| 22 | m$^3$ | | 6.40 | 8.54 | $1.3 \times 10^{-4}$ | 2.8 | [18,34,41] |
| 23 | m$^3$ | | 3.50 | 4.44 | $1.2 \times 10^{-5}$ | 5.4 | [18,23,41,47] |
| 24 | m$^3$ | | 10.71 | | $7.2 \times 10^{-5}$ | 8.32 | [34] |
| 25 | tonnes | | 155.90 | | $3.7 \times 10^{-4}$ | 239 | [24,49] |
| 26 | tonnes | | 27.36 | 93.90 | $3.7 \times 10^{-4}$ | 11.71 | [25,34] |
| 27 | kWh | | | | | 0.41 | [31] |
| 28 | kWh | | | | | 0.41 | [31] |
| 29 | kWh | | | | $4.3 \times 10^{-8}$ | 0.41 | [18,31] |
| 30 | tonnes | | 62.03 | | | 169 | [36,50] |

**Table A1.** *Cont.*

| Process by number | Indicator | Forest and other wooded land area (Hectare) | Production costs (Euro) | Local Added Value (Euro) | Employment (Person-years) | Greenhouse gas emissions (kg of $CO_2$ equivalent) | Reference |
|---|---|---|---|---|---|---|---|
| 31 | tonnes | | 8.93 | | | 6.04 | [35,51] |
| 32 | tonnes | | 82.90 | | | 177 | [36] |
| 33 | tonnes | | 22.78 | −402.28 | $2.0 \times 10^{-4}$ | 17.9 | [33,35,48] |
| 34 | tonnes | | 24.70 | −715.24 | $2.2 \times 10^{-4}$ | 19.4 | [33,35,48] |
| 35 | kWh | | | | $4.3 \times 10^{-8}$ | 0.28 | [18,34] |
| 36 | kWh | | | | | 0.27 | [52] |

Note: * The Local Value Added including subsidies for management of young stands and chipping of energy wood is represented between parentheses.

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