EVALUATING THE FEASIBILITY OF BIO-ENERGY BASED HEAT AND POWER PRODUCTION IN RURAL COMMUNITY

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ABSTRACT

The paper discusses alternatives for biofuel-based district heating using simulation analysis in a real-life case example. First, the paper illustrates the current supply chain structure of forest chips from harvest to the heat energy plant. Usually the chips are naturally dried, chipped on the roadside and transported to the heating plant based on the orders. Second, the study demonstrates how a regional bioenergy system could be developed with the help of a simulation model for evaluating the feasibility of different wood fuel supply chain options. The model mimics a real-life example of an industrial area in a small Finnish municipality planning to invest in a CHP plant. The results show that the investment in a CHP plant and use of artificially dried wood fuel can be profitable in the circumstances where local demand exists for heat energy. The simulation-based vision can be compared with the presently dominant concept of highly decentralized supply chains for wood chips that is widely used among energy suppliers. However, to optimize the transportation costs and the moisture content of the chips changes are needed in the supply chain processes and structure. The results of this study are usable for practical decision-making and offer useful ideas for continuing research on alternative ways to produce energy wood biomass in the future.

KEYWORDS wood biomass supply chain, wood chips, energy wood, simulation, bioenergy, forest fuel

1 Introduction

There is an increasing interest in the use of biomass to replace fossil fuels for the production of heat, electricity and transportation fuels [1]. Although the production of renewable energy has increased in the EU over 65 % between 2000 and 2017, approx. 72 % of all energy was produced from coals, crude oil and natural gas while renewable energies account for 14 % of energy consumption in the EU-28 according to Eurostat [2]. Biomass is the largest renewable energy source globally, accounting for 70 % of the total renewable energy supply. The biggest energy use of biomass globally is for cooking and heating in developing regions. Nevertheless, with the growing use of modern biomass energy solutions, the contribution of modern bioenergy sources will be a major part in the future renewable energy mix [3].

The European Commission as well as countries outside the EU have set targets to increase the share of renewable energy sources, the so called 20/20/20 targets with the goal to mitigate climate change [4]. The "Directive for renewable energy" promotes the use of forest biomass for energy purposes. Each member state has their own targets, for example Finland should produce 38 % and Sweden 49 % of their energy from renewable sources by 2020 [5]. Within the concept of renewable energy, bio-energy can play a decisive role during the next decades. In this respect, efficient and effective supply chain and logistics management represent one key parameter [6].

In the majority of EU countries, the main sources for renewable energy come from wood and especially primary forest fuels [7]. In Finland, wood fuels represent the biggest source covering 27 % of total energy consumption in 2018, according to Natural Resources Institute Finland [8], which is the highest share in European countries after Latvia [7,9]. The major part of the renewable fuels from the forests are by-products such as black liqueurs, bark, saw dust, and shavings form the conventional forest industries. [10]. In Finland, heating and power plants consumed a total of 20 million cubic meters of solid fuels in 2018. The consumption of forest chips was 7.4 million cubic meters in heating and power plants, accounting for 37 % of all solid wood fuels used [8]. According to the Association of heat entrepreneurs [11], there were around 310 companies that operated 520 heat plants using wood fuel in 2013. In Finland, forest chips are produced mainly from small sized roundwood, consisting of small-sized whole trees, delimbed stem wood and pulp wood [12]. A total of 3.9 million cubic meters of small-sized trees were used as raw materials for forest chips in 2018 [8]. Young forests, which require tending to ensure efficient wood production, need treatments where the extraction of small-sized stems offers an energy source. The use of energy wood extraction from forests can thus be seen as part of effective forest management [13].

Despite the benefits of using forest biomass, technical and economic challenges hinder its use. There is variability in the amount and quality of forest biomass due to forest accessibility issues during a year, weather conditions, pre-processing, transportation and storage conditions, and competition for other end users. Forest wood has lower energy density than many other competing fossil fuels [14]. These result in a costly and complex logistics of procuring, transporting and using forest biomass. A cost-efficient design of the forest biomass supply chain is critical to overcome these challenges [2]. In Finland, there is a long tradition of using wood chips and many studies have been done related to e.g. supply operations and logistics solutions for forest fuels [5,13,15,16].

This paper discusses how to supply energy wood for district heating based on a real-life case example. The study is founded on a project during 2016-18 between Utajärvi, a small rural municipality situated in Northern Finland, the local business community and the university. The target was to promote the usage of forest resources available in the area for developing a wood fuel processing center in the industrial area called Mustikkakangas. In a preliminary study a vision was created for a business model to develop the industrial area based on sorting, handling and processing of the incoming wood material for the use of energy sector and wood processing companies. The idea of artificial drying of energy wood as "high quality forest chips" was also introduced in the preliminary study. This paper highlights the current structure of energy wood supply chains and discusses the quality criteria of supplied forest chips in heat plants. In addition, the paper demonstrates a vision for energy and material flows in the selected industrial area. For this purpose, a simulation model was developed for estimating the feasibility of investment in a combined heat and power (CHP) plant and artificial drying of forest chips.

The structure of the paper is as follows. First, the background information of the study is presented. Then, the research material and methods are discussed, together with an illustration of the current supply chain structure of forest chips from harvest to an energy plant. Next, the paper describes how the simulation model was created for examining the feasibility of the CHP investment in the case environment, followed by the results of the simulation. Finally, the conclusions are presented summarizing the feasibility of alternative supply chain options and discussing further research suggestions based on the results of the study.

2. Material and methods

In order to create an understanding about the supply chains of forest chips (presented in Figure 1) and their utilization in small heat plants a total of 16 non-formal qualitative interviews were carried out in 2016. The purpose of the interviews was to find answers to the following questions:

- How does the supply chain of wood chips from forest to a heat plant function?
- Is there a market for high quality chips with low moisture content among customers?
- What kind of business opportunities does the handling and processing of energy wood offer for this particular industrial area?

The list of interviews and the interview questions are presented in Appendix A. The interviewees included local entrepreneurs of wood-related firms, six heating companies, suppliers of bio-based materials, equipment suppliers and entrepreneurs of comminution and transport of energy wood. The face-to-face interviews lasted from one to two hours. Based on the interviews a schematic illustration of the current state of the industrial area was established (Figure 2) and a future vision was created (Figure 3).

The final stage of the study included the development of a discrete event simulation model (DES) to investigate the future business opportunities in the industrial area. The model estimates the materials and energy flows regarding two options for a future investment in the CHP plant and artificial drying of quality chips in the area. The simulation model calculates 10-year (520 weeks) scenarios on a weekly basis estimating the material and energy flows of the CHP plant and artificial drying of chips in the area. The data for the simulation model was collected by interviewing the companies in the area and the heat plant suppliers. Statistics concerning the energy and heat consumption were received from the municipality and public sources. The simulation model was created with the Vensim simulation tool version available freely from the internet. (https://vensim.com).

2.1 The supply chain of forest chips

The first step of a forest chip supply chain is harvesting. The forest chips used in heat and power plants are produced mainly from small-sized energy wood (53 %), crown mass (37 %), stumps (5 %) and round wood (6%). Crown mass and stumps are used in large heating plants. [8] A typical small-sized energy wood harvesting site in Finland is an overstocked and unproductive hardwood or pine stand where good tending practices have been neglected. [17]. During the harvesting the wood is separated for different purposes, i.e. the sorting of wood material is done at the first stage of the chain. In general, round wood will be used for energy purpose if it is not used for sawn logs or pulpwood or there is no other demand [5].

The development of machinery for the harvesting of small-diameter trees has been rapid in the last decade. The harvesting can be integrated with timber harvesting or it can be totally separated [18]. After the harvesting, the energy wood material is transported by tractors or harvesters to the roadside.

The quality characteristic with the most influence on the efficiency of the supply chain of forest chips is its moisture content [19, 20]. Moisture has a negative impact on transportation efficiency and costs, heat value of fuel, combustion efficiency, emissions, dry matter losses during storage as well as handling functionality especially during the frost period in winter. In Finland, all forest energy wood is naturally dried. The forest raw materials are kept usually in the open-air storage for about a year before chipping. According to Röser et al. [20] natural drying is a viable and effective method in order to enhance the energy efficiency of wood-based fuels. Challenges arise in forest chip supply due to variations in fuel quality and moisture during the storage. The moisture content of stored biomass is lowest during the summer, when the demand for heat and power is low, and highest during the winter, when the heat and power demand peaks. In addition, winter conditions cause various challenges [13]. Milder winters and declined quality of forest road conditions increase the exposure of forest chip supply operations to weather sensitive conditions. However, also traditional winters with snow cover require ploughing of forest roads to provide access by mobile chippers to feed stocks.

The supply chains of forest chips are strongly defined by the location of wood chipping. The main options as described by Kärhä [15] are listed below. A graphical illustration of the most common types is shown in Figure 1.

•Terrain chipping: comminution at the harvesting site and transportation to the plant

•Roadside chipping (separate chipper and chip truck): comminution with a chipper crusher at the roadside landing and road transportation of chips using a separate chip truck from the roadside to the plant.

•Roadside chipping (integrated chipper – chip truck) the comminution and road transportation of chips with the same unit, so called integrated chipper

•Terminal chipping: forest raw materials to the terminal for comminution and then transportation of the chips from the terminal to the plant.

•On-site chipping: Forest raw materials transportation to the plant for comminution.

Figure 1. Here

Roadside chipping is the most commonly used option when delivering chips to small heat plants. Terminals have become more common in the forest fuel chains, especially in countries that use a lot of forest fuels for heating and energy [21, 22]. In general, terminal chipping is used with larger heat and power plants. The use of on-site chipping is rare. In that case, the distance between the harvesting site and the heat plant is usually very short [15]. According to Metsäteho Oy [23], a Finnish company specializing in forest-related R&D activities, roadside chipping accounts for 50-60 % of forest chip supply while terminal chipping and on-site chipping account for 35 % and 10 %, respectively. Terrain chipping is not used in any large scale. At the heat plants, the chips are stored for a short time period under roof cover to avoid wetting of the dried material. Based on the order dried forest raw materials are selected, chipped and transported to the heat plant on regular basis. Due to spatial distribution, low mass density, low energy density and low bulk density, the transportation of primary forest fuel is crucial for economic efficiency as well as reduced CO_2 emissions [24].

The main reason for decentralized comminution is the low transportation payload and therefore high transportation costs of raw wood materials [13]. In the terminal chipping model, the distance between the terminals and end-use points cannot be more than 100-150 kilometers. Although terminals add costs to the supply chain through additional operations in the process, this is accepted in order to secure the supply of forest fuel throughout the year in all conditions [13,22]. Terminals help balancing the utilization of production and transport capacity over the year and thereby reduce supply costs [25].

2.2 Fuel quality aspects

A lot of effort has been addressed to the improvement of forest biomass quality because of its critical role for the energy conversion efficiency of the supplied biomass. [13]. Especially the moisture content has a big impact on biomass combustion efficiency. Normally the moisture content of wood fuel in smaller plants (< 1MW) should not exceed 40% [26,27] whereas in bigger plants also higher moisture contents can be accepted. However, also in bigger plants the combustion efficiency is weakened by high moisture content and for this reason the biomass is often dried before combustion [28]. Lowering the moisture content generally increases the combustion efficiency of biomass fuel [28] and also improves the productivity of trucks and thereby reduce the logistics cost of biomass fuel supply [19,29]. With regard to the durability of wood chips in storage, the moisture content should not exceed 25 % [30].

Natural drying is an effective method for improving the energy efficiency of wood-based fuel products. During a one-summer drying period a moisture content below 40 % can be achieved [26], but it should be remembered that drying results are sensitive to wood quality, prevailing weather conditions, stacking methods, pile covering, etc. [20]. A more homogeneous result can be achieved with artificial drying methods. With these methods (e.g. thermal drying, cold-air drying, compression) it is possible to achieve lower moisture contents, even down to the level of 15 % [31,32]. However, in practice the fuel quality requirements are determined by the specific features of the plants in their particular circumstances.

In addition to moisture, other important quality factors related to wood fuel are heat value, energy density, share of green particles (needles), ash content and particle size [5, 19,33]. Fuel quality is closely related to the efficiency of energy production. Thus, the energy producers pay for their wood fuel suppliers based on the heat value of delivered material. However, the quality of fuel has also other consequences, for instance in logistics [13]. Impurities in forest biomass may cause breakdowns and increase the ash content of the material [18]. In the winter, moist wood freezes and may cause handling problems or blockages in silos and conveyors. Also decaying fungi thrive in moist chips, the optimum moisture content for fungi being about 50 % [34].

2.3 Modeling of industrial area and its energy flows

Utajärvi municipality is situated in Northern Finland, approx. 60 kilometers east of the City of Oulu. Some 20 years ago, the industrial area called “Mustikkakangas”, five kilometers away from the village center, was established. The municipality owns the premises in the industrial area and the main task of the area is to maintain and rent the premises for companies, sell industrial properties and to enhance the establishment of new companies. There is also another plant in the village providing heat for its inhabitants. No heat pipeline currently exists between the Mustikkakangas area and the village center.

The present status of the Mustikkakangas industrial area is shown in Figure 2. As seen from the figure there is not very much synergy concerning the materials flows. An old small heat plant (900 kW output) produces the heat energy for the companies in the industrial area. One half of the fuel for the heat plant comes from wood chips and the other half from waste wood from the construction industry. The heat plant is operating in the public-private partnership model [35] so that the local entrepreneur takes care of the fuel supply and heat production. Electricity is purchased from the national electricity network. A sawmill, a glulam factory and a few other non-wood related companies operate in the area. The sawmill generates a lot of bark and sawdust as side-products of its processes. However, the sawdust is transported over 60 kilometers to a larger heat plant, and the bark material should be dried and chipped before it can be used for heating. There is also a terminal area for forest energy wood in the area. The raw wood is chipped and then transported to other bigger heat plants. However, the use of this terminal has decreased during the last few years. In the area there has been an investment in a dryer, but it does not have any use nowadays and it is not suitable for drying forest chips. In the center of the municipality the main heat plant uses forest chips as the main source of energy for district heating. In addition, the wood companies located in the center are able to deliver their sawdust and other dry secondary wood material to the main heat plant.

Figure 3. shows the vision for new model of the Mustikkakangas area. The vision for the area was outlined based on the interviews and the results of the preliminary project carried out in 2015. The vision is based

on the circular economy perspective so that the produced energy and side streams are utilized in the area or sold as a service to outsiders. The idea was to invest in new CHP plant producing both heat and electricity. The basic assumption was that the municipality will invest 2.3 million euro in the purchase and installation of a 2 MW CHP plant, infrastructure and a new drying plant. The target is to attract new companies to the area by offering lower price heat energy and electricity than is available from the open market. The excess electricity will be sold to the national electricity market. In the long run, there is also the question if the municipality should invest in a heating pipeline between the industrial area and the village center to combine the heat production in these two areas. In the vision, forest raw materials and residuals or side streams of wood companies are used for energy fuel e.g. they are chipped, dried and used in the CHP plant. The comminution of wood biomass material is centralized in the area that operates also as a terminal for energy wood. The chips are first dried artificially to low moisture content and then used in the CHP plant or sold to customers. In the vision, there will be new wood companies in the area so that the consumption of energy and the amount of secondary wood material increases considerably.

The vision is based on the situation where several existing and new companies are operating in the area. The sawmill is the biggest operating company. Logs are supplied to the sawmill and processed to balk sold mostly to the export market. The side-products such as sawdust and peel are dried and used as energy wood for the CHP plant. The glulam factory gets its raw material from the sawmill and other timber companies. Also new wood processing companies using timber are located in the area. The waste wood from the process are dried and used as energy wood. The crushed residuals are dried and used as chips for the CHP plant or stored for later use.

The industrial area has a terminal area for wood biomass. The incoming wood material is chipped and dried in the area and then either sold or used in the CHP plant. The integration of different energy wood flows in the area provides cost savings in handling and machinery costs. An idea has been presented that in addition to professional wood energy companies also private farmers could chip and dry their own wood in the area.

Figure 2 here

Figure 3 here

2.4 Simulation model

The target of the model is to demonstrate how raw materials get processed to side and final products and combustible materials for the CHP plant. The model tries to answer the following question: When is it profitable to invest in the CHP plant and artificial drying of energy wood so that the dried wood chips are used in CHP plant, but also sold to the markets. The model shows the impact of current and new companies in the area for electricity and heat consumption; it mimics the seasonal impact on raw material, heat and electricity consumption, CHP production and prices. The hypothesis was that the investment in a 2 MW CHP plant would be profitable and investment loan is paid back within ten years. The investment costs contain CHP plant (2 million euro), infrastructure including electricity transmission in the area (200 000 €) and new drying plant (100 000 €). It is assumed that the heat is consumed in the area and the investment cost of a new pipeline to the village were not included in the model.

The input data are based on estimates using the following information sources: (a) discussions with local wood entrepreneurs; (b) history data of the heat and power consumption of the industrial area available from the municipality; (c) discussions with a company delivering CHP plants and public information [36]; and (d) public price information.

The model was generated under the following assumptions:

- Maximum simulation time is 10 years
- Minimum simulation time unit is one week
- The maximum capacity is the CHP plant is 336 MWh per week (c)
- The CHP plant has seasonal production and 40 % is electricity and 60 % heat. (c)

- The inflow of log (LogWood) is maximum 250 sm3 (sold cubic meters) per week (a)
- The inflow of timber (Woodmaterial) is maximum 100 sm3 per week (a)
- The inflow of forest biomass (Coppice) is maximum 300 sm3 per week (a)
- For each company operating in the area a parameter has been generated to calculate the expected seasonal electricity and heat consumption (b)
- The dried quality chips produced inside the area (DryCipPrice) cost 41 €/sm3 and dried chips coming from outside (Quality ChipPrice) cost 45 €/sm3. (d)
- Electricity prices are seasonal (ElecPurchasePrice) and the total price paid for electricity without VAT to an outside provider is 8 cent/kWh.(b), (d)
- The electricity is sold to national market (CHPElecExtPrice) at an average price of 7 cent/kWh, the price (CHPElecPrice) the companies in the area is 6 cents/kWh. (b),(d)
- Heat prices are stable. Heat price (CHPHeatPrice) for enterprises in the area is 55 € per MWh and the price of excess heat sold out is 60 € per MWh. (d)
- Interest is 3 % (b).

Exogenous parameters are the amount of raw material entering the system, the division of flows, consumptions and the amount available for investments. Values for expected electricity and energy demand are taken from an earlier feasibility study and information received from the Municipality of Utajärvi. Endogenous parameters are calculated from demands and costs. The simulation model is shown in Appendix B.

4. RESULTS

In order to understand the vision of the industrial area and the behavior of the markets, four different cases were simulated. The first case (A) describes the original vision setup, where the CHP plant produces both heat and electricity and all wood material including side streams are used in the CHP plant. The second case (B) shows the situation where only dried quality chips are used in the CHP plant, so the price of sourced energy wood is higher than in case A. The third case (C) describes the present situation, where both electricity and heat are produced and the extra heat generated at the CHP plant cannot be sold elsewhere. If the extra heat could be utilized in municipal heating, a new pipeline for 5 kilometers has to be built from the industrial area to the municipality center. The fourth case (D) presents the situation where only heat is produced, so the plant does not produce any electricity. In summary, the four cases are:

A) The CHP plant produces both heat and electricity and uses all available wood raw materials.

B) The CHP plant uses only more expensive quality wood chips for fuel.

C) The CHP plant produces both heat and electricity, but the extra heat generated at the CHP plant cannot be sold elsewhere.

D) The CHP plant produces only heat.

The simulation results are shown in Figure 4.

Figure 4a describes the first case A which shows that the CHP plant producing both heat and electricity is profitable after 7 years and 50 weeks when interest (Profit) is not taken into consideration. The profit adds up to 607 775 € at the end of the simulation period. When interest is taken into consideration (ProfitInterests) the CHP plant is profitable after 9 years and 2 weeks with profit adding up to 274 223 €. In case A it is assumed that the extra heat finds a buyer outside the industrial area. This is a major assumption since a pipeline connection is needed between the industrial area and the municipality center.

In case B (Figure 4b), the CHP plant uses only quality chips for fuel, if for instance residuals and cheap side-materials from companies are not available. The simulation model shows that the CHP plant is not profitable after 10 years, but the trend indicates that profitability will be achieved fairly soon after the 10-year simulation period. When interest is not taken into consideration (Profit), at the end of the simulation period the loan taken by the municipality has been reduced to 382 851 €. When interest is taken into consideration, the investment loan of 2.3 million euro has been reduced to 875 000 € at the end of simulation period.

Case C (Figure 4c) demonstrates the situation when the CHP plant produces both heat and electricity, but extra produced heat cannot be sold elsewhere because of the missing pipeline between the industrial area and the municipality center. Figure 4c shows that CHP plant is not profitable after 10 years and indeed, the debt increases all the time. When interest is not taken into consideration (Profit) at the end of the simulation period, the loan has increased to 3 129 060 €. When interest is taken into account, the loan has increased to 4 074 120 €.

In case D (Figure 4d) the CHP plant produces only heat. The option is commonly used when the market price of electricity is low compared to production costs. In this case, the CHP is not profitable after 10 years and the debt increases in steps. When interest is not taken into consideration (Profit), the loan has increased from 2.3 million to 2.53 million euro at the end of the simulation period. When interest is taken into consideration (ProfitInterests), the loan has increased to 3 387 680 €.

To summarize the simulation results it can be seen that cases A and B confirm the hypothesis that the CHP plant will be profitable over a long time period, and case B also indicates that even in the situation that no cheaper wood raw material is available, the CHP plant can operate in a profitable way.

The heat consumption of the companies in Mustikkakangas varies from 0.2 to 142 MWh per week, which means that a 2 MW CHP plant producing heat from 202 to 336 MWh per week is too big when compared to the heat consumption, even when the expected growth of the companies in the future is considered. In other words, the extra heat needs to be sold to the market or used inside the area. In this case, the municipality should invest in a new heat pipeline between the industrial area and the village center. An alternative would be to attract more companies to the area.

The simulation results implicate that investing in the CHP plant and artificial drying of wood chips may encourage other wood biomass companies to enter the area since heat and electricity will be available at a competitive price. The synergy generated between the wood materials flow can act as a catalyst and increase the number of operators in the area. Overall, the results are promising but they do not unequivocally confirm the hypothesis that changing the old power plant with a CHP is a good solution.

Figure 4. HERE

4 Discussion

Forest-based biomass is increasing its popularity as an energy source for heating and electricity production. In Finland, for instance, the use of wood fuels is increasing as many energy producers aim to improve their climate footprint by changing from fossil fuels to renewable energy sources. Utilization of wood fuels can also have other positive impacts for instance in forest tending and increasing the use of side products from wood-based industries.

However, forest-based fuels also have many challenges as an energy source. Among these challenges, logistics problems are often encountered in the supply chains of wood fuels. Raw material supply is fragmented and distances to the production sites are often long. In addition, the quality of the raw material must match the requirements of the energy production unit, making it difficult to secure the availability of right material and to optimize the flows from different supply sources.

This study demonstrates how a regional bioenergy system could be developed with the help of a simulation model for evaluating the feasibility of different wood fuel supply chain options. The model mimics a real-life example of an industrial area in a rural municipality planning to invest in small-scale CHP installation with a drying plant. A vision for future material and energy flows is presented where both side-steams from wood companies and forest wood material are handled, dried and used as energy fuel in the heating plant. The dried chips can be stored in the area and delivered to the customers especially in the wintertime. In an ideal case, the CHP plant can provide cheap heat and electricity for the companies in the industrial area while the extra heat and electricity can be sold.

The simulation-based vision can be compared with the presently dominant concept of highly decentralized supply chains for wood chips that is widely used among energy suppliers. Usually the chips are naturally dried, chipped on the roadside and transported to the heating plant based on the orders. However, to optimize the transportation costs and the moisture content of the chips, changes are needed in the supply chain processes and structure. The proposed solution involves centralized handling and storage of different wood-based materials at the site together with actors who operate in the area to secure the supply of wood fuel and make use of the energy generated at the plant.

The technology and size of the heating plant determine the quality of forest biomass fuel used for energy production. In small heating plants a high heat value can be achieved by artificially lowering the moisture content of the wood chips. However, the investment in artificial drying does not seem profitable due to the high energy costs. The simulation shows that the CHP plant can be profitable if local demand exists for heat energy and the waste heat of the plant can be used for drying of the chips.

The results of the study are specific to this particular industry site, but the methodology and the principles of the simulation model can be applied to other investment studies in similar situations. Creating the simulation model can also serve as a useful exercise for public and private organizations and political decision makers when discussing and evaluating the possible solutions for local energy production. Compared to more conventional methods of feasibility studies, simulation models offer the opportunity to incorporate dynamic elements such as fluctuations and uncertainties into the analysis. Therefore, the method can be useful also in other industries where for instance seasonal variations or supply chain fluctuations affect the business conditions.

As in all simulation models, choices had to be made in this study regarding the complexity of the model and the verification of its accuracy. The input values were obtained from a limited group of local stakeholders and for example different technological parameters were not cross-checked from equipment suppliers and other specialists. However, the values and results appear plausible in the light of previous studies [13,37] on wood-fueled CHP installations. Unfortunately, the validation of the model could not be performed with numerical data from the actual installation on the site. The municipality decided to outsource its district heating operations to an external operator that uses crop residues from a local grain mill as the fuel for its heating plant. Continuing research would be needed to study the economic and political rationale of the decision and to compare the results of the new arrangement with the wood-based CHP alternative.

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