TACTICAL TECHNO-ECONOMIC ANALYSIS OF ELECTRICITY GENERATION FROM FOREST, FOSSIL, AND WOOD WASTE FUELS IN A HEATING PLANT

by

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Original scientific paper
DOI: 10.2298/TSCI120106118P

The Finnish energy industry is subject to policy decisions regarding renewable energy production and energy efficiency regulation. Conventional electricity generation has environmental side-effects that may cause global warming. Renewable fuels are superior because they offer near-zero net emissions. In this study, we investigated a heating mill's ability to generate electricity from forest fuels in southern Finland on a 1-year strategic decision-making horizon. The electricity-generation, -purchase, and -sales decisions are made using three different energy efficiency and forest technology rates. Then the decision environment was complicated by the sequence-dependent procurement chains for forest fuels (below-ground) on a tactical decision-making horizon. With this aim, fuel data of three forest fuel procurement teams were collected for 3 months. The strategic fuel procurement decisions were adjusted to the changed decision environment based on a tactical techno-economic analysis using forest technology rates. The optimal energy product and fuel mixtures were solved by minimizing procurement costs, maximizing production revenues, and minimizing energy losses.

Key words: *renewable fuels, forest technology rate, energy efficiency*

Introduction

As part of the EU's response to climate change [1], the Finnish government has proposed that renewable energy production should account for 38% of the national total by 2020, and believes that the utilization of forest fuels in energy production is a promising approach to accomplish this goal [2]. In Finland, 3.4 million solid m^3 of forest chips were used to generate 6.8 TWh of energy in 2006 [3]. There are currently targets to increase the annual use of forest chips to between 8 and 12 million solid m^3 per year (16 to 24 TWh) by 2015 [4, 5]. These targets presuppose that the delivery of forest fuels to the energy-production sector can be tripled or even quadrupled compared with the current delivery volume. This will require significant changes in the logistics environment of energy plants for fossil and wood-waste fuels, but the changes are complicated by the sequence-dependent procurement chains involved in the production of forest fuels.

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In this paper, we have defined combined heat and power (CHP) to mean heat produced by combustion of fuel to drive a steam-based generator, and power in the form of electrical energy; both forms of energy can be used by the plant that produces them, or sold to other customers, including other units of the same company. This is also referred to as co-generation [6]. According to a recent survey, managers of Finish energy plants will aim to increase energy production from renewable fuels at the expense of fossil fuels [7]. However, in light of the country's emission--reduction targets, it is interesting to note that manager believe that peat will continue to be an important fuel in Finnish CHP production in the future. A typical Finnish plant that produces energy from peat fuel purchases less than 5% of its energy needs from the national electrical grid and can sell power about 40% to the grid [7]. Because of Finland's large areas of water and wetlands, extensive areas of peat have developed. The easy availability of this biomass means that about 40% of the energy generated by power plants is provided by burning peat. It is not a renewable fuel because it regenerates too slowly.

Finland expects to achieve its renewable energy target through the implementation of additional policy measures [2]. This target will require incentive-based policies, including the use of carbon taxes and fuel taxes that will increase the relative cost of non-renewable fuels [8-11], which will both decrease consumption of fossil fuels and improve energy efficiency (20%) by 2020. The Finnish government’s policy includes taxes for heating fuels that will increase the costs of fossil and peat fuels. For example, the energy content tax for fuel peat will be 1.9 €/MWh from January 1, 2011 to December 31, 2012 and will increase to 3.9 €/MWh from January 1, 2013 to December 31, 2014. A tax on emissions would motivate plants to cut back on their emissions if the cost of doing so was less than the cost of paying the tax. The key principle of the Finnish energy taxation legislation is that all fuels consumed in the production of electricity are exempt from the tax, whereas the fuels consumed in the production of heat are subject to the tax. When the same plant can produce both electricity and heat, the fuels used by the plant for these two purposes are considered separately for calculating the taxes.

The efficient use of available raw materials is vitally important to the energy production industry. Procurement decisions for raw materials play a key role in achieving this goal, which can only be reached using accurate information provided by optimization methods. Therefore, for decision-support systems to be efficient, they must be based on the right methodology for solving the problem at hand. Two of the earliest continuous-time formulations for solving the linear problem of scheduling energy production from forest fuels were presented by Eriksson *et al.* [12] and Bjorheden *et al.* [13]. Decision-making models and a recent review of the various techniques for scheduling wood procurement as a system or as an energy flow have also been published [14-16]. In the present paper, available decision alternatives are assumed to be defined by means of a mathematical model [17-21]. The term "dynamic multiple-objective linear programming" is used to refer to this model [21].

In the present paper, we focus on integrated forest fuel procurement and energy production process, and the resulting problem in multiple-objective decision-making: how it is possible to optimize a multiple-objective model with possibly conflicting decision-making principles (*e. g.,* reducing costs, maximizing revenues). The problem studied in the present paper is based on long-term and middle-term production scheduling at an energy plant in Finland, where mixtures of energy are provided by CHP production, fig. 1. The electricity production from CHP plants is expected to increase by more than 25% by 2050 [22, 23]. On the other hand, increases in industrial energy efficiency are expected to increase electricity production by (8%) 2050 [7]. According to the World Energy Council, energy efficiency refers to the ratio of energy outputs to the inputs used to produce those outputs. In addition to generation of more electricity with heat, there are many other ways to improve energy efficiency, such as improvements in the transmission and storage of primary fuels; in this sense, improvements result from the technologies used in CHP production.

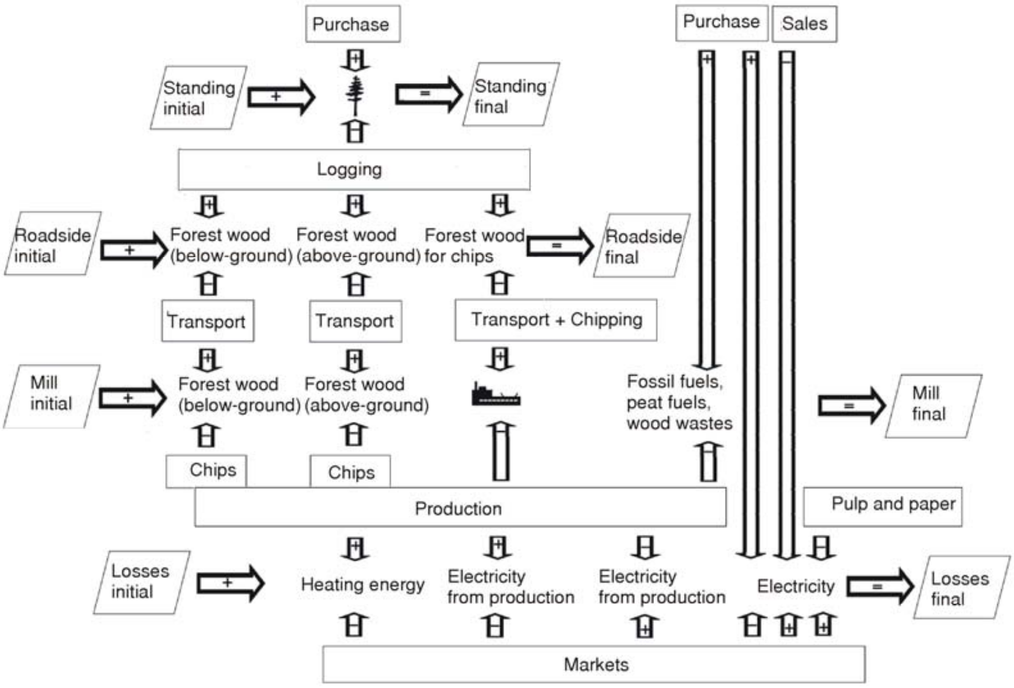

Figure 1. Dynamics of the energy-resource inventories for an energy (CHP) plant
Vertical arrows represent sequence-dependent effects for the system; horizontal arrows represent time-dependent effects for the system. Arrows labelled with + represent inputs to a component of the system; arrows labelled with – represent withdrawals from a component

Electricity market prices have increased rapidly in recent years, which makes important to produce and sell additional electricity because this is an important factor in determining a heating plant's profitability [24]. Recently, Finland has decided to support the sales price of electricity from CHP plants so that the market price will remain constant, thereby encouraging the production of electricity and its input into a district's electrical network. This price driver is a feed-in tariff for renewable energy sources, which guarantees the price and sales of electricity so as to give producers more confidence in its production. The Finnish forest fuel market therefore faces an interesting opportunity, because the feed-in tariff is also used for forest fuel production. The size of this tariff is suggested to be 6.9 €/MWh. In this study, we assumed that a high energy efficiency for electricity production can be achieved by using the right mixture of fuels. We also assume that local delivering problems of this mixture can be avoided by using an effective decision-support methodology. However, there has been little research about the topic of electricity pricing and production from renewable forest fuels [2, 21].

Our main focus was on the tests of solution methodology, not on optimizing the supply chains among multiple plants, therefore we have only considered the case for a single energy plant with restrictions based on forest technology rate of forest fuel procurement and energy efficiency level of energy production. To calculate costs and profits, we assumed three basic scenarios for the use of forest fuels based on Finland's plans to increase the use of these fuels: 100% to represent the current baseline, 300% to represent an increase to 3 × the baseline value, and 1000% to represent an increase to 10× the baseline value. However, the overall method has been developed in such a way that it could be easily expanded to include two or more plants simply by modifying the value of K in the model (see next section for details). Because the planning horizon for such facilities is typically annual, with a monthly procurement schedule, we performed our strategic analysis for a 12-month period, with iterations at 1-month intervals. Then we performed our tactical analyses for a 3-month period at 1-month intervals. To adjust a strategic plan to the changed decision environment, we assumed an example for the use of forest fuels (below-ground) based on teams' tactical plans to change the harvesting of the fuels for three months: 150% to represent a decrease to 0.5 × 3 × the baseline value for one team, and 450% to represent an increase to 1.5 × 3 × the baseline value for three teams. In this example one team has forest fuel delivering problems to the heating plant which are aimed to solve by increasing forest fuel procurement from areas of other teams.

Method and materials

Consider N different tasks (obtaining different mixtures of energy products), each of which must be completed for a given day by a CHP plant, fig. 1. For short-term planning, every task n has a given release date r_n, which describes a lower bound for the delivery time t_n to produce the products required by the task (most often due to other production operations before delivery of the energy product), and a pre-specified production time, pro_n. When two tasks, n and l, are performed immediately after each other, a setup time s_{nl} is required. The setup time is strongly sequence-dependent. It is required to adjust the energy plant's infeed system to accept a different mixture of fuels or as a supply time required to obtain the new mixture of fuels defined by task l. The setup times can be derived from the parameters (*e. g*., the energy content of fuels) for the tasks in question with acceptable accuracy. For short-term planning, each task n has a due date d_n before which the task should be completed. If a task n is completed after d_n, the tardiness of task n is defined as $Tar_n = \max\{0, t_n + pro_n - d_n\}$. Palander *et al.* [20] have described how procurement organizations obtain mixtures of fuels and construct optimal procurement schedules in this context. On the other hand, Palander [21] has described how a production organization obtains mixtures of electricity and constructs optimal strategic production schedules.

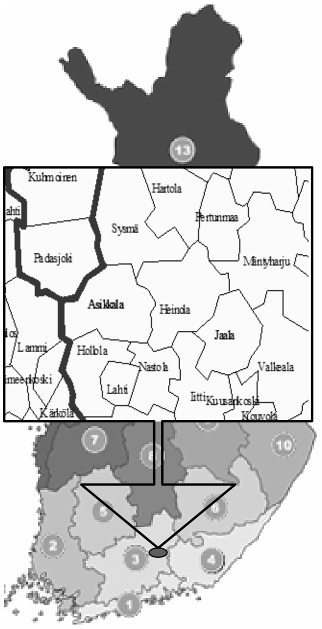

Figure 2. Forest fuel procurement area locates in the southern Finland, which is described by the municipalities (teams) on the map

According to Palander [21], in a large-scale and long-term strategic case, the tardiness penalty for task n is assumed to equal zero because there is a sufficiently large supply area, fig. 2, and a sufficiently long planning horizon that delivery deadlines are unlikely to be missed and other, more important, properties must be included in the optimization methodology, such as certain energy flows, intermediate storage times, and transition times. In middle term case, the tardiness penalty for task *n* can be assumed to be zero, if it is not required to adjust the energy plant's infeed system to accept a different mixture of fuels or as a supply time required to obtain the new mixture of fuels defined by task *l*. These are crucial components of the tactical planning method in an actual dynamic supply chain, in which task *n* (obtaining a specific energy-product and a energy-fuel mixture) happens during period *t*. The energy-flow model of Palander [21] can be further developed and converted into software to solve this problem task. In mathematical terms, the goal programming model was described using the following objective function:

$$\text{Minimize}\, Z = w_1D_1 + w_2D_2 + w_3D_3 + w_4D_4 + w_5D_5 + w_6D_6 \tag{1}$$

where Z is the optimum weighted sum of D_g, which represents the deviations (€) above and below the decision-maker's goals of the problem, the parameter w_g is a positive weight that reflects the decision-maker's preferences regarding to the relative importance of each objective, and G is the number deviations of decision-maker goals (1, …, g, …, 6). Equation (1), was subjected to thirty-one restrictions [21]. The new restrictions of the tactical model for purchase and logging of forest fuels can be described using the equations:

$$L_{ijt} \le Lmax_{ijt} \tag{2}$$

$$L_{ijt} \ge Lmin_{ijt} \tag{3}$$

$$L_{ijt=6} + L_{ijt=7} + L_{ijt=8} = Lmax_i \tag{4}$$

In eqs. (2), (3), and (4) $Lmax_{ijt}$ and $Lmin_{ijt}$ [MWhm^{-3}] are the maximum and minimum (respectively) energy contents of fuel mixture *i* purchased from and logged by team *j* during period *t*, and L_{ijt} [MWhm^{-3}] is the energy content of fuel mixture *i* purchased from and logged by teams during three periods of the decision-making horizon.

Results and discussion

The tactical example achieved global optimality, with total processing time of 212 seconds and the total number of multiple-objective linear programming iterations of 454. The resulting ranges of the decision objectives in the strategic scenarios increased from € 0.1 thousand, at a high forest technology rate (1000%) and a low energy efficiency (19%), to € 650.6 thousand with a high forest technology rate (1000%) and a high energy efficiency (42%), tab. 1.

The methodology guaranteed a globally optimal solution within a realistic range of values for the objectives and within a few minutes of computational time using a standard desktop computer. The results are accordance with Pareto-optimality theory [25]. The results also indicate that the Pareto frontier is useful in tactical simulations of forest technology: by restricting attention to the set of choices that are Pareto-efficient, a manager can make trade-offs within a non-dominated objective set rather than considering the full range of every parameter. The software clearly performed well, although the model could undoubtedly be improved by improving the parameterization of each of the underlying functions that describes the supply chain.

Table 1. Ranges of objective values for globally optimal non-dominated decision alternatives for supply chain management of a CHP plant

Strategic scenario	Total costs			Total revenues			Total loss costs		
	I [€/1000]	Goal [Million €]	D [€/1000]	I [€/1000]	Goal [Million €]	D [€/1000]	I [€/1000]	Goal [Million €]	D [€/1000]
A1	7.2	48.7	0.8	1.0	55.5	8.6	1.0	49.2	1.9
A2	4.8	48.7	12.7	17.6	55.5	5.5	14.4	49.2	7.3
A3	4.4	48.7	0.3	0.3	55.5	5.0	0.1	49.2	1.0
B1	4.1	48.7	3.1	4.2	55.5	5.6	6.9	49.2	9.1
B2	30.1	48.7	43.0	88.1	55.5	61.3	99.3	49.2	69.1
B3	234.0	48.7	10.5	93.3	55.5	650.6	24.2	49.2	540.0
Tactical example for the scenario B2									
B2T1	13.9	47.3	11.3	12.8	55.5	15.8	24.9	49.2	30.7
B2T2	47.1	48.7	54.8	63.2	55.5	64.7	121.3	49.2	104.5

I = Increase, D = Decrease; A1, A2, and A3 = supply chains that include an energy efficiency of 19% and forest technology rates of 100, 300, and 1000%, respectively; B1, B2, and B3 = supply chains that include an energy efficiency of 42% and forest technology rates of 100, 300, and 1000%, respectively; B2T1 and B2T2 = supply chains that include an energy efficiency of 42% and tactical forest technology rates of 150% (team C, Jaala) and 450% (other teams)

The objective values were also reasonable based on the available data for energy production by the plant whose data was used as inputs for the model. Including the feed-in tariff revenues and effects of increased energy efficiency increase the total revenues from the energy products, while also decreasing the total loss costs of energy products during production and sales. For comparison, the increased energy efficiency that was reported as the best policy alternative in a recent Finnish energy policy study [2] is presented next to those values presented in tab. 1. Bundling the energy efficiency and renewable fuels together seems to be an interesting opportunity for a CHP plant. Due to space limitations, we have presented only a basic set of results, but a complete set of test results is available from authors (tactical example) and as online supplemental material on the journals Web site (strategic scenarios) [21].

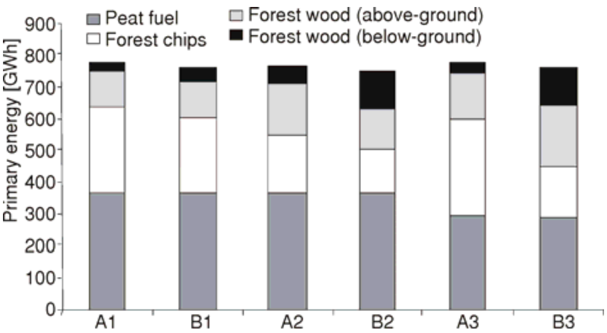

Figure 3. Changes in the peat and forest fuel procurement volumes
A1, A2, and A3, supply chains that include an energy efficiency of 19% and forest technology rates of 100, 300, and 1000%, respectively; B1, B2, and B3, supply chains that include an energy efficiency of 42% and forest technology rates of 100, 300, and 1000%, respectively

To clarify the differences between the supply chains in the six scenarios, we summarized the energy flows from different energy-fuel mixtures for a 1-year decision horizon, fig. 3. The co-generation process has a direct influence on fuel consumption. Same results have also reported abroad [6]. Increasing the forest technology rate clearly affected the levels of the peat and forest fuels. For example, the annual mean peat procurement level decreased by 22% in the A and B scenarios when the forest technology rate increased from 100% to 1000%. At the same time, the higher energy efficiency in the B scenarios did not affect the peat procurement levels. The differences between the levels of the various forest fuels that resulted from inclusion of the energy-efficiency targets in the optimization also resulted from the increased forest technology rates. The proportion of total forest energy accounted for by the forest wood (below-ground) component increased by 17% moving from A1 to B2 and B3, fig. 3.

Including an improved energy efficiency for electricity generation in scenarios B1, B2, and B3 clearly affected the levels of electricity generation, fig. 4. For the 12 monthly planning periods, the larger levels of electricity generation (a mean increase of 96%) that occurs at the higher energy efficiency (42%) resulted from the feed-in tariff for electricity (+6.9 €/MWh), which increased profitability. The levels of heat production in the scenarios were constant for the 12-month planning horizon (data not shown). For comparison, the increased energy efficiency that was reported as the best policy alternative in a recent Finnish energy policy study [2] is presented next to those values presented in tab. 1. Discussions with the manager of the energy plant that provided the data indicated that the differences revealed by the optimal solutions for the six scenarios were reasonable based on the actual long-term energy production environment for the plant; the six scenarios are within the range of electricity delivery targets that are currently being used by the plant. Therefore, the remainder of the discussion concentrates on differences in electricity sales, although electricity was also delivered for use by the plant and by the company's paper mill.

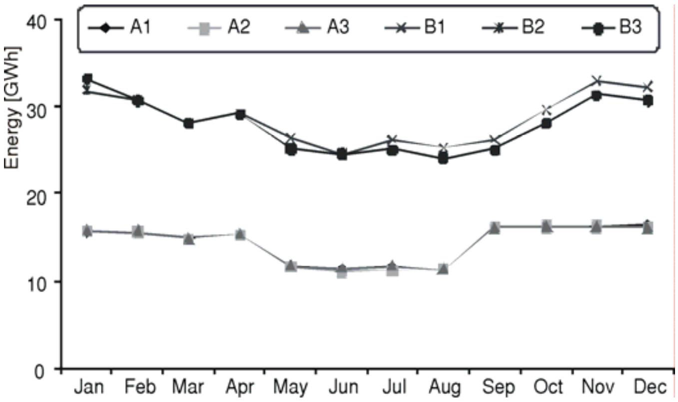

Figure 4. Electricity production schedules
A1, A2, and A3, supply chains that include an energy efficiency of 19% and forest technology rates of 100, 300, and 1000%, respectively; B1, B2, and B3, supply chain plans that include an energy efficiency of 42% and forest technology rates of 100, 300, and 1000%, respectively

Whether the plant sells electricity in a given scenario will depend on the net economic benefits: sales will increase when the plant can produce electricity for a lower cost than the market price. Including an increase in the forest technology rate for forest fuels clearly affected the levels of the electricity sales in the A and B scenarios at the beginning of the planning horizon, fig. 5. Remarkable changes in the characteristics of the electricity mixture can be seen throughout the year in the optimal solutions in the A scenarios. However, starting in around May in the B scenarios, the electricity sales patterns were nearly identical for all three scenarios; a similar trend existed for the A scenarios, but the differences between scenarios were larger.

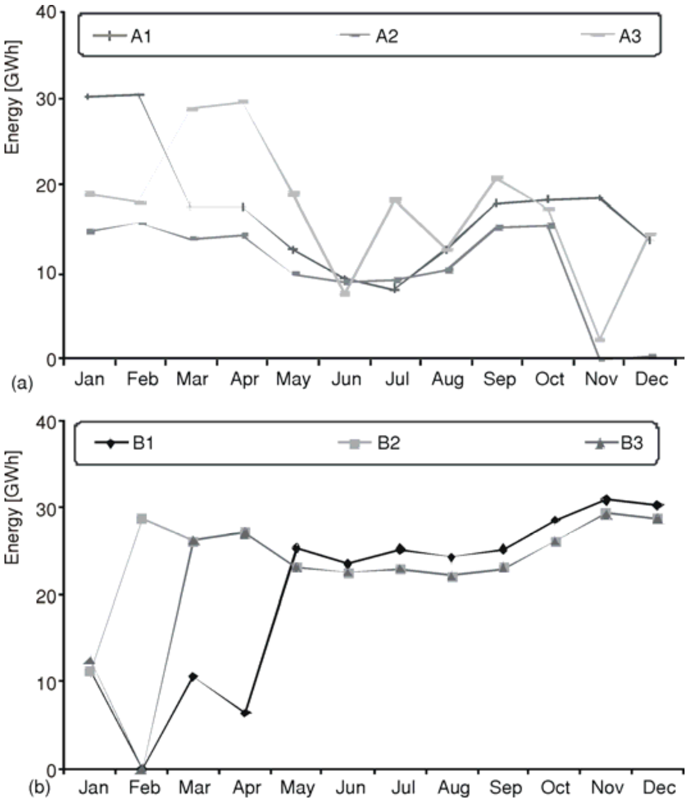

Figure 5. Electricity sales in the supply chain plans for scenarios (a) A1, A2, A3 and (b) B1, B2, and B3, which include energy efficiencies of 19%, 42% and forest technology rates of 100, 300, and 1000%, respectively

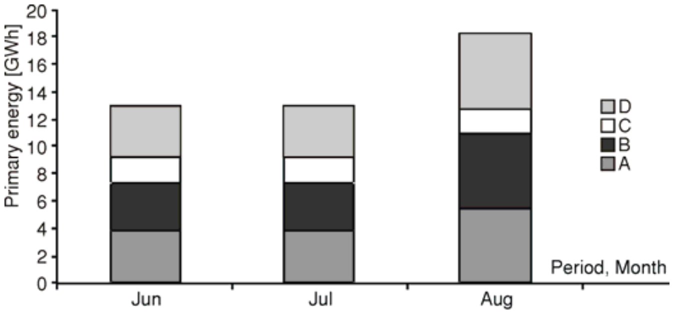

Figure 6. Procurement schedules of forest energy-fuel (below-ground) for teams (A, B, C, D) in the example that includes a tactical adaptation of strategic plan for three months

To clarify the differences between the supply chains in the tactical planning example, we summarized the energy flows from a forest energy-fuel (below-ground) for three months, fig. 6. Increasing the forest technology rate clearly affected the levels of the forest fuel. For example, the mean procurement level of forest fuel (below-ground) increased by 24% in August when the forest technology rate of teams A, B, and D increased from 300% to 450%. At the same decision horizon, the higher technology rate did not affect the procurement levels in June and July. The proportion of total forest energy accounted for by the forest wood (below-ground) component increased by 49% in teams A, B, and D, fig. 6. Any other differences between the levels of the various forest fuels of procurement teams did not resulted from the increased forest technology rates.

The results show that it was not required to adjust the energy plant's infeed system to accept a different mixture of fuels. The results also show that it was not required to adjust a supply time to obtain the new mixture of fuels. These are crucial components of the tactical planning method in an actual dynamic supply chain, in which obtaining a specific energy-product mixture happens during certain periods (strategic plan). Using the planning method of this study the energy-flow model of Palander [21] was successfully developed and converted into software to solve this forest fuel procurement problem.

Conclusions

In this study, we examined an illustrative tactical planning example based on real-life data from the Finnish energy-production industry, allowing an assessment of the impacts for the industry of including the potential forest technology rates. In the planning process the strategic decisions are adjusted to the changed decision environment based on a tactical techno-economic analysis using three forest fuel procurement teams. The energy industry as a whole is subject to policy decisions regarding electricity trading and energy efficiency regulation. These decisions should be made on the basis of comprehensive technical and economic analyses of the driving forces for renewable energy. The decisions should also be made accounting for the local forest energy procurement effects in a holistic model of the energy supply chain. The results illustrate the advantages of local planning of forest fuel procurement and the potential impacts of local electricity production for the Finnish industry. Further studies will be needed to demonstrate the efficiency of the tactical planning method for managers in various real-life environments.

Nomenclature

D_g	– deviation above and below the decision-makers' goals defined by the study problem, [€]
d_n	– due date of task *n*, [–]
G	– number of deviations from the decision-maker's goals (1, …, *g*, …, 6)
I	– number of energy-fuel mixtures (1, …, *i*, …, *I*)
J	– number of teams (1, …, *j*, …, *J*)
K	– number of plants (1, …, *k*, …, *K*)
L_{ijt}	– energy content of fuel mixture *i* purchased from and logged by team *j* during period *t*, [MWhm^{-3}]
$Lmax_{ijt}$	– maximum energy content of fuel mixture *i* purchased from and logged by team *j* during period *t*, [MWhm^{-3}]
$Lmin_{ijt}$	– minimum energy content of fuel mixture *i* purchased from and logged by team *j* during period *t*, [MWhm^{-3}]
N	– number of tasks (1, …, *n*, …, *N*) represents the delivery of a given mixture of products
pro_n	– pre-specified production time for task *n*, [–]
r_n	– release date (*i. e*., time when fuel resources become available) of task *n*, [–]
s_{nl}	– setup time between tasks *n* and *l*, [–]
T	– number of periods (1, …, *t*, …, *T*)
Tar_n	– tardiness of task *n*, [–]
t_n	– delivery time of task *n*, [–]
w_g	– positive weight that reflect the decision-maker's preferences regarding the relative importance of objective *g*, [–]
Z	– is the optimum weighted sum of w_gD_g during the decision-making horizon, [€]

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Paper submitted: January 23, 2012
Paper revised: February 29, 2012
Paper accepted: March 5, 2012