Degree Project in Technology and Learning

Second cycle, 30 credits

Analysis of the Feasibility of Integrating Pellet Production to an Existing Combined Heat and Power Plant: A Case Study of Bristaverket

A Techno-Economic Analysis and an Investigation of Possibilities for Organizational Learning

FILIPPA BANCK
ALBIN WESTLIN

TRITA – ITM-EX 2024:271
Stockholm, Sweden 2024

www.kth.se

KTH Industrial Engineering
and Management

Master of Science Thesis TRITA-ITM-EX 2024:271

Analysis of the Feasibility of Integrating Pellet Production to an Existing Combined Heat and Power Plant: A Case Study of Bristaverket

A Techno-Economic Analysis and an Investigation of Possibilities for Organizational Learning

Filippa Banck
Albin Westlin

Approved 2024-06-12	Examiner Björn Hedin	Supervisor Helena Lennholm
	Commissioner Stockholm Exergi	Contact Person Fred Birath

Abstract

This study explored the feasibility of integrating pellet production to the combined heat and power plant Bristaverket, owned by the energy company Stockholm Exergi, with the aim of achieving a more energy and resource efficient process. The study was divided into three parts: development of a technical process, evaluation of techno-economic performance, and examination of organizational learning opportunities. A limitation of the study was to only consider the process at Bristaverket. The technical process was developed following a general modeling design process, utilizing MATLAB as software. Economic performance was assessed through investment and sensitivity analysis. Organizational learning opportunities were identified through interviews and thematic analysis using the 4I-framework. The proposed technical process involved transferring heat from Bristaverket to a 4 MW water-heated belt dryer. The annual pellet production amounted to 50.4 kilotons with 85% plant operation, and the specific energy consumption was 717 kWh/t_{pellet}. The pellets achieved the classification I3 for industrial use and the specific production cost was 2,218 SEK/t_{pellet}. The investment analysis was executed for three scenarios: a future scenario, a 2020 scenario and a 2023 scenario. The future scenario yielded a net present value (NPV) of 270 MSEK, an investment return rate (IRR) of 74%, and a payback time (PBT) of 1.4 years. For the 2020 scenario and 2023 scenario, the NPV was -1 MSEK and 88 MSEK, the IRR was 8% and 32%, and the PBT was 9.5 years and 3.3 years respectively. The investment was sensitive to changes in operational costs, foremost changes in pellet and wood chip prices. The study's techno-economic findings could contribute to organizational learning at Stockholm Exergi during meetings, through questions, at the final presentation, and through conversations between colleagues. Suggestions for enhancing organizational learning included establishing routines for knowledge sharing and discussions during and after thesis projects.

Keywords: Combined heat and power plant, integrated pellet production, pellets, organizational learning

KTH Industrial Engineering and Management

Examensarbete TRITA-ITM-EX 2024:271

Analys av genomförbarheten att integrera pelletsproduktion med ett existerande kraftvärmeverk: En fallstudie av Bristaverket

En teknoekonomisk analys och en undersökning av möjligheter till organisatoriskt lärande

Filippa Banck
Albin Westlin

Godkänt 2024-06-12	Examinator Björn Hedin	Handledare Helena Lennholm
	Uppdragsgivare Stockholm Exergi	Kontaktperson Fred Birath

Sammanfattning

Denna studie utforskade möjligheten att integrera pelletsproduktion vid kraftvärmeverket Bristaverket, som ägs av energiföretaget Stockholm Exergi, med syfte att uppnå en mer energi- och resurseffektiv process. Studien delades in i tre delar: utveckling av en teknisk process, utvärdering av teknoekonomiskt resultat och undersökning av möjligheter till organisatoriskt lärande. En avgränsning som gjordes i studien var att bara undersöka processen i Bristaverket. Den tekniska processen utvecklades genom att följa en allmän modelleringsdesignprocess med MATLAB som programvara. Det ekonomiska resultatet utvärderades genom investerings- och känslighetsanalys. Möjligheter till organisatoriskt lärande identifierades genom intervjuer och tematisk analys med hjälp av 4I-ramverket. Den föreslagna tekniska processen innebar överföring av värme från Bristaverket till en 4 MW vattenuppvärmd bandtork. Den årliga pelletsproduktionen uppgick till 50,4 kiloton med 85% drifttid och den specifika energiförbrukning var 717 $\text{kWh/t}_{\text{pellet}}$. Pelletsen klassificerades som I3 för industriellt bruk och den specifika produktionskostnaden var 2 218 $\text{SEK/t}_{\text{pellet}}$. Investeringsanalysen gjordes för tre scenarios: ett framtidsscenario, ett 2020-scenario och ett 2023-scenario. Framtidsscenariot gav ett nettonuvärde på 270 MSEK, en internränta på 74 % och en återbetalningstid på 1,4 år. För 2020- och 2023-scenariot var nettonuvärdet -1 respektive 88 MSEK, internräntan 8 respektive 32 % och återbetalningstiden 9,5 respektive 3,3 år. Investeringen var känslig mot förändringar i driftkostnader, framför allt i form av pellets- och flispriser. Studiens teknoekonomiska resultat skulle kunna bidra till organisatoriskt lärande på Stockholm Exergi genom möten, frågor, vid slutpresentationen och genom samtal mellan kollegor. Förslag för att förbättra möjligheterna till organisatoriskt lärande inkluderade att etablera rutiner för kunskapsdelning och diskussioner under och efter examensprojekt.

Nyckelord: Kraftvärmeverk, integrerad pelletsproduktion, pellets, organisatoriskt lärande

Acknowledgements

First, we would like to express our sincere gratitude to our supervisor at Stockholm Exergi, Fred Birath, for his continuous support, guidance, and insights. We are thankful to him and to Stockholm Exergi for the opportunity to work on this interesting topic. We also extend our gratitude to the previous thesis advisors who participated in our study, as well as to everyone else that we interacted with at Stockholm Exergi.

Furthermore, we wish to thank Helena Lennholm, our supervisor at KTH Royal Institute of Technology, for her guidance and encouragement throughout this semester.

Finally, as we approach our graduation, we want to thank our families and friends for their unwavering support during these five years at KTH Royal Institute of Technology.

Filippa Banck & Albin Westlin
Stockholm, May 2024

Table of Contents

Nomenclature

a	Annual net cash flow, SEK
C_p	Molar heat capacity, kJ/(K mol)
c_p	Specific heat capacity, kJ/(K kg)
EPK	The cost of producing one MWh of district heating, SEK/MWh
H	Enthalpy, kJ/mol
h	Specific enthalpy, kJ/kg
Inv	Investment cost, SEK
IRR	Investment Return Rate, %
M	Molar weight, kg/mol
$\dot{m}$	Mass flow, kg/s
NPV	Net Present Value, MSEK
n	Lifetime of investment, years
η	Efficiency, %
P	Plant size (pellet production capacity), ton/year
PBT	Payback Time, years
Q	Heat flow, kW or MW
r	Discount rate, %
T	Temperature, K
t	Tax rate, %
y	Scaling factor

1 Introduction

Climate change is a widely debated topic and the world is facing challenges in the aspiration to achieve sustainable development. A significant part of the challenge is the need to utilize energy and resources in a more efficient way. The demand for clean and more efficient energy globally is mentioned in the United Nations Sustainable Development Goals (UNDP, n.d.). Energy efficiency and a clean, green energy transition is also emphasized by the European Union as a part of their aim to be climate-neutral by 2050 (European Commission, 2021, 2022). In line with the European climate goal, the municipality of Stockholm aims to be free from fossil fuels and be climate positive by 2040 (Viable Cities, 2022). A vital contributor in striving towards a climate positive city is the energy company Stockholm Exergi, 50% owned by the municipality of Stockholm (Stockholm Exergi, n.d.). Stockholm Exergi produces district heating, district cooling, and electricity to Stockholm's residents.

As a part of Stockholm Exergi's work towards increased energy efficiency, one suggestion is to integrate pellet production to an existing combined heat and power (CHP) plant. Such a facility can be called an energy combine, as there are simultaneous production of both energy and an industrial product, in this case pellets (Nationalencyklopedin, n.d.). This type of energy combine has shown great potential to increase the efficiency in a system (Wahlund et al., 2002). Further, Wahlund (2002) concludes that the realization of such an energy combine is dependent on several non-technical factors. Therefore, this study will focus on both techno-economic factors and non-technical factors in form of learning possibilities related to the topic. The research is conducted as a case study of Bristaverket, which is one of Stockholm Exergi's CHP plants. Bristaverket is chosen because of its location and the surrounding area, which facilitate expansion through pellet production.

1.1 Bristaverket

Bristaverket is located in the northernmost part of Stockholm Exergi's northwestern district heating network (F. Birath, personal communication, February 2, 2024). The plant has an annual energy production of 1.8–1.9 TWh. At Bristaverket there are two CHP plants, Brista 1 and Brista 2, fueled by wood chips and waste respectively. The production at Bristaverket depends on the demand for district heating, which varies highly throughout the year due to varying outdoor temperatures. The plant generates power and district heating when it operates which provides financial incentives to maximize the operation. Simultaneously, the plant requires continuous removal of heat to function which hinders operation during periods with low demand for district heating. One consequence of these fluctuations in district heating demand is that there occasionally exists excess heating potential. Integrating pellet production generates an opportunity to use this heating potential when the district heating demand is low relative to planned production.

From a system perspective, the production planning of a specific CHP plant depends on the entire district heating network. At Stockholm Exergi, production planning is based on the cost of producing one MWh of district heating, here denoted energy per Swedish krona, EPK (note that EPK is measured in SEK/MWh, and not MWh/SEK as the notation suggests). Stockholm Exergi receives compensation for managing waste, which implies that Brista 2 has a low EPK and operates continuously, except for short periods of maintenance work. Brista 1 has a higher EPK and operates around two thirds of the year. Integrated pellet production could potentially reduce the overall EPK of Bristaverket. Furthermore, Stockholm Exergi is a large pellet consumer (Bioenergitidningen, 2023). One pellet-fueled CHP plant at Stockholm Exergi is Hässelbyverket, also located in the northwestern district heating network. Pellet production at Bristaverket could thus enable inhouse production of pellets.

Lastly, the feasibility of integrating pellet production to an existing Swedish CHP plant depends on non-technical factors (Wahlund et al., 2002). This case study is performed as a master's thesis project. Stockholm Exergi considers master's theses important for decision making regarding projects related to the subject concerned. Thus, the way results from this study are received and integrated, in the organization of Stockholm Exergi, is relevant for the evaluation of the feasibility of integrating pellet production at Bristaverket. The evaluation is implemented through examining possibilities for organizational learning within Stockholm Exergi connected to the techno-economic results of this study.

1.2 Aim of Thesis and Research Questions

The aim of this thesis is to investigate the feasibility of integrating pellet production at Bristaverket through a techno-economic analysis. Further, the aim is to evaluate how this study affects the feasibility of integrating pellet production at Bristaverket. Thus, the techno-economic analysis will be supplemented by investigating how the techno-economic results from this study can contribute to organizational learning at Stockholm Exergi. The research questions to be answered in this study are:

- What would be a suitable technical process for integration of pellet production at Bristaverket?
- What is the techno-economic performance of such an integrated pellet production?
- In which ways can the techno-economic results of this study create possibilities for organizational learning at Stockholm Exergi?

1.3 Limitations

This study is implemented from an academic perspective. This entails that calculations are based on theoretical values and not on technical instruments from specific manufacturers. The system boundary for the pellet production is set to the process at Bristaverket. Thus, the techno-economic analysis excludes the relation between the integrated pellet plant and the northwestern district heating network. Storage and transportation of pellets is also excluded from the analysis. Additionally, neither the physical size and design of the pellet plant nor any physical or mechanical properties of the produced pellets are considered.

2 Background and Previous Research

In this section, results from previous research regarding integration of pellet production and CHP plants are presented. Thereafter, information regarding dryers, pellet production and the pellet market is introduced. Finally, the concept organizational learning is described.

2.1 CHP Plants and Integration of Pellet Production

CHP plants use heat engines, such as boilers, to generate electricity while utilizing generated heat (Frederiksen, 2014). The most common type of CHP plant is based on steam cycles, sometimes called Rankine cycles. Such steam cycles consist of a boiler and one or many turbines, condensers, and pumps. The boiler heats and vaporizes water indirectly, typically by combusting fuel which otherwise would have gone to waste, such as residues from forest felling or waste from households or industries. The produced steam is expanded in the turbine, generating power, and is thereafter condensed to water, generating heat which is often used for district heating. The water is pumped and recirculated to the boiler, restarting the cycle. As the boiler provides heat indirectly, the combustion process occurs separately from the steam cycle. In combustion processes, flue gases are produced. These gases are filtered from harmful substances and are often recondensed in a flue gas condenser which also generates heat for district heating (Stenström, 2017). Remaining gases are exhausted to the outside air through a stack.

Various methods exist for integrating pellet production with CHP plants. These involve using different heat sources from the CHP plant to facilitate the drying process of pellet production. Previous work has studied possibilities to utilize heat sources such as flue gas (Anderson & Toffolo, 2013; Song et al., 2011; Vigants et al., 2017), steam (Anderson & Toffolo, 2013; Kohl et al., 2013; Song et al., 2011; Thek & Obernberger, 2004; Wahlund et al., 2002), and hot water (Thek & Obernberger, 2004; Yrjölä, 2004).

Previous studies suggest that integration of pellet production with CHP can lead to optimization of the system and increased resource efficiency (Kohl et al., 2013; Song et al., 2011; Wahlund et al., 2002). In a study, using steam as heat source for the dryer, the annual operating days of the CHP plant increased from 212 to 266 days and the overall energy efficiency increased from 88.3% to 91.3% (Kohl et al., 2013). In another study, the overall energy efficiency increased from 91% to 93% when utilizing steam as heat source, and to 98% when also utilizing flue gas (Song et al., 2011).

One way to evaluate the economic performance of a pellet plant is through calculating the specific pellet production cost. In the study from Song et al. (2011), this cost amounts to 110 EUR per ton of pellets produced (denoted €/t_{pellet}), provided that the pellet production is integrated using steam from the CHP plant. In a study of different pellet plants, the specific pellet production cost of a pellet production with a water-heated belt dryer is calculated to 90.2 €/t_{pellet} (Thek & Obernberger, 2004).

2.2 Description of Dryers

The drying process is central for pellet production. Various types of dryers exist, with over 400 types documented in literature and over 100 types commonly available (Haque & Somerville, 2013). Different dryers function differently depending on requirements of the drying material, utilized heat source and its temperature, and chosen heating techniques. Three types of dryers commonly used for drying biomass are presented below: the fluidized bed dryer, the belt dryer, and the rotary dryer. Emphasis is put on heat sources, given their importance for CHP plant integration.

In a fluidized bed dryer hot gas is circulated from below, holding the drying material suspended in the air and making it exhibit fluid-like behavior (Kumar & Sharma, 2022). This technique requires uniform drying materials, such as sawdust, to function correctly (Stenström, 2017). For CHP plant integration, steam or flue gas would be used as direct heating mediums.

Belt dryers (also known as bed dryers or conveyor dryers), in contrast, are versatile with respect to the drying material's shape and size distribution (Stenström, 2017). Belt dryers use heated air or flue gases to gently heat the drying material which travels along conveyor belts (Yi et al., 2020). When flue gases are utilized, they heat the drying material directly. When air is utilized, it is often heated indirectly by another heat source, through heat exchangers. With indirect heating, the heat source and temperature are flexible. For CHP plant integration, flue gas could be used as direct heating medium, while either steam, flue gas, or hot water could be used as indirect heat sources.

Rotary dryers (also known as drum dryers) are similarly versatile with respect to the drying material's shape and size distribution (Stenström, 2017). Drying material is fed through a slightly inclined rotating cylinder where it is either directly or indirectly heated by a hot gas (Yi et al., 2020). For CHP plant integration, steam or flue gas would be used.

When selecting a dryer for a particular purpose, there are many other factors that could be considered. These include, but are not limited to, location, space, energy consumption, batch or continuous processes, treatment of drying material, capital and operational costs, maintenance requirements, simplicity of use, and environmental impact.

2.3 Pellet Production

Pellets are compressed particles of wood or agricultural materials (Kocsis & Csanády, 2019). In this study, pellets always refer to wood pellets. Pellet manufacturing varies depending on factors such as type, size distribution, moisture content, and mechanical properties of the raw material (Kocsis & Csanády, 2019). The first step of the manufacturing process typically involves pre-treating raw material by cutting it into 10–20 mm pieces, followed by drying to reduce moisture content to 10–13%. Following the drying process, a hammer mill is often used for further size reduction. Then, conditioning may be required which means that material is re-wetted through steaming to compensate for any overdried portions. Overdrying often occurs when high-temperature dryers are used. After conditioning, the material is pressed through ring die channels, typically 6–10 mm in diameter, and cut to desired lengths, forming pellets. Then, the pellets are cooled, either in a dedicated cooler or at room temperature, from about 90°C to around 20°C. Finally, the pellets are sieved or screened from dust before packaging for transportation or use.

Pellet manufacturing is an energy intensive process, primarily in heat, but also in electricity. According to Thek & Obernberger (2004), the specific energy consumption for pellets produced from sawdust using a rotary dryer in Swedish conditions are 504.0 kWh/t_{pellet} for heat and 137.7 kWh/t_{pellet} for electricity. In another scenario, using a water-heated belt dryer in Austrian conditions, the specific electricity consumption is 171.4 kWh/t_{pellet}. The World Bioenergy Association (2014) suggests that specific electricity consumption can vary between 100–200 kWh/t_{pellet}, depending on factors such as plant efficiency and raw material quality.

2.4 The Pellet Market

Over the past decade, several European countries have transitioned from fossil fuels to pellets to mitigate greenhouse gas emissions from power generation (Thrän et al., 2018). This has entailed a dramatic increase in the pellet market. During the period 2016–2022, analytical assessments suggest that the annual pellet consumption in the European Union surged from 15.8 to 24.8 million tons, while pellet production increased from 14.6 to 20.3 million tons (Bolla & Flach, 2023). This implies that pellet production in the European Union has not been able to keep up with the increasing demand. Notably, pellet production in Sweden remained relatively stable, rising from 1.74 to 1.80 million tons, during the same period. However, there are several recently completed and upcoming pellet production sites in Sweden. Examples of upcoming sites are Moelven (NCC, 2024) and Grycksbo (Arctic Paper, 2023) with annual pellet production of 80,000 tons and 50,000 tons respectively. Regarding pellet consumption, Göteborg Energi is planning to build three pellet combustion plants, the first scheduled to start operating during the third quarter of 2026 (Göteborgs Stadshus AB, 2023; Siopi, Bäfver, & Andersen, 2022; Siopi, Bäfver, Johansson, et al., 2022). This development could indicate an increased pellet demand in Sweden.

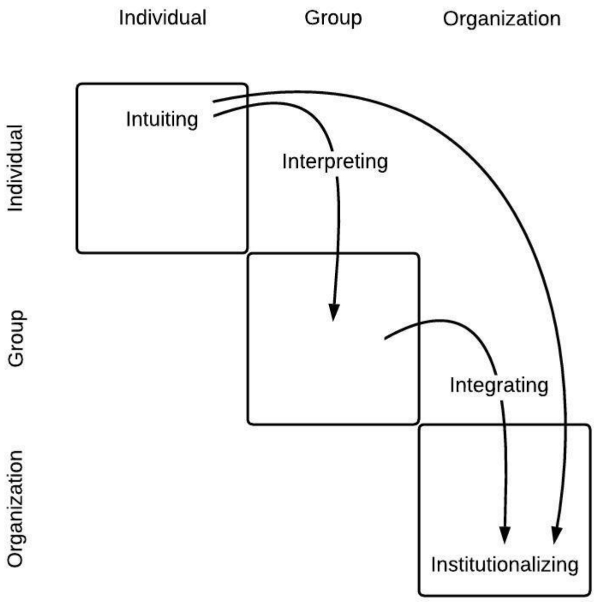
The pellet market is divided into industrial use and commercial and residential use (Swedish Standards Institute [SIS], 2021a). The Swedish Standards Institute (2021b) defines six classes of pellets based on criteria for various quality properties, including mechanical properties and elemental composition. For commercial and residential use, pellets are classified A1, A2, and B, where A1 represents the highest quality and B the lowest. Similarly, pellets for industrial use are classified I1, I2, and I3.

2.5 Organizational Learning

Organizational learning refers to the study of the learning processes of and within organizations (Tsang, 1997). Organizational learning is interconnected with the field of knowledge management, where organizational learning focuses on theory and process, while knowledge management focuses on practice and content (Easterby-Smith & Lyles, 2012). Thus, knowledge management aims to gain understanding of the nature of knowledge as an asset, while organizational learning focuses on the processes through which knowledge flows (Vera et al., 2012). In itself, the term organizational learning is multi-faceted and can be understood from various theoretical backgrounds including; individual and social learning perspectives (Brandi & Elkjaer, 2012), practice approaches (Gherardi, 2012), psychological perspectives (Shipton & Defillippi, 2012), and via knowledge management, which in turn involves socio-cultural, organizational, behavioral, and technical dimensions (Alavi & Denford, 2012).

In addition to multiple theoretical backgrounds from which to understand organizational learning, there exists several conceptual frameworks of organizational learning. One of which is the 4I-framework, introduced by Crossan et al. (1999). The 4I-framework outlines the process of organizational learning, presenting it as comprising four processes: intuiting, interpreting, integrating, and institutionalizing. These processes serve to bridge the individual, group, and organizational levels of organizational learning, as visualized in Figure 1.

Figure 1
Diagram over selected parts of the 4I-framework for organizational learning (Crossan et al., 1999). It outlines how knowledge flows between individual, group, and organizational level.



Intuiting is part of the individual learning process and focuses on subconscious processes of developing insight (Crossan et al., 1999). Interpreting picks up conscious elements of said processes and takes place in relation to a domain or an environment where language plays a significant role. It enables individuals and groups to develop a shared understanding. When shared understanding is achieved, the integrating process, which focuses on coherence and collective action, can form. Within the integrating process, insights and shared language from intuiting and interpreting extends to larger contexts such as workgroups, organizations, or communities. Lastly, institutionalizing sets aside individual and group learning, and instead focuses on learning embedded in organizational systems, structures, and routines.

The 4I-framework is used across various research contexts (Nielsen et al., 2018). The framework can be used for empirical examinations, for instance Crossan & Bedrow (2003) and Kaur & Hirudayaraj (2021) use the framework to explore the phenomenon of strategic renewal and the role of leader's emotional intelligence respectively. Furthermore, the framework's theoretical utility is demonstrated by researchers such as Lawrence et al. (2005) who expand the framework by encompassing three social political processes. Using this expanded framework, Schilling & Kluge (2009) further develop a theoretical foundation of impediments to organizational learning, by categorizing, discussing, and analyzing the impact of barriers to organizational learning.

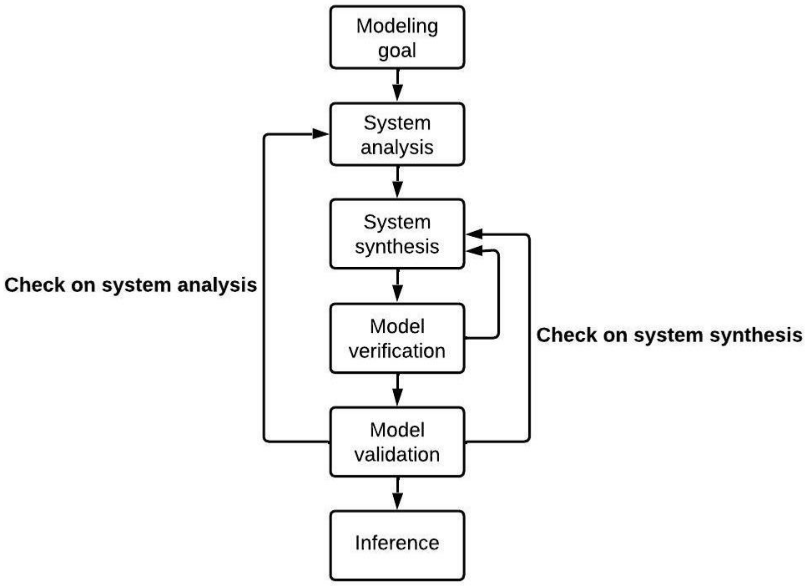
3 Method

The aim of this study was to evaluate the feasibility of integrating pellet production at Bristaverket. To achieve this, the first step was to develop a suitable technical process for the plant and create a model over the system. The second step was to analyze the overall economic performance of the proposed energy combine. The third step was to examine how the techno-economic results from this study could be received by Stockholm Exergi and incorporated in their decision regarding future investigations of integrated pellet production at Bristaverket. This was done through examining how results from master's thesis projects are transferred to Stockholm Exergi and analyze if it contributes to possibilities for organizational learning.

3.1 Technical System Design

A suitable technical system design for the integrated pellet production at Bristaverket was developed through a design process suitable for general modeling, according to Ertas (2018). This design process can be seen in Figure 2.

Figure 2
The design process for general modeling (Ertas, 2018).



The first step was to define the goal of the model. This was done through determining the research questions and what needs they entailed on the model. The second step was a system analysis, which according to Ertas (2018) aims to isolate system components and interactions between them. This was executed through literature review and consulting with employees at Stockholm Exergi for technical expertise. The third step was system synthesis. In this step the model was built, which is explained further in Section 3.1.1. The model building was an iterative process, including verification and validation steps. The model verification ensured that the model worked as intended. Validation of the model designated the process of comparing results from the model with data from actual systems. This was done through comparing the model output with results from academic papers, as suggested by Ertas (2018). Lastly, the model was used for inference of the techno-economic performance of a potential pellet plant at Bristaverket.

3.1.1 System Synthesis

The software MATLAB was used to construct a model which simulated pellet production at Bristaverket. MATLAB was selected due to its robust capabilities in numerical computation and modelling as well as its user-friendly interface. The model encompassed a theoretical representation of the technical process for the integrated pellet production, which was designed based on findings in the system analysis.

The model accounted for dynamic factors such as ambient temperature, moisture content of the wood chips used as material for the pellets, electricity prices, district heating prices, and operation of Brista 1, Brista 2, and Hässelbyverket. Ambient temperature data was sourced from a weather station at Arlanda (SMHI, 2024), chosen due to its geographical location close to Bristaverket. It was assumed that the temperature of the wood chips used for pellet manufacturing matched the ambient temperature. Data of prices and plant operations were obtained from Stockholm Exergi. In addition to dynamic data, the model accounted for static data of elemental composition and calorimetric heat value of wood chips, net fees, taxes for electricity, electricity consumption, and costs of wood chips, pellets, waste, and heat. Assumptions regarding the static data used in the model can be found in Appendix 1. Data were processed by interpolating missing values and removing outliers when needed.

Moreover, several calculations were made using MATLAB. The relation between the heat demand of the dryer and the inlet and outlet moisture content and temperature of the wood chips was calculated using mass and energy balances as well as changes in enthalpy. Further, the heating potential from Brista 1 and Brista 2 was calculated as the difference between the maximum capacity of the plant and historical data of the plant operation. Small variations in operation were assumed to depend on variations in fuel quality and were therefore not regarded as heating potential. If there was excess heating potential, the simulated plant prioritized heat from Brista 2 over Brista 1 due to its lower EPK. From a system perspective of the northwestern district heating network, there should not be any excess heating potential at Bristaverket when Hässelbyverket operates. Therefore, an additional cost was added to the pellet production if Hässelbyverket was operating. If the heating potential from Brista 1 and Brista 2 was insufficient, an electrical heater supplied the remaining heat.

The simulated plant was programmed to operate when the pellet production income exceeded the total cost of raw materials, electricity, and heat, on an hourly basis. Additionally, it was assumed that the first hour of operation after a shutdown caused full energy costs without yielding any production.

3.1.2 Drying

Calculations made regarding the drying process were assumed to consist of energy balances and physical material balances without chemical reactions. The chemical reactions related to thermal degradation of wood, such as breakdown of chemical bonds in extractives and lignin, are typically initiated at temperatures above 100°C (Sundararaj, 2022). Below 100°C, such chemical reactions were considered negligible in the drying process. By considering the dryer as a steady-state system without chemical reactions, it was assumed that the total masses of any substance entering and leaving the system are equal, adhering to the law of mass conservation (Ashrafizadeh & Tan, 2018). Similarly, energy balances were expected to adhere to the law of energy conservation.

The heat needed to dry wood chips to a moisture content fit for pellet production was calculated by determining the difference in enthalpy between the two states, from wet and low-temperature, T_1, wood chips to dry and warm-temperature, T_2, wood chips. As enthalpy, H, is a state function, changes in enthalpy remain the same regardless of chosen paths between initial and final states (Burrows, 2009). This property also holds for specific enthalpy, h. The chosen paths are shown in Equation (1), (2), and (3), where evaporated water, dry substance of wood chips, and remaining water in the wood chips respectively are seen as separate substances as their specific changes in enthalpy differ. Enthalpy of vaporization of water is denoted ΔH°_{vap}, while the vaporization temperature of water is denoted T_{vap}.

$$\Delta h_{H_2O,\,evap} = \frac{\int_{T_1}^{T_{vap}} C_{p,\,H_2O,\,liq}\,dT \; + \Delta H^{\circ}_{vap} + \int_{T_{vap}}^{T_2} C_{p,\,H_2O,\,vap}\,dT}{M_{H_2O}} \tag{1}$$

$$\Delta h_{wood,dry} = \int_{T_1}^{T_2} c_{p,\,wood,\,dry}\,dT \tag{2}$$

$$\Delta h_{H_2O\;in\;wood} = \frac{\int_{T_1}^{T_2} C_{p,\,H_2O,\,liq}\,dT}{M_{H_2O}} \tag{3}$$

The molar weight, M, was used for unit conversions between mass and moles when necessary and static molar heat capacities of liquid water and steam, C_p, used in Equation (1), were used as they remained rather constant in the given temperature ranges (see Appendix 1). However, the specific heat capacity, c_p, of dry wood chips, varied with temperature, T, but was seen as independent of its elemental composition, as shown in Equation (4) proposed by Kollman (as cited in Peduzzi et al., 2016).

$$c_{p,wood,dry}(T) = 0.00486 \cdot T - 0.21293 \tag{4}$$

The heat required for drying, $Q_{req,dryer}$, was expressed as the sum of changes in specific enthalpy of evaporated water, dry wood chips, and water in wood chips multiplied by respective mass flows, $\dot{m}$. Assuming that dryers cannot operate with 100% efficiency, the required heat was divided by an assumed dryer efficiency, η, as shown in Equation (5).

$$Q_{req,dryer} = \frac{\Delta h_{H_2O,\,evap}\dot{\mathrm{m}}_{H_2O,\,evap} + \Delta h_{wood,dry}\dot{\mathrm{m}}_{wood,dry} + \Delta h_{H_2O\ in\ wood}\dot{\mathrm{m}}_{H_2O\ in\ wood}}{\eta} \tag{5}$$

Water vapor evaporated during the drying process could be recovered as heat by condensation or regarded as heat loss if recovery is not feasible. Regardless of whether it is seen as a loss or a potential for heat recovery, calculations for this aspect remain the same. The maximum amount of recoverable heat, $Q_{recoverable/loss}$, was calculated as the change in specific enthalpy between water vapor and liquid water at the outlet temperature, T_2, multiplied with the mass flow of the evaporated water, as shown in Equation (6).

$$Q_{recoverable/loss} = \frac{\int_{T_2}^{T_{vap}} C_{p,\,H_2O,\,vap}\,dT + \Delta H^{\circ}_{vap} + \int_{T_{vap}}^{T_2} C_{p,\,H_2O,\,liq}\,dT}{M_{H_2O}} \cdot \dot{\mathrm{m}}_{H_2O,evap} \tag{6}$$

3.2 Evaluation of the Economic Performance

The economic performance of the pellet plant was evaluated through an investment analysis. Three fundamental methods were used: calculating Net Present Value (NPV), Investment Return Rate (IRR) and Payback Time (PBT). Moreover, a sensitivity analysis was made. A sensitivity analysis examines how variations in input data to the model affects the results (Lantz et al., 2018). It was used to map which parameters that are most sensible to change, and thus determine which changes that are most probable to affect the profitability of the investment.

The first step was to map the investment cost. It was done using the investment cost from academic sources and scaling it to the relevant plant size (see Appendix 1). This was calculated as described in Equation (7), in accordance with Song et al. (2011). The investment cost and plant size from the source was denoted Inv_L and P_L respectively. The scaling factor y determines how the price is affected by the equipment sizing, and was set to 0.7 in line with a similar study by Song et al. (2011). The investment cost of the pellet plant in this study, with the plant size P_p, was designated *Inv.* For the electrical heater, the investment cost was decided using a specific investment cost according to Zuberi et al. (2022). The investment cost was scaled to today's monetary value, taking the inflation into account.

$$Inv = Inv_L \cdot \left(\frac{P_p}{P_L}\right)^y \tag{7}$$

The next step was to chart the annual payments and incomes. The difference between them formed the annual cash flow. The investment analysis was done in nominal terms, which means that the inflation was taken into account (Lantz et al., 2018). Future inflation was assumed to be 2%. Furthermore, the investment analysis included depreciation due to tax effects. In an investment context, depreciation can be seen as a tax saving according to Lantz et al. (2018), provided that the company makes a profit. Thus, the depreciation was calculated as an income. The depreciation was made linear over the lifetime of the investment, *n*, according to Equation (8). In this investment analysis, the lifetime was set to 15 years. The tax rate, *t*, was designated to the Swedish corporation tax 20.6% (Skatteverket, n.d.).

$$Depreciation = \frac{1}{n} \cdot Inv \cdot t \tag{8}$$

In addition to depreciation, the analysis considered the tax of the annual payment surplus. After the annual tax was subtracted, the NPV was calculated. The NPV is a summation of the annual net cash flows, a_i, discounted to a reference year (Lantz et al., 2018). It was calculated corresponding to Equation (9). The discounting was conducted using the discount rate, *r*, set to 8%. In this analysis, the first year of the investment was chosen as reference year. The lifetime of the investment was denoted *n*, as in previous calculations. Consequently, the NPV can be interpreted as a measure of how much future cash inflows will exceed the initial cost of the investment.

$$NPV = \sum_{i=0}^{n} \frac{a_i}{(1+r)^i} \tag{9}$$

The IRR of the investment measures the average interest yield during the lifetime of the investment and was calculated as seen in Equation (10). It was denoted *IRR* and is the interest rate for which the sum of all net cash flows, attributed to the reference year, is zero (Lantz et al., 2018). Hence, the IRR can be interpreted as an estimate of the value of tied-up capital. An investment is profitable if the IRR is greater than the pre-determined discount rate.

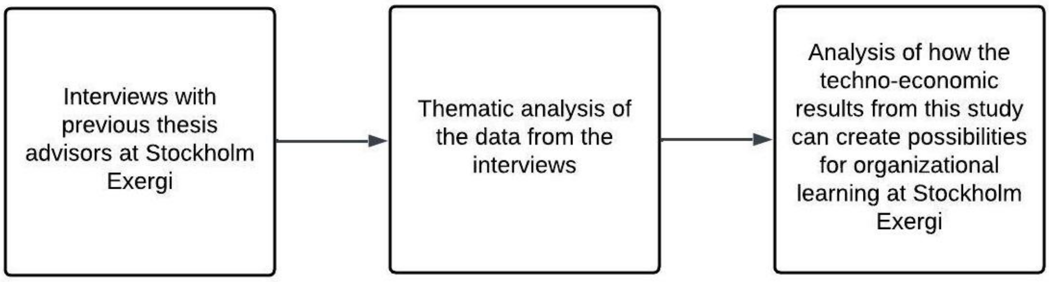
$$0 = \sum_{i=0}^{n} \frac{a_i}{(1+IRR)^i} \tag{10}$$

The last method used, the PBT, measures the amount of years it takes until the sum of the cash flows equals the initial cost of the investment (Lantz et al., 2018). It was calculated by dividing the investment cost by the annual net cash flow.

3.3 Qualitative Study of Possibilities for Organizational Learning

A qualitative study was conducted to explore how the techno-economic findings of this thesis could create possibilities for organizational learning at Stockholm Exergi. Organizational learning was viewed from a social learning perspective, placing learning in the organizational context, rather than in individual minds (Brandi & Elkjaer, 2012). A schematic diagram of the steps of the qualitative study can be seen in Figure 3.

Figure 3
A schematic diagram of the steps of the qualitative study.



3.3.1 Data Collection

Data was collected through three interviews with previous thesis advisors, hereby named Respondent 1, 2, and 3. These interviews aimed to gain insights into the employees' experiences of past master's thesis projects at Stockholm Exergi. The questions that the interviews were based on are found in Appendix 2. Employing interviews as a method of data collection was chosen, as nuanced phenomena like experiences were investigated (Denscombe, 2018). Furthermore, the interviews were semi-structured. Semi-structured interviews were chosen to foster productive conversation, as structured interviews may lack interactive elements and unstructured interviews risk not yielding answers to the research questions (Alvehus, 2013).

The interviewees were informed about the research ethic principles that the study followed (Vetenskapsrådet, 2002). The interviews were recorded and transcribed. They were conducted in Swedish and subsequently translated into English.

3.3.2 Data Analysis

Deductive thematic analysis, as outlined by Braun & Clarke (2006), was chosen as the method of analysis. Thematic analysis was selected as an appropriate method due to its suitability for capturing experiences and seeking common or shared meanings (Kiger & Varpio, 2020), aligning well with the objective of understanding how previous master's thesis projects had facilitated learning within the organization of Stockholm Exergi. The 4I-framework, proposed by Crossan et al. (1999), was chosen as the theoretical framework for thematization due to its systematic approach to understanding organizational learning processes. This aimed to uncover insights into how the techno-economic results from this study could create possibilities for organizational learning at Stockholm Exergi.

In addition to the predefined deductive themes from the 4I-framework, the analysis remained open to identifying inductive themes that may have emerged during data exploration. Although these themes may not necessarily align with the 4I-framework, they were considered for flexibility of the analysis and because they could provide valuable insights into the research question at hand.

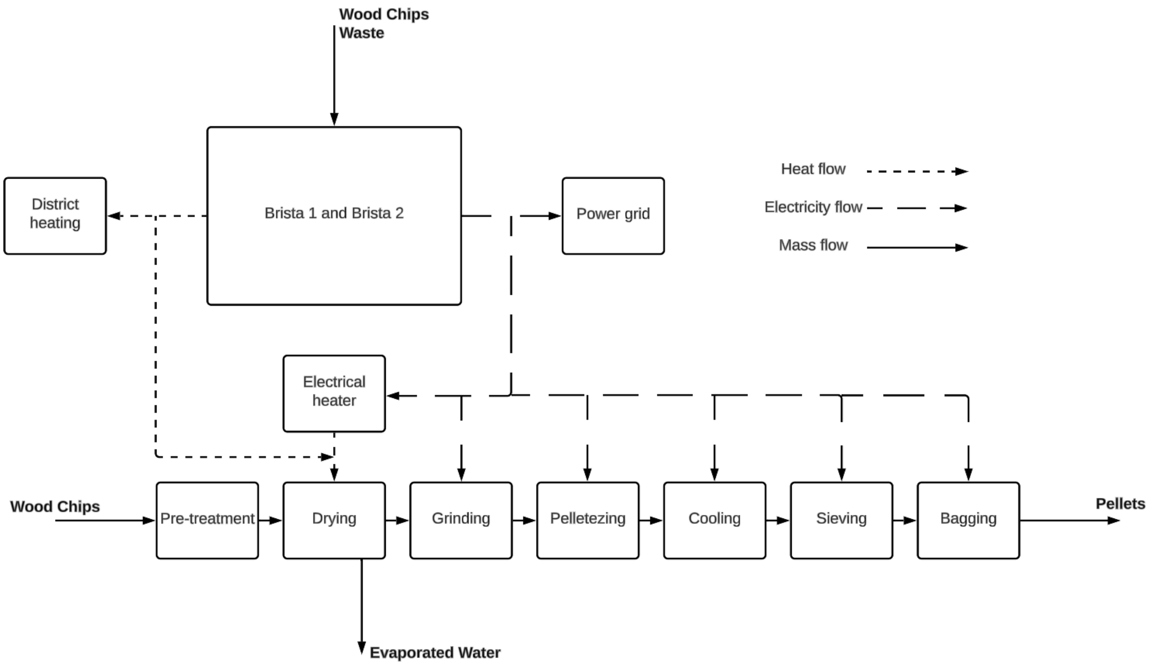
4 Results

This study is divided into three parts: The technical process, techno-economic analysis, and possibilities for organizational learning. In this section, these results are presented in the following order. First, the technical process of the integration of pellet production at Bristaverket is presented. Second, the techno-economic analysis is presented. This analysis examines a simulated future pellet plant, using 2024 as reference year. Performance of simulated pellet production during 2020–2023 is found in Appendix 3. Third, the analysis on how techno-economic results from this study can create possibilities for organizational learning at Stockholm Exergi is presented.

4.1 The Technical Process

In this section, the technical process is presented in two steps. First, it covers the integration of pellet production at Bristaverket. Then, it delves into the specifics of the pellet plant itself. The technical process integrates a water-heated dryer, connected to Bristaverket with a heat exchanger. The options to use flue gas or steam were also investigated, but neither of these were deemed a viable solution. Flue gas was opted out of because the existing process in Bristaverket includes a flue gas condenser. Thereby, the residual heat in the flue gases is already utilized and is therefore not an option to use for pellet production. To use steam as heating source for the pellet production could be a viable option, but it would affect the district heating production. Due to the limitations of this study, this is not considered an option. Rather, the residual heating potential from Brista 1 and Brista 2 is used. Further, an electrical heater is added in the process to enable pellet production at times when the heating potential from Brista 1 and Brista 2 is insufficient for the heat demand of the dryer. The technical process developed can be seen in Figure 4.

Figure 4
The developed technical process for integrated pellet production at Bristaverket.



The steps of pellet production, illustrated by the boxes moving from left (pre-treatment) to right (bagging) in Figure 4, are assumed to function as described in Section 2.3. Choices and specifications are summarized in Table 1. For drying, a belt dryer was chosen as it is suitable using hot water as heat source (Thek & Obernberger, 2004). The temperature used is 90°C and the drying capacity is 4 MW. This choice is based on an aspiration to maximize the operating hours as well as the use of heating potential from Brista 1 and Brista 2. The capacity of the dryer enables drying of wood chips at the rate of 10.8 ton/h after factoring in a dryer efficiency of 75%. This dryer efficiency was chosen to match the efficiency of the water-heated belt dryer described by Thek & Obernberger (2004). The wood chips are dried to a moisture content of 10%, to comply with current standards (Swedish Standards Institute [SIS], 2021b). To obtain an appropriate size distribution of the wood chips, the grinding equipment selected is a hammer mill, as it is suitable for such heterogeneous materials. For pelletizing, a ring die that produces pellets with a diameter of 8 mm is selected. Cooling is assumed to be possible in room temperature rather than in a designated cooler, due to the small scale of the pellet production. The process results in a pellet production of 6.7–7.4 ton/h. This production rate varies due to variations in moisture content of the wood chips, between 38–44%.

Table 1
Conditions for the pellet production process developed.

Parameters	Value	Unit
Wood chip inlet	10.8	ton/h
Inlet Moisture Content	38–44	%
Pellet Outlet	6.7–7.4	ton/h
Evaporated Water Outlet	3.4–4.1	ton/h
Outlet Moisture Content	10.0	%
Dryer type	Belt dryer	-
Dryer efficiency	75.0	%
Temperature of district heating water	90.0	°C
Grinding unit type	Hammer mill	-
Pellet mill type	Ring die pellet mill	-
Pellet diameter	8.0	mm

4.2 Techno-Economic Analysis

To assess the technical and economic performance of the process, some forecasting assumptions are made regarding prices and data. The price of wood chips is set to 300 SEK/MWh and the price of pellets is set to 600 SEK/MWh. The price of electricity is based on the electricity prices of 2023, but linearly scaled to average 1,000 SEK/MWh before taxes and net fees. Other time-based data, including weather, moisture content of wood chips, and the operation of Brista 1, Brista 2, and Hässelbyverket are assumed to be the same as for the year 2023.

4.2.1 Technical Performance

The pellet plant annually produces 50.4 kilotons of pellets, consuming 77.1 kilotons of wood chips, which, if measured in heating value, is equivalent to 255.5 GWh (see Table 2). This process evaporates 26.7 kilotons of water, which if recondensed could release up to 16.6 GWh of heat. As the evaporated water is diluted in an air stream in the belt dryer, recondensation is not possible, resulting in a heat loss.

Table 2
Total mass of inlet and outlet substance flows, with related energy amounts.

Flow	Total mass (kiloton)	Energy* (GWh)
Wood chips inlet	77.1	255.5
Water outlet (evaporation)	26.7	16.6
Pellets outlet	50.4	255.5

*Heating value for wood chips and pellets. Condensation energy for water.

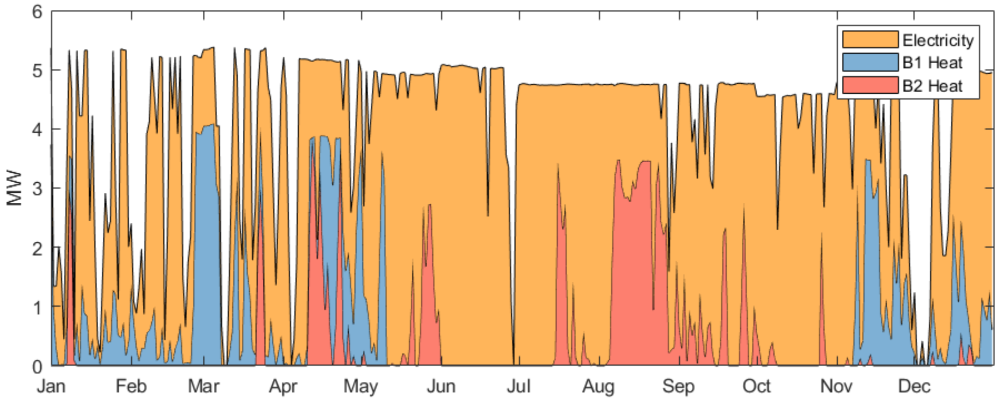
The total annual energy demand for the pellet plant is 36.1 GWh, as detailed in Table 3. The most energy-intensive process is drying, which accounts for 26.7 GWh of heat. For the process steps of pre-treatment, drying (electrical heater excluded), grinding, pelleting, cooling, sieving, and bagging 9.4 GWh of electricity is required.

Table 3
Total energy consumption by energy type.

Energy type	Energy consumption (GWh)
Heat	26.7
Electricity (electrical heater excluded)	9.4
Total	36.1

The energy consumption of the pellet plant fluctuates throughout the year, visualized in daily averages in Figure 5. During days with few operational hours, the energy consumption is low. The variations in maximal energy consumption are contributed to varying temperature and moisture content of the wood chips. There are fewer operational hours during the winter because of high electricity prices and low heating potential. In total, the pellet plant is operational during 85% of the year.

Figure 5
Energy consumption over the duration of the reference year. Daily time steps for improved readability.



In Figure 5, the heat provided by Brista 1 and Brista 2 is visualized by the blue and red fields respectively. Furthermore, the yellow field indicates electricity consumption for both the electricity required for the electrical heater and the various process steps. Focusing solely on heat, proportions of heat utilized from the different sources are found in Table 4.

Table 4
Proportions of heat by source.

Heat source	Percentage (%)
Brista 1	17
Brista 2	15
Electrical heater	68

Energy consumption in relation to produced pellets, referred to as specific energy consumption, can serve as a key measure for assessing resource efficiency. Depending on the context, the electrical heater could be classed as either heat or electricity. In Table 5 this is addressed by differentiating between demand and consumption. In total, 717 kWh/t_{pellet} is required. Pellet production requires 530 kWh/t_{pellet} of heat and 187 kWh/t_{pellet} of electricity. However, as the electrical heater provides heat through electricity, the specific heat consumption is 171 kWh/t_{pellet} and the electricity consumption is 546 kWh/t_{pellet}. Heat requirements vary annually, from 434 kWh/t_{pellet} when wood chips are hot and dry to 626 kWh/t_{pellet} when they are cold and wet. The specific electricity demand remains constant.

Table 5
Average specific energy demand and consumption for heat and electricity.

Energy type	Specific energy demand (kWh/t_{pellet})	Specific energy consumption (kWh/t_{pellet})
Heat	530	171
Electricity	187	546
Total	717	717

To examine the quality of pellets, their compositional properties are compared to the requirements of the Swedish Standards Institute (2021b). In Table 6 the most prevalent criteria from the standard are listed along with which grading the simulated pellets achieve. The standard also contains requirements for trace elements, for which the pellets achieve the highest grading, A1 and I1.

Table 6

Excerpt of criteria in the pellet standard (Swedish Standards Institute [SIS], 2021b). Grading achieved of the simulated pellets for each criterion.

Criteria	Unit	A1	A2	B	I1	I2	I3	Grading
Moisture	weight%, wb*	≤ 10	≤ 10	≤ 10	≤ 10	≤ 10	≤ 10	A1 & I1
Ash	weight%, db**	≤ 0.7	≤ 1.2	≤ 1.5	≤ 1.0	≤ 1.5	≤ 3.0	I3
Calorific value	MJ/kg	≥ 16.5	≥ 16.5	≥ 16.5	≥ 16.5	≥ 16.5	≥ 16.5	A1 & I1
Nitrogen	weight%, db**	≤ 0.3	≤ 0.5	≤ 1.0	≤ 0.3	≤ 0.3	≤ 0.6	A2 & I3
Sulphur	weight%, db**	≤ 0.04	≤ 0.04	≤ 0.05	≤ 0.05	≤ 0.05	≤ 0.05	A1 & I1
Chlorine	weight%, db**	≤ 0.02	≤ 0.02	≤ 0.03	≤ 0.03	≤ 0.05	≤ 0.1	A1 & I1

*wb = wet basis. **db = dry basis.

The pellets fail to achieve the lowest grading, B, for commercial and residential usage due to elevated ash levels. However, they achieve the grading I3 for industrial usage, not meeting higher grades due to elevated ash and nitrogen levels. Requirements for A1 and I1 are otherwise met. Thus, the application should be limited to industrial usage.

4.2.2 Economic Performance

The specific costs of producing one MWh and one ton of pellets respectively are presented in Table 7. The total specific cost is 438 SEK/MWh$_{pellet}$, which converted to ton is 2,223 SEK/t$_{pellet}$. Note that the specific costs vary throughout the year. The minimum specific cost is 260 SEK/MWh$_{pellet}$, occurring when electricity prices are low and heat is provided by Brista 2, due to the negative cost of heat from Brista 2. The maximum specific cost amounts to 684 SEK/MWh$_{pellet}$, which occurs when the electricity price spike and the electrical heater maintains operation to avoid the added cost of interrupting production.

Table 7

Specific costs of producing one MWh and one ton of pellets for the simulated pellet plant, in terms of material and energy.

Source	Specific cost (SEK/MWh$_{pellet}$)	Specific cost (SEK/t$_{pellet}$)
Wood chips	300	1,522
Heat Brista 1	17	86
Heat Brista 2	-3	-13
Electricity	124	628
Total	438	2,223

The total investment cost, operational cost, and revenue of the pellet plant is found in Table 8. The investment cost is 46 MSEK. The operational cost is the sum of the costs for wood chips, heat from Brista 1 and Brista 2, and electricity during the reference year. Additionally, a fixed operational cost of 2% of the investment cost is included to cover labor expenses. The revenue is the income from pellets. This results in a total operational cost of 113 MSEK and total revenue of 153 MSEK.

Table 8
The total investment cost, operational cost, and revenue of the pellet plant during the reference year.

Monetary Term	Value	Unit
Investment cost	46	MSEK
Operational cost	113	MSEK
Revenue	153	MSEK

The financial metrics of the investment are presented in Table 9. In addition to presentation of financial metrics of the simulated future pellet plant, two additional historical scenarios are presented, using input data from the years 2020 and 2023 (see Appendix 3), rather than the forecasted assumptions mentioned in Section 4.2. This is done to highlight the impact of using different input data. For the simulated future pellet plant, the NPV is 270 MSEK, which means that the sum of future cashflows is assumed to exceed the initial investment cost with that amount. The IRR implies that the predicted annual return rate, provided that the sum of the NPV of all future cash flows is zero, is 74%. The investment cost is presumed to be paid back in 1.4 years. For 2020 and 2023, the NPV is -1 MSEK and 88 MSEK, the IRR is 8% and 32%, and the PBT is 9.5 years and 3.3 years respectively.

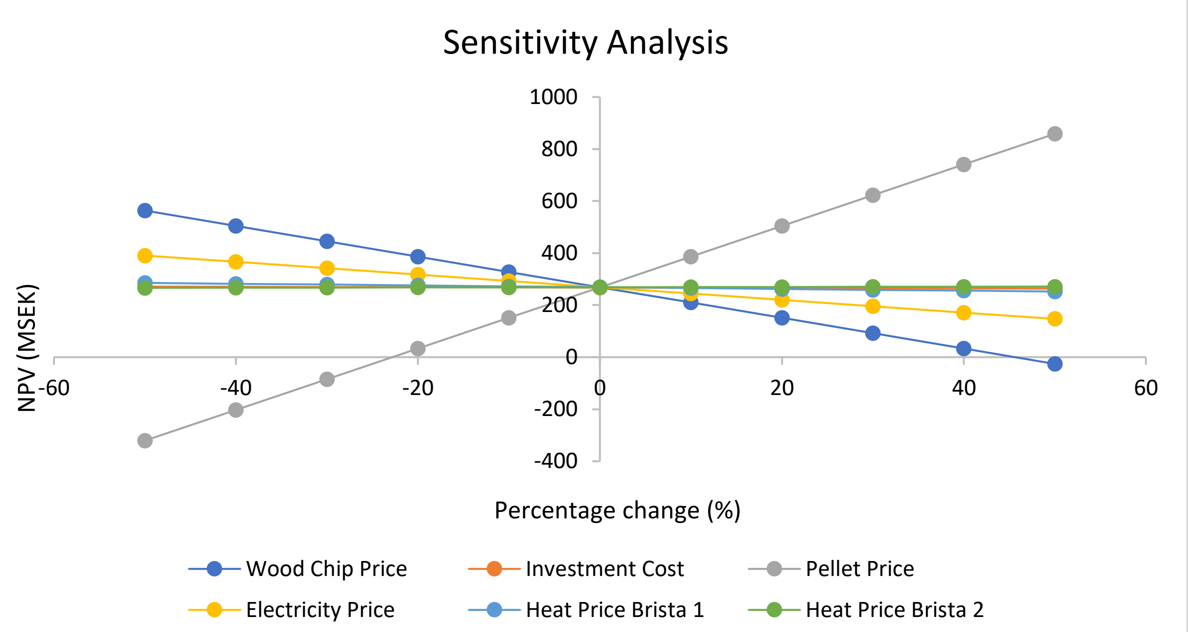
Table 9
Financial metrics of the investment.

Financial Metric	Future Scenario	2020 Scenario	2023 Scenario	Unit
Net Present Value (NPV)	270	-1	88	MSEK
Investment Return Rate (IRR)	74	8	32	%
Payback Time (PBT)	1.4	9.5	3.3	years

The sensitivity analysis is made of the future pellet plant and shows that the NPV is most sensitive to changes in pellet price, followed by changes in wood chips price and thereafter changes in electricity price (see Figure 6). It is seen that the NPV would be negative, which implies an unprofitable investment, if the pellet price reduces with over 23% or if the wood chip price increases with over 46%. Critically, the investment cost shows low sensitivity to changes, while operational costs exhibit higher sensitivity. Note that the wood chip price and pellet price correlate and thus are not independent variables.

Figure 6

A sensitivity analysis of the NPV of the investment in a future pellet plant at Bristaverket.



4.3 Possibilities for Organizational Learning

The results in this section are presented in two parts, a thematic analysis of the interview data and an analysis of possibilities for organizational learning at Stockholm Exergi connected to this study. In the thematic analysis, experiences from previous master's thesis projects at Stockholm Exergi were mapped to the selected themes; intuiting, interpreting, integrating, and institutionalizing. The mapping between themes and the experiences detected in interview data is seen in Table 10. One additional theme was detected and added, namely the commitment from the thesis advisor. In Sections 4.3.1 to 4.3.5, the results from the thematic analysis were used to analyze how the techno-economic results from this master's thesis can create possibilities for organizational learning at Stockholm Exergi.

Table 10
Thematic analysis of experiences detected in interview data.

Theme	Experiences Detected in Interview Data
Intuiting	• Master's thesis projects are initiated by an individual question or idea. • A person involved in a larger project at Stockholm Exergi detects a specific problem and formulate research questions suitable for a master's thesis. • Master's thesis projects are initiated by an individual who gets an idea in a conversation with a colleague.
Interpreting	• Regular meetings between student and thesis advisor. • Students ask questions to employees at Stockholm Exergi concerning their projects. • Thesis advisors ask questions to colleagues concerning the projects they are supervising. • Students present their master's thesis projects for selected employees at Stockholm Exergi. • In discussions regarding a topic that has been covered in a master's thesis report, the thesis supervisor shares the report with colleagues.
Integrating	• Discussions between colleagues about master's thesis projects. • Presentation of results from master's thesis projects at a unit meeting.
Institutionalizing	• No existing routine regarding how master's thesis projects are initiated or what happens with the results when the project is finished.
Commitment from Thesis Advisor	• A key for a master's thesis project's success is that there is a need in the organization and a commitment from the thesis advisor.

4.3.1 Intuiting

Intuiting is a subconscious process that involves an individual's ability to perceive patterns, which can generate new insights or ideas for future possibilities (Crossan et al., 1999). At Stockholm Exergi, master's thesis projects begin with an idea from an individual, a conversation between colleagues or as a specific problem that is of reasonable size to be investigated as a master's thesis (see Table 10). When asked about the relation between themselves and master's thesis projects at Stockholm Exergi, one interviewee responded:

> Well, I am involved if it concerns my area, you could say. It might be that I get involved if I have my own idea that perhaps becomes a master's thesis project. (Respondent 2).

This can be seen as a form of intuiting. Thus, the results from this study can contribute to increased knowledge on individual level and to an enhanced ability to see patterns and possibilities within the topic of integrated pellet production and CHP plants.

4.3.2 Interpreting

At Stockholm Exergi, respondents describe having regular meetings between students and thesis advisors. One interviewee stated:

> If you are a thesis advisor, you have fairly regular meetings. (Respondent 2).

It is also common that master's thesis projects induce questions both from students to employees and between colleagues. For example, one interviewee mentioned:

> When I have been thesis advisor, I have asked several colleagues about such things that I do not know so much about. (Respondent 2).

These kinds of questions between colleagues also create possibilities for organizational learning. Thus, this study can contribute to that knowledge of integrating pellet production is taken from individual level to a shared understanding on group level. Moreover, at the end of a master's thesis project at Stockholm Exergi there is a final presentation for selected employees. That is a viable way to interpret knowledge from individual level to group level. Moreover, an interviewee said:

> If a discussion occurs regarding a topic that has been covered in a master's thesis report, a thesis supervisor can share the report with a colleague. (Respondent 2).

In that way, there is a possibility for organizational learning in terms of interpreting even after the project is finished. Although, this is dependent on whether the people that attend the presentation remain at the company. Hence, the techno-economic result of this thesis can create possibilities for interpreting knowledge during meetings with the thesis advisor, through questions, at the final presentation and through conversations between colleagues.

4.3.3 Integrating

Regarding integrating, one interviewee described a scenario where a thesis advisor brought up findings from an ongoing master's thesis project to their unit meeting and recollects:

> I think we invited [the thesis student] to present [at the unit meeting] at some point. (Respondent 3).

By presenting and discussing results from a master's thesis project in the context of a unit meeting, opportunities for organizational learning can emerge, as this presentation and subsequent discussions could influence decisions affecting the organization. This study can contribute to organizational learning if its findings are brought up in meetings regarding decisions concerning further investigations in integrating pellet production at Bristaverket.

However, responses indicated that thesis students usually only present their findings during meetings with their advisor and during the final presentation, as none of the respondents knew about any other established activities or platforms for thesis students and colleagues at Stockholm Exergi. To further enhance integration with master’s thesis projects, Stockholm Exergi can take proactive steps, such as establishing regular forums or platforms where thesis students can present their findings to relevant departments or teams and engage in structured discussions with colleagues and advisors. Responses from the interviews indicate that discussions of master’s thesis projects do occur among colleagues, although the specifics of these discussions were not fully detailed. Establishing platforms for such discussions could potentially enhance engagement and integration.

4.3.4 Institutionalizing

Responses from interviews indicate a lack of clear connections regarding how findings from master’s thesis projects contribute to organizational learning through institutionalization at Stockholm Exergi. After the completion of a master’s thesis project and the final presentation, there appears to be a lack of established routines regarding utilization of findings of the project. One interviewee noted:

> We don't really have a portal like this or anything on the intranet. It might actually be a good idea to have a centralized collection of master’s thesis projects and links to what has been published, along with any presentations that have been developed. (Respondent 1).

Two out of three interviewees mentioned discussing previous master’s thesis projects after their completion. One of them highlighted instances where previous thesis students were hired as consultants. However, this informal approach suggests a potential demand for a more structured way to collect and organize findings from master’s thesis projects. In addressing this gap, suggestions for establishing a centralized platform or repository for master’s thesis project findings, publications, and presentations emerge. Such a system could facilitate institutionalized organizational learning through accessibility of insights generated through this, and upcoming, master’s thesis projects.

4.3.5 Commitment from Thesis Advisor

A recurrent theme in the interviews is that the engagement from the thesis advisor is of great importance. One interviewee formulated that:

> So, this is kind of a key thing that I've observed. You should bring in thesis students to get help and solve problems, because that's when you'll get answers to questions, as it's then that you'll get engagement from the thesis advisor at the company. (Respondent 3).

Thus, the results from a master's thesis will be spread within individuals and groups of the organization if there is a commitment to the subject from the thesis advisor. For the results of this study to create possibilities for learning, engagement from the thesis advisor is important.

5 Discussion

In this section, the results are discussed and contrasted against previous research and alternative solutions. First, the techno-economic results are compared with previous research, then alternative technical solutions are discussed, and finally possibilities for organizational learning are discussed.

5.1 Comparison of Techno-Economic Results

The results indicate that integration of pellet production at Bristaverket is technically feasible and economically profitable. The specific pellet production cost of 2,223 SEK/t_{pellet} can be compared to 1,672 SEK/t_{pellet} and 1,509 SEK/t_{pellet} presented in Thek & Obernberger (2004) and Song et al. (2011) respectively. The values are converted to today's monetary value and to SEK. In that manner, the specific pellet production cost is higher than similar plants. However, the financial metrics of the future pellet plant indicate that the investment is highly profitable, with an NPV of 270 MSEK. This may depend on the assumption that the pellet plant only operates when it is profitable, with the constraint that an extra cost is added every time the plant is turned on or off. In actuality, it might be difficult to anticipate when the plant will operate with profit. Therefore, operating the plant as modeled might not be possible. Moreover, the investment cost tends to exceed the estimated value. In Appendix 4, the financial results, where the investment cost is multiplied by four, are presented. Additionally, a limitation in this study is to only consider the process at Bristaverket and therefore the cost for transportation and storage of pellets is not included. Furthermore, the high NPV may depend on the assumed pellet price. In Appendix 5, the results when the pellet price is assumed to be 450 SEK/MWh, instead of 600 SEK/MWh, are presented.

The financial results for the 2020 and 2023 scenario show a more varied indication of the profitability of integrating pellet production to Bristaverket, with a NPV of -1 MSEK and 88 MSEK respectively. The input data used for these historical metrics are taken from Energimyndighetens statistics of prices of processed wood products. These prices include pellets but does not differentiate pellets from other processed wood products such as briquettes. Therefore, it is probable that these prices are lower than the actual pellet prices. Despite potential inaccuracies, Energimyndigheten's prices are utilized because they represent the most reliable and broadly verified data available on pellet prices. However, the assumptions of future prices made in the scenario for a future pellet plant are also probable to differ from the actual future prices. Moreover, the increase in NPV between 2020 and 2023 may depend on the absence of Russian and Belarusian pellets on the market during 2023 (Energimyndigheten, 2023).

5.2 Alternative Technical Solutions

A starting point of this study was that pellet production at Bristaverket could improve resource and energy efficiency. The selected dryer has a heat demand of 4 MW, which is a small part of the total capacity of Brista 1 and Brista 2. Because of this, all excess heating potential is not utilized. Therefore, an alternative technical solution would be to dimension a larger dryer. In Appendix 6, the techno-economic results for the process with a 11 MW dryer can be seen. The used heating potential from Brista 1 and Brista 2 increases from 26.7 to 69.8 GWh. The specific pellet production cost and the annual operation time is approximately the same. Although, the proportion of heat produced by the electrical heater increases. Another alternative is to simulate a pellet plant that operates only when there is sufficient heating potential from Brista 1 and Brista 2, in contrast to operate only when profitable. This leads to the techno-economic results presented in Appendix 7. It yields a lower specific pellet production cost. Although, the annual operating time decreases to around 23%, which significantly reduces the NPV and IRR of the investment.

Moreover, the use of an electrical heater can be discussed. In the results, it is shown to be profitable to operate the plant during periods where all heat is produced by the electrical heater. However, the overall techno-economic performance would not be improved if operating the pellet plant only using the electrical heater (see Appendix 8). This indicates that it is desirable to use excess heat from Brista 1 and Brista 2. Therefore, an alternative technical solution would be to use heat from the district heating production at times when there is no excess heating potential. That would imply a change in operation of Brista 1 and Brista 2, which affect the production planning of the northwestern district heating network. The production planning of the northwestern district heating network would also depend on how the integrated pellet production affects the EPK. Future exploration in these directions could lead to more resource efficient solutions, as well as enabling the possibility to explore pellet production of larger scale.

A further technical aspect to discuss is the choice of dryer. The water-heated belt dryer uses low-quality energy when fueled by heat from Brista 1 and Brista 2. However, the results indicate that the pellet plant is profitable even during periods when heat is provided by the electrical heater. From a resource efficiency and energy quality perspective, this is not optimal as the electrical heater uses considerable amounts of high-quality electricity (Wall, 1990). One alternative solution of interest is employing a dryer heated by steam. Steam dryers could have the opportunity for heat recovery through recondensation of the evaporated water, depending on type and manufacturer of the dryer. This heat can be utilized for district heating, making a more energy efficient solution. However, drawbacks include higher investment costs and potential reduction in power production from the CHP plant in cases where portions of the steam are diverted to the dryer instead of the turbine.

The sensitivity analysis shows that the economic performance of the pellet plant is primarily sensitive to changes in pellet prices. Thus, variation in pellet prices is a risk in integrating pellet production at

Bristaverket. According to Thrän et al. (2018), projections for the future pellet market are difficult and are strongly dependent on policy frameworks. Subsequently, future pellet prices depend on the development of policies and the perception of pellets as a sustainable energy source. Furthermore, the pellets concerned in this study are assumed to be used at the pellet-fueled CHP plant Hässelbyverket. However, Hässelbyverket requires pellets of high-quality standards, which the simulated pellets do not fulfill. Investing in upgrading Hässelbyverket to accept lower quality pellets could be a viable solution. Another suggestion is to examine potential strategies for reducing ash and nitrogen levels to enhance pellet quality and expand possible areas of use.

5.3 Discussion of Possibilities for Organizational Learning

To explore how the techno-economic results of this study can create possibilities for organizational learning at Stockholm Exergi a thematic analysis and the 4I-framework were utilized. As mentioned in Section 2.5, the 4I-framework can be used across various research contexts. This study was conducted as a case study to gain specific contextual insights of possibilities for organizational learning using selected parts of the 4I-framework, whereas Schilling & Kluge (2009) contrastingly conducted a literature review to develop a general theoretical foundation for barriers to organizational learning using an extension of the 4I-framework.

Possibilities for organizational learning were found within intuiting, in form of increased knowledge about integrated pellet production, and within interpreting and integrating, in form of spreading knowledge during meetings, through questions, at the final presentation, and through conversations between colleagues. However, no clear opportunities for institutionalization were found as Stockholm Exergi lacks established routines for utilizing findings of master's thesis projects. In the study conducted by Schilling & Kluge (2009), it was found that one barrier for organizational learning on the institutional level is the absence of clear responsibility for implementation or storage of necessary resources to support such learning. This barrier could possibly explain the lack of established routines at Stockholm Exergi. While this is speculative, it highlights the potential value of integrating results from this study with broader theoretical frameworks to better understand and address learning obstacles.

As with all qualitative research, different data collection methods, data analysis methods, and theoretical frameworks could have altered the findings in various ways. In this case, data collection was limited to a few interviews with previous thesis advisors at Stockholm Exergi, potentially providing a limited perspective on how master's thesis projects create possibilities for organizational learning. Furthermore, the fact that the researchers themselves were master's thesis students might have influenced the interviewees' answers through the interviewer effect, where the characteristics of the interviewers affect the responses (Denscombe, 2018). The researchers' biases and theoretical viewpoints could also have impacted the results, as numerous decisions and judgments were made throughout the thematic analysis process (Braun & Clarke, 2006). In this case the theoretical foundations of a social learning perspective and selected parts of the 4I-framework (Crossan et al., 1999) provided specific direction rather than comprehensive coverage of how master's thesis projects create possibilities for organizational learning at Stockholm Exergi.

It would be interesting to further study how master's thesis projects create possibilities for organizational learning at Stockholm Exergi by interviewing employees who are not directly involved with master's thesis projects. Coupled with an investigation of what previous master's thesis projects have led to in terms of decision-making, a more nuanced and comprehensive depiction of the role of master's thesis projects at Stockholm Exergi could be achieved. Moreover, future research could explore organizational learning beyond master's thesis projects, focusing on knowledge management as a more practice-focused alternative. Such studies could aim to identify barriers hindering organizational learning and propose strategies to overcome them. Alternatively, research could explore the mechanics, motivation, and circumstances influencing how knowledge is shared throughout the organization.

6 Conclusion

The aim of this thesis was to develop a suitable technical process for integration of pellet production at Bristaverket, to evaluate the techno-economic performance of such a plant and examine in which ways the techno-economic results can create possibilities for organizational learning at Stockholm Exergi. The selected technical process is presented in Figure 4 and it integrates pellet production through heat transfer from Bristaverket to a 4 MW water-heated belt dryer. This yields a production of 50.4 kilotons of pellets per year and the plant operates 85% of the year. The annual energy demand is 36.1 GWh which implies a specific energy consumption of 717 kWh/t_{pellet}. The pellets achieve the classification I3 for industrial usage, due to high levels of ash and nitrogen. The specific production cost amounts to 2,218 SEK/t_{pellet}. The investment analysis was executed for three scenarios: a future scenario, a 2020 scenario and a 2023 scenario. The future scenario yielded a NPV of 270 MSEK, an IRR of 74%, and a PBT of 1.4 years. For the 2020 scenario and 2023 scenario, the NPV was -1 MSEK and 88 MSEK, the IRR was 8% and 32%, and the PBT was 9.5 years and 3.3 years respectively. The investment is more sensitive to changes in operational costs than in investment costs, foremost to changes in pellet and wood chip prices.

The specific production cost is slightly higher than in similar studies. Despite that, the results indicate that it is a profitable investment. This implicates that it is worth to continue to investigate in integration of pellet production at Stockholm Exergi. A limitation of the study was to only examine the process at Bristaverket. This entailed that the relation between changes in operation at Bristaverket and the northwestern district heating network was not investigated. Thus, a proposition for future studies is to examine a suitable technical process where the heat is taken from the district heating network, instead of using an electrical heater. It would also be interesting to analyze the techno-economic performance if a steam dryer with recondensation is used.

The techno-economic results from this study can contribute to organizational learning at Stockholm Exergi in several ways. It can increase the intuition within individuals regarding the topic. Further, knowledge can be interpreted and integrated during meetings, through questions, at the final presentation, and through conversations between colleagues. To further increase the possibilities for organizational learning Stockholm Exergi could establish routines for knowledge sharing and discussions during and after thesis projects. It was also concluded that the commitment from the thesis advisor is of great importance for the learning process. The scope of the qualitative research was limited to interviewing thesis advisors. A suggestion for future studies is to include other employees at Stockholm Exergi in a similar study to examine the possibilities for organizational learning on a broader scale. It would also be interesting to implement other frameworks to analyze the organizational learning at Stockholm Exergi.

References

Alavi, M., & Denford, J. S. (2012). Knowledge Management: Process, Practice, and Web 2.0. In *Handbook of Organizational Learning and Knowledge Management* (pp. 105–124). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781119207245.ch6

Alvehus, J. (2013). *Skriva uppsats med kvalitativ metod—En handbok* (2nd ed.). Liber AB.

Anderson, J.-O., & Toffolo, A. (2013). Improving energy efficiency of sawmill industrial sites by integration with pellet and CHP plants. *Applied Energy*, *111*, 791–800. https://doi.org/10.1016/j.apenergy.2013.05.066

Arctic Paper. (2023, August 9). *Press release—Arctic Paper invests SEK 285 million in bioenergy in Grycksbo*. https://www.arcticpapergroup.com/globalassets/arcticpapergroup.com/07-news/01-regulatory/2023/arp-pm-expanding-biofuel-boiler-in-grycksbo-eng.pdf

Ashrafizadeh, S. A., & Tan, Z. (2018). *Mass and Energy Balances: Basic Principles for Calculation, Design, and Optimization of Macro/Nano Systems* (1st ed. 2018). Springer International Publishing : Imprint: Springer. https://doi.org/10.1007/978-3-319-72290-0

Bioenergitidningen. (2023). Pellets i Sverige 2023. *Bioenergi Nr 2-2023*.

Bolla, S., & Flach, B. (2023). *Wood Pellets Annual* (E42023-0034). United States Department of Agriculture Foreign Agricultual Service. https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Wood%20Pellets%20Annual_The%20Hague_European%20Union_E42023-0034.pdf

Brandi, U., & Elkjaer, B. (2012). Organizational Learning Viewed from a Social Learning Perspective. In *Handbook of Organizational Learning and Knowledge Management* (pp. 21–41). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781119207245.ch2

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Burrows, A. (Ed.). (2009). *Chemistry3: Introducing inorganic, organic and physical chemistry*. Oxford University Press.

Crossan, M. M., & Berdrow, I. (2003). Organizational learning and strategic renewal. *Strategic Management Journal*, *24*(11), 1087–1105. https://doi.org/10.1002/smj.342

Crossan, M. M., Lane, H. W., & White, R. E. (1999). An Organizational Learning Framework: From Intuition to Institution. *The Academy of Management Review*, *24*(3), 522–537. https://doi.org/10.2307/259140

Denscombe, M. (2018). *Forskningshandboken: För småskaliga forskningsprojekt inom samhällsvetenskaperna* (P. Larson, Trans.; Fjärde upplagan). Studentlitteratur.

Easterby-Smith, M., & Lyles, M. A. (2012). The Evolving Field of Organizational Learning and Knowledge Management. In *Handbook of Organizational Learning and Knowledge Management* (pp. 1–20). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781119207245.ch1

Energimyndigheten. (2023, September 5). *Läget på energimarknaderna—Biodrivmedel och fasta biobränslen*. https://www.energimyndigheten.se/4a4fb8/globalassets/om-oss/lagesrapporter/biobransle/2023/laget-pa-energimarknaderna---biodrivmedel-och-fasta-biobranslen---september-2023.pdf

Energimyndigheten. (2024, January 26). *Trädbränsle-, torv- och avfallspriser*. https://www.energimyndigheten.se/statistik/den-officiella-statistiken/statistikprodukter/tradbransle--och-torvpriser/

Ertas, A. (2018). *Transdisciplinary engineering design process* (First edition.). Wiley.

European Commission. (2021, July 14). *The European Green Deal—European Commission*. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

European Commission. (2022, April 8). *Energy and the Green Deal*. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/energy-and-green-deal_en

Frederiksen, S. (2014). *Fjärrvärme och fjärrkyla* (första upplagan). Studentlitteratur.

Gherardi, S. (2012). Organizational Learning: The Sociology of Practice. In *Handbook of Organizational Learning and Knowledge Management* (pp. 43–65). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781119207245.ch3

Göteborgs Stadshus AB. (2023, June 12). *Yttrande över hemställan från Göteborg Energi AB avseende inriktning att investera i en pelletspanna på Riskullaområdet i Mölndals kommun*. https://goteborg.se/wps/PA_Pabolagshandlingar/file?id=45954

Haque, N., & Somerville, M. (2013). Techno-Economic and Environmental Evaluation of Biomass Dryer. *Procedia Engineering*, *56*, 650–655. https://doi.org/10.1016/j.proeng.2013.03.173

Kaur, N., & Hirudayaraj, M. (2021). The Role of Leader Emotional Intelligence in Organizational Learning: A literature Review Using 4I Framework. *New Horizons in Adult Education and Human Resource Development*, *33*(1), 51–68. https://doi.org/10.1002/nha3.20305

Kiger, M. E., & Varpio, L. (2020). Thematic analysis of qualitative data: AMEE Guide No. 131. *Medical Teacher*, *42*(8), 846–854. https://doi.org/10.1080/0142159X.2020.1755030

Kocsis, Z., & Csanády, E. (2019). *Theory and practice of wood pellet production*. Springer.

Kohl, T., Laukkanen, T., Järvinen, M., & Fogelholm, C.-J. (2013). Energetic and environmental performance of three biomass upgrading processes integrated with a CHP plant. *Applied Energy*, *107*, 124–134. https://doi.org/10.1016/j.apenergy.2013.02.021

Kumar, N., & Sharma, H. K. (2022). Drying. In H. K. Sharma & N. Kumar (Eds.), *Agro-Processing and Food Engineering: Operational and Application Aspects* (pp. 147–215). Springer. https://doi.org/10.1007/978-981-16-7289-7_5

Lantz, B., Löfsten, H., & Isaksson, A. (2018). *Industriell ekonomi—Grundläggande ekonomisk analys* (2:3). Studentlitteratur.

Lawrence, T. B., Mauws, M. K., Dyck, B., & Kleysen, R. F. (2005). The Politics of Organizational Learning: Integrating Power into the 4i Framework. *Academy of Management Review*, *30*(1), 180–191. https://doi.org/10.5465/AMR.2005.15281451

Nationalencyklopedin. (n.d.). *Energikombinat*. Retrieved June 3, 2024, from https://www.ne.se/uppslagsverk/encyklopedi/l%C3%A5ng/energikombinat

NCC. (2024, January 29). *Pressmeddelande—NCC bygger Moelvens nya pelletsfabrik i Karlskoga*. https://mb.cision.com/Main/197/3916590/2565688.pdf

Nielsen, J. A., Mathiassen, L., & Hansen, A. M. (2018). Exploration and Exploitation in Organizational Learning: A Critical Application of the 4I Model. *British Journal of Management*, *29*(4), 835–850. https://doi.org/10.1111/1467-8551.12324

Peduzzi, E., Boissonnet, G., & Maréchal, F. (2016). Biomass modelling: Estimating thermodynamic properties from the elemental composition. *Fuel*, *181*, 207–217. https://doi.org/10.1016/j.fuel.2016.04.111

Schilling, J., & Kluge, A. (2009). Barriers to organizational learning: An integration of theory and research. *International Journal of Management Reviews*, *11*(3), 337–360. https://doi.org/10.1111/j.1468-2370.2008.00242.x

Shipton, H., & Defillippi, R. (2012). Psychological Perspectives in Organizational Learning: A Four-Quadrant Approach. In *Handbook of Organizational Learning and Knowledge Management* (pp. 67–81). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781119207245.ch4

Siopi, A., Bäfver, L., & Andersen, E. (2022). *Ny biobränsleanläggning på fastigheten Sävenäs 170:9*. Göteborg Energi AB. https://www.goteborgenergi.se/Files/Webb20/Kategoriserad%20information/Informationsmaterial/%c3%96vriga%20dokument/Samr%c3%a5dshandling%20S%c3%a4ven%c3%a4s.pdf?TS=637825203850536715

Siopi, A., Bäfver, L., Johansson, E., & Andersen, E. (2022). *Förbränningsanläggning på fastigheten Sörred 12:37*. Göteborg Energi AB. https://www.goteborgenergi.se/Files/Webb20/Kategoriserad%20information/Informationsmaterial/%c3%96vriga%20dokument/Samr%c3%a5dshandling%20S%c3%b6rred.pdf?TS=637973546893583759

Skatteverket. (n.d.). *Aktiebolag* [Text]. Retrieved May 22, 2024, from https://www.skatteverket.se/foretag/drivaforetag/foretagsformer/aktiebolag.4.5c13cb6b1198121ee8580002546.html

Skatteverket. (2023, October 30). *Ändrad skattesats för el från 1 januari 2024*. https://www.skatteverket.se/foretag/skatterochavdrag/punktskatter/nyheterinompunktskatter/2023/nyheterinompunktskatter/andradskattesatsforelfran1januari2024.5.7d2cc99c18b24bd07c38602.html

SMHI. (2024). *Ladda ner meteorologiska observationer | SMHI*. https://www.smhi.se/data/meteorologi/ladda-ner-meteorologiska-observationer#param=airtemperatureInstant,stations=core

Song, H., Dotzauer, E., Thorin, E., & Yan, J. (2011). Annual performance analysis and comparison of pellet production integrated with an existing combined heat and power plant. *Bioresource Technology*, *102*(10), 6317–6325. https://doi.org/10.1016/j.biortech.2011.02.042

Stenström, S. (2017). Drying of biofuels from the forest—A review. *Drying Technology*, *35*(10), 1167–1181. Scopus. https://doi.org/10.1080/07373937.2016.1258571

Stockholm Exergi. (n.d.). *Fakta om oss*. Retrieved May 3, 2024, from https://www.stockholmexergi.se/om-stockholm-exergi/varma-fakta-om-stockholm-exergi/

Sundararaj, R. (Ed.). (2022). *Science of wood degradation and its protection*. Springer.

Swedish Standards Institute [SIS]. (2021a, May 31). *Standard - Fasta biobränslen - Specifikationer och klassificering - Del 1: Allmänna krav (ISO 17225-1:2021) SS-EN ISO 17225-1:2021*. Svenska institutet för standarder, SIS. https://www.sis.se/produkter/energi--och-varmeoverforing-2feba892/biologiska-och-alternativa-energikallor/ss-en-iso-17225-12021/

Swedish Standards Institute [SIS]. (2021b, May 31). *Standard - Fasta biobränslen - Specifikationer och klassificering - Del 2: Träpellets (ISO 17225-2:2021) SS-EN ISO 17225-2:2021*. Svenska institutet för standarder, SIS. https://www.sis.se/produkter/energi--och-varmeoverforing-2feba892/biologiska-och-alternativa-energikallor/ss-en-iso-17225-22021/

Thek, G., & Obernberger, I. (2004). Wood pellet production costs under Austrian and in comparison to Swedish framework conditions. *Biomass and Bioenergy*, *27*(6), 671–693. https://doi.org/10.1016/j.biombioe.2003.07.007

Thrän, D., Schaubach, K., Peetz, D., Junginger, M., Mai-Moulin, T., Schipfer, F., Olsson, O., & Lamers, P. (2018). The dynamics of the global wood pellet markets and trade - key regions, developments and impact factors: The rise of the global wood pellet market, the intensification of trade and future challenges scrutinized in detail. *Biofuels, Bioproducts and Biorefining*, *13*. https://doi.org/10.1002/bbb.1910

Tsang, E. W. K. (1997). Organizational Learning and the Learning Organization: A Dichotomy Between Descriptive and Prescriptive Research. *Human Relations*, *50*(1), 73–89. https://doi.org/10.1177/001872679705000104

UNDP. (n.d.). *Goal 7: Affordable and clean energy | Sustainable Development Goals | United Nations Development Programme*. UNDP. Retrieved April 11, 2024, from https://www.undp.org/sustainable-development-goals/affordable-and-clean-energy

Vera, D., Crossan, M., & Apaydin, M. (2012). A Framework for Integrating Organizational Learning, Knowledge, Capabilities, and Absorptive Capacity. In *Handbook of Organizational Learning and Knowledge Management* (pp. 153–180). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781119207245.ch8

Vetenskapsrådet. (2002). *Forskningsetiska principer inom humanistisk-samhällsvetenskaplig forskning*. Vetenskapsrådet.

Viable Cities. (2022). *Klimatkontrakt 2030—Mellan Stockholms stad och myndigheterna Energimyndigheten, Vinnova, Formas, Tillväxtverket, Trafikverket, Naturvårdsverket samt Viable Cities.* https://start.stockholm/globalassets/aktuellt/nyheter/viable-cities-klimatkontrakt-stockholm-final.pdf

Vigants, H., Priedniece, V., Veidenbergs, I., & Blumberga, D. (2017). Process Optimization for Pellets Production. *Energy Procedia*, *113*, 396–402. https://doi.org/10.1016/j.egypro.2017.04.021

Wahlund, B., Yan, J., & Westermark, M. (2002). A total energy system of fuel upgrading by drying biomass feedstock for cogeneration: A case study of Skellefteå bioenergy combine. *Biomass and Bioenergy*, *23*(4), 271–281. https://doi.org/10.1016/S0961-9534(02)00055-7

Wall, G. (1990). Exergy conversion in the Japanese society. *Energy*, *15*(5), 435–444. https://doi.org/10.1016/0360-5442(90)90040-9

World Bioenergy Association. (2014). *Pellets – A fast growing energy carrier*. World Bioenergy Association. https://www.worldbioenergy.org/uploads/Factsheet%20-%20Pellets.pdf

Yi, J., Li, X., He, J., & Duan, X. (2020). Drying efficiency and product quality of biomass drying: A review. *Drying Technology*, *38*(15), 2039–2054. https://doi.org/10.1080/07373937.2019.1628772

Yrjölä, J. (2004). Production of dry wood chips in connection with a district heating plant. *Thermal Science - THERM SCI*, *8*, 143–155. https://doi.org/10.2298/TSCI0402143Y

Zuberi, J., Hasanbeigi, A., & Morrow, W. (2022). Electrification of industrial boilers in the USA: Potentials, challenges, and policy implications. *Energy Efficiency*, *15*. https://doi.org/10.1007/s12053-022-10079-0

Appendix 1

In this appendix, assumptions and data used in the calculations are presented.

Table 11
Assumptions regarding fees and taxes.

Parameter	Value	Unit	Reference
Net fee	21	SEK/MWh	(F. Birath, personal communication, March 1, 2024)
Energy tax	428	SEK/MWh	(Skatteverket, 2023)

Table 12
Assumptions regarding district heating and waste costs.

Parameter	Value	Unit	Reference
Waste cost	-161	SEK/MWh	(Energimyndigheten, 2024)
Heat Cost Deduction*	40	SEK/MWh	(F. Birath, personal communication, March 1, 2024)

*This cost is deducted from the regular district heating cost when calculating the cost of heat from Brista 1. This is done as it is assumed that parts of the operational and maintenance costs related to district heating can be avoided as the pellet plant utilizing the heat is integrated with Brista 1.

Table 13
Assumptions regarding investment costs, calculated using Equation (7).

Major equipment	Inv_L (EUR)	P_L (Plant Capacity)	Reference
Dryer	500,000	26,280	(Thek & Obernberger, 2004)
Hammer mill	360,000	87,600	(Thek & Obernberger, 2004)
Ring die	600,000	87,600	(Thek & Obernberger, 2004)
Cooling storage	240,000	87,600	(Thek & Obernberger, 2004)
Equipment data	435,000	87,600	(Thek & Obernberger, 2004)
Construction	870,000	87,600	(Thek & Obernberger, 2004)
Data processing	100,000	87,600	(Thek & Obernberger, 2004)

Table 14
Assumptions regarding the investment cost of the electrical heater.

Parameter	Specific investment cost	Unit	Reference
4 MW electrical heater	120	$/kW	(Zuberi et al., 2022)
11 MW electrical heater	100	$/kW	(Zuberi et al., 2022)

Table 15
Assumptions regarding electricity consumption of major process steps.

Process	Reference value	Scaling factor	Value	Unit	Reference
Drying	160	2.5	400	kW	(Thek & Obernberger, 2004)
Grinding	110	2.5	275	kW	(Thek & Obernberger, 2004)
Pelletizing	233	2.5	583	kW	(Thek & Obernberger, 2004)

Table 16
Used thermodynamic constants.

Thermodynamic Constant	Value	Unit	Reference
Molar heat capacity liquid water	75.3	J/(mol K)	(Burrows, 2009)
Molar heat capacity water vapor	33.6	J/(mol K)	(Burrows, 2009)
Molar weight water	18.015	g/mol	(Burrows, 2009)

Table 17
Assumptions regarding composition and calorimetric heat value of wood chips, dry basis.

Property	Value	Unit
C	50.2460	weight%
H	7.6151	weight%
O	39.3939	weight%
N	0.3935	weight%
S	0.0197	weight%
Cl	0.0098	weight%
Ash	2.3219	weight%
Calorimetric Heating Value (of dry substance)	20.2876	MJ/kg

Appendix 2

In this appendix, the questions that the semi-structured interviews were based on are presented.

The questions are translated into English. The questions were:

1. What is your role in relation to master’s thesis projects executed at Stockholm Exergi?
2. How are master’s theses initiated at Stockholm Exergi?
3. Does Stockholm Exergi organize any activities related to the master’s theses during the time the project is ongoing?
4. Have you participated in discussions about master’s theses while they are in progress?
5. How are the results from completed master’s theses presented to employees at Stockholm Exergi?
6. Have you participated in discussions about previous master’s theses after they have been completed?

Appendix 3

In this appendix, the techno-economic results of the simulated integrated pellet production, if it existed during the period 2020–2023, are presented. Quarterly wood chip and pellets prices from Energimyndigheten (2024) are used. Wood chip prices range between 190–351 SEK/MWh while pellet prices range between 301–484 SEK/MWh. Historical data are used for operation of Brista 1, Brista 2, and Hässelbyverket, electricity prices, and weather. The operation time of the pellet plant amounts to 75%, 46%, 40%, and 73% for 2020, 2021, 2022, and 2023 respectively. For visualization of plant operation and its energy consumption, see Figure 7 and Figure 8.

Figure 7

Energy consumption over 2020-2023. Daily time steps.

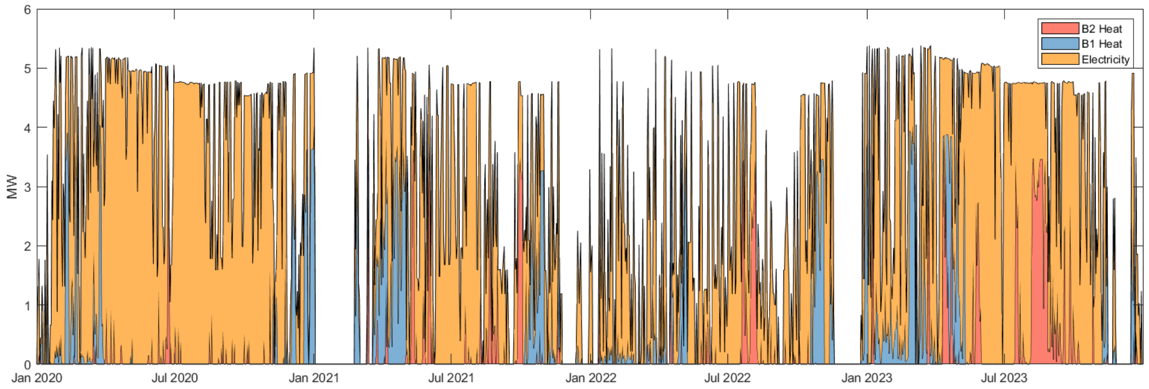


Figure 8

Energy consumption over 2020-2023. Weekly time steps for improved readability.

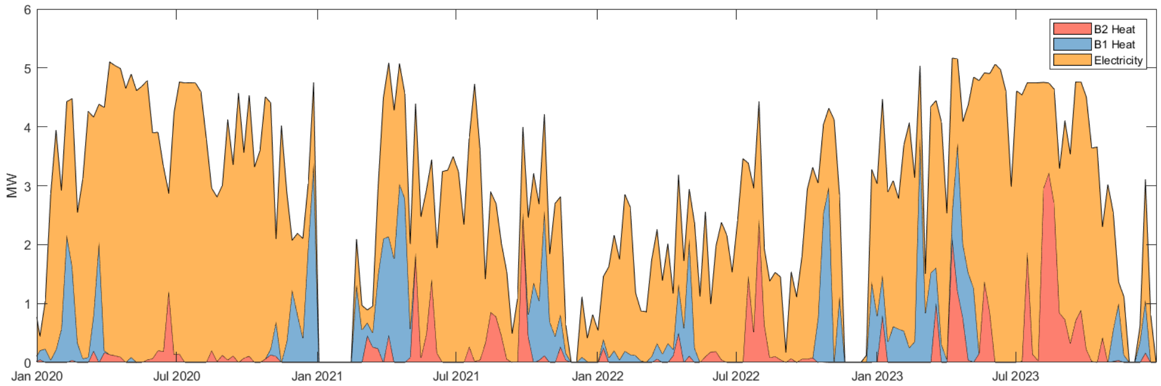


Table 18
Total mass of inlet and outlet substance flows, with related energy amounts.

	Mass (kiloton)				Energy* (GWh)			
Year	2020	2021	2022	2023	2020	2021	2022	2023
Wood chips inlet	68.9	40.6	35.1	67.5	228.2	134.9	116.9	222.8
Water outlet (evaporation)	23.9	14.0	12.1	23.6	14.9	8.7	7.5	14.7
Pellets outlet	45.0	26.6	23.0	43.9	228.2	134.9	116.9	222.8

*Heating value for wood chips and pellets. Condensation energy for water.

Table 19
Annual energy consumption by energy type.

	Annual energy consumption (GWh)			
Year	2020	2021	2022	2023
Heat	24.2	14.4	12.8	23.6
Electricity (electrical heater excluded)	8.5	5.1	4.6	8.3
Total	32.7	19.5	17.3	31.9

Table 20
Annual proportions of heat by source.

	Percentage (%)			
Year	2020	2021	2022	2023
Brista 1	11	27	19	15
Brista 2	3	14	9	17
Electrical heater	86	69	72	68

Table 21
Annual average specific energy demand and consumption for heat and electricity.

	Specific energy demand** (kWh/t_{pellet})				Specific energy consumption** (kWh/t_{pellet})			
Year	2020	2021	2022	2023	2020	2021	2022	2023
Heat	537	542	555	537	74	222	156	171
Electricity	190	193	198	188	652	512	597	554
Total*	726	735	752	725	726	735	752	725

*Variations in total energy demand and consumption for the different years are caused by added costs related to interrupting production. For example, production is interrupted more frequently in 2022 than in 2023 causing higher specific energy consumption.

**Differentiation between demand and consumption is done as the electrical heater could be classed as either heat or electricity. The dryer demands heat, but as the electrical heater provides part of the heat, electricity is consumed.

Table 22
Specific costs of producing one MWh and one ton of pellets for the simulated pellet plant, in terms of material and energy.

	Specific cost (SEK/MWh_{pellet})				Specific cost (SEK/t_{pellet})			
Year	2020	2021	2022	2023	2020	2021	2022	2023
Wood chips	198	191	212	298	1,005	968	1,073	1,509
Heat Brista 1	8	11	10	13	41	57	50	68
Heat Brista 2	-0	-2	-2	-3	-2	-12	-9	-15
Electricity	78	88	88	89	397	447	444	452
Total	284	388	308	397	1,440	1,460	1,558	2,014

Table 23
The total investment cost, operational cost, and revenue of the pellet plant.

	Value				Unit
Monetary Term	2020	2021	2022	2023	
Investment cost	46	46	46	46	MSEK
Operational cost	66	40	37	89	MSEK
Revenue	71	44	42	106	MSEK

Table 24
Financial metrics of the investment, based on data for the specific year 2020 to 2023 respectively.

	Value				Unit
Year	2020	2021	2022	2023	
Net Present Value (NPV)	-1	-8	-4	88	MSEK
Investment Return Rate (IRR)	8	5	6	32	%
Payback Time (PBT)	9.5	11.2	10.3	3.3	years

Appendix 4

In this appendix, the financial metrics for the investment are presented, with an investment cost four times bigger than in the results of this study, see Section 4.2.2. Other input parameters and conditions are the same as in the results, see Section 4.2.

Table 25
The total investment cost, operational cost, and revenue of the pellet plant.

Monetary Term	Value	Unit
Investment cost	185	MSEK
Operational cost	116	MSEK
Revenue	153	MSEK

Table 26
Financial metrics of the investment.

Financial Metric	Value	Unit
Net Present Value (NPV)	126	MSEK
Investment Return Rate (IRR)	17	%
Payback Time (PBT)	5.6	years

Appendix 5

In this appendix the techno-economic results are presented for the simulated plant with the same conditions and input parameters as in the results, Section 4.2, except that there the pellet price is set to 450 SEK/MWh rather than 600 SEK/MWh. This results in an operation time of 56%.

Figure 9

Energy consumption over the duration of the year. Daily time steps for improved readability.

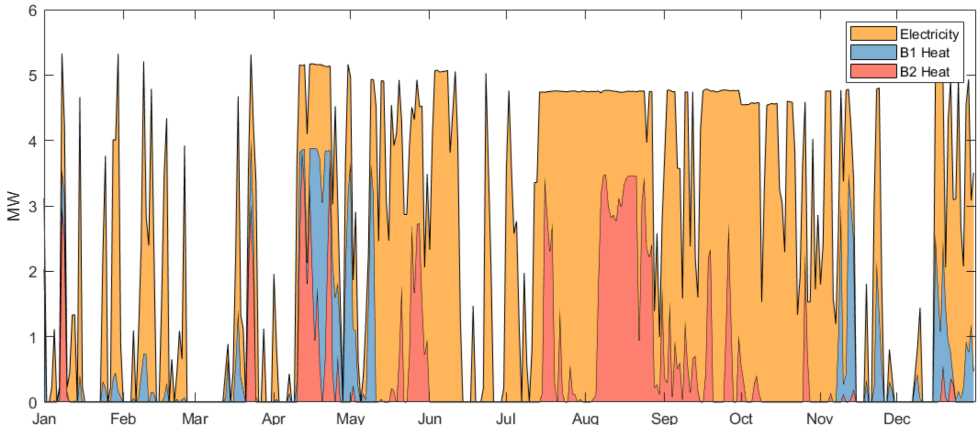


Table 27

Total mass of inlet and outlet substance flows, with related energy amounts.

Flow	Mass (kiloton)	Energy* (GWh)
Wood chips inlet	51.1	170.5
Water outlet (evaporation)	17.4	10.8
Pellets outlet	33.6	170.5

*Heating value for wood chips and pellets. Condensation energy for water.

Table 28

Total energy consumption by energy type.

Energy type	Energy consumption (GWh)
Heat	17.7
Electricity (electrical heater excluded)	6.3
Total	24.0

Table 29
Proportions of heat by source.

Heat source	Percentage (%)
Brista 1	13
Brista 2	22
Electrical heater	65

Table 30
Average specific energy demand and consumption for heat and electricity.

Energy type	Specific energy demand* (kWh/t_{pellet})	Specific energy consumption* (kWh/t_{pellet})
Heat	525	185
Electricity	189	529
Total	714	714

*Differentiation between demand and consumption is done as the electrical heater could be classed as either heat or electricity. The dryer demands heat, but as the electrical heater provides the heat, electricity is consumed.

Table 31
Specific costs of producing one MWh and one ton of pellets for the simulated pellet plant, in terms of material and energy.

Source	Specific cost (SEK/MWh_{pellet})	Specific cost (SEK/t_{pellet})
Wood chips	300	1,522
Heat Brista 1	8	39
Heat Brista 2	-4	-19
Electricity	89	450
Total	393	1,992

Table 32
The total investment cost, operational cost, and revenue of the pellet plant.

Monetary Term	Value	Unit
Investment cost	46	MSEK
Operational cost	68	MSEK
Revenue	82	MSEK

Table 33
Financial metrics of the investment.

Financial metric	Value	Unit
Net Present Value (NPV)	66	MSEK
Investment Return Rate (IRR)	27	%
Payback Time (PBT)	3.9	years

Appendix 6

In this appendix the techno-economic results are presented for the simulated plant with the same conditions and input parameters as in the results, Section 4.2, except for an increased dryer capacity from 4 MW to 11 MW. This results in an operation time of 82%.

Figure 10

Energy consumption over the duration of the year. Daily time steps for improved readability.

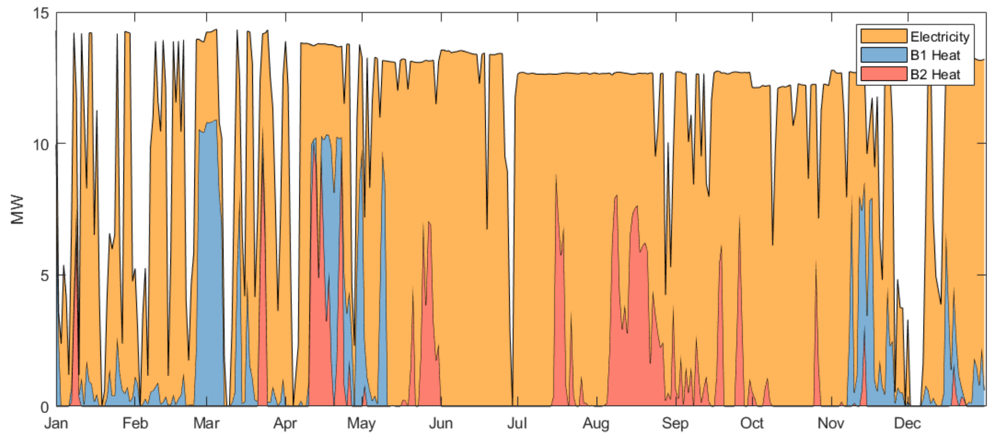


Table 34

Total mass of inlet and outlet substance flows, with related energy amounts.

Flow	Mass (kiloton)	Energy* (GWh)
Wood chips inlet	20.2	669.4
Water outlet (evaporation)	7.0	43.5
Pellets outlet	13.2	669.4

*Heating value for wood chips and pellets. Condensation energy for water.

Table 35

Total energy consumption by energy type.

Energy type	Energy consumption (GWh)
Heat	69.8
Electricity (electrical heater excluded)	24.6
Total	94.4

Table 36
Proportions of heat by source.

Heat source	Percentage (%)
Brista 1	13
Brista 2	12
Electrical heater	75

Table 37
Average specific energy demand and consumption for heat and electricity.

Energy type	Specific energy demand* (kWh/t_{pellet})	Specific energy consumption* (kWh/t_{pellet})
Heat	528	134
Electricity	187	581
Total	715	715

*Differentiation between demand and consumption is done as the electrical heater could be classed as either heat or electricity. The dryer demands heat, but as the electrical heater provides part of the heat, electricity is consumed.

Table 38
Specific costs of producing one MWh and one ton of pellets for the simulated pellet plant, in terms of material and energy.

Source	Specific cost (SEK/MWh_{pellet})	Specific cost (SEK/t_{pellet})
Wood chips	300	1,522
Heat Brista 1	12	62
Heat Brista 2	-2	-11
Electricity	130	660
Total	440	2,233

Table 39
The total investment cost, operational cost, and revenue of the pellet plant.

Monetary Term	Value	Unit
Investment cost	93	MSEK
Operational cost	297	MSEK
Revenue	402	MSEK

Table 40
Financial metrics of the investment.

Financial metric	Value	Unit
Net Present Value (NPV)	727	MSEK
Investment Return Rate (IRR)	95	%
Payback Time (PBT)	1.1	years

Appendix 7

In this appendix the techno-economic results are presented for the simulated plant with the same conditions and input parameters as in the results, Section 4.2, except that the pellet plant operates when there is sufficient heating potential (at least 70%) from Brista 1 and Brista 2, in contrast to operate only when profitable. This results in an operation time of 23%.

Figure 11

Energy consumption over the duration of the year. Daily time steps for improved readability.

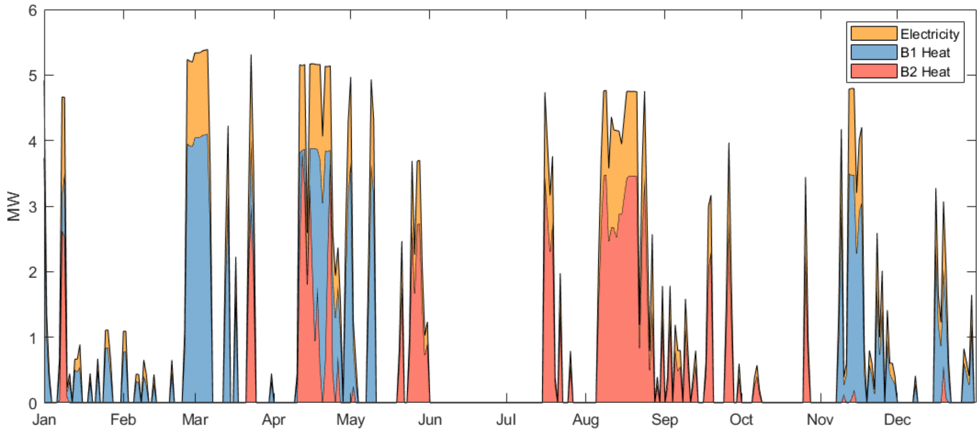


Table 41

Total mass of inlet and outlet substance flows, with related energy amounts.

Flow	Mass (kiloton)	Energy* (GWh)
Wood chips inlet	19.9	65.6
Water outlet (evaporation)	7.0	4.4
Pellets outlet	12.9	65.6

*Heating value for wood chips and pellets. Condensation energy for water.

Table 42

Total energy consumption by energy type.

Energy type	Energy consumption (GWh)
Heat	7.4
Electricity (electrical heater excluded)	2.6
Total	10.0

Table 43
Proportions of heat by source.

Heat source	Percentage (%)
Brista 1	49
Brista 2	49
Electrical heater	2

Table 44
Average specific energy demand and consumption for heat and electricity.

Energy type	Specific energy demand* (kWh/t_{pellet})	Specific energy consumption* (kWh/t_{pellet})
Heat	570	560
Electricity	199	209
Total	769	769

*Differentiation between demand and consumption is done as the electrical heater could be classed as either heat or electricity. The dryer demands heat, but as the electrical heater provides part of the heat, electricity is consumed.

Table 45
Specific costs of producing one MWh and one ton of pellets for the simulated pellet plant, in terms of material and energy.

Source	Specific cost (SEK/MWh_{pellet})	Specific cost (SEK/t_{pellet})
Wood chips	300	1522
Heat Brista 1	52	261
Heat Brista 2	-9	-47
Electricity	56	286
Total	399	2,022

Table 46
The total investment cost, operational cost, and revenue of the pellet plant.

Monetary Term	Value	Unit
Investment cost	46	MSEK
Operational cost	27	MSEK
Revenue	39	MSEK

Table 47
Financial metrics of the investment.

Financial metric	Value	Unit
Net Present Value (NPV)	54	MSEK
Investment Return Rate (IRR)	23	%
Payback Time (PBT)	4.4	years

Appendix 8

In this appendix the techno-economic results are presented for the simulated plant with the same conditions and input parameters as in the results, Section 4.2, except that there is no heat from Brista 1 and Brista 2. The pellet plant is driven solely on electricity, whenever profitable. This results in an operation time of 78%.

Figure 12

Energy consumption over the duration of the year. Daily time steps for improved readability.

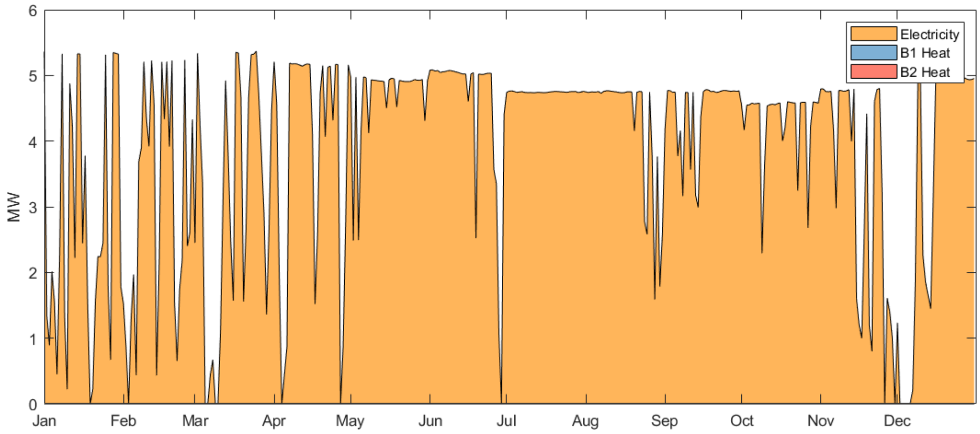


Table 48

Total mass of inlet and outlet substance flows, with related energy amounts.

Flow	Mass (kiloton)	Energy* (GWh)
Wood chips inlet	72.1	239.2
Water outlet (evaporation)	24.9	15.5
Pellets outlet	47.2	239.2

*Heating value for wood chips and pellets. Condensation energy for water.

Table 49

Total energy consumption by energy type.

Energy type	Energy consumption (GWh)
Heat	24.9
Electricity (electrical heater excluded)	8.8
Total	33.7

Table 50
Proportions of heat by source.

Heat source	Percentage (%)
Brista 1	0
Brista 2	0
Electrical heater	100

Table 51
Average specific energy demand and consumption for heat and electricity.

Energy type	Specific energy demand* (kWh/t_{pellet})	Specific energy consumption* (kWh/t_{pellet})
Heat	529	0
Electricity	187	716
Total	716	716

*Differentiation between demand and consumption is done as the electrical heater could be classed as either heat or electricity. The dryer demands heat, but as the electrical heater provides the heat, electricity is consumed.

Table 52
Specific costs of producing one MWh and one ton of pellets for the simulated pellet plant, in terms of material and energy.

Source	Specific cost (SEK/MWh_{pellet})	Specific cost (SEK/t_{pellet})
Wood chips	300	1,522
Heat Brista 1	0	0
Heat Brista 2	0	0
Electricity	153	778
Total	453	2,300

Table 53
The total investment cost, operational cost, and revenue of the pellet plant.

Monetary Term	Value	Unit
Investment cost	46	MSEK
Operational cost	109	MSEK
Revenue	144	MSEK

Table 54
Financial metrics of the investment.

Financial metric	Value	Unit
Net Present Value (NPV)	222	MSEK
Investment Return Rate (IRR)	63	%
Payback Time (PBT)	1.6	years