Environmental Engineering and Management Journal

March 2018, Vol.17, No. 3, 685-696
http://www.eemj.icpm.tuiasi.ro/; http://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

MANAGEMENT PLANNING METHOD FOR SUSTAINABLE ENERGY PRODUCTION FROM FOREST BIOMASS: DEVELOPMENT OF AN OPTIMIZATION SYSTEM AND CASE STUDY FOR A FINNISH ENERGY PLANT

Teijo Sakari Palander[1*], Ari Hietanen[2]

[1]*Faculty of Science and Forestry, University of Eastern Finland, Joensuu, Finland*
[2]*Stora-Enso, Fluting Mill, Heinola, Finland*

Abstract

In this study, we consider a potential Finnish solution to sustainable energy production to satisfy the European Union's forest-related energy policies related to climate change. Conventional energy production includes a number of fossil fuel, peat, and renewable fuel procurement chains that supply a combined heat and power (CHP) plant during different periods of the year. In Finland, peat is commonly used as fuel by energy plants. However, it is not environmentally friendly because it is considered a non-renewable fuel that increases CO_2 emissions and promotes climate change. In this study, we developed a management planning method for more sustainable energy production and tested it using the Finnish government's tax policy decisions to replace peat with wood and the available wood harvesting capacity to increase use of renewable forest fuels. The methodology used data from a geographically decentralized wood procurement organisation to calculate resource availability and costs. The resulting databases were then used for adaptive optimisation in a manner relevant to a decentralized organisation. We combined this approach with the CHP plant's electricity procurement and energy production objectives to describe the complexity of forest-energy flows. Using the developed management planning system, we found that meeting the peat tax and forest technology targets may not meet Finland's targets for sustainable energy production. However, forest biomass has potential rural, technical, and bio-economical capabilities for decentralized energy production by Finnish CHP plants

Key words: CHP, forest biomass, forest technology, fossil fuel, peat, wood procurement

Received: August, 2012; Revised final: June, 2014; Accepted: July, 2014; Published in final edited form: March 2018

1. Introduction

1.1. Background

The Finnish government has proposed that sustainable energy production from renewable sources should account for 38% of the national gross final consumption by 2020, and believes that the utilization of renewable fuels (14% of total consumption in 2009) instead of peat (16% in 2009) in energy production is a promising approach to accomplish this goal (NREAP, 2009). A series of measures in Finland and European countries could be implemented in the energy production sector to improve sustainable energy production by member states (EC Directive, 2009). In Finland, timber harvesting has been negatively affected in recent years by the EU's policy responses to climate change as well as by the economic recession that has decreased demand for wood by EU countries since 2009. One Finnish response to both problems has been to promote energy production from forest biomass using sustainable management of fuel procurement processes that promote the growth of decentralized energy

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[*] Author to whom all correspondence should be addressed: e-mail: teijo.s.palander@uef.fi; Phone: +358 13 2513638; Fax: :+358 13 2511111

production (NREAP, 2009; Palander and Hietanen, 2012). In addition to the Finnish studies, studies from other regions have investigated better use of current and potential capabilities of forest and other biomass sources for green energy production and decentralized rural energy (Hamzeh et al., 2011; Mohammed et al., 2013).

In Finland, 13.5 million solid m^3 of wood chips were used as forest biomass to generate 26 TWh of energy in 2009 (VTV, 2010). This represents 35% of the total energy produced from wood and 7% of the total energy produced in Finland. Because wood chips are an important component of the rural wood resource, Finland has set targets to increase the annual use of forest chips to between 8 and 12 million solid m^3 per year, to produce 16 to 24 TWh of energy, by 2015 (FMAF, 2008). This target presupposes that the decentralized delivery of forest chips to the energy-production industry can be doubled compared with the current delivery volume (6.2 million solid m^3). Such increased consumption of forest biomass may be possible, because up to 20 Mt of woody biomass are left unused in Finland, mainly due to wood that is not recovered during forestry operations (Kuokkanen et al., 2009). However, this will require significant changes in the logistics environment for fossil and peat fuels, and the changes are also complicated by the sequence-dependent procurement chains for forest fuels that are shown in Fig. 1 (Palander and Vesa, 2009; Palander and Hietanen, 2009).

Finland expects to achieve its sustainable energy target through the implementation of policy measures to promote the use of renewable fuels (Lund, 2007). New installations of combined heat and power (CHP) plants for sustainable energy production have, as a result of their decentralized nature and the country's regional investment structure, contributed significantly to sustainable development in rural areas and have offered new income opportunities both to forestry machine enterprises (e.g., companies that produce wood chippers) and to small forestry enterprises that are capable of harvesting significant volumes of wood (EC Directive, 2009). Several incentive-based policies have been implemented to increase the procurement of forest biomass. For example, CHP plants can be developed (an expected 7 TWh by 2020) to utilize forest biomass (NREAP, 2009). Meeting the target has also required the use of carbon taxes as disincentives that increase the relative cost of non-renewable fuels (FFRI, 2012; Poyry Management Consulting, 2010; VTV, 2010). For example, the policy measures have included taxes that will increase the cost of peat fuels, with the goal of reducing the use of this resource (VTV, 2010). In Finland, peat is considered non-renewable because it is replaced only over geological time periods rather than human lifespans (Keddy, 2010). On the other hand, market prices for electricity have increased rapidly in recent years and feed-in tariffs represent an important incentive-based policy to improve a CHP plant's profitability (MSO, 2010; NREAP, 2009; Palander, 2011b). However, profitability analyses of this study have been confined to a constant feed-in tariff rate. Therefore, the impacts of differences in the feed-in tariffs for electricity based on peat or forest chips have not been accounted for.

1.2. Sustainable energy production challenges for CHP plants

Sustainable production of energy from renewable sources often depends on small and medium-sized local or regional enterprises (EC Directive, 2009). Therefore, the research problem we addressed in the present study is how to optimize long-term production scheduling at a medium-sized Finnish CHP plant, where fossil, peat, and wood-based fuels are used to produce energy (Fig. 1).

The wood-based fuels mainly consist of fuelwood separated from more valuable products in the forest, waste wood produced by mills (both sawmills and pulp mills), and mixtures of waste wood and liquefied natural gas that are combusted by the plant. For the forest fuels, we have distinguished between aboveground wood (mostly stems and branches) and belowground wood (roots and stumps that are provided by some harvesting operations). Thus, the sustainable component of the energy production that we studied is based on fuels from renewable forest biomass that are produced and harvested using sustainable production processes (Fig. 2) (Laukkanen et al., 2004; Petty and Kärhä, 2011); in Finland, most forest harvesting is now considered to be sustainable (FMAF, 2008).

To maintain a wide mixture of fuel assortments and minimise production costs, orders from the CHP plant (the customer) are directly transformed into procurement tasks, ideally without storing considerable volumes of fuels as a buffer at the plant or as roadside inventories and without the remarkable sequence-dependent setup times for operation of the energy flow (Fig. 1). For example, this can be done without the long delays between harvesting and delivery that are typical of forestry supply chains as a result of sequence dependencies. The challenge is to allocate the tasks in the procurement chains to supply sufficient fuels for energy production while also obeying the release (harvesting) periods and the delivery dates (production timing), and minimizing the total procurement and inventory cost. Because procurement management over a long period will rely on many different energy-fuel sources, including overall fossil fuel delivery chains and national peat fuel procurement chains, scheduling a company's flows of forest fuels is too difficult to handle manually. The efficient use of available energy sources is vitally important to a CHP plant.

Local procurement decisions for energy fuels play a key role in achieving this goal, which can only be reached using accurate information provided by optimization methods. Therefore, for an energy production management planning system to be efficient, it must be based on a sound methodology for solving the supply problem.

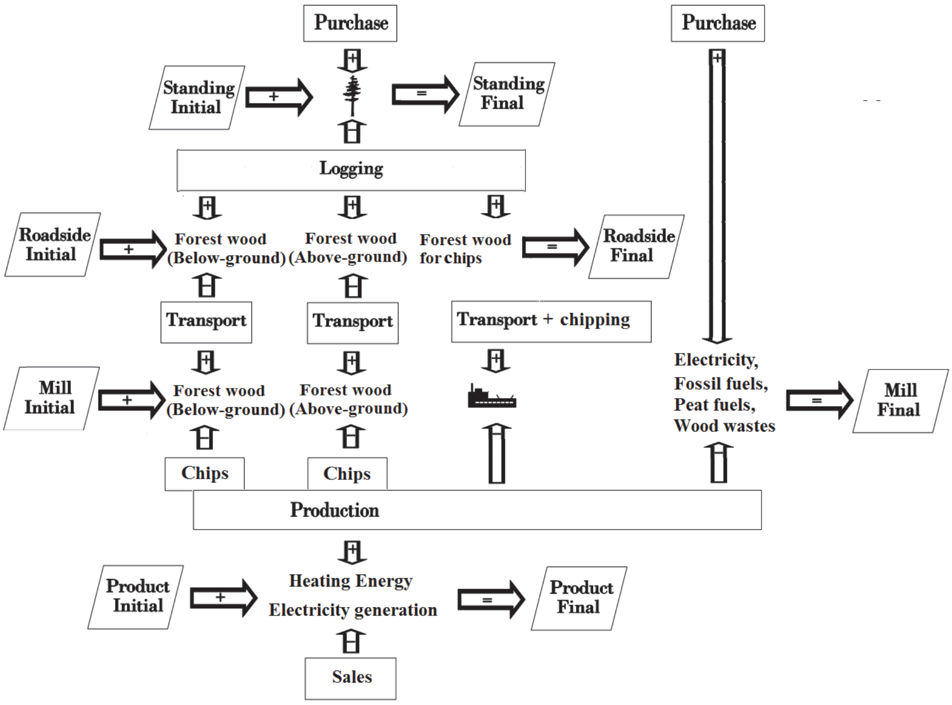


Fig.1. Dynamics of the energy-resource inventories for the Stora Enso CHP plant in the present study. Vertical arrows represent sequence-dependent effects of functions for the system; horizontal arrows represent time-dependent effects for the system. Arrows labelled with + represent inputs to a resource component of the system; arrows labelled with – represent withdrawals from a resource component

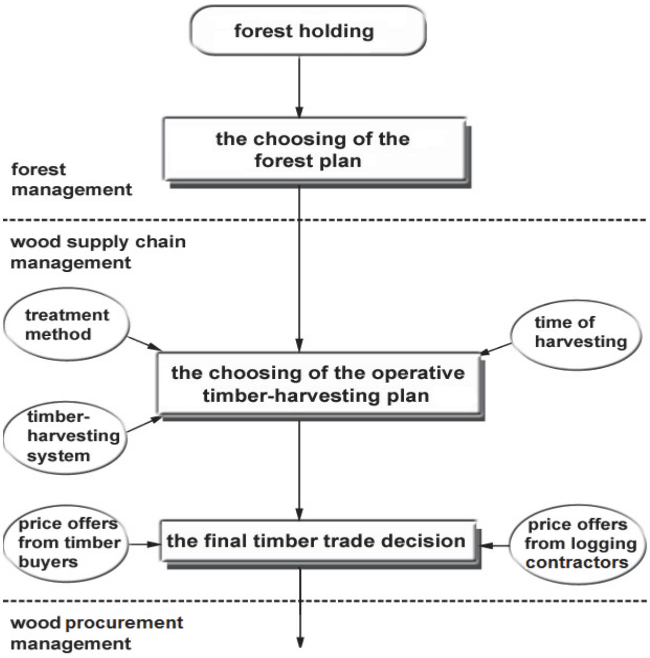


Fig. 2. The links between sustainable forest management and wood procurement management

Various energy-flow and dynamic multi-objective heating optimization problems have also been solved (Li et al., 2006, 2010; Palander, 2011a, 2011b; Shekdar and Mistry, 2001). Shabani et al. (2013) have reviewed studies which used deterministic and stochastic mathematical models to optimize forest biomass supply chains for electricity, heat and biofuels production. Mainly, economic objectives were considered in these models. In the present paper, we defined multiple objectives for optimally supplying a CHP plant and the available decision alternatives based on the constraints defined in a single-objective mathematical model. The term "adaptive dynamic linear programming" has been used to describe this method (Palander, 1995; Palander and Hietanen, 2012; Taha, 2010). Many problems related to the procurement of fuels have conventionally been solved manually by experienced managers. That is usually the case, even today, despite the development of powerful computer technology and more effective decision-support systems (Eriksson et al., 2003; Palander et al., 2002). One of the main reasons for this approach is the combinatorial complexity of large, real-life management problems (i.e., due to the complex interactions and feedbacks among the many factors that affect such problems), which results in poor performance of many sophisticated optimisation-based methods, and this problem is exacerbated by the questionable ability of stand-alone heuristic rules to produce good-quality solutions (Palander and Vesa, 2009). A strong demand therefore exists among energy-fuel procurement managers to apply traditional approaches for efficient logistics, such as linear programming, in large planning systems, without any significant deviation from optimality (Palander, 2011b).

If the procurement problem is solved in the traditional way (i.e., manually), it is often necessary to simplify the planning process, since managers have neither the time nor the ability to consider the entire procurement network. This can easily produce suboptimal procurement schedules, particularly if the problem is solved using only a short-term planning method (e.g., daily schedules). In addition to requiring daily decision-support, managers of the CHP plant require a tool that they can use to develop an optimal long-term fuel mixture strategy that can adapt as the logistics environment changes (Palander and Hietanen, 2012). Managers cannot resolve this kind of monthly schedule on a daily basis using standard computer programs. It is therefore necessary to develop more flexible adaptive systems that can respond to changes in the management environment.

In this study, our main objective was to construct tools for defining an optimal procurement schedule, for use by local procurement (wood harvesting and transportation) teams, and to evaluate the quality of the management planning methodology. (For the CHP plant in our study, a total of nine teams currently supply wood from the forest.) In addition, we considered aspects of the management planning to support sustainable energy production from both methodological and practical points of view. We used a temporally continuous dynamic linear programming method to solve this scheduling problem on a large scale and over a long time period by considering the release and due dates (i.e., the production and delivery dates) as well as the sequence-dependent setup times for the energy flow operations. Instead of solving only for the flows of energy fuels, we addressed the combinatorial complexity of the problem by solving for the energy flow of electricity, and used adaptive programming techniques to provide an updated multi-objective procurement schedule. Our main focus in this paper is on the methodology, not on optimising the allocation of energy flows among multiple plants (which remains a challenge for future research). Therefore, we have only considered the case for a single CHP plant. Because the planning horizon for such facilities is typically annual, supported by the development of monthly procurement schedules, we performed our analysis for a 12-month period, at 1-month intervals.

2. Mathematical methodology for incorporating procurement management planning into the system

2.1. Multiple objectives of sustainable energy production

Several multi-objective planning methods have been introduced for sustainable management of natural resources, but these methods are suitable for different planning environments. One way to support management is to apply mathematical computing theory for developing a planning system (Fig. 3). There are three main objectives in constructing the optimal procurement schedule for sustainable energy production.

First, the natural goal is to fulfil the plant's orders; that is, the group of procurement tasks should be completed on time. Second, the monetary goal is to minimize the total procurement cost. Third, the most important property of the schedule from a practical procurement perspective is that the setup times for the energy-fuel mixtures are minimized and an efficient delivery sequence is guaranteed.

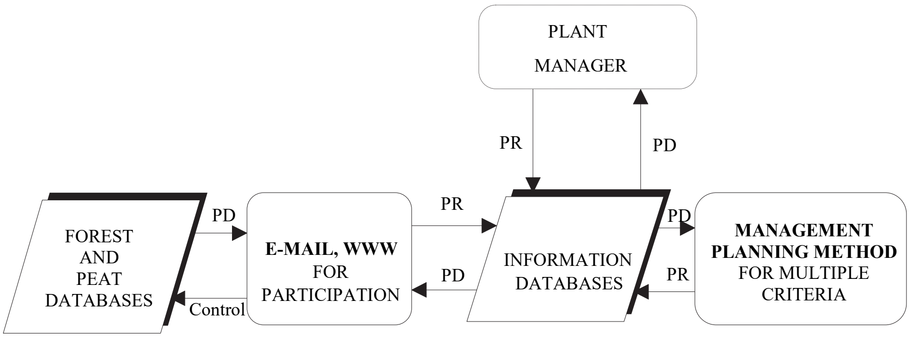


Fig. 3. Basic structure of the planning system and its information flow: PD = planning data, PR = planning result

In practice, short-term scheduling work involves a continuous balancing of the three goals. For example, fuel quality changes can be compensated for by paying additional procurement costs to obtain more or better fuel. According to the manager of the Stora Enso CHP plant that we used as the model for developing our solution, the optimization methodology must support large-scale and long-term planning, and must include energy-fuel flows, intermediate storage times, and transition times between procurement operations. Further, there must be a sufficiently large supply area and a sufficiently long planning horizon that delivery deadlines are unlikely to be missed (Palander and Hietanen, 2012).

We formulated the research problem using an objective function that is subjected to resource-allocation constraints (Dantzig, 1951; Taha, 2010). Data from 2006 to 2012 were provided by the managers of the Stora Enso Heinola Fluting Mill and the CHP plant in southern Finland. In this study, we added the procurement costs of electricity, costs incurred (to an energy producer) as a result of Finland's peat tax, and a technology rate (the wood-procurement capacity based on current harvesting capacity, i.e., the number of forestry machines and workers in the study area, for renewable forest fuels) for renewable forest fuels to the methodology developed by Palander and Vesa (2009). These are crucial components of multiple-objective sustainable energy production, in which tasks (obtaining a specific energy-fuel mixture) happen during specific periods in the decentralized geographical organization. Decentralized procurement of energy fuels operates based on a monthly order-driven policy according to the CHP plant's predetermined energy production schedule, which we simulated in the planning system to help managers solve this multi-objective task. The dynamics of the system were based on 12 monthly planning periods with no periods during which energy was not produced.

Three renewable forest fuels were considered in this study. Forest wood (above-ground) is defined as wood which are transported to the plant without chipping at roadside. Forest wood (below-ground) is defined as stumps and roots which are transported to the plant without chipping at roadside. Forest chips are defined as wood which are chipped at roadside before transportation to the plant. Unit costs for purchases, harvesting of trees, electricity procurement, non-renewable fuel procurement, forest fuel procurement, chipping, transportation, and production in the objective function were determined from the materialized average unit costs provided by Stora Enso in 2010, 2011, and 2012. The peat fuel tax cost was used as an additional parameter of the model. Based on Stora Enso data, plant inventory costs were calculated to be 1 € MWh^{-1}. To ensure a profitable investment, we applied the annual interest rate that is commonly used in Finland (8%) to the value of the wood to determine the unit cost for the roadside inventory. To simplify our calculations and clarify the use of the planning system, we confined our analysis to a single CHP plant and a single wood-supply region; in future research, we hope to relax these constraints.

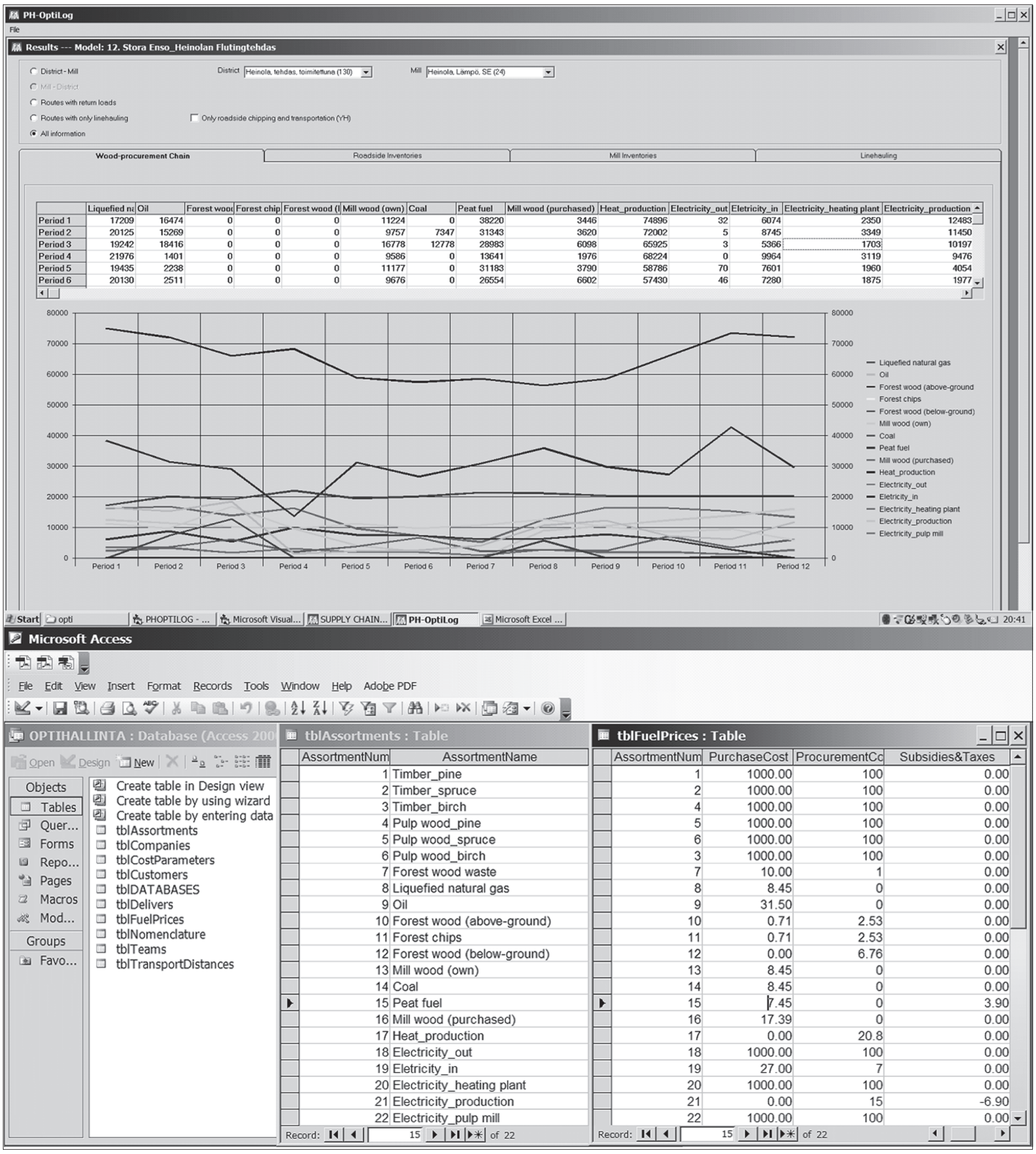
Allocation constraints for the objective function were formulated at the plant level. Based on these constraints, the main objectives were included in the solution method that we incorporated in the computer software. The maximum procurement energy content (MWh m^{-3}) was determined for every "team" from the materialized procurement volumes (m^3) for the CHP plant in 2010, 2011, and 2012. Here, we defined "teams" as the local business units (cost centres) that harvest and deliver wood to the CHP plant (Palander, 1997, 1998). The profitability of energy production by a CHP plant depends on maximizing the energy production (thus, the profits) and minimizing the total operating cost. Our system minimizes the costs for the heating energy and electricity required by the plant during the decision-making horizon; *ceteris paribus*, this will improve the plant's profitability. To estimate the profits and permit a calculation of profitability, we calculated the energy equivalent provided by each volume of energy fuel.

Initial levels (4 weeks of production) were determined for the roadside and plant inventories using data from the Stora Enso plant. Roadside inventory levels were set to correspond *a priori* to the weekly energy-fuel requirement for the plant at the beginning of the planning horizon (here, each month), and were changed linearly to reflect *a priori* the weekly energy-fuel requirement for the plant at the end of the planning horizon. Roadside inventory levels were scaled to reflect the proportion of the total harvest allocated to each of the harvesting teams. In practice, this proportion of the teams cannot be changed much from levels of previous procurement years. The minimum plant inventory was defined as 50% of the *a priori* weekly energy-fuel requirement for the plant; the maximum level was set 10% higher than this weekly requirement. All plant inventories were set at their minimum levels at the beginning of the planning horizon. In this specific case, initial levels were also determined for the purchased and logged forest fuels, which amounted to 21 and 2 weeks of production, respectively.

We analyzed the research problem by varying the maximum forest technology rate from 100% (the current level) to 500% (a much higher future rate that could potentially meet Finnish targets for energy production from renewable fuels). The forest technology rate of 100% was the actual procurement capacity for renewable forest fuels based on data from 2006 to 2012 in the study area. In Finland, procurement of renewable forest fuels from sustainable sources depends on the private forest owners and local enterprises that own harvesting machines. The differences between the technology rates were calculated by analysing the solutions for each optimization run during each time period. We assumed that the presence of a clear difference indicated good quality of the methodology and confirmed this by asking the managers of the plant whether the results were realistic based on their experience. Furthermore, if the differences are reasonable and acceptable, they also reveal the importance of the procurement planning system for local managers. If the solutions are also global optimums (i.e., optimal for the system being studied), the methodology can be considered to have reached a good-quality solution (Taha, 2010).

The optimization runs of the planning system to solve the research problem were performed using three scenarios on a standard desktop computer (2.4 GHz x86 processor) with 4 GB of RAM that ran the Microsoft Windows XP Professional operating system. The scheduling algorithm was implemented using the Microsoft C programming language and the user interface was created using Microsoft Visual Basic from version 6.0 of the Microsoft Visual Studio suite (Fig. 4). We mathematically described (encoded) the dynamic linear optimization method and implemented the results using version 5.0 of the Lindo API software (http://www.lindo.com/), with its standard settings, as the linear programming solver. The user interface of our software was designed to make it easy for plant managers to adapt the system to changing management environments simply by changing the constraints and the parameter values for each of the parameters described in the solution method. This makes the approach usable by the managers without requiring them to learn advanced programming skills.

The optimization runs achieved global optimality, with the total processing time increasing from 62 s to 81 s as a result of adding the peat fuel tax cost to the solution method of Palander and Vesa (2009), which also increased the total number of linear programming iterations from 678 to 730.



District: Heinola, tehdas, toimitettuna (130)
Mill: Heinola, Lämpö, SE (24)
● All information

	Liquefied na	Oil	Forest wood	Forest chip	Forest wood (l	Mill wood (own)	Coal	Peat fuel	Mill wood (purchased)	Heat_production	Electricity_out	Eletricity_in	Electricity_heating plant	Electricity_production
Period 1	17209	16474	0	0	0	11224	0	38220	3446	74896	32	6074	2350	12483
Period 2	20125	15269	0	0	0	9757	7347	31343	3620	72002	5	8745	3349	11450
Period 3	19242	18416	0	0	0	16778	12778	28983	6098	65925	3	5366	1703	10197
Period 4	21976	1401	0	0	0	9586	0	13641	1976	68224	0	9964	3119	9476
Period 5	19435	2238	0	0	0	11177	0	31183	3790	58786	70	7601	1960	4054
Period 6	20130	2511	0	0	0	9676	0	26554	6602	57430	46	7280	1875	1977

tblAssortments : Table

AssortmentNum	AssortmentName
1	Timber_pine
2	Timber_spruce
3	Timber_birch
4	Pulp wood_pine
5	Pulp wood_spruce
6	Pulp wood_birch
7	Forest wood waste
8	Liquefied natural gas
9	Oil
10	Forest wood (above-ground)
11	Forest chips
12	Forest wood (below-ground)
13	Mill wood (own)
14	Coal
15	Peat fuel
16	Mill wood (purchased)
17	Heat_production
18	Electricity_out
19	Eletricity_in
20	Electricity_heating plant
21	Electricity_production
22	Electricity_pulp mill

Record: 15 of 22

tblFuelPrices : Table

AssortmentNum	PurchaseCost	ProcurementCo	Subsidies&Taxes
1	1000.00	100	0.00
2	1000.00	100	0.00
4	1000.00	100	0.00
5	1000.00	100	0.00
6	1000.00	100	0.00
3	1000.00	100	0.00
7	10.00	1	0.00
8	8.45	0	0.00
9	31.50	0	0.00
10	0.71	2.53	0.00
11	0.71	2.53	0.00
12	0.00	6.76	0.00
13	8.45	0	0.00
14	8.45	0	0.00
15	7.45	0	3.90
16	17.39	0	0.00
17	0.00	20.8	0.00
18	1000.00	100	0.00
19	27.00	7	0.00
20	1000.00	100	0.00
21	0.00	15	-6.90
22	1000.00	100	0.00

Record: 15 of 22

Fig. 4. Our supply-management system runs under the Microsoft Windows XP Professional operating system

2.2. Application and scenarios

To demonstrate the applicability of the management planning method, we performed a case study for the operating areas of the Kymenlaakso and South Karelia provinces in southeastern Finland. The provinces were divided into nine procurement areas, which were used to represent the wood procurement teams that currently supply Stora Enso's Heinola Fluting Mill and the CHP plant. During 2012, the CHP plant implemented investments in energy production that increased the maximum proportion of forest fuels in the fuel mixture from 60% to 80%. After these investments, the plant's energy generation capacity increased from 120 MWh to 145 MWh. During this study, the plant’s manager successfully used the management planning system that we developed to adjust the energy flows to the characteristics of the new production system. Fig. 5 summarizes the general production costs of Finnish energy plants for production structures based on fossil fuels and on partially renewable (peat plus wood) fuels (Poyry Management Consulting, 2010). In this figure, fossil fuels, peat, forest wood, and other wood-based fuels are presented together as energy fuels and cost differences are due to taxes and emissions.

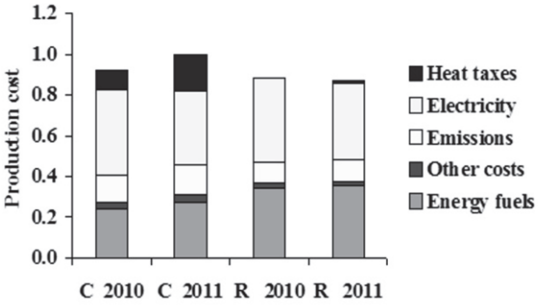


Fig. 5. Energy plant production costs for production structures based entirely on fossil fuel (C = coal) and based on partially renewable fuel (R = 60% peat + 40% forest fuels). The cost for coal in 2011 was set to 1.0; all other values were normalized with respect to that cost

In the present study, the non-renewable energy production cost was similar to or lower than the costs of using renewable fuels in 2010 based on the same quantity of energy production. During 2011, the heat tax decreased peat’s competitive advantage, because the energy production cost of peat was higher than that of the forest fuels. Based on the Finnish CO_2 tax, the peat tax’s increase was 1.9 € MWh^{-1} (VTV, 2010). To account for the effects of the peat fuel tax on energy production costs, we assumed in our scenarios that this tax would increase by 1.9 or 3.9 € MWh^{-1} in 2013. Therefore, peat’s competitive advantage in relation to forest and other fuels decreased in 2013.

Conventionally, energy production costs determine the fuel mixture used by energy plants to produce energy (i.e., plants choose the least-expensive fuel that will meet their needs), even though other factors (such as the availability of the different fuel types) are clearly important. The most cost-efficient fuel is used first and more of it is consumed than other fuels. The fuel mixture may also change when the technology changes or when market prices for CO_2 emissions and electricity change. In this study, we optimised energy production scenarios in which the fuel mixtures were affected by the peat fuel taxes and by increasing use of renewable fuels. To illustrate the management planning method, we will discuss three real-life scenarios: Scenario A is based on the data provided by the CHP plant that our system simulated (Palander and Hietanen, 2012), and follows an old procurement structure that did not account for the peat fuel tax costs or technology rate constraints for increasing the use of renewable forest fuels.

Scenario B is similar, but included the peat tax cost that accounts for the CO_2 released by the CHP plant and that therefore increased the unit cost of the purchase function (Fig. 1). Thus, additional costs were incurred by the energy producer as a result of the tax. Scenario B also included a forest technology rate that accounts for the volumes of renewable forest fuels procured by the plant and that therefore decreased the cost of the harvesting function (Fig. 1). However, it increased the cost of the transportation function. We subdivided Scenario B into two related scenarios that used the same underlying data, but that used increases of 1.9 and 3.9 € MWh^{-1} in the peat fuel tax in scenarios B1 and B2, respectively, and forest fuel procurement volumes (MWh) in the supply chain were predicted based on a forest technology rate of 500% of the current value.

3. Results and discussion

3.1. Management planning method

The management planning method was capable of providing a better global optimum than previous systems for multi-objective sustainable energy production. The energy-flow method used in our previous research (Palander and Vesa, 2009) did not account for the profitability of integrated procurement of electricity and energy fuels. The previous energy-flow method allocated only a volume of fuels (based on their energy content in MWh) to ensure that the best possible fuel mixture was selected by the model, but it did not ensure that this solution was the most profitable for energy production. Therefore, some of the delivery alternatives would presumably have decreased rather than increased the manager’s ability to achieve a profitable mixture of energy fuels. Although we did not calculate the profits from sales of energy produced by the CHP plant (Palander, 2011a, 2011b), it is clear that minimizing the total operating cost will increase profitability under a given fuel procurement and energy production scenario. We developed software to encode the optimization method and let the system adapt to a changing planning environment, such as changing the forest technology rate from 100% to 500%. As in our previous study (Palander and Vesa, 2009), the methodology successfully used the dynamic linear programming approach for forest fuel scheduling to account for both production and procurement considerations. The results meet the conditions and constraints for global optimality (general optimality theory), as defined by Dantzig (1951) and Taha (2010). Further, our new software was sufficiently flexible that it could adapt easily to a changing planning environment without requiring the users to learn sophisticated programming skills. This approach differs from previous work by Li et al. (2006, 2010), Palander (2011a, 2011b), Shekdar and Mistry (2001) and who studied multi-objective heating optimisation problems using goal-based programming. In the present study, the handling of different goals is a minor part of the manager's responsibility compared with the management activities required to supply appropriate types and quantities of fuel to the CHP plant. Managers of the CHP plant require such software for their daily work, as well as to solve larger multiple-objective procurement problems, because it is too laborious to adapt such systems manually (Palander et al., 2002; Eriksson et al., 2003). The resulting objective function value (annual operating costs) increased by 2.1% when the peat fuel tax increased by 1.9 € MWh^{-1} (Scenario B1). In this decision environment, the operating costs increased by 1.4% in the A and B1 scenarios when the forest technology rate was increased from 100% to 500%. The operating costs increased by 4.0% when the peat fuel tax increased by 3.9 € MWh^{-1} (Scenario B2). In this decision environment, the production costs increased by 2.1% in the A and B2 scenarios when the forest technology rate increased from 100% to 500%. Based on these results, the methodology clearly produces logical conclusions and the solution method guaranteed a global optimum within a realistic range of values for the study area. Moreover, according to the CHP plant's procurement managers, whose data we used in the study, the values were also reasonable based on the available data and their experience. Including the peat tax cost dramatically increased the total energy production cost, which could not be offset by increasing the regional forest technology rate. This suggests that it will be difficult to meet Finland's targets for renewable energy production without importing wood from other regions. Due to space limitations, we have presented only a basic set of results, but a complete set of our test results is available on request from the authors.

3.2. Sustainable energy production with forest biomass

The applicability of the methodology was tested by the CHP plant's procurement manager. To clarify the differences between the procurement chains in the three scenarios, we summarized the energy flows from electricity and from different energy-fuel assortments for the 12 monthly planning periods using a 1-year decision horizon (Figs. 6-9). Changes in the characteristics of the energy-fuel mixture throughout the year in the optimal solution can be seen in scenario A (Fig. 6). Including the 1.9 € MWh^{-1} increase in the peat tax and the 500% increase in the forest technology rate in Scenario B1 clearly affected the volumes of the various energy flows (Fig. 7). The unit cost structure of the energy assortments reveals clearly different solutions in the two scenarios. The increase in the volumes of forest energy fuels (MWh) that occurs when the forest technology rate is included resulted from decreased volumes of other fuels. Discussions with the CHP plant's production manager indicated that the differences revealed by our optimal solutions are reasonable based on the plant's actual long-term energy production environment; all available wood-waste energy sources are currently being used by the plant as renewable fuels.

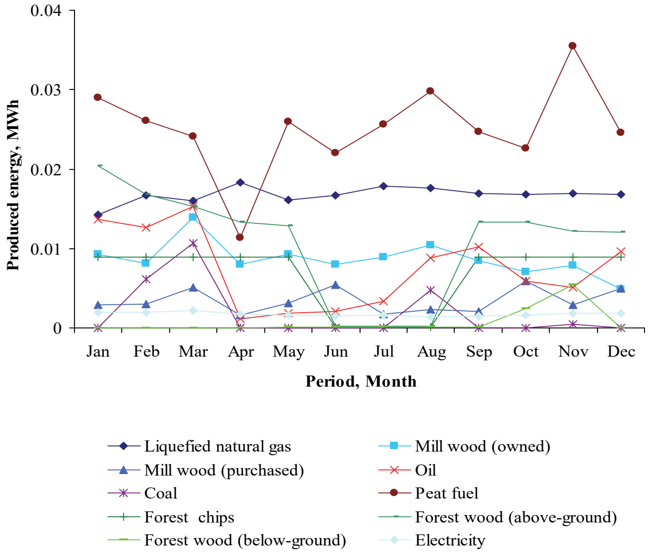


Fig. 6. The composition of fuel and electricity procurements (MWh) in Scenario A, which does not include the peat fuel tax costs and assumes a forest technology rate of 100% (the current level)

Therefore, the remainder of our discussion will concentrate on differences in the primary forest energy sources and peat energy sources. In our analysis, we assumed that all wood-waste fuels (but not peat) have a neutral CO_2 balance.

In the least-cost solution, the relationship between the procurement volumes for peat and forest fuels without including the peat fuel tax costs (Scenario A, Fig. 6) was 58% peat and 42% forest fuels. Because customers purchase varying volumes of heat and electricity during different seasons of year, the annual average procurement volumes do not adequately describe the seasonal dynamics and the changes in the composition of peat and forest fuels. During summer (July), the procurement composition was 97% peat and 3% forest fuels (Fig. 6). During the autumn (November), forest fuel procurement was 30% of the total produced energy, and during spring (May), the procurement volume of forest fuels was 46% of the total. The Finnish peat fuel tax system was launched shortly before we wrote this paper. Therefore, reliable data on how this system will work is not yet available, and we were forced to examine the impacts of the peat tax cost at a relatively high level of abstraction, especially in our determination of the unit costs that we used as basic data in the procurement problem. Obviously, the assumed costs will differ from the real costs in different plants, but the analysis remains relevant because the purpose was to consider the natural variations in these costs in the energy industry. For example, transportation costs depend on the transportation distance from each harvesting team to the CHP plant in a geographically decentralized organization. The high level of abstraction also affected determination of the schedule for the forest-fuel procurement, because we only solved the optimization problem for a single CHP plant. Therefore, we did not account for the possibility that forest fuels owned by Stora Enso could be transported to the enterprise's other plants if doing so would further optimize the profitability of decentralized energy production.

Fig. 7 shows the peat and forest energy-fuel procurement volumes for the fuel mixtures in Scenarios A and B1. Scenario B1 included an increase of 1.9 € MWh^{-1} in the peat fuel tax and a forest technology rate of 500% of the current level. The differences between the scheduled decision alternatives that resulted from inclusion of the peat tax cost in the optimization also resulted from the potential increase in the proportion of the forest fuels. In this scenario, the annual procurement shares were 47% for peat and 53% for forest fuels. During the summer, the difference in the procurement shares was largest, with peat procurement (93%) much more important than forest fuel procurement (7%). During autumn (November), peat procurement decreased to 8% of the total, and forest fuel procurement increased to 40% of the total. It is noteworthy that during the spring (May), procurement of forest fuels became more important than during the other seasons, reaching 44% of the total; even procurement of forest wood (above-ground) was more important than peat procurement in this scenario.

The competition for forest biomass appears likely to significantly intensify in the near future (FMAF, 2008). The proposed Finnish investments in energy production using renewable resources will further increase the demand for forest biomass (NREAP, 2009). In addition to peat as the non-renewable fuel, the changes in wood and peat shares can affect the procurement of fossil fuels of the CHP plant, which we're not considered in this study.

In this context, the present study provides a simple tool that plant managers can use to analyze the optimal fuel mixture while the prices of fuels and forest technology rates are changing. The differences between the procurement volumes of the various forest fuels can be resulted from the increased forest technology rate.

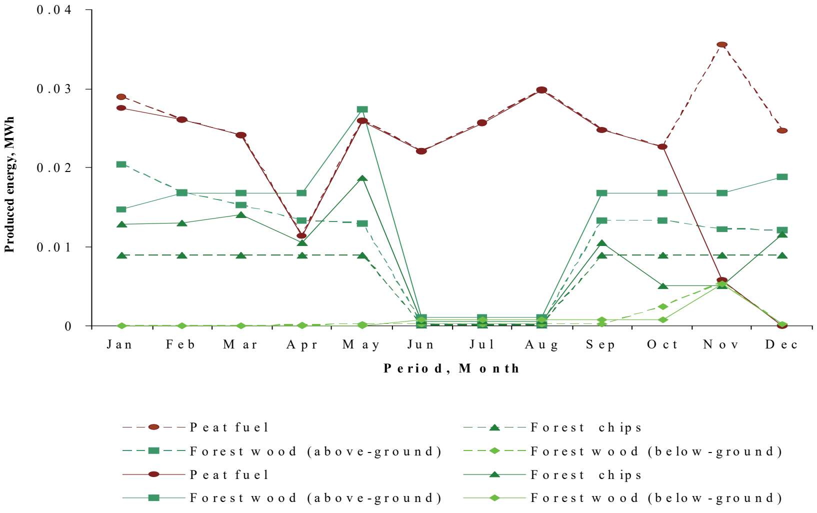


Fig. 7. The differences of fuel procurements in Scenario A (dashed line) and B1 (solid line), which includes a forest technology rate of 500% and an increase of 1.9 € MWh^{-1} in the peat fuel tax

In this respect, we determined the optimal solutions by calculating relative changes in the procurement volumes from the CHP plant's harvesting teams in Scenario B1 compared to the volumes in Scenario A (Fig. 8). Some values increased and others decreased. To clarify the relative changes, we compared each team's result with the largest increase (for Team 7), which we set to 100%. The team's forest wood (above-ground) procurement volume was 400% larger than the volume in 2010 in Scenario A. Deliveries of forest chips (at roadside) were remarkably larger, to 182% and 201% compared with 2010 levels, for teams 8 and 9. These deliveries increased even more for Team 5 (to 253% compared with the 2010 value). However, its forest wood (above-ground) deliveries were lower (to 75% compared with the 2010 value), as they were for teams 1, 2, 8, and 9. There were no large differences in deliveries of forest wood (below-ground), and for some teams (e.g., Team 6), the peat tax cost (an increase of 1.9 € MWh^{-1}) and forest technology rate (500%) did not greatly affect procurement volumes for the forest fuels. The average procurement volumes of forest fuels increased by 60% between scenarios A and B1 as a result of the theoretical possible increase of 500% over the level of locally produced forest fuels compared with the level in 2010 in Scenario A. These results reveal the procurement potential of harvesting teams for a local increase of the forest technology rate during the management planning horizon. Fig. 9 shows the electricity and energy-fuel procurement volumes of the fuel mixtures in Scenario B2, and Fig. 10 shows the changes in the procurement volumes from each harvesting team in this scenario compared with Scenario A. The average procurement volumes of forest fuels increased by 61.2% moving from Scenario A to Scenario B2. The average procurement of forest fuels increased by only 1.2% between scenarios B1 and B2. The annual procurement shares were 52% for peat and 48% for forest fuels in Scenario B2.

The main differences in the scheduled decision alternatives that resulted from inclusion of the peat tax cost (an increase of 3.9 € MWh^{-1}) in the optimization resulted from the potential increase in the purchased mill wood. As a consequence of the large cost increase for peat, the procurement cost for the purchased mill wood became most economical for the CHP plant, because the long transportation distances in the larger geographical area managed by the wood procurement organization increased the cost of the forest fuels.

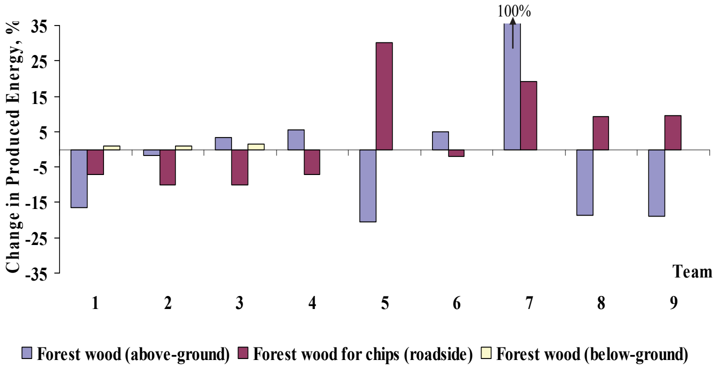


Fig. 8. Changes in the forest fuel procurement volumes in Scenario B1, which includes a forest technology rate of 500% and an increase of 1.9 € MWh^{-1} in the peat fuel tax cost. Teams are compared to team 7 (which was assigned a value of 100% for aboveground forest wood, representing 106 896 MWh of energy content)

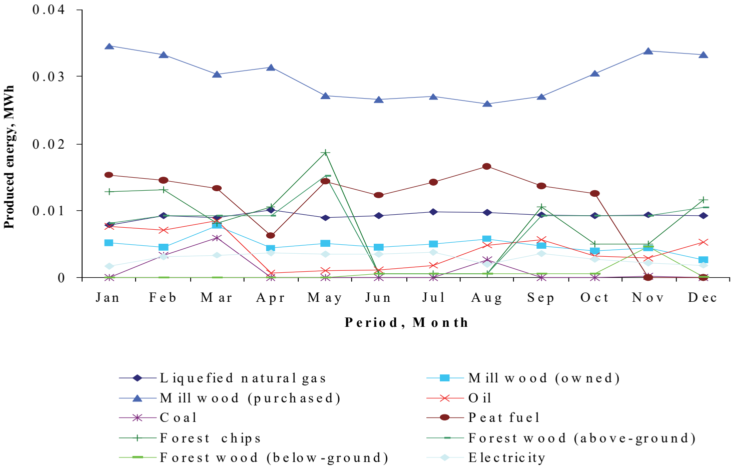


Fig. 9. The composition of fuel and electricity procurements in Scenario B2, which includes a forest technology rate of 500% and an increase of 3.9 € MWh^{-1} in the peat fuel tax

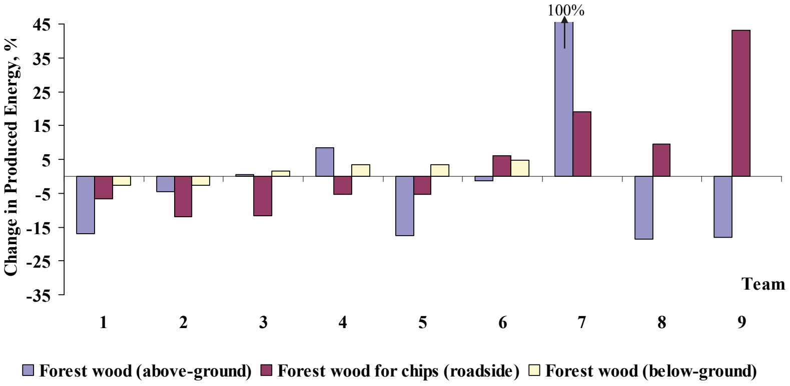


Fig. 10. Changes in the forest fuel procurement volumes in Scenario B2, which includes a forest technology rate of 500% and an increase of 3.9 € MWh^{-1} in the peat fuel tax. Teams are compared to team 7 (which was assigned a value of 100% for aboveground forest wood, representing 106 896 MWh of energy content)

Actually the average procurement cost of forest fuels increased 3.4 € MWh^{-1} in 2012. The changes in the relative volumes of the different forest fuels compared with Scenario A clearly differed from the changes for Scenario B1 (an increase of 1.9 € MWh^{-1}). In Scenario B2, the procurement volume of forest wood (above-ground) for the harvesting teams was 21.6% larger than the volume in 2010 in Scenario A. Deliveries of forest chips (at roadside) and forest wood (below-ground) were also larger, by 48.3% and 112.2%, respectively, than the 2010 values. There were relatively small differences in the deliveries of forest fuels between scenarios B1 and B2, and for many of the harvesting teams, the peat tax cost (an increase of 3.9 € MWh^{-1}) and forest technology rate (500%) did not greatly increase the procurement volumes of the forest fuels in the decentralized wood procurement organization. These results can reveal an economic potential for a local increase of the forest technology rate of the harvesting teams during the management planning horizon.

The results show that meeting Finland's peat tax and forest technology policy targets may not be sufficient to ensure sustainable energy production, because a 500% increase in the available wood harvesting capacity was not sufficient. However, there is the need for future research, because our analysis of the wood procurement management planning system has been confined to a constant feed-in tariff rate. Therefore, the impacts of differences in the feed-in tariffs for electricity in the CHP plant based on peat or forest chips have not been accounted for.

4. Conclusions

In this study, we developed a management planning method that generated globally optimal solutions for the sustainable energy production problem, within a reasonable computational time (processing times in minutes, not hours). Using dynamic linear programming made it possible to efficiently solve the problem, and the solution should scale well to larger geographically decentralized planning problems that account for precedence objective functions and additional constraints. Because the program's operating constraints and parameters can be easily modified by managers of the CHP plant without requiring advanced programming skills, the program allows the managers to rapidly adapt the system to a changing planning environment. Furthermore, the methodology can be used as a powerful core for future management planning systems, as it has a high potential to improve the logistics of procurement planning for forest biomass.

Our comparison of three scenarios illustrated the potential impacts of increasing the forest technology rate to increase the sustainability of energy production in Finland. The increase in the volumes of forest energy fuels that occurs when the forest technology rate is included resulted from decreased volumes of non-renewable peat fuels. Further, the scenarios were based on the same real-life data from the Finnish energy-production industry, which allowed us to assess the impacts of including the effects of peat fuel tax costs for the CHP plant.

The results show that meeting Finland's peat tax and forest technology policy targets may not be sufficient to ensure sustainable energy production. A local increase of the forest technology rate did not increase sufficiently procurement volumes of harvesting teams during the management planning horizon. Further studies will be needed to find a suitable mixture of policy measures that will increase the sustainability of energy production in a geographically decentralized forest biomass procurement organization.

Further studies are also needed to demonstrate the efficiency of the methodology for managers in multiple CHP plants with a larger decentralized network under various real-life production and procurement environments.

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