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Decarbonizing Heating at Municipal Wastewater Treatment Plants with Power-to-Heat

Techno-Economic and Environmental Evaluation of Heat
Pumps and Electric Boilers

MUHAMMED AHSAN IRSHAD HUSSAIN

KTH School of Industrial Engineering and Management
Energy Technology - TRITA-ITM-EX 2025:509
Division of Heat and Power Technology
SE-100 44 STOCKHOLM

Authors

Maih2@kth.se
Energy Technology
KTH Royal Institute of Technology

TRITA-ITM-EX 2025:509

Place for Project

KTH, Stockholm, Sweden
Oskarshamn Kommun, Oskarshamn, Sweden

Examiner

Jeevan Jayasuriya
Stockholm, Sweden
KTH Royal Institute of Technology

Supervisor

Jeevan Jayasuriya
KTH, Stockholm, Sweden

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**Decarbonizing Heating at Municipal Wastewater
Treatment Plants with Power-to-Heat**

Author Name: Muhammed Ahsan Irshad Hussain

Approved Date:2026.04.27	Examiner Jeevan Jayasuriya	Supervisor Jeevan Jayasuriya
TRITA: TRITA-ITM-EX 2025:509	Industrial Supervisor Marcus Westholm	Contact person Muhammed A. I. Hussain

Abstract

Municipal wastewater treatment plants (WWTPs) in cold climates often rely on fossil fuels to meet seasonal heating demands, especially during winter months when biogas production is insufficient. The Ernemar WWTP in Oskarshamn, Sweden, exemplifies this challenge—burning heating oil in winter while flaring surplus biogas during summer. This seasonal mismatch leads to avoidable greenhouse gas emissions and increased operational costs.

This thesis presents a techno-economic case study evaluating Power-to-Heat (P2H) technologies—specifically heat pumps and electric boilers—as low-carbon alternatives for decarbonizing heating at the Ernemar WWTP. Using real plant data, local climate conditions, and technology performance parameters, the study models different design configurations to simulate load sharing, investment needs, energy costs, and emission reductions.

The analysis identifies a hybrid solution—combining a 100kW heat pump for base and intermediate loads with a 150kW electric boiler for peak demands—as the most effective setup. This system can fully replace oil-based heating during winter, reducing CO₂ emissions by 98.1% and cutting operational costs by 74%, with a payback period of 6.55 years and a net present value of 319,464 SEK over ten years. Sensitivity analyses confirm the robustness of the solution under varying economic and technical assumptions.

The findings demonstrate that Power-to-Heat integration is both technically feasible and financially justifiable for small to mid-scale WWTPs, offering a practical pathway to support municipal decarbonization goals using commercially available technologies.

Keywords:

Power-to-Heat Technologies, Wastewater Treatment Plant, Heat Pump, Electric Boiler, Techno-Economic Assessment, Decarbonization

Sammanfattning

Kommunala avloppsreningsverk (WWTP) i kalla klimat är ofta beroende av fossila bränslen för att möta säsongsbetonade uppvärmningsbehov, särskilt under vintermånaderna när biogasproduktionen är otillräcklig. Ernemars reningsverk i Oskarshamn, Sverige, exemplifierar denna utmaning – att bränna eldningsolja på vintern medan överskottsbiogas facklas under sommaren. Denna säsongsbetonade skillnad leder till undvikbara utsläpp av växthusgaser och ökade driftskostnader.

Denna avhandling presenterar en teknoekonomisk fallstudie som utvärderar Power-to-Heat (P2H)-tekniker – specifikt värmepumpar och elpannor – som koldioxidnära alternativ för att minska koldioxidutsläppen vid Ernemars reningsverk. Med hjälp av verkliga anläggningsdata, lokala klimatförhållanden och teknikens prestandaparametrar modellerar studien olika designkonfigurationer för att simulera lastdelning, investeringsbehov, energikostnader och utsläppsminskningar.

Analysen identifierar en hybridlösning – att kombinera en 100 kW värmepump för bas- och mellanbelastning med en 150 kW elpanna för toppbehov – som den mest effektiva lösningen. Detta system kan helt ersätta oljebaserad uppvärmning under vintern, vilket minskar koldioxidutsläppen med över 98,2 % och driftskostnaderna med mer än 74 %, med en beräknad återbetalningstid på 6,5 år. Känslighetsanalyser bekräftar lösningens robusthet under varierande ekonomiska och tekniska antaganden.

Resultaten visar att Power-to-Heat-integration är både tekniskt genomförbar och ekonomiskt motiverad för små till medelstora avloppsreningsverk, och erbjuder en praktisk väg att stödja kommunala mål för minskade koldioxidutsläpp med hjälp av kommersiellt tillgängliga tekniker.

Nyckelord:

Power-to-Heat-teknik, Avloppsreningsverk, Värmepump, Elpanna, Tekno-ekonomisk analys, Avkarbonisering

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Lastly, I confirm that all figures and data included in this thesis are either original, permitted for use, or fall within public domain guidelines. No copyrighted material has been reproduced without appropriate permission.

Nomenclature, Acronyms, Symbols

CAPEX	Capital Expenditure
CHP	Combined Heat and Power
CO₂	Carbon Dioxide
COP	Coefficient of Performance
EB	Electric Boiler
HP	Heat Pump
LHV	Lower Heating Value
NPV	Net Present Value
OPEX	Operating Expenditure
P2H	Power-to-Heat
PE	Population Equivalent
SCADA	Supervisory Control and Data Acquisition
SEK	Swedish Krona
VFD	Variable Frequency Drive
WWTP	Wastewater Treatment Plant

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Chapter 1: Introduction

The Introduction chapter presents the overall context and motivation of the study, focusing on the operational and sustainability challenges at the Oskarshamn Ernemar Wastewater Treatment Plant (WWTP). It provides an overview of the plant's processes, biogas generation, and seasonal heating imbalance that leads to fossil oil dependency during colder months. The chapter outlines the research objectives, scope, and central questions guiding the investigation into replacing fossil-based heating through Power-to-Heat solutions such as electric boilers and heat pumps. It also introduces the techno-economic modeling approach developed in Microsoft Excel and concludes by outlining the structure of the thesis.

1.1 Introduction

Oskarshamn Ernemar Wastewater Treatment plant (WWTP) serves as the central treatment plant in Oskarshamn, Sweden, for about 20,000 population equivalents (PE) (Jayasuriya, 2024). It uses an activated sludge process with removal of nutrients (phosphorus and nitrogen) prior to releasing treated effluent to the Baltic Sea (Jayasuriya, 2024). Sludge from treatment is stabilized through mesophilic anaerobic digestion on site. Pre-treatment excess sludge is mechanically thickened from ~1% to 4–8% dry solids with polymer flocculant (Jayasuriya, 2024). This thickening process decreases volume to heat and increases digester retention time, enhancing gas yield and minimizing volume of residual biosolids to manage (Jayasuriya, 2024). Produced biogas (the approximately 60–65% methane, 35–40% CO₂ mixture) is briefly stored in a small gasholder (“gasholder”) and consumed in a boiler to generate hot water to heat digester and buildings of the plant (Jayasuriya, 2024). Biogas produced over and above real-time requirement is fed to a flare. On the contrary, if biogas supply does not meet heat requirement, a supplementary heat from an oil-fired backup boiler is supplied.

Operational records show that Ernemar WWTP is producing on the order of 650 Nm³ of biogas every day, amounting to approximately 237,000 Nm³ every year, and it burns approximately 15-16 m³ of fuel oil every year for supplementary heating (Jayasuriya, 2024). In terms of energy, the biogas returns approximately 1.4–1.5 GWh every year (assuming ~6 kWh/Nm³), while that of the oil is equivalent to ~15 MWh (assuming ~10 kWh/l for heating oil). Based on present operation, biogas production is usually in surplus to provide all the heating requirements of the plant for warmer months, but in colder months (November–March), biogas supply cannot meet additional heating requirements, with use of the oil boiler (Jayasuriya, 2024). Summer months, together with times of minimal heat requirements, mean that part of the biogas is surplus and must be flared due to a lack of space for storage. This seasonal equilibrium – surplus biogas in summer, deficit in winter – means that there is both wasted renewable energy

and minimal use of fossil fuels. **Figure 1** displays an estimated progression of biogas provision compared with heating requirement at Ernemar, showing times of surplus biogas (flared) in summer and use of oil in winter months when there is maximum heat requirement in excess of biogas provision.

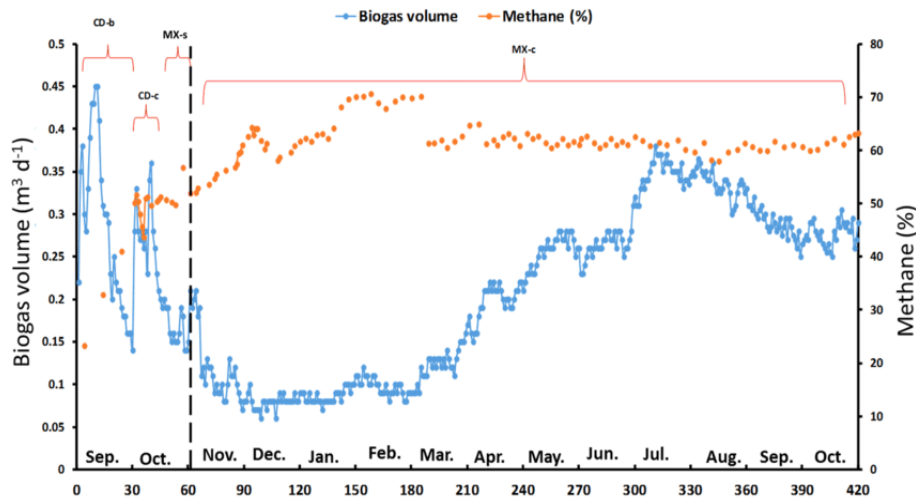


Figure 1: A figure representing the Intermittency of Biogas for Heating during the Colder Months in a WWTP

1.2 Thesis Objectives

Ernemar WWTP presently uses a small quantity of oil ($\approx 16 \text{ m}^3/\text{year}$) to supplement heating in winter, but flares excess biogas in summer due to supply–demand mismatch. The central issue is reducing or eliminating use of fossil oil by optimizing biogas production, storage, and utilization. To address this, the thesis pursues the following structured objectives:

- Objective 1 – Energy Demand Characterization: Quantify the seasonal heating deficit at Ernemar WWTP by analysing hourly SCADA data, oil consumption records, and effluent temperature profiles to establish the thermal load that must be displaced. This objective is addressed in Sections 4.4 and 5.1.
- Objective 2 – Technology Selection and Sizing: Evaluate and size Power-to-Heat technologies (heat pump and electric boiler) to meet the identified heating deficit, using an hourly COP model that accounts for real effluent temperature variations rather than a static assumption. This objective is addressed in Sections 3.2 and 5.6.
- Objective 3 – Techno-Economic Assessment: Develop a transparent Excel-based model to compare the lifecycle costs, emissions, and financial returns of the proposed P2H system against the oil-based baseline,

incorporating CAPEX, OPEX, payback period, and NPV calculations. This objective is addressed in Sections 5.3–5.5.

- Objective 4 – Sensitivity and Risk Analysis: Test the robustness of the economic case under plausible variations in oil price, electricity price, COP, carbon tax, heat pump sizing, and discount rate, and introduce multi-variable analyses (electricity price × COP matrix, carbon tax trajectory projections, and technology mix optimisation). This objective is addressed in Sections 5.7 and 5.8.
- Objective 5 – Operational Decision Support: Deliver a practical operator tool (Excel workbook and interactive HTML dashboard) that enables plant personnel to evaluate scenarios, visualise load allocation, and make informed operational decisions using the Heat Exchanger (HEX) control valve data as a real-time demand proxy. This objective is addressed in Section 5.9.

1.3 Scope of the Work

This research is centered on the Ernemar WWTP in Oskarshamn, with a specific focus on meeting its internal heating demands during the colder months. The study primarily explores two pathways: storing excess biogas produced during the summer for later use in winter, and implementing P2H technologies — specifically electric boilers and heat pumps — to replace the current use of oil for heating.

While other solutions, such as recovering waste heat from the WWTP process, were initially considered, they have been excluded from this analysis. This is because previous attempts by the company to harness internal waste heat were unsuccessful. Although a potential solution from Alfa Laval has recently emerged, which may address these technical challenges, it is not explored in this report and is instead flagged for future investigation.

Additionally, the option of upgrading and using flared biogas as compressed natural gas (CNG) for vehicle fuel — a promising long-term opportunity — is also considered out of scope for this phase. This alternative would require a deeper technical and economic assessment of gas upgrading systems, including CO₂ and H₂S removal, and therefore falls outside the current focus on heating solutions.

1.4 Research Questions

This thesis investigates how oil dependency at the Oskarshamn WWTP can be eliminated by evaluating feasible alternatives such as Electric Boilers (EB) and Heat

Pumps. It compares these solutions in terms of cost, emissions, and energy performance, to guide future transition strategies for WWTPs in cold climates.

Main research question:

What is the most viable and sustainable method for replacing fossil-based heating at WWTPs facing seasonal biogas shortages?

Sub-questions:

1. What is the most cost-effective and technically feasible pathway to eliminate oil-fired heating at the Ernemar WWTP?
2. Can Power-to-Heat (P2H) technologies (heat pumps and electric boilers) meet the winter heating demand reliably?
3. What are the energy, cost, and emissions implications of integrating heat pumps and electric boilers into the current system?
4. Why is the electrification (P2H) approach more suitable than other alternatives (e.g., biogas upgrading, gas storage, or waste heat recovery) for a small WWTP like Ernemar?
5. How sensitive is the economic viability of the proposed solution to external variables such as oil price, electricity tariff, carbon tax, and financing conditions?
6. What is the optimal sizing of heat pump and electric boiler systems to balance Capital Expenditure (CAPEX) with operating cost and carbon savings?
7. How can the findings of this case study be generalized or adapted for other small-to-medium WWTPs facing similar challenges?
8. What data gaps or operational uncertainties present the biggest barriers to accurate energy modeling and investment decisions at small-scale WWTPs?

What role do policy mechanisms, such as carbon taxation or renewable electricity pricing, play in influencing the adoption of electrified heating in the water sector?

1.5 Overview of Research Methodology

- A techno-economic model was developed developed in Microsoft Excel in order to examine these options. Excel was selected because it is transparent and accessible to WWTP personnel as well as decision makers. Some of the key reasons that Excel is appropriate for this study are:
- Level of Transparency: Everything that is calculated (mass balances, energy balances, and cost calculations) is clearly delineated in worksheets so that stakeholders can track every step for themselves and review assumptions. This develops confidence in the output and facilitates simple auditing of the model.
- Ease of Use: Plant managers and engineers are accustomed to using spreadsheets, reducing the threshold to conducting "what-if" calculations. Inputs can be easily changed (e.g. sludge properties, fuel costs, equipment prices) by managers without advanced knowledge of the underlying software.

- **Flexibility:** It is possible to merge information from different sources (literature benchmarks, historical plant data), and easily extend it to incorporate additional scenarios. Special training is generally required for complex process models, but an Excel model can be extended or adjusted internally.
- **Affordability:** Excel is easily accessible and does not involve buying supplementary software packages or licenses, which supports the project's goal of an economical and didactic product.

1.6 Structure of the Thesis

Chapter 1 – Introduction:

Introduces the project context, problem statement, significance, and research objectives related to eliminating fossil-based heating at the Ernemar WWTP.

Chapter 2 – Background (Literature Review and Theoretical Context):

Summarizes existing studies on wastewater treatment, biogas utilization, seasonal heat imbalance, and Power-to-Heat technologies such as electric boilers and heat pumps.

Chapter 3 – Methodology and Tools:

Describes the methodological framework and Excel-based techno-economic model used to evaluate different renewable heating scenarios.

Chapter 4 – Data Collection and Analysis:

Presents operational data, input parameters, and analytical methods applied to assess the energy, cost, and emissions performance of proposed solutions.

Chapter 5 – Results and Evaluation:

Reports and compares scenario outcomes—baseline, biogas storage, electric boiler, and heat pump—along with sensitivity analyses for key variables.

Chapter 6 – Discussion, Conclusion, and Future Work:

Interprets the results, outlines key findings and implications for WWTP decarbonization, and suggests directions for further research.

Chapter 2: Background

2.1 Wastewater Treatment Plant Process

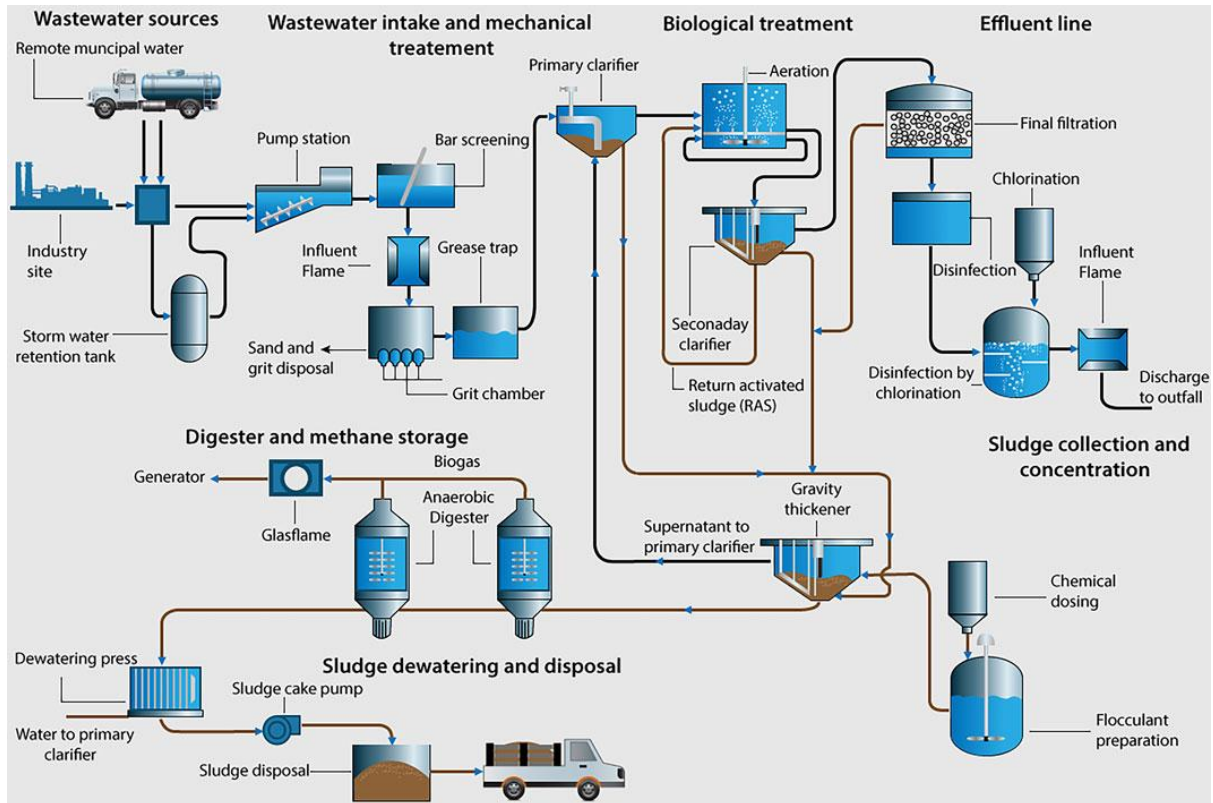


Figure 2: WWTP Process with Anaerobic Digestion (Robertson et al., 2018)

Figure 2 outlines the complete flow of a modern WWTP, capturing both treated water and biogas production pathways. The process begins with the collection of wastewater from households, industries, and stormwater runoff. These incoming flows are lifted via a pump station to ensure gravity-driven flow through the rest of the plant. This initial step is critical for maintaining hydraulic consistency, especially in flat terrain.

Once lifted, the water enters the preliminary treatment stage. Here, large debris like rags and plastics are removed using bar screens, while sand and grease are separated through grit chambers and grease traps. This prevents mechanical wear and clogging in later treatment units. Afterward, the water enters a primary clarifier, where gravity causes suspended solids to settle. These solids form what's known as primary sludge, which is collected for further treatment.

The clarified water then undergoes biological treatment in aeration tanks, where microorganisms consume dissolved organic matter. Most commonly, the activated sludge process is used—where air is bubbled through the tanks to supply oxygen,

fostering microbial activity. Once the microbes break down pollutants, the water moves into a secondary clarifier. Here, the biomass settles again, and a portion of it is returned to the aeration tank to keep the process going. This stage can remove more than 85% of the organic load in the water (Tchobanoglus et al., 2003).

After biological treatment, the water undergoes final polishing. This usually involves filtration and disinfection, most often with chlorine or UV, to remove pathogens. The clean water is then either released to nearby water bodies or reused for irrigation and industrial applications, depending on local regulations.

Meanwhile, the collected sludge from the primary and secondary stages is thickened and sent to anaerobic digesters. In these oxygen-free tanks, specialized bacteria break down organic material to produce biogas—mainly methane—which can be used to generate electricity or heat. The leftover sludge is dewatered and safely disposed of or repurposed, for example, as fertilizer (Appels et al., 2008).

This dual-stream setup not only ensures treated water meets environmental standards but also recovers energy, supporting sustainable and circular wastewater management practices.

2.2 Literature Review

Case studies of wastewater treatment plants that have successfully minimized fossil fuel use through similar strategies will be examined to support the chosen research methodologies.

Table 1: Literature Review

S. No.	Title	Year	Author(s)	Findings	Gap
1.	An overview of biogas production and utilization at full-scale WWTPs in the United States: Challenges and opportunities towards energy-neutral WWTPs (Puig von Friesen et al., 2018)	2015	Shen Yanwen, Jessica L. Linville, Meltem Urgun-Demirtas, Marianne M. Mintz, Seth W. Snyder.	The paper identifies biogas as a viable renewable energy source and stresses the importance of decentralized systems for small-scale applications. It also highlights seasonal variability in	However, it lacks a WWTP-specific focus, omits thermal demand profiles like 37°C for digesters, and does not assess the feasibility of P2H technologies. Scaling and economic limitations for seasonal storage

				biomass, relevant to biogas intermittency in WWTPs during winter	at small WWTPs are not addressed.
2.	Seasonal Energy Storage Potential Assessment of WWTPs with Power-to-Methane Technology (Csedő et al., 2023)	2020	Zoltán Csedo, Botond Sinóros-Szabó, and Máté Zavarkó	Assesses seasonal energy storage in WWTPs using Power-to-Methane systems, showing feasibility at larger plants. Highlights technical viability, but financial dependency on favorable electricity prices and policy incentives for practical implementation.	The study centers on ≥ 1 MW systems, making it less applicable to small WWTPs. It overlooks heating-specific demands, biogas intermittency, and alternatives like heat pumps or e-boilers, leaving smaller-scale, heating-focused strategies unexplored.
3.	From the Wastewater Treatment Plant to the Turnstiles of Urban Water and District Heating Networks (Gruber-Glatzl et al., 2020)	2020	Wolfgang Gruber-Glatzl, Christoph Brunner, Sarah Meitz, Hans Schnitzer	Demonstrates how the integration of a 50 kW _t heat pump at Gleisdorf WWTP, alongside biogas, covered internal heat demands and delivered surplus to district heating—achieving net annual savings up to €57,700.	Focuses on mid-sized WWTPs ($\approx 30,000$ PE) with district heating integration, leaving small plants like Ernemar ($\sim 10,000$ PE) unexplored. It doesn't evaluate standalone e-boilers, nor address seasonal biogas shortages or internal-only heating scenarios
4.	More efficient use of biogas at wastewater	2018	Puig von Friesen, M., Odhner, P.,	Seasonal biogas surplus (summer) vs.	Small/medium-scale solutions for storing or using

	treatment plants (Puig von Friesen et al., 2018)		Arnell, M., Svensson, M., Ivarsson, P., Jannasch, A.-K., Boss, A., and Hjörnhede, A.	shortfall (winter) leads to ~10% flaring annually at many Swedish WWTPs. Matches Ernemar's situation of flaring in warm months and relying on oil in cold months. Highlights potential strategies for more efficient biogas utilization (e.g., storage, alternative uses).	surplus gas remain uneconomic under typical Swedish electricity prices. Policy or technological innovations may be needed to close cost gaps for microturbines, ORC, or partial storage expansions.
5.	Life cycle performance evaluation of cascade-heating high temperature heat pump system for waste heat utilization: Energy consumption, emissions and financial analyses (Dai et al., 2022)	2022	Baomin Dai, Xiao Liu, Shengchun Liu, Dabiao Wang, Chenyang Meng, Qi Wang, Yifan Song, Tonghua Zou	Performs a life cycle assessment of a cascade heating system—heat pumps paired with electric boilers—and reveals it reduces carbon emissions by 76.5% compared to electric boilers alone, and by 1.7–6.1% compared to high-temperature heat pumps, making hybrid systems notably effective.	Analysis is conducted on large-scale industrial systems, not tailored to small WWTPs like Ernemar. It lacks application-specific insights on real-world biogas intermittency, heating demands (e.g., digester, office), or economic scaling for smaller installations.
6.	Carbon Footprints of Scandinavian	2013	Gustavsson, D. J. I., & Tumlin, S.	Assessment of 16 Scandinavian WWTPs found	More long-term field measurements

	Wastewater Treatment Plants (Gustavsson et al., 2013)			no carbon neutral facilities; carbon footprints ranged 7–108 kg CO ₂ e P.E. ⁻¹ year ⁻¹ . Major contributors included nitrous oxide (N ₂ O) from biological treatment, electricity demand, and external carbon usage. Plants with higher biogas utilization (e.g. CHP or vehicle fuel) and minimal external carbon dosing had significantly lower footprints.	(especially for N ₂ O) are needed to establish reliable emission factors and identify best operational strategies. Policy and technological developments (e.g. optimizing energy recovery, alternative carbon sources, advanced N-removal) are essential to approach or achieve carbon-neutral municipal WWTP operations in Scandinavia.
7.	An Exploration of the Company Perspective on the Adoption of Industrial Electric Boilers (Lagendijk et al., 2023)	2023	J.S. Lagendijk	Papers stresses on the importance of partial electrification of heat. Looks into the complexity of adopting e-boilers by companies. Heat pumps are found to be the preferred option over e-boilers but most companies are not willing to redesign their facility to accumulate a heat pump as most of them produce centralized	Does not really talk about the integration of both P2H technologies, as both, when integrated into the facility for heat, synergize well together to tackle the required demands within the facility. Interviews were most-likely not conducted for companies with WWTPs and hence lacks input from them.

				heating (similar to Ernemar) using gas boilers.	
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2.3 Key Insights and Concepts Evaluation Based on Literature

2.3.1 Small Scale WWTPs & Heating Challenges

WWTPs such as Ernemar face distinctive heating challenges due to their size, operational design, and biogas production limitations. The primary heat demand stems from maintaining mesophilic digester temperatures (approximately 37°C) and supplying space heating to auxiliary buildings and offices. Unlike larger plants, small WWTPs lack the scale needed for continuous Combined Heat and Power (CHP) operations or large-scale thermal storage underscore that seasonal variability in biomass supply—particularly during winter—creates biogas shortfalls at many WWTPs (Puig von Friesen et al., 2018). In Sweden, a similar pattern is seen where biogas production declines during the colder months, precisely when heat demand is at its peak (Puig von Friesen et al., 2018). The result is an intermittent reliance on fossil fuels, typically heating oil, to bridge the heating gap. This seasonal imbalance introduces sustainability and economic challenges, especially for plants serving populations under 10,000 PE like Ernemar (Jayasuriya, 2024).

2.3.2 Techno-Economic Studies on Seasonal Biogas Storage

Co-initial assumptions in this project favoured storing summer-surplus biogas for winter reuse. However, literature suggests that this approach is technically feasible but economically impractical for small-scale plants. For instance, Zoltán et al. (2020) analyzed seasonal energy storage using power-to-methane systems, demonstrating viability at larger (>1 MW) scales but citing cost barriers for smaller facilities due to infrastructure and operational expenses (Csedő et al., 2023). Puig et al. (2018) also highlight that despite Swedish WWTPs experiencing up to 10% annual flaring due to biogas surplus, micro-scale storage systems (such as balloon tanks, underground vessels, or compressed biogas tanks) remain financially unattractive without strong policy incentives. These findings were reinforced by site-level discussions, where spatial constraints further complicated the feasibility of underground or modular tank-based systems (Puig von Friesen et al., 2018). In summary, while biogas storage could conceptually balance energy supply and demand, its scalability and affordability for small WWTPs like Ernemar are significantly limited.

2.3.3 Power-to-Heat Technologies (Electric Boilers and Heat Pumps)

Due to the seasonal drawbacks of biogas storage, electric boilers (e-boilers) and heat pumps emerge as promising P2H alternatives. Lagendijk (2023) evaluated industrial-scale e-boilers and found them to be technically robust, emissions-free at the point of use, and increasingly competitive due to dynamic electricity pricing. For small WWTPs, they offer a modular, easy-to-install heating option with low maintenance requirements. However, their efficiency is relatively low, and operational costs can spike under unfavorable electricity tariffs (Lagendijk et al., 2023). On the other hand, heat pumps—especially those integrated with ambient sources like seawater—provide significantly higher Coefficients of Performance (COP), translating into reduced operating costs and carbon emissions. Gruber-Glatzl et al. (2020) demonstrated this with a 50 kW_t system at a mid-sized WWTP, where internal heating needs were met while exporting surplus to a district heating network. Though Ernemar is smaller and not linked to a district grid, similar internal-only designs could yield net economic and environmental benefits (Gruber-Glatzl et al., 2020). Dai et al. (2022) further suggest that hybrid systems—heat pumps backed by e-boilers—achieve up to 76.5% carbon reductions compared to standalone e-boilers, making them highly attractive for variable heat loads (Dai et al., 2022).

2.3.4 Carbon and Energy Impact of Oil vs P2H

From a climate impact perspective, switching from oil to P2H technologies significantly reduces greenhouse gas emissions. Gustavsson and Tumlin (2013) report that Scandinavian WWTPs have carbon footprints ranging from 7–108 kg CO₂e PE⁻¹ yr⁻¹, largely driven by external energy use and biogenic gas flaring (Gustavsson et al., 2013). Lifecycle assessments by Dai et al. (2022) emphasize that while e-boilers are carbon-free at the point of use, their impact is tied to grid electricity's source. In Sweden's decarbonized grid, this renders e-boilers a relatively clean option. Heat pumps, due to their high energy efficiency (COP > 2.5), outperform e-boilers in both energy consumption and emissions. Still, both technologies contribute toward a carbon-neutral plant when replacing fossil-based heating (Dai et al., 2022). This is particularly relevant to Ernemar WWTP, where current reliance on ~15.5 m³/year of heating oil creates an outsized climate burden compared to viable P2H alternatives.

2.4 Summary of Literature Gaps and Implications

Despite multiple studies affirming the benefits of P2H solutions, gaps remain concerning small WWTPs operating with constrained budgets and limited spatial flexibility. Most literature focuses on either large plants or those integrated into district

energy systems. There is a clear need for tailored research on hybrid P2H systems suited for plants like Ernemar. Furthermore, techno-economic comparisons between e-boilers and heat pumps specific to low-load and highly intermittent heat demands remain scarce. This thesis addresses these gaps by simulating demand-specific sizing of both technologies, evaluating their financial and carbon performance, and recommending the optimal configuration. Ultimately, this positions P2H as a scalable, sustainable solution for heating self-sufficiency in small municipal wastewater treatment settings.

2.5 Other Literatures Assessed for Initial Considerations

Many scientific papers were investigated as part of the literature review process during the initial phase of the thesis. All of them were exploring potential approaches or methodologies that could be integrated into the WWTP of Ernemar. These papers explored the possibilities in the integration of renewable technologies with biogas, or that which explored the possibilities of enhancing the anaerobic digestion process within the WWTP, or the one which looked into the possibility of hydrolysis pre-treatment. These papers were considered invaluable to the current research, as the issue with the WWTP is not that of “Not enough Biogas” but that of leveraging the biogas produced to supply heat to the facility. When the biogas was not there, an alternative methodology was used to provide heat for the WWTP. This would mean looking into the potential of waste-heat produced from the WWTP, or assessing the temperature to be maintained within the WWTP to integrate P2H technologies (Chen et al., 2023)(Phothilangka et al., 2008)(Campo et al., 2024)(Lima et al., 2023)(Nguyen et al., 2021)(Baş et al., 2022)(Masłoń et al., 2020)(Campello et al., 2021)(Kumar et al., 2020)(Appels et al., 2008).

Chapter 3: Methodology and Tools

This chapter outlines the methodological framework applied to evaluate the most viable replacement for fossil-based heating at the Ernemar Wastewater Treatment Plant (WWTP) in Oskarshamn, Sweden. The approach integrates empirical data, mass and energy balancing, economic feasibility assessment, emissions analysis, and scenario modeling to compare Power-to-Heat (P2H) technologies—specifically electric boilers and heat pumps. The methodology is structured to allow transparent evaluation and reproducibility and is built on both field data provided by Oskarshamn Kommun and literature-backed assumptions.

3.1 Power-to-Heat Technologies

P2H technologies provide a way to convert surplus or grid electricity into usable thermal energy, which can be applied directly in heating systems. In the context of WWTPs, this is particularly beneficial as it offers an alternative to fossil-based heating, often required in colder months when biogas availability is limited. The two primary P2H solutions considered for the Ernemar WWTP are electric boilers and heat pumps.

3.1.1 Electric Boilers

3.1.1.1 *Technology Description*

Electric boilers, or e-boilers, are systems that use electricity to generate heat for producing hot water or steam. Instead of burning fossil fuels like oil or gas, they rely on electric resistance elements or electrodes that directly heat water. The design is relatively simple: electricity flows through heating elements, converting electrical energy into thermal energy with almost 100% efficiency at the point of use. E-boilers come in various sizes, from small units for buildings to large industrial-scale systems that can reach tens of megawatts. Because there is no combustion, e-boilers do not release flue gases or on-site CO₂ emissions. They can be integrated into existing heating networks or operate as standalone systems, making them a flexible option for different facilities. In recent years, as electricity grids become greener, e-boilers have gained attention as a cleaner alternative to conventional boilers ([FIRN Energy, n.d.](#))([Piel et al., 2022](#))([Verheyen et al., 2025](#)). **Figure 3** provides an image of a mounted e-boiler in an industrial setup.



Figure 3: Electric Boiler

3.1.1.2 Functionality

E-boilers work by transferring electricity into heat using either resistance heating or electrode heating. In resistance heating, electric current passes through metal elements submerged in water, which warms up and circulates as hot water or steam. Electrode boilers use electric current passing directly through water between electrodes, which heats the water more rapidly and allows higher capacity. The system is controlled by temperature and pressure sensors that adjust power input to meet the required thermal demand. E-boilers can be switched on or off quickly, making them ideal for supporting variable heating needs or responding to fluctuating electricity prices. In industrial and municipal applications, such as district heating or wastewater treatment plants, they can act as a backup or main heat source. Their fast response time and precise control help facilities balance energy loads and maintain steady operation (Euroheat & Power, 2025)(Maruf et al., 2022)(Gerhardt et al., 2017).

3.1.1.3 Advantages and Disadvantages

Table 2: E-Boilers Advantages and Disadvantages

Advantages	Disadvantages
No on-site Carbon Dioxide (CO ₂) emissions since no fuel combustion.	High operational costs if electricity is expensive.
Simple design and lower maintenance needs.	Dependant on electricity availability and grid capacity.

Quick start-up and flexible load response.	May require upgrades to electrical infrastructure.
Compatible with renewable electricity, supporting decarbonisation goals.	Less efficient than heat pumps in terms of energy input-to-output ratio.

3.1.1.4 Relevance to WWTP

For Ernemar WWTP, integrating an e-boiler involves connecting it directly to the existing hot water loop that serves the digesters and facility heating circuits. Since the plant already has a centralized thermal distribution system fed by biogas and oil boilers, an e-boiler can be added as an auxiliary or backup heat source without major process redesign. The main technical considerations include ensuring sufficient electrical connection capacity, as e-boilers draw high power loads, and assessing the available transformer and grid infrastructure on-site.

E-boilers at WWTPs are typically used for maintaining digester temperatures during periods of biogas shortage, for reheating sludge before digestion, and for building heating needs in winter. Unlike fossil boilers, they can start and stop quickly, making them ideal for covering sudden drops in biogas production or for short-term high heat demand.

At Ernemar, this integration would require planning around peak electrical demand and possible electricity price fluctuations. Additional considerations include safety systems for high-power equipment and minimal space requirements, which is important since space at municipal WWTPs can be limited. Overall, an e-boiler is technically straightforward to integrate at Ernemar due to the existing water-based heat distribution and well-defined seasonal heat demand profile. (Verheyen et al., 2025)(Piel et al., 2022)(Boshell et al., 2020).

3.1.2 Heat Pumps

3.1.2.1 Description of Technology

Heat pumps are systems that use electricity to move heat from a low-temperature source to a higher-temperature target, instead of generating heat directly. In industrial and wastewater applications, they typically extract heat from treated effluent or nearby surface water, which maintains a more stable temperature year-round. The basic components include an evaporator (where heat is absorbed), a compressor (which raises the temperature), a condenser (where heat is released), and an expansion valve (which lowers the pressure before the cycle repeats).

Heat pumps stand out because of their high energy efficiency, measured by the COP. A typical large-scale heat pump used in wastewater or district heating applications can

reach COP values between 3 and 4, meaning they can deliver three to four times more heat energy than the electricity they consume. Their ability to provide consistent, renewable heat has led to wider adoption in municipal heating and industrial facilities in Europe and Asia, including wastewater treatment plants aiming for low-carbon operation (Gruber-Glatzl et al., 2020)(Łokietek et al., 2022)(IEA, 2022)(Ziemele et al., 2023). **Figure 4** shows what typical heat pump looks like.

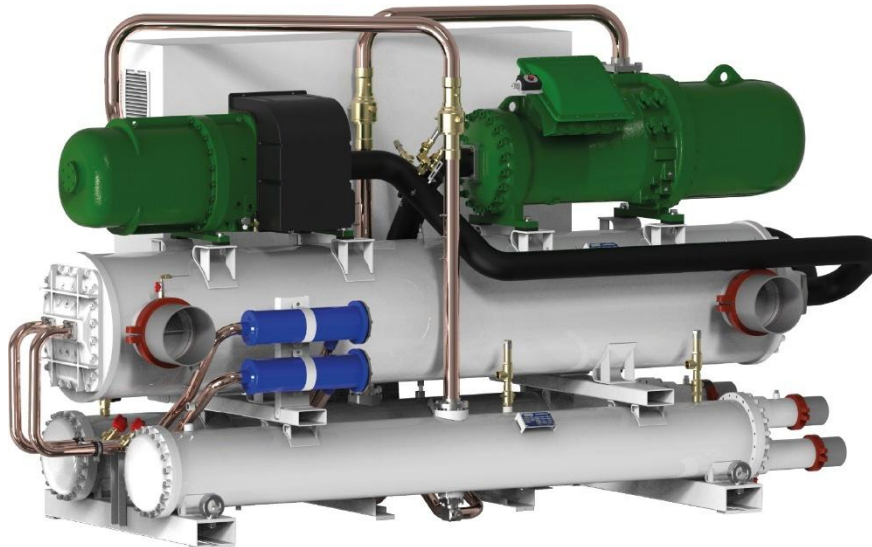


Figure 4: Heat Pump

3.1.2.2 *Functionality*

A heat pump cycle begins when a low-temperature fluid (refrigerant) absorbs heat from the source (like treated wastewater). The compressor then increases the fluid's pressure and temperature. This high-temperature fluid passes through a condenser, where it releases heat to the desired system (such as digester heating or building circuits). After releasing heat, the refrigerant returns to a lower pressure through an expansion valve and repeats the cycle (Nagpal et al., 2021)(Fadnes et al., 2024).

For wastewater treatment plants, heat pumps are particularly attractive because final effluent offers a continuous and relatively stable heat source, even during winter. This helps maintain a steady supply of heat to processes like anaerobic digestion, which require stable operating temperatures around 35–37 °C. Compared to direct electric heating, heat pumps consume less electricity per unit of heat delivered, making them more efficient over time. Moreover, they can operate continuously as a base load provider, reducing the need for fossil backup systems and minimizing operational fluctuations (Łokietek et al., 2022)(Ivezić et al., 2023).

3.1.2.3 Advantages and Disadvantages

Table 3: Heat Pump Advantages and Disadvantages

Advantages	Disadvantages
High energy efficiency with COP often above 3.0 (Kordana-Obuch et al., 2023)	High upfront investment and installation costs.
Enables use of stable local heat sources like treated wastewater.	Requires a large, reliable heat source at low temperature.
Continuous, steady thermal output suitable for base heating.	More complex system integration than simple boilers (Bartnicki et al., 2022)
Significant CO ₂ emission reductions when powered by green electricity.	Efficiency drops if very high output temperatures are needed (IEA, 2022)(Golek, 2024)

3.1.2.4 Relevance to WWTP

For Ernemar WWTP, a heat pump would be integrated by using the plant's final treated effluent as a heat source. This effluent flow is relatively stable in temperature (usually above 5 °C in winter), making it an excellent source for extracting heat. The evaporator side of the heat pump would be connected to this effluent loop, while the condenser side would tie into the central hot-water network used to heat digesters and office buildings.

Technical steps involve designing heat exchangers to avoid fouling from residual solids, ensuring sufficient flow rates, and incorporating system controls to maintain optimal evaporator temperatures. Similar setups have been successfully implemented in Austria (Gleisdorf WWTP), where heat pumps handle most of the base heating needs, and in Poland, where effluent-based heat pumps support stable digester operation (Gruber-Glatzl et al., 2020)(Łokietek et al., 2022)(Nagpal et al., 2021).

At Ernemar, a heat pump would ideally run continuously to cover base heating demand, allowing biogas boilers or electric boilers to serve as backup or peaking units. Important considerations for Ernemar include verifying space for heat pump units and associated equipment, evaluating grid capacity for electric loads, and aligning new system controls with existing supervisory control and data acquisition (SCADA) monitoring. This approach could significantly reduce reliance on oil and ensure stable operation during cold periods (Ivezić et al., 2023).

3.2 Technology Sizing

The technologies to be sized (e-boilers and heat pumps) are sized based on the power that is required to be supplied to the technology. In this case both technologies are highly efficient and face nearly no losses at all. In the case of an e-boiler, the electrical power required by the boiler is the heat demand divided by the efficiency of the boiler. Since boilers are highly efficient (~99% efficiency) they encounter minimal heat losses. The formula is as shown below:

$$P_{electric} = \frac{Q_{thermal}}{\eta}$$

Where, $Q_{thermal}$ is the heat demand (Highest hourly).

In the case of a heat pump, there are multiple considerations and assumptions. We need to determine the supply temperature of the heat pump and hence need to find out $T_{setpoint}$ and ΔT as,

$$T_{supply} = T_{setpoint} + \Delta T$$

Where, $T_{setpoint}$ is the temperature to be maintained at the office, facility, and digester (20°C, 10°C, and 37°C, respectively).

And, ΔT is the temperature that is to be raised by the heat pump from the $T_{setpoint}$ so heat exchange can take place in such a way that the required temperature is achieved.

The water-source is about 7°C and is taken from the treated waste-water from the plant. This is the temperature of the waste water that is estimated during the winter months at Oskarshamn. Then, we proceed to calculate the COP of the heat pump. Here, we look at two COP (Ideal Carnot and Realistic). Realistic COP is about 0.4 times the ideal Carnot COP. The COP formula is as follows,

$$COP_{carnot} = \frac{T_{hot}}{T_{hot} - T_{cold}}$$

$$COP_{real} = 0.4 \times COP_{carnot}$$

It is then possible to calculate the $P_{electric}$,

$$P_{electric} = \frac{Q_{thermal}}{COP_{real}}$$

These formulas determine the approximate sizes of the heat pump and e-boiler and the calculation of these will be reflected in the result section of the report.

3.2.1 Hourly COP Model (Variable COP Approach)

The initial technology sizing in Section 3.2 uses a static COP of 4.0 for approximate system dimensioning. However, this assumption overestimates heat pump performance because it ignores the seasonal variation in effluent temperature — the heat pump's cold-side source. In reality, the COP of a water-source heat pump fluctuates with the temperature of the treated wastewater, which at Ernemar ranges from 6.23°C (February) to 12.01°C (July).

To capture this effect, an hourly COP model was developed. For each of the 2,553 winter operating hours (November 2023 – April 2024), the model calculates a real COP using the daily effluent temperature recorded by the plant's SCADA system:

$$COP_{real}(t) = 0.4 \times \frac{T_{hot}}{T_{hot} - T_{eff}(t)}$$

Where T_{hot} is the supply temperature (52°C for digester heating) and $T_{eff}(t)$ is the daily average effluent temperature on day t . Each hour's heat pump electricity consumption is then:

$$E_{HP}(t) = \min(Q_{demand}(t), 100 \text{ kW}) \times COP_{real}(t)$$

Any demand exceeding 100 kW is assigned to the electric boiler at $COP \approx 1$. The weighted-average COP across all 2,553 hours is:

$$COP_{weighted} = \frac{\sum Q_{HP}(t)}{\sum E_{HP}(t)}$$

$$COP_{weighted} = \frac{136,775}{46,813} = 2.922$$

This is significantly lower than the static COP of 4.0 used in the initial sizing. The difference arises because the coldest months (January–February), when effluent temperatures drop below 7°C and COP falls to 2.85–2.87, coincide with the highest heating demand — meaning more electricity is consumed precisely when the heat pump is least efficient.

The implications of this finding are substantial and are discussed in Section 5.2, where the hourly model reveals 120% higher heat pump electricity consumption than the static assumption predicts. All financial metrics reported in this thesis (NPV, payback, OPEX) use the hourly COP model values unless otherwise stated.

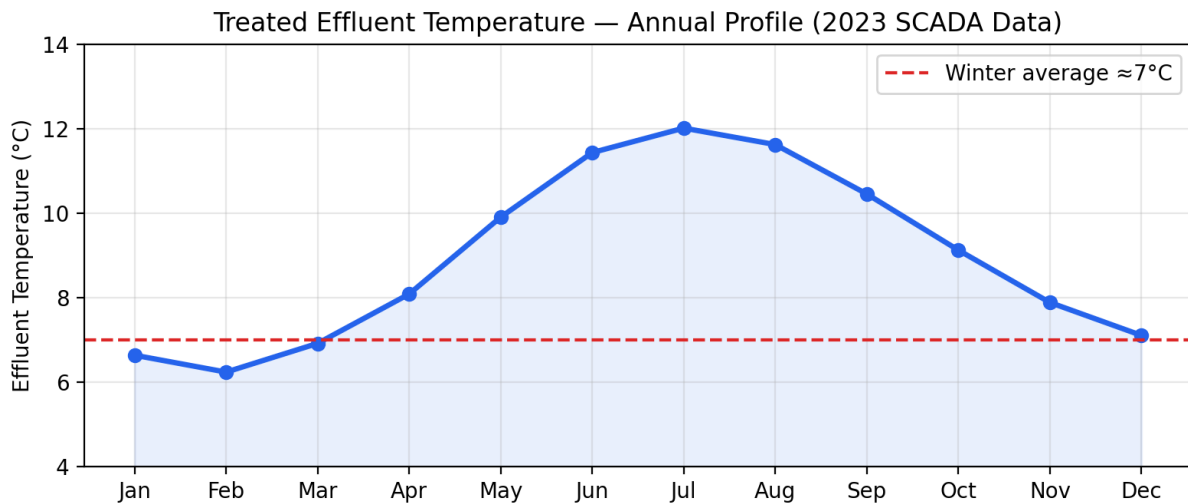


Figure 5: Treated Effluent Temperature — Annual Profile

The winter average of $\approx 7^{\circ}\text{C}$ drives the COP down to 2.85–3.08 during the heating season, as seen in **Figure 5**.

3.2.2 HEX Control Valve vs Demand Proxy

The Ernemar WWTP operates a biogas-fired heat exchanger (HEX) that transfers thermal energy from the biogas boiler circuit to the plant's hot water distribution loop. The HEX is equipped with a modulating control valve whose position (0–100%) is logged hourly by the plant's SCADA system. A higher valve position indicates a greater thermal demand being served by the biogas boiler — and by extension, a point at which the biogas system is approaching or exceeding its capacity.

The SCADA dataset contains 10,224 hourly HEX records spanning the full monitoring period. These were aggregated into 427 daily averages to smooth out short-term noise and reveal operational trends. The key metrics extracted are:

- Daily average valve position (%): Ranges from 25.8% (low demand) to 78.1% (high demand)
- Daily average HEX temperature ($^{\circ}\text{C}$): Ranges from 83.2°C to 87.2°C , inversely correlated with demand
- Correlation coefficient ($r = 0.398$): Moderate positive correlation between valve position and heating demand

3.3 Techno-Economic Analysis and Approach

After building the mass and energy balance, the next step will be integrating financial data to see how different operational or technological changes could impact the plant's overall economic picture. This means gathering:

- OPEX such as oil costs, electricity bills, and routine maintenance.
- CAPEX for potential upgrades, like storage expansion or alternative heating systems.

All of these figures will feed into the same Excel model, but on a separate worksheet where cost and revenue factors are combined. The model will then calculate metrics such as payback period—how many years it takes to recoup initial investments—and net present value (NPV) over a chosen project timeframe, likely 15 to 20 years, using a discount rate appropriate for municipal or utility-scale projects. P2H technologies are prioritized over any storage systems and therefore CAPEX and OPEX of P2H only will be provided.

Initially, it was important to understand how much of the load the heat pump covers in order to accurately size it. Yes, the heat pump and e-boiler are being utilized in an interdependent fashion where one covers the base load and the other looks after the peak. This is determined based on the functional advantages of both these technologies. Then, based on the determined sizes of these technologies a cost breakdown is tabulated to discretely visualize the different parameters under CAPEX and OPEX. The same will be done for oil-powered boilers. From there, we provide a tabulated summary of the CAPEX and OPEX and determine the savings, net present value, and payback period for the technology mix with visually pleasing graphs. **Figure 7**, shown below provides a basic insight into the path followed to perform a techno-economic assessment.

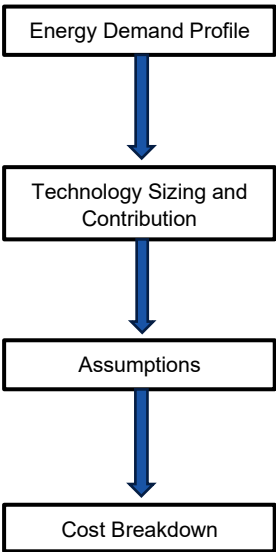


Figure 5: Methodology Process Flow

Tables 4, 5, and 6 provides the different formulas used in the techno-economic analysis:

Table 4: Cost Calculation Formulas

Purpose	Formula	Notes
Oil Cost	$C_{oil} = V_{oil} \times P_{oil}$	Volume \times Price
Carbon Emissions (Oil)	$E_{CO_2} = V_{oil} \times EF_{oil}$	EF = emission factor
Carbon Tax (Oil)	$T_{CO_2} = E_{CO_2} \times P_{tax}$	kg \times SEK/kg
Total Oil Expense	$C_{oil,tot} = C_{oil} + T_{CO_2}$	Used for comparison
Electricity Cost for HP	$C_{HP} = E_{el,HP} \times P_{el}$	kWh \times SEK/kWh
Electricity Cost for EB	$C_{EB} = E_{el,EB} \times P_{el}$	Same method

Table 5: Financial Evaluation

Purpose	Formula	Notes
Total OPEX	$OPEX_{total} = C_{HP} + C_{EB} + C_{buffer}$	Annual operating cost
Annual Savings	$S = C_{oil,tot} - OPEX_{total}$	Compared to old system
Payback Period	PP = Initial Investment/Annual Savings	Years to recover investment
NPV	$NPV = S \times (1 - (1 + r)^{-n} / r) - CAPEX$	r is the discount rate

Table 6: Emission Calculation Formulas

Purpose	Formula	Notes
Electric Grid CO₂ Emissions (HP or EB)	$E_{CO_2,grid} = E_{el} \times EF_{grid}$	12 gCO ₂ /kWh = 0.012 kg/kWh
Total Emissions (P2H system)	Sum of HP and EB emissions	Compared to oil baseline

3.4 Scenario Definitions and Selected Mix

Comparisons between the “Base Case” and possible improvements will be key. The “Base Case” is referred to as the current use of oil-powered boilers in Ernemar WWTP in Oskarshamn. The Base case is compared to the proposed scenario where P2H technologies are introduced. But it is important to determine whether other

possibilities can be integrated or not. For example, biogas storage has been ruled out of the scenario due to the high-volume capacity required, with lots of space occupation and high investment with less returns. Waste heat was a good proposal, but since it has already been tried and didn't really work out, it is also ruled out. Although it does open up opportunities for further research into why it has failed, and whether there are other companies out there that can provide a better solution for Oskarshamn Kommun? This can be another research conducted down the line. The feasibility of biogas storage within Oskarshamn Kommun can also be investigated. Now, the proposal for integration of P2H technologies, such as heat pumps and e-boilers, began due to it being practical and feasible in all senses. But what is the most practical mix even with the integration of such technologies? How do we determine the optimal sizing for the plant for heat production while also promising returns? Here, we need to determine the best case, and for that, some extra scenarios also need to be ruled out, such as:

- Completely relying on e-boilers (Extremely high electricity prices; not practical)
- Completely relying on heat pumps (Extremely high investment costs; not practical)

Therefore, it should be a mix of the two. The two technologies have their own advantages and disadvantages, which were discussed in the above sections, and based on that, it is wise to determine that e-boilers should only be used to mitigate the peak loads (which are highly varying) and the heat pump for a more stable heat production. Now, the best mix of these is to be determined based on the results from the energy balance and techno-economic analysis, which will be shown in the results.

3.5 Sensitivity Analysis

Sensitivity analysis is a crucial methodological step in techno-economic assessments. It helps identify how the outputs—particularly operational cost, emissions, payback period, and NPV—respond to fluctuations in key input variables (Kenton et al., 2025). Given that many of the parameters used in this study (e.g., electricity prices, oil costs, technology performance) are subject to change over time due to market trends, weather conditions, or policy adjustments, this analysis ensures that the model's conclusions remain robust under varying future conditions.

The primary purpose of performing a sensitivity analysis in this study is to evaluate the reliability and resilience of the proposed hybrid P2H system under a range of plausible future scenarios. It provides insights into how sensitive the financial and environmental outcomes are to changes in core assumptions. By identifying which variables have the most significant influence on outcomes like annual savings and payback period, the analysis enables more informed decision-making and risk mitigation strategies for the plant operators and stakeholders.

The Ernemar WWTP operates in a dynamic context where both fuel costs and environmental regulations are in flux. For example, oil prices have historically shown volatility, and future increases could make fossil-based heating even more expensive (Pion et al., 2025). Similarly, changes in electricity pricing or carbon taxation could either strengthen or weaken the case for electrification. Therefore, conducting sensitivity analysis is particularly relevant for this facility, where even moderate shifts in input assumptions could significantly affect the financial viability of the heating upgrade.

The following sensitivity scenarios have been selected to represent realistic and strategically important variations:

1. Oil Price Variations

Why it matters: The cost savings of the electrified system are benchmarked against the cost of oil. Fluctuations in oil prices can significantly affect payback period and NPV.

Scenarios:

- 15 SEK/L (low)
- 20.1 SEK/L (base case)
- 25 SEK/L (high)

2. Electricity Price Variations

Why it matters: Electricity prices directly impact operational costs, especially due to the large energy consumption by the electric boiler.

Scenarios:

- SEK/kWh (low)
- 1.35 SEK/kWh (base case)
- 1.6 SEK/kWh (high/future scenario)

3. Carbon Tax Evolution

Why it matters: The carbon tax directly affects the cost of oil-based systems. A policy-driven increase would improve the economic attractiveness of electrification.

Scenarios:

- 1.33 SEK/kg CO₂ (base case)
- 2.00 SEK/kg CO₂ (moderate policy shift)
- SEK/kg CO₂ (aggressive decarbonization scenario)

4. Discount Rate Changes

Why it matters: Financial metrics like NPV are highly sensitive to the discount rate, especially in long-term investments like heating systems.

Scenarios:

- 3% (low discount/public financing scenario)

- 5% (base case)
- 7% (private sector scenario)

5. Multivariable Sensitivity

Why it matters: Single-variable sweeps assume all other inputs stay fixed, which rarely reflects reality. Combining two or more parameters in a single analysis reveals interactions that individual sweeps miss, such as how a rising electricity price and a falling COP can compound each other's effect on payback.

Scenarios:

- Electricity Price × COP Payback Matrix
- Carbon Tax Trajectory Projection
- Technology Mix Optimisation

3.6 Methodology Summary and Connection to Objectives

Table 7: Methodology Summary and Objective Connection

Objective	Methodological Approach	Data Source	Results Section
Energy Demand Characterization	Hourly energy balance from SCADA oil flow data; LHV conversion; winter filtering (Nov 2023–Apr 2024)	Oskarshamn Kommun SCADA export (14-month dataset)	Section 5.1
Technology Selection and Sizing	Hourly COP model: $COP_{real} = 0.4 \times T_{hot} / (T_{hot} - T_{cold})$ applied to each of 2,553 winter hours using daily effluent temperatures; load duration curve analysis for HP/EB split	SCADA effluent temp data (181 daily readings, 2023); manufacturer specs	Section 5.2,5.6
Techno-Economic Assessment	CAPEX/OPEX comparison; NPV via discounted cash flow; payback period calculation	Plant fuel purchase records; Eurostat electricity prices; Swedish carbon tax policy	Section 5.3-5.5
Sensitivity and Risk Analysis	Single-variable sweeps + multi-	Literature-based parameter ranges;	Section 5.7

	variable matrices (Elec × COP payback; Oil × CT NPV); carbon tax trajectory modelling; technology mix optimisation	EU ETS price forecasts	
Operational Decision Support	Excel workbook (13 sheets, 43,000+ formulas); HTML dashboard (6 interactive tabs); HEX valve correlation analysis	SCADA HEX data (10,224 hourly records aggregated to 427 daily)	Section 5.9

This mapping ensures that each research question posed in Section 1.4 is traceable through a defined analytical method to a quantified result, addressing the requirement for structured connection between objectives and outcomes.

Chapter 4: Data Collection and Analysis

4.1 Validation and Collaboration

Throughout this process, regular communication with WWTP personnel is planned, with preliminary Excel-model outputs shared so that incorrect assumptions can be identified as early as possible. One such event was when the WWTP data was provided certain claims were already made by the company such as the plant uses about 14 m³ of oil annually. Based on the data they provided and the calculations performed this was not the case as the data showed it only uses 1.4 m³ which did not align true to the claim and brought confusion. The result was shared and the personnel reached out specifying the discrepancies was due to wrong values provided by their system and it turned out the final result matched up with the claim of 14 m³ as during the winter months the plant did consume about 15,584.7347 Litres (15.58 m³) of oil.

4.2 Study Visit to Ernemar WWTP

Field trip to the Ernemar wastewater treatment facility in Oskarshamn offered a hands-on view of how every step in the wastewater treatment process is interrelated. Seeing the different operating units in action in real time helped explain the type of data needed in subsequent analysis, and in particular, the specifics of flow rates, sludge properties, energy consumption, and biogas treatment. Guided tour conducted by the plant's process engineer enabled one to trace the path of incoming wastewater—from preliminary screening and grit removal, through primary and secondary treatment, up to disinfection stage and final release of treated wastewater into the sea and handling of excess sludge in the anaerobic digesters, respectively—while also demonstrating how excess sludge is treated in the digesters. Visualizing the configuration of the pipes, tanks, and related controls first-hand assisted in ascertaining the types of measurements that need to be gathered (for example, the rate of sludge loadings per day, digester volume, or levels of heating demand) to model the plant's entire system and examine possible optimizations thereto. **Figure 6**, is an image of one of the screening processes in Ernemar WWTP.



Figure 6: View of the clarifier units used to separate sludge from treated water—an important step in ensuring effluent quality.

A more in-depth look at the entire treatment train revealed how preliminary screens eliminate bulk debris, followed by settling tanks (primary clarifiers) that eliminate heavier solids from the water column. Wastewater then progresses through a biological (secondary) treatment phase, wherein dissolved organic compounds are consumed by microorganisms, and secondary clarifiers settle out microbial biomass. Depending on the facility design, additional polishing steps or tertiary treatment eliminate the residual nutrients or finer particles, while disinfection guarantees pathogens are inactivated before discharge. In parallel, solids and biological sludges are thickened and pumped to a mesophilic digester, generating biogas that will either be stored or flared if not consumed onsite. This on-the-ground walkthrough reinforced how every measurement point—whether correlated to sludge feed, chemical additions, biogas yields, or terminal effluent quality—is part of interpreting the plant's mass balance and the energy balance. Seeing the workflows firsthand it became evident which data streams will prove to be the most paramount in the development of a sound process model. **Figure 7**, shown below is a chart that explains the WWTP process.

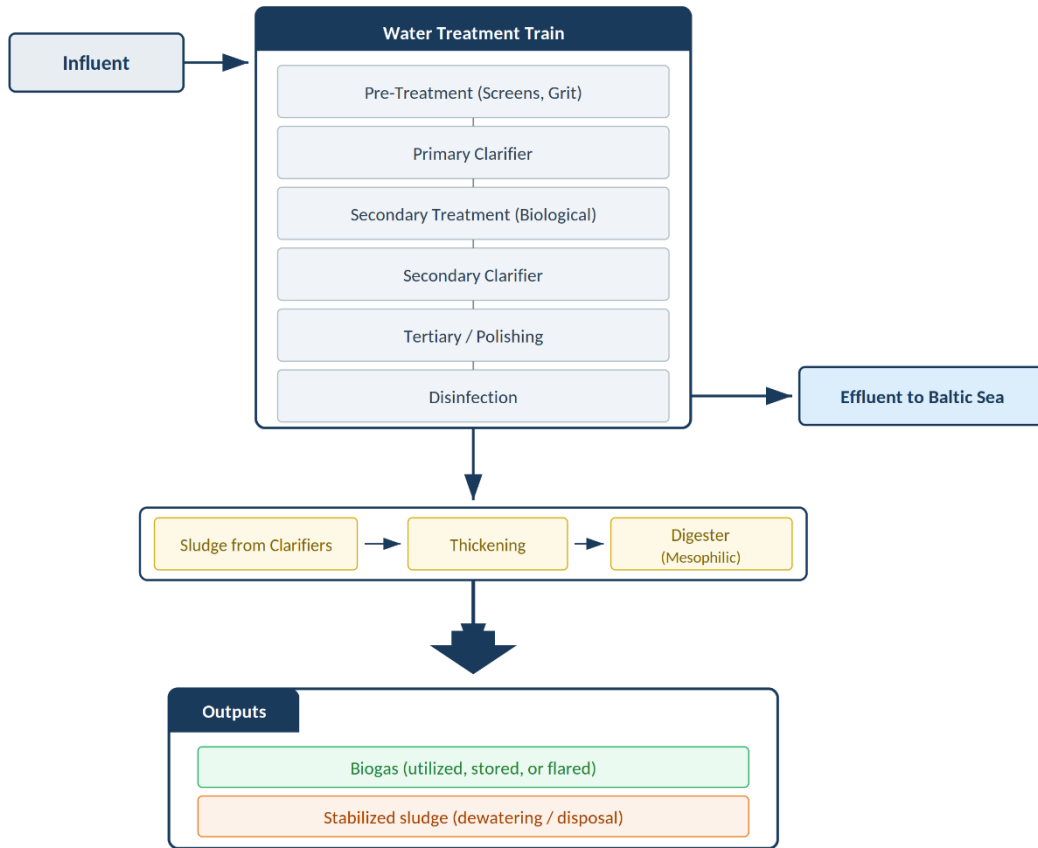


Figure 7: A Basic flow chart explaining the occurring process in Ernemar WWTP based on understanding.

4.3 Data Collection and Organization

The initial idea for this research focused on exploring various strategies to improve the overall energy efficiency of the Ernemar WWTP. This included investigating sludge pretreatment, co-digestion with other substrates, and the potential for seasonal biogas storage. Accordingly, the first phase of data collection was broad, encompassing parameters beyond just heating. Initially considered parameters are as shown in **Table 8**.

Table 8: Initially Considered Parameters

Parameter	Source	Purpose
Sludge input and characteristics	Oskarshamn Kommun	To evaluate potential for co-digestion and thermal pretreatment
Monthly Production Biogas	Oskarshamn Kommun	To assess potential for seasonal storage

Flaring Records	Oskarshamn Kommun	To quantify unused biogas volume and energy equivalence
Heating Demand Estimates	Facility Communication	For calculating energy needs across WWTP zones
Literature on Sludge Technologies	Scientific Journals	To benchmark improvement potential through THP and co-digestion

These data points were collected to support an initially broad research scope. However, after technical consultation and literature review, strategies like sludge pretreatment and biogas storage were found either too costly or technically infeasible for a plant the size of Ernemar. Consequently, these parameters became irrelevant to the current approach and were excluded from further analysis.

With the pivot in focus, the study began concentrating solely on heating challenges and how they could be addressed using P2H technologies. This meant narrowing the dataset to variables directly affecting heating supply and demand, such as fuel use, heat load variation, temperature profiles, and equipment specs. Data requested from the plant is provided below in **Table 9**.

Table 9: Relevant Data Type

Data Type	Source	Relevance
Monthly oil consumption (litres)	Oskarshamn Kommun	Baseline for heating-related energy and emissions
Heat demand profile (Nov–Apr)	Oskarshamn Kommun	Input for sizing P2H technologies and calculating thermal coverage
P2H technology specs (e.g., COP, capacity)	Manufacturer catalogs	Helps estimate cost, space, and integration feasibility
Electricity prices (winter rates)	Eurostat (Eurostat, 2025)(IEA, 2022)	Required for calculating OPEX and LCOH
Oil Prices	Oskarshamn Kommun	Required for final OPEX of oil boiler

The relevance of these datasets lies in their direct linkage to the techno-economic and emissions performance of electric boilers and heat pumps. By narrowing the scope, the analysis can now provide actionable recommendations based on realistic and

context-specific assumptions. The collected data aims to answer key research questions on the feasibility, sustainability, and replicability of P2H technologies at small WWTPs in Sweden.

The following sections will highlight the relevant steps taken to achieve what is required by the company.

4.4 Mass and Energy Balance Framework

A mass and energy balance was essential to quantify the annual and seasonal heating requirements and to benchmark the oil-based baseline against P2H alternatives. The balance started with an assessment of total oil consumption, converted to energy content using standard heating values. For electric boilers, energy input calculations assumed a COP of 1, while heat pump models incorporated a seasonal COP of 2.5 to 3.0.

The calculation is done based on:

- Oil usage from the provided data – The oil usage provided by the company accounts for 14 months (November 1st, 2023 – December 30th, 2024).
- This, when calculated, should provide the overall oil usage recorded in the plant.
- Then we need to decide on what should be considered. In this case, our consideration should only be for the winter months, and hence we account for the oil usage from November 2023 to April 2024. This is a period of 6 months. These are the colder months, and hence, the oil usage is highest during this period.
- After calculating that we translate the oil usage (Litres) to energy covered in kWh. Then we can get an exact amount of excess heat demand during the winter months.
- This excess heat is what needs to be covered by the P2H technologies, i.e., e-boiler or a heat pump. From this, we can size these technologies to meet the heating demand. P2H technologies are what is going to be considered for covering the heat demand over biogas storage or waste-heat recovery (Reasons mentioned in the above sections).
- The calculations of this will be reflected in the results. All calculations are done with values provided by the WWTP plant.

Chapter 5: Results and Evaluation

This section presents the quantitative findings of the techno-economic evaluation carried out for the proposed heating system upgrade at Ernemar WWTP. The results focus on energy consumption, electricity use, cost breakdowns, emissions, and system sizing logic. The analysis uses real operational data from the plant and compares current oil-based heating performance with the projected performance of a hybrid P2H system consisting of a heat pump and an electric boiler. Supporting visuals and tabulated outputs are included where applicable to demonstrate the system's load allocation and economic feasibility.

To ensure transparency and replicability, the analysis was carried out using the following key assumptions as shown in **Table 10**:

Table 10: Assumptions

Parameter	Assumed Value	Justification
Lower Heating Value (LHV) of Oil	10.1 kWh/L	Based on fuel specification provided by the plant
Emission Factor of Heating Oil	2.68 kg CO ₂ /L	Standard factor used for light fuel oil
Grid Emission Factor	0.012 kg CO ₂ /kWh	Reflects Sweden's low-carbon electricity mix
Heat Pump COP	4 (Static) 2.922 (Variable)	Calculated
E-Boiler Efficiency	99–100%	Assumes near-total conversion from electrical to thermal energy
Electricity Price	1.35 SEK/kWh	Average winter tariff as per regional utility estimates. Although as per Eurostat Electricity prices on average every year is 0.95 SEK/kWh (Eurostat, 2025)
Oil Price	20.1 SEK/L	Based on plant's fuel purchase records
Carbon Tax	1.33 SEK/kg CO ₂	Based on current Swedish policy

5.1 Energy Demand and System Coverage

The plant data provided (which was from November 1st 2023 upto December 30th 2024) was a total of 14 months and the total oil consumption from the provided data accounted for 16.6109 m³ which means with an LHV of 10.1 kWh/L the energy covered by oil comes upto 167.7709 MWh. But since our research only accounts for the winter months we considered the plant values only from November 1st 2023 upto April 30th 2024 which is 6 months altogether and accounted for atleast 94% of the energy demand from the plant data provided and the rest of the 6% falls under the months November and December in 2024 (Reasons why these 2 months are not accounted has been discussed in the above section). **Table 11 & 12** clarifies the distribution.

Table 11: Raw Data Values

	From November 1st, 2023 to December 30th, 2024	Units
Oil Consumption	16610.9795	L
	16.61097946	m3
Energy Covered by Oil	167770.8926	kWh
	167.7708926	MWh

Table 12: Winter Month Values

	From November 1st, 2023 to April 30th, 2024	Units
Oil Consumption	15584.7347	L
	15.5847347	m3
Energy Covered by Oil	157405.8205	kWh
	157,406	MWh

Therefore, it is clearly seen that about 157 MWh of heat demand cannot be met by biogas and is instead covered by oil-powered boilers. And hence, there is a clear need for decarbonisation through electrification and that's where e-boilers and heat pumps enter. **Table 13** provided below shows the variation and distribution of heat demand throughout the winter months:

Table 13: Monthly Values (Winter)

Monthly	Oil Consumption (Litres)	Energy Covered by Oil (kWh)
Nov-23	1516.5712	15317.36884
Dec-23	3504.3915	35394.35409
Jan-24	5520.2118	55754.13896
Feb-24	3608.6734	36447.60153
Mar-24	1149.3406	11608.3396

Apr-24	285.5463	2884.017495
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Based on the provided data the highest daily demand was 4.409900378 MWh (oil consumption is 436.6238) and the highest hourly demand (which falls under the highest daily) was found to be 265.0325077 kWh with an oil consumption of 26.2408 Litres. This hourly demand is our deciding factor for the sizes of the technologies. And the massive oil consumption during these hours really spikes up the operational expenses of the plant hence requiring a shift towards electrification of the heating system which could promise cheaper operation.

Now, from the above sections we determined the best possible heating solution is not either an e-boiler or a just a heat pump but a mix of them for various reasons such as managing varying loads, efficiencies, ramp-up times, etc. Hence, the wise decision devised from the aforementioned reasoning was to go with a heat pump that can manage the base and intermediate loads and an e-boiler for the peak loads. But how much coverage of the loads do both of them get? Both are great technologies with near perfect fit to what the WWTP needs. Heat pumps do a good job at covering the base loads and even the middle loads and not the most ideal for peak as they can have a 20-30 min startup time. Therefore we determine that the heat pump could cover the majority of the load and the e-boiler can be used for the heavy peak loads. Thus, a range is determined by a lower bound and an upper bound, where the lower bound is 4.044 kWh and the upper bound is 100 kWh which is equal to covering 2,553 hours but mostly continuous. The total energy to be covered by the heat pump is then 136,775 kWh and the rest of the loads which is equal to a total of 20,631 kWh have lower occurrences and at random times too in fact making it more variable. Thus, an e-boiler which has a fast ramp-up time can be used in place to cover these hours (519). This only works if both are designed for parallel operation. **Figure 8** provided below shows the clear variation of loads during the winter months.

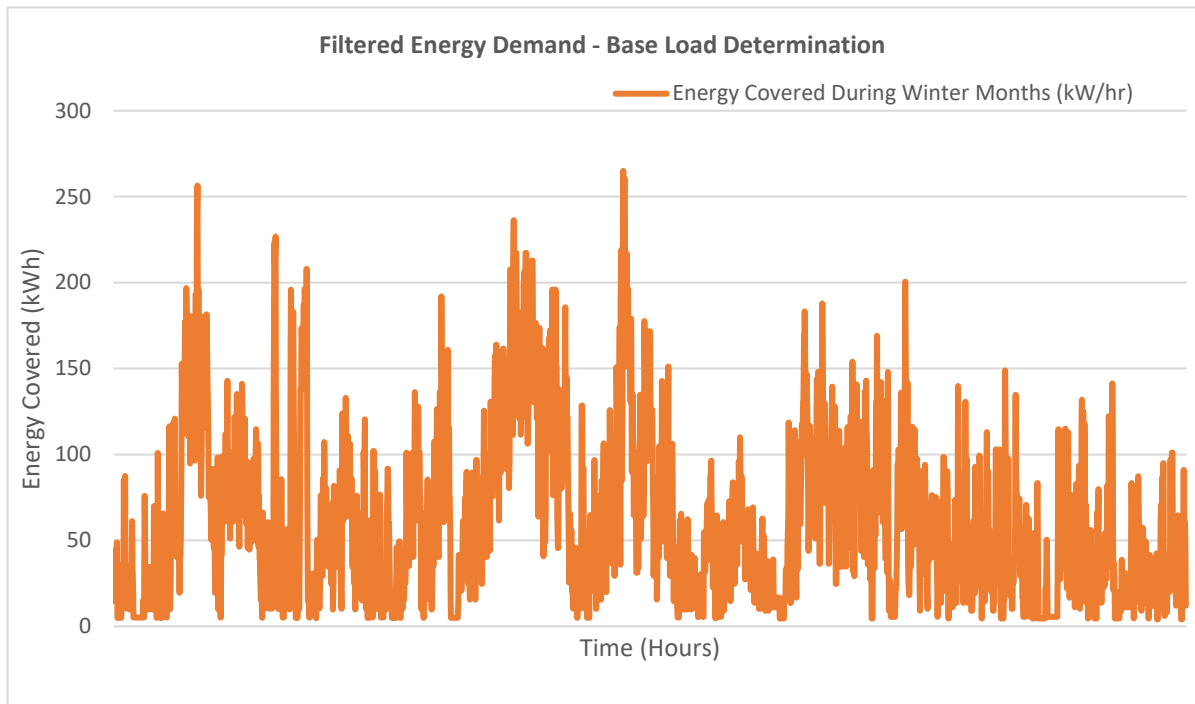


Figure 8: Filtered Energy Demand During the Winter Months

From the above graph it is clear how varying the loads are and with 2,553 hours of the loads falling at the range of 4-100kWh with good continuity in its occurrences makes heat pump the clear choice at handling the base load. Yes, 4-100 kWh is a huge margin it will be a challenge for the heat pump to handle those variations. Thus, we also integrate a variable frequency drive (VFD) to manage the frequency variations efficiently. A buffer tank is also considered as a backup to cover loads for it is a cost-effective and reliable measure. **Table 14** provides clarity on the size of the technologies used and **Figure 9** which is a bar graph that follows the table shows a comparison between the energy demands covered by technologies. A clearer understanding of the bar graph is achieved when the Electricity Consumption by Technology graph is viewed (This graph will be provided in the next sub-heading).

Table 14: Technology Sizes

Sizing		
	Heat Pumps	E-boilers
Thermal Capacity (kW)	100	150
Electrical Power Input	34 kW (COP = 2.922)	150 kW (99-100% eff.)
Hours Working (hrs)	2,553	519
Total Energy Covered (kWh)	136,775	20,631

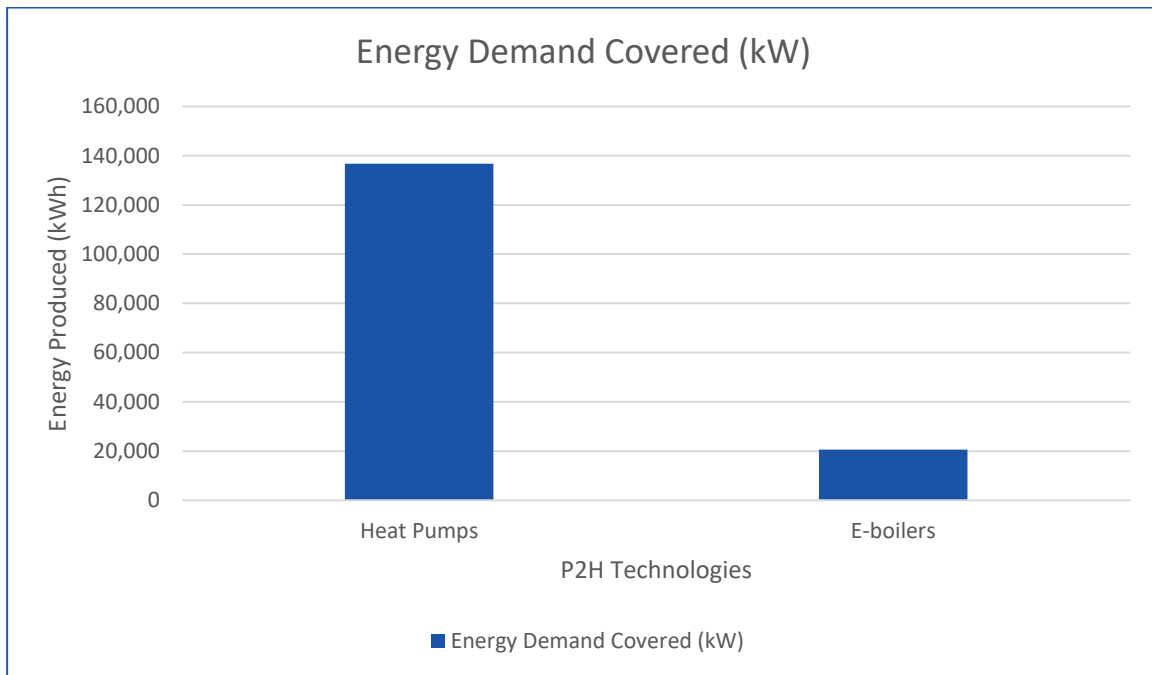


Figure 9: Energy Demand Covered (kW)

5.2 Electricity Consumption

Electrification of the heating system at the WWTP naturally means an increased demand for electricity. While this introduces dependency on the grid, it is also what enables complete decarbonisation — especially considering Sweden's highly clean electricity mix. In this section, we present the actual electrical energy consumed by the heat pump and electric boiler, calculated using the hourly COP model described in Section 3.2.1.

Using the hourly COP model (Section 3.2.1), where each operating hour is matched to the actual effluent temperature, the heat pump covers 136,775 kWh of thermal demand with a weighted average COP of 2.922. The total electrical input required is:

$$E_{HP} = \frac{136,775}{2.922} = 46,813 \text{ kWh}$$

The electric boiler, at COP = 1, covers the remaining 20,631 kWh of thermal demand, consuming 20,839 kWh of electricity. The combined system electricity demand is 67,652 kWh per winter season.

$$E_{boiler} = 20,839 \text{ kWh}$$

Therefore, the combined electricity consumption of the two systems is:

$$Total = 46,813 + 20,839 = 67,652 \text{ kWh}$$

This breakdown is essential when analyzing operational expenses and emissions (discussed in the next sections), but also to understand the load imposed on the grid and any potential need for reinforcement or flexible control strategies.

Figure 10 which is a bar graph provides a clear comparison between the electricity consumption of the two technologies, helping visualize the electricity draw of each technology. Despite covering 87% of the thermal demand across 2,553 hours, the heat pump consumes 46,813 kWh owing to its COP of 2.922, while the electric boiler consumes 20,839 kWh during its 519 peak hours at COP of 1. The heat pump's higher total electricity consumption reflects its far greater operating hours, while its per-kWh efficiency still makes it the more economical choice for base load operation.

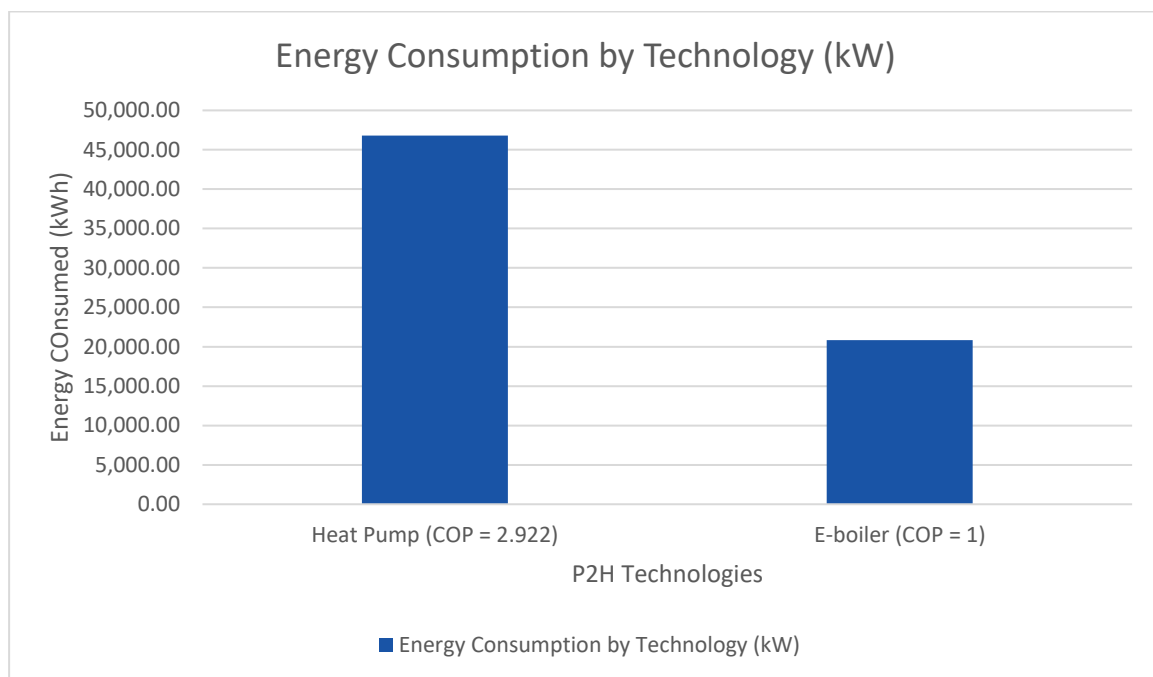


Figure 10: Energy Consumption by Technology (kW)

The initial sizing in Section 3.2 assumed a static COP of 4.0 for the heat pump, which is a standard design-stage approximation. However, when the hourly COP model is applied, matching each of the 2,553 operating hours to its actual daily effluent temperature, the results change dramatically.

Table 15 presents the month-by-month results of the hourly COP model across the 2,553 winter operating hours. The COP varies from a low of 2.849 in February, when effluent temperatures drop to 6.41°C and heating demand peaks at 36,448 kWh, to a high of 3.079 in November when effluent is warmer at 9.81°C. January alone accounts for 905 operating hours and 15,571 kWh of heat pump electricity, making it the most electricity-intensive month despite the heat pump covering only a portion of that month's 55,754 kWh total demand.

Table 15: Monthly Hourly COP Results (November 2023 - April 2024)

Month	Hours	Eff. Temp (C)	COP	HP Elec (kWh)	EB Elec (kWh)	Demand (kWh)
Nov	184	9.81	3.079	3,916	3,294	15,317
Dec	515	8.71	3.006	10,643	3,438	35,394
Jan	905	6.63	2.870	15,571	11,182	55,754
Feb	634	6.41	2.849	11,864	2,670	36,448
Mar	254	7.67	2.934	3,872	252	11,608
Apr	61	9.26	3.043	947	2	2,884
TOTAL	2,553	7.73 avg	2.922	46,813	20,839	157,406
				67,652 kWh		

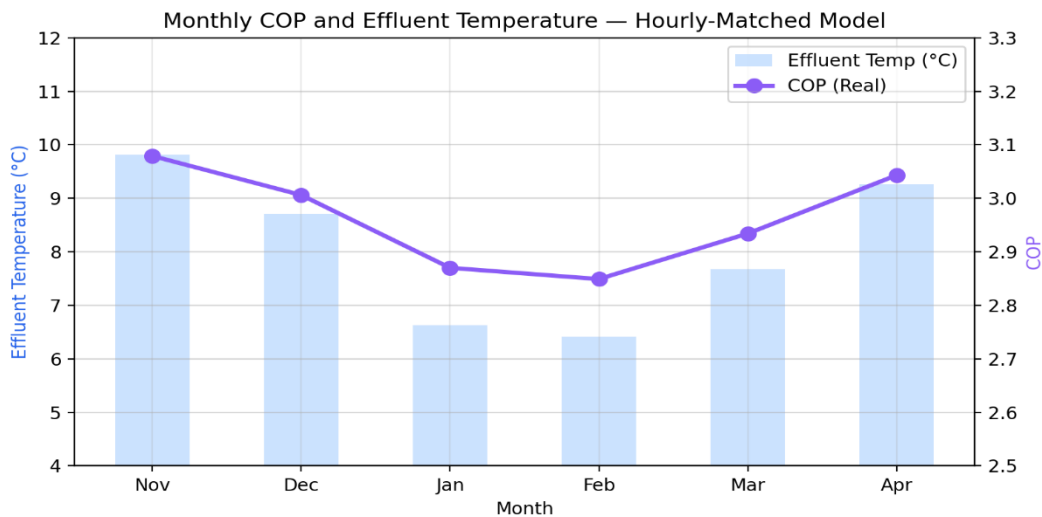


Figure 11: Monthly COP and Effluent Temperature from Hourly Model

This seasonal pattern is visualised in **Figure 11**, where the bar chart of monthly effluent temperatures and the overlaid COP curve clearly show that COP tracks the effluent temperature: both dip sharply from November through February and recover in March and April. The practical consequence is that the heat pump consumes the most electricity precisely when conditions are least favourable, a correlation that a static COP assumption would entirely miss.

Table 16: Static vs Hourly COP

Parameter	Static COP = 4.0	Hourly COP = 2.92	Difference
HP Electricity Consumption	21,244 kWh	46,813 kWh	+120%
EB Electricity Consumption	72,431 kWh	20,839 kWh	-71%

Total Electricity Consumption	93,675 kWh	67,652 kWh	-28%
HP Thermal Output	84,975 kWh	136,775 kWh	+61%
EB Thermal Output	72,431 kWh	20,631 kWh	-72%
HP Share of Thermal Load	54%	87%	+33 pp
Annual OPEX (@ 1.35 SEK/kWh)	131,461 SEK	96,330 SEK	-27%

Table 16 quantifies the impact of this correction by comparing the static COP = 4.0 model against the hourly COP = 2.922 model. The heat pump electricity consumption rises by 120% (from 21,244 to 46,813 kWh) because the real COP is substantially lower than 4.0 during peak demand months. Simultaneously, the electric boiler consumption drops by 71% (from 72,431 to 20,839 kWh) because the hourly model reassigns far more thermal load to the heat pump, increasing its share from 54% to 87%. The net effect is a 28% reduction in total system electricity (from 93,675 to 67,652 kWh) and a 27% reduction in annual OPEX (from 131,461 to 96,330 SEK), confirming that while the heat pump works harder per unit of heat delivered, the overall system becomes cheaper to operate because it displaces the less efficient electric boiler across the majority of operating hours.

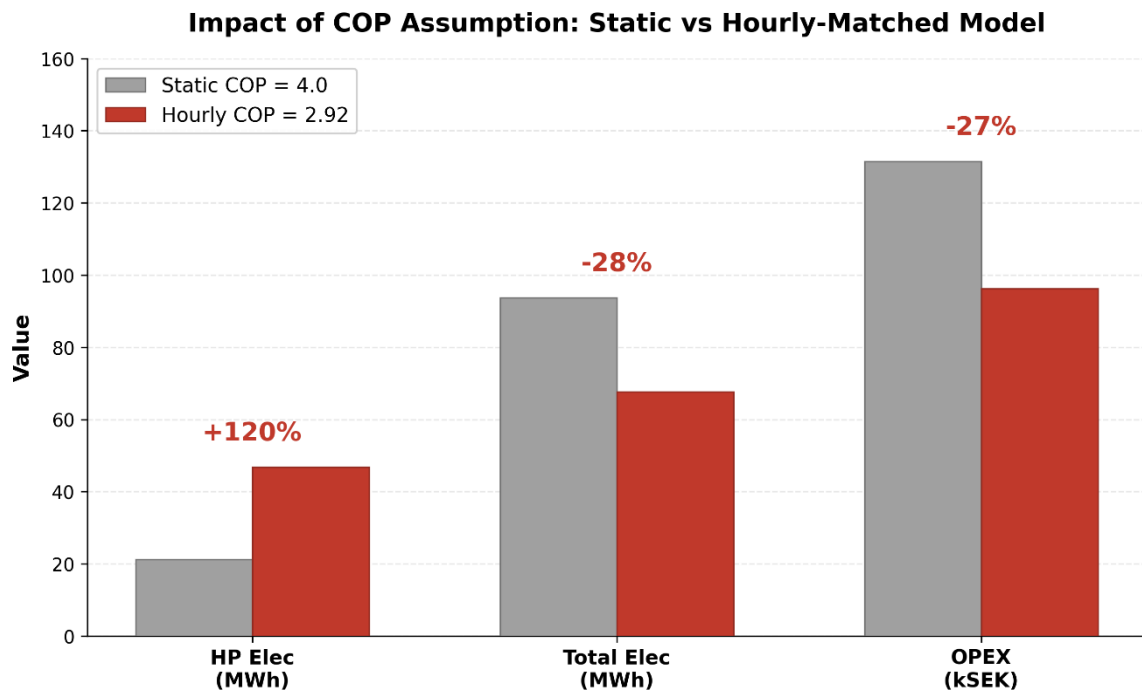


Figure 12: Impact of COP Assumption: Static vs Hourly-Matched Model

Figure 12 illustrates this shift graphically, contrasting the static and hourly models across heat pump electricity, total system electricity, and operating cost.

5.3 Cost Analysis

Cost remains one of the most defining parameters when evaluating the practicality of transitioning to electrified heating systems, especially in municipal facilities like Ernemar WWTP where budgets are tight, and operational efficiency is paramount. This section breaks down both the upfront investment and the recurring yearly expenses associated with the proposed P2H solution which includes a 100 kW heat pump, a 150 kW e-boiler, and a 200 kWh buffer tank.

As per **Table 17**, the total capital required for the full hybrid setup is 1,784,500 Swedish Krona (SEK). Unsurprisingly, the heat pump takes up the bulk of the CAPEX (1,397,000 SEK) largely due to its mechanical complexity and installation requirements. The e-boiler, while rated higher in thermal output, costs significantly less (187,500 SEK) due to its simpler resistance-based design. The buffer tank, used for thermal storage and load flexibility, adds 200,000 SEK, which is an essential cost for ensuring smooth ramping and avoiding short cycling during low load hours.

Table 17: Technology CAPEX

Component	Capacity	Unit Cost (SEK)	Total Cost (SEK)
Heat Pump	100 kW (thermal)	13,970 SEK/kW	1,397,000
Electric Boiler	150 kW	1,250 SEK/kW	187,500
Buffer Tank	200 kWh	1,000 SEK/kWh	200,000
Total CAPEX			1,784,500

As per **Table 18**, annual operating costs are primarily driven by electricity consumption. The heat pump, operating at a COP of 2.922, consumes 46,813 kWh/year, costing around 63,198 SEK/year at an electricity rate of 1.35 SEK/kWh. Meanwhile, the e-boiler, despite working only ~500 hours per season, draws 20,839 kWh/year, resulting in 28,133 SEK/year in operating cost due to its lower efficiency (COP ≈ 1). An additional 5,000 SEK/year is estimated for operating the buffer tank, making the total annual OPEX:

$$OPEX_{total} = 63,198 + 28,133 + 5,000 = 96,330 \text{ SEK/year}$$

Table 18: Technology OPEX

Component	Electricity Use (kW)	Electricity Cost (SEK/kWh)	Annual Cost (SEK)
Heat Pump	46,813	1.35	63,198
Electric Boiler	20,839	1.35	28,133
Buffer Tank	-	-	5,000

Total OPEX	96,330
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To truly understand the economic advantage of transitioning to a P2H system, it is essential to benchmark the proposed setup against the current oil-fired heating system that has been in place at Ernemar WWTP. This comparative analysis not only helps quantify the cost savings but also highlights the long-term benefits of decarbonization through electrification.

Based on the data provided by the plant, the annual oil consumption during the winter months amounts to approximately 15,584.73 litres. At an oil price of 20.1 SEK per litre, the plant incurs an annual fuel expense of 313,253 SEK just to meet its thermal energy requirements during colder periods. However, this is only part of the cost burden. Due to the high carbon content of heating oil and the resulting greenhouse gas emissions — approximately 41,767 kg of CO₂ per year — the facility is also subject to a carbon tax of 1.33 SEK per kilogram of CO₂ emitted. This results in an additional carbon tax expense of 55,550 SEK annually.

When these two components are combined, the total yearly cost of operating the oil-based heating system reaches a substantial 368,803 SEK. This figure does not even factor in potential future increases in oil prices or tightening carbon tax regulations, both of which are quite likely given global climate policy trends. It also doesn't reflect the environmental and reputational costs of continuing to rely on fossil fuels in a sector that is increasingly expected to lead by example in sustainability.

In contrast, the proposed hybrid P2H system — comprised of a 100 kW heat pump and a 150 kW e-boiler, supported by a 200 kWh buffer tank — incurs a total annual operating cost of just 96,330 SEK. This includes all electricity costs for both technologies as well as a conservative estimate for buffer tank operation. Even without subsidies or optimization strategies such as time-of-use electricity tariffs or energy storage enhancements, the P2H system is already significantly cheaper to run.

As per **Table 19**, the result is a net annual saving of 272,473 SEK, which represents about 74% reduction in yearly operating expenses when switching from oil to electricity-based heating. This dramatic decrease is a result of both improved energy efficiency and the inherently lower carbon footprint of Sweden's electricity grid, which minimizes associated emissions and carbon tax burdens.

Table 19: Annual Savings

System	Annual Cost (SEK)
Oil-Based Heating	368,803
P2H (HP+EB+Buffer)	96,330
Annual Savings	272,473

These savings serve as a core justification for the transition and form the basis for key financial indicators, such as the payback period and net present value, which are

discussed in the subsequent section. Over a multi-year period, such savings could free up substantial capital for other plant upgrades or operational improvements — especially in small to mid-sized WWTPs like Ernemar that operate under constrained budgets.

Furthermore, reducing oil dependency helps the plant stay aligned with Sweden's climate goals while addressing a practical concern: cost volatility. Oil prices are known to fluctuate based on global supply chains, which adds uncertainty to long-term budgeting. In contrast, electricity — especially when procured through long-term agreements or renewable sources — tends to offer greater price predictability. This shift improves financial planning and reduces exposure to fuel price shocks. For a municipal facility with a fixed budget and critical services to maintain, that kind of stability is just as important as reducing emissions.

5.4 Emission Analysis

Operational cost is one side of the equation — the other is emissions. This section evaluates the greenhouse gas impact of the existing oil-based heating system and compares it to the proposed P2H setup. The outcome clearly shows how electrification enables not just economic savings, but also a major step toward decarbonizing the facility.

Currently, the WWTP burns 15,584.73 litres of heating oil during the winter period to cover its thermal demand. With an emission factor of 2.68 kg CO₂ per litre, this results in approximately 41,767 kg of CO₂ emitted every winter. This figure doesn't vary much year to year unless drastic changes are made in either fuel efficiency or heat demand — and in Ernemar's case, the operational pattern has stayed fairly consistent.

With the proposed hybrid system in place, this fossil-based heating would be replaced with electricity-driven technologies: a heat pump and an electric boiler. Electricity used to operate both systems is drawn from Sweden's national grid, which is heavily decarbonized. The emission factor used here is 0.012 kg CO₂ per kWh, reflecting the grid mix dominated by hydropower and nuclear.

Based on this:

- The heat pump draws 46,813 kWh/year, resulting in ~562 kg CO₂.
- The electric boiler consumes 20,839 kWh/year, resulting in ~250 kg CO₂.
- This leads to a combined annual emission of just 811.82 kg CO₂.

Compared to the 41,767 kg CO₂ from the current oil-based system, this represents a 98.1% reduction in emissions, which is shown in **Table 20** below.

Table 20: Emissions Reduction

Source	Energy (kWh)	Use	Emission Factor (kg CO ₂ /kWh)	Emissions (kg CO ₂)
Heat Pump	46,813		0.012	562
Electric Boiler	20,839		0.012	250
Total P2H	–		–	812
Oil-Based System	–		–	41,767
Reduction	–		–	~98.1%

It’s difficult to ignore the scale of this difference. Even if grid emissions were to increase slightly in the future — say due to changes in the energy mix or temporary outages in nuclear/hydro — the emissions from electricity-based heating would remain far lower than those of burning fuel oil.

On a per-MWh basis, the difference is even more striking:

- Oil-based heating emits roughly 265.4 kg CO₂/MWh (41,767 kg ÷ 157.4 MWh)
- The P2H system emits just 5.16 kg CO₂/MWh

This drastic reduction offers long-term compliance benefits as well. If future regulations increase penalties on CO₂ emissions or introduce more stringent reporting standards, Ernemar WWTP will be well ahead of the curve. The system would also likely qualify for climate-related incentives or carbon credits under certain Swedish or EU sustainability programs, improving its financial case even further.

The chart below provided as **Figure 13**, visually highlights the difference in emissions between the current oil-based system and the proposed P2H system, offering a clear illustration of just how much lower the climate impact becomes with electrification.

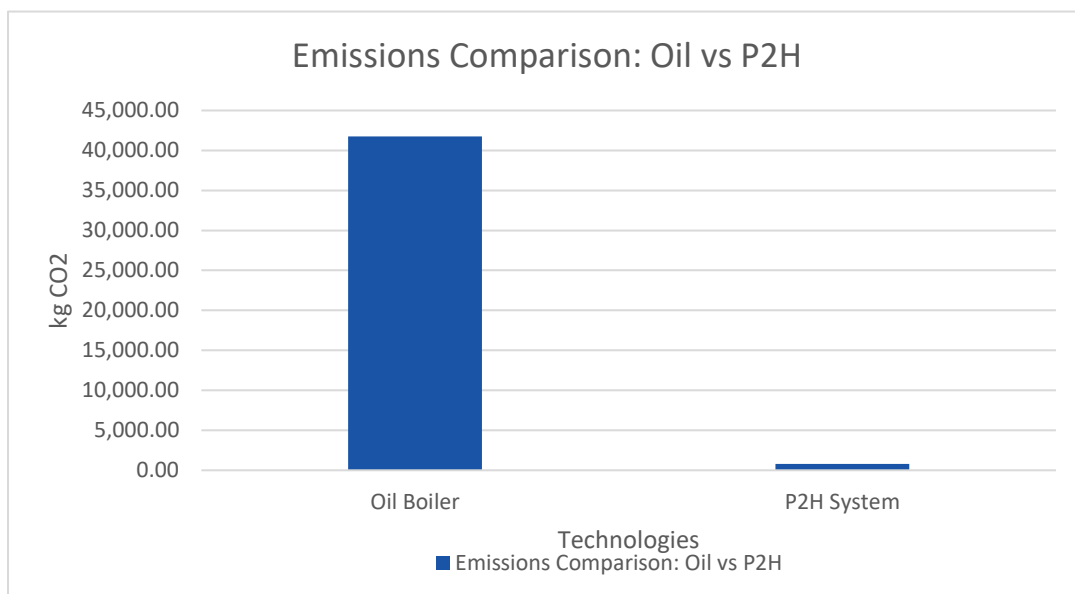


Figure 13: Emission Comparison: Oil vs P2H

5.5 Financial Metrics

Evaluating the financial viability of the proposed P2H system requires more than just comparing operating costs. While previous sections demonstrated substantial annual savings, it is equally important to determine how quickly the investment pays off and what economic value it generates over the system's lifetime. This is where financial indicators such as the Payback Period and NPV come into play. These metrics help assess the return on investment by considering both the time taken to recover costs and the cumulative financial benefit after accounting for the time value of money.

The starting point for both indicators is a clear understanding of the annual savings enabled by the transition from an oil-based system to an electrified one. These savings are derived by subtracting the total annual operating expenses of the P2H system from those of the existing oil-fired heating setup. The following breakdown outlines this calculation in detail.

According to the plant data, winter oil consumption averages 15,584.73 litres. With an oil price of 20.1 SEK per litre, the plant's annual fuel cost becomes:

$$\text{Fuel Cost} = 15,584.73 \times 20.1 = 313,253 \frac{\text{SEK}}{\text{yr}}$$

However, this direct fuel expense does not fully capture the system's economic impact. Due to the combustion of heating oil, the plant emits approximately 41,767 kg of CO₂ annually (based on an emission factor of 2.68 kg CO₂ per litre). Sweden imposes a carbon tax of 1.33 SEK per kg of CO₂, resulting in an additional carbon tax burden of:

$$\text{Carbon Tax} = 41,767 \times 1.33 = 55,550 \frac{\text{SEK}}{\text{yr}}$$

Thus, the total annual cost of the oil-based system is:

$$\text{Total Oil - Based Cost} = 313,253 + 55,550 = 368,803 \frac{\text{SEK}}{\text{yr}}$$

On the other hand, the electrified P2H system comprises a 100 kW heat pump, a 150 kW electric boiler, and a 200 kWh buffer tank. Their annual electricity consumption was previously estimated as follows:

- Heat Pump:

Thermal output: 136,775 kWh

COP = 2.922 ⇒ Electrical input = 136,775 ÷ 2.922 = 46,813 kWh

Cost @ 1.35 SEK/kWh ⇒ 63,198 SEK/year

- Electric Boiler:

Thermal output: 20,631 kWh

COP \approx 1 \Rightarrow Electrical input = 20,839 kWh

Cost @ 1.35 SEK/kWh \Rightarrow 28,133 SEK/year

- Buffer Tank OPEX (maintenance and control systems): 5,000 SEK/year

$$\text{Total P2H Cost} = 63,198 + 28,133 + 5000 = 96,330 \frac{\text{SEK}}{\text{yr}}$$

The difference in operating costs directly translates into annual savings:

$$\text{Annual Saving} = 368,803 - 96,330 = 272,473 \frac{\text{SEK}}{\text{yr}}$$

This annual cost reduction represents a ~74% decrease in operational expenditure, freeing up considerable financial resources for reinvestment in maintenance, technology upgrades, or even staffing and training. The scale of these savings forms the financial backbone for evaluating the investment.

The Payback Period is a measure of how long it takes for cumulative savings to offset the CAPEX. It is a straightforward yet powerful tool for assessing whether the project timeline aligns with budgeting constraints and strategic planning goals.

Formula:

$$\text{Payback Period} = \frac{\text{Capital Investment}}{\text{Annual Savings}}$$

CAPEX:

- Heat Pump (100 kW): 1,397,000 SEK
- E-boiler (150 kW): 187,500 SEK
- Buffer Tank (200 kWh): 200,000 SEK

$$\text{Total CAPEX} = 1,397,000 + 187,500 + 200,000 = 1,784,500 \text{ SEK}$$

$$\text{Payback Period} = \frac{1,784,500}{272,473} = 6.55 \text{ years}$$

The investment is therefore fully recovered in approximately 6 years and 5 months. Given the system's expected operational life of at least 15 years, this leaves a significant post-payback period where the plant operates at substantially lower costs which is a strong indicator of financial prudence.

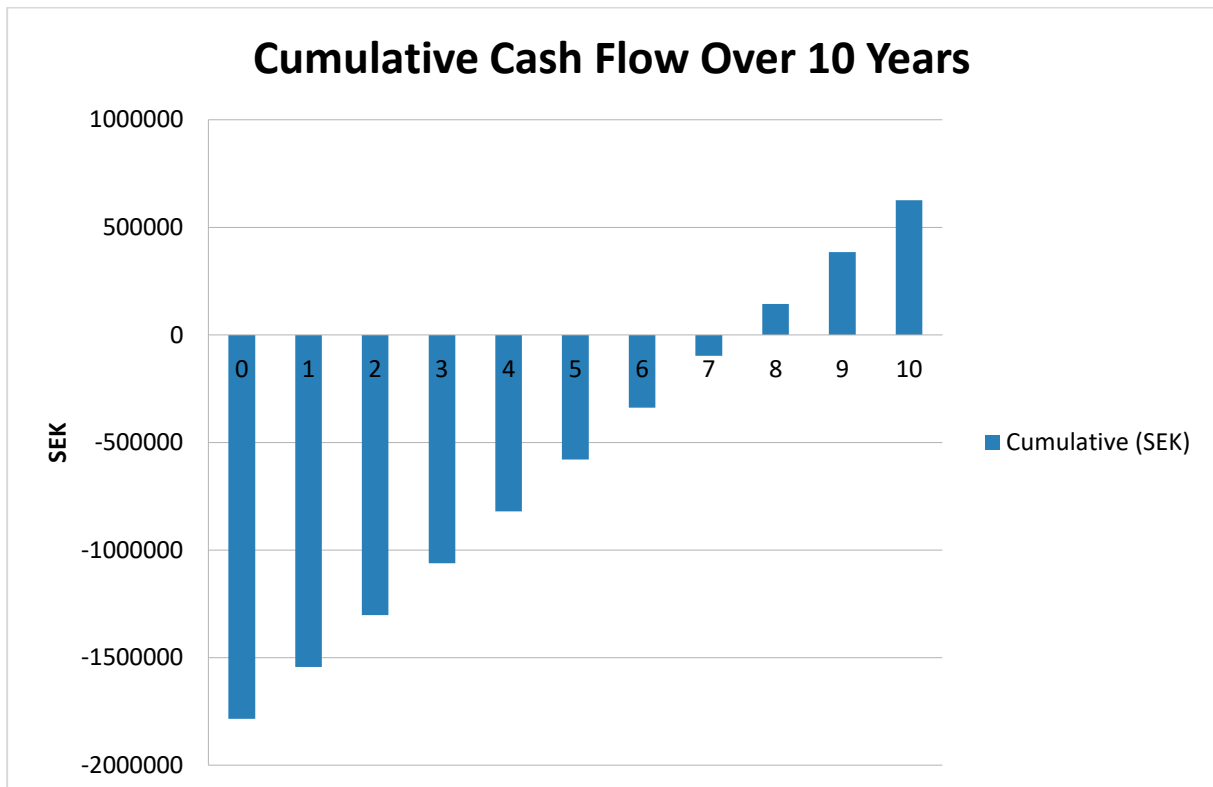


Figure 14: Cumulative Cashflow -Hourly COP Model (10-Yr Horizon)

While the payback period tells us when the investment breaks even, the NPV quantifies how much value the project generates over time after discounting future savings. This approach accounts for the fact that money saved in the future is worth less than money saved today.

Formula:

$$NPV = \sum_{t=1}^n \frac{s}{(1+r)^t} - I$$

Where,

- S = Annual savings = 272,473 SEK
- r = Discount rate = 5% = 0.05
- n = Project lifetime = 10 years
- I = Initial investment = 1,784,500 SEK

We first compute the Present Value Annuity Factor (PVAF):

$$PVAF_{10,5\%} = \frac{1 - (1+r)^{-n}}{r} = \frac{1 - (1.05)^{-10}}{0.05} = 7.7217$$

Then calculate:

$$NPV = (272,473 \times 7.7217) - 1,784,500 = 2,132,197 - 1,784,500 = 319,464 \text{ SEK}$$

A positive NPV of 319,464 SEK means the project is not just cost-neutral—it generates value over time, even under conservative assumptions. This reinforces that the proposed P2H system is economically sound. Moreover, this figure does not include several factors that could improve it further, such as:

- Increased carbon taxes or stricter policy enforcement
- Oil price volatility, which historically trends upward
- Potential subsidies or grant funding from national or EU-level programs
- Tariff optimization using time-of-use or dynamic electricity pricing
- Further integration with renewable sources (e.g., solar PV)

Finally, the financial case is strengthened by the non-monetary benefits such as reduced dependence on fossil fuels, alignment with national climate goals, and a significantly lower emissions profile. Together, these advantages position the hybrid heating system not just as a smart technical upgrade, but as a responsible and forward-thinking investment for the Ernemar WWTP.

5.6 Demand Distribution and Allocation

One of the most important steps in designing the heating system for Ernemar WWTP was understanding how the demand changes over time — not just how much energy is needed, but when and how frequently different levels of demand occur. This matters because choosing the right technology to meet each part of that load can make the system far more efficient and affordable to run.

The hourly heating demand during the winter months (November to April) showed a wide variation. For a large share of the time, about 2553 hours, the demand remained somewhere between 4 and 100 kWh. These were relatively stable hours, with no sharp fluctuations. During other periods, however, the load spiked above 100 kWh, sometimes reaching up to 250 kWh within an hour. These spikes were less frequent but intense, often caused by very cold days or sudden operational loads from the treatment process.

Given this pattern, it made sense to divide the job between two systems. The heat pump was assigned to cover the steady, moderate demands basically all hours where the load was up to 100 kWh. It works most efficiently in this range and doesn't need to ramp up quickly. For any demand above 100 kWh, the electric boiler takes over the excess. It reacts quickly and is better suited for those sudden spikes. This way, we avoid overloading the heat pump or having to size it much larger than necessary.

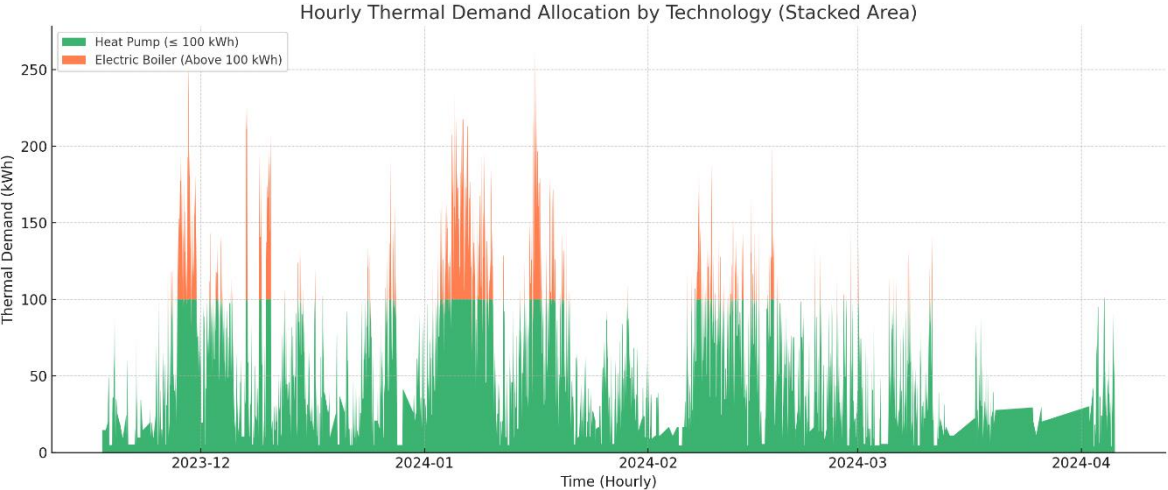


Figure 15: Hourly Demand Allocation by The Sized Technologies

In **Figure 15** above, the green area shows the demand covered by the heat pump. You can see that it handles the bulk of the workload throughout the winter, including long stretches in December, January, and March. The orange peaks above the green areas mark the hours where the electric boiler kicks in. These are the high-demand moments, often clustered around colder periods or process-heavy days.

The choice to limit the heat pump to 100 kWh per hour wasn't random. This threshold was based on analyzing the data and finding that loads below this level made up the majority of the season's hours. At the same time, it was a size that allowed us to avoid overspending on a system that would rarely run at full capacity. The electric boiler, sized at 150 kW, could then handle anything beyond that. Not regularly, but when needed. **Table 21** highlights the demand allocation.

Table 21: Demand Allocation

Parameter	Heat Pump (≤ 100 kWh)	Electric Boiler (> 100 kWh)
Installed capacity	100	150
% of Seasonal Demand Covered	87%	13%
Operational Focus	Base & Intermediate	Peak loads only

These values show that the heat pump handles the bulk of the seasonal energy at 87%, while the electric boiler covers the remaining 13% during peak demand periods.

By dividing the load this way, the system avoids underutilizing one technology while overworking another. It also keeps electricity costs in check, since the heat pump, which is more efficient, handles the larger number of hours. On top of that, the plant benefits from improved reliability, since both systems are running in parallel and can support each other if needed.

The buffer tank, mentioned earlier in the report, adds extra flexibility here. It helps smooth out any short-term gaps, especially if the heat pump needs time to ramp up. And the VFD attached to the heat pump lets it adjust output in real time, so it isn't forced to turn on and off constantly when loads shift slightly above or below certain levels.

In short, this section of the analysis helped make sure that the system isn't just technically capable, but also tuned to the plant's actual needs. It's not overbuilt, it's not underbuilt — it's built to match the demand profile of Ernemar WWTP in a way that makes technical and economic sense.

5.7 Sensitivity Analysis

The sensitivity analysis conducted evaluates how key assumptions influence the financial viability of the proposed electrification strategy at Ernemar WWTP. By systematically varying parameters such as oil price, electricity cost, heat pump sizing, COP, carbon tax, and discount rate, the analysis highlights the robustness and risks of the investment. Results show that oil price has a dominant impact on savings and payback period: when oil price rises from 15 SEK/L to 25 SEK/L, annual savings improve from 196,649 SEK to 352,496 SEK, and NPV increases from -266,039 SEK to 937,367 SEK. Similarly, electricity price fluctuations can erode profitability. At 1.6 SEK/kWh, payback stretches to 6.9 years and NPV drops to just 217,100 SEK. Heat pump sizing also plays a critical role; although a 150 kW unit reduces OPEX, the higher capital cost leads to a negative NPV. COP changes reflect seasonal performance shifts, affecting energy consumption and total savings, while changes in carbon tax demonstrate the benefit of future decarbonization policies. Lastly, NPV sensitivity to discount rate confirms that project viability is stronger under public-sector style financing (e.g., 3%) than with higher private-sector hurdle rates. Overall, this analysis provides confidence in the electrification proposal's feasibility under a range of plausible future conditions and serves as a decision-support tool for municipal planners. It also underscores that external market and policy factors (particularly oil and electricity prices) significantly shape the payback timeline and long-term economic benefit.

5.7.1 Oil Price Variations

Heating oil is a traded commodity whose price can swing dramatically with global supply and demand. For a wastewater treatment plant, these swings determine how much money is spent on fuel each winter. The base case of this study assumes an oil price of 20.1 SEK per litre. To test the resilience of the electrification project, the sensitivity analysis varies the price to 15 SEK/L and 25 SEK/L. A low price might occur if global markets are oversupplied or if tax reductions are enacted; a high price could arise from geopolitical shocks or tightening climate policies. Importantly, the cost of the oil-fired baseline includes both the purchase of fuel and the payment of a carbon tax, so any increase in oil price has a compound effect on the plant's OPEX. At 15 SEK/L the oil-based system costs 292 978.631 SEK per year. Because the electrified system's operating cost does not change with the oil price, annual savings fall to 196,649 SEK. A payback period of 9.075 years and a negative 10-year NPV (-266,039 SEK) show that the investment would not be attractive if heating oil became cheap. The base case (20.1 SEK/L) delivers savings of 272,473 SEK, paying back the 1 784 500 SEK capital cost in about 6.55 years with a positive NPV of 319,464 SEK. If oil climbs to 25 SEK/L the annual savings grow to 352,496 SEK, reducing the payback to 5.062 years and increasing the 10-year NPV to 937,367 SEK. These results underscore that the economic case for electrification is highly sensitive to fuel prices. The larger the gap between the oil-fired baseline and the electric alternative, the more compelling the investment becomes; conversely, cheap oil weakens the business case. Operators should therefore monitor oil markets and consider hedging or long-term supply contracts to manage this risk. **Table 22** shows the effect of oil price variation on NPV and Payback and **Figures 16 & 17** visualizes it graphically.

Table 22: Effect of Oil Price Variation on NPV and Payback

Oil price (SEK/L)	Oil-based OPEX (SEK/yr)	Annual savings (SEK/yr)	Payback (yr)	NPV (SEK)
15	292,979	196,649	9.075	-266,039
20.1	368,803	272,473	6.553	319,464
25	448,826	352,496	5.062	937,367

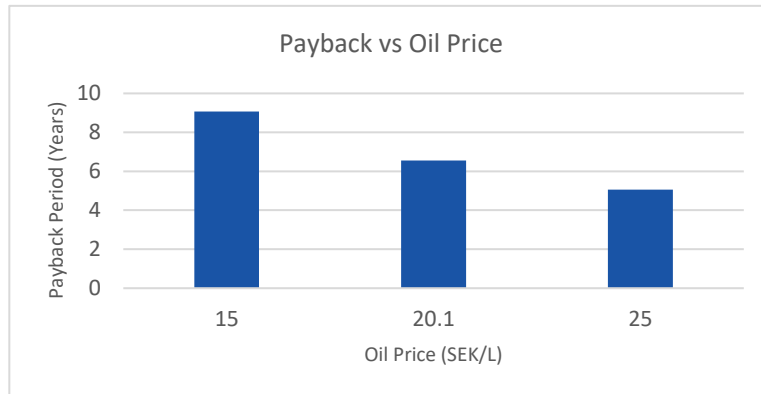


Figure 16: Payback vs Oil Price

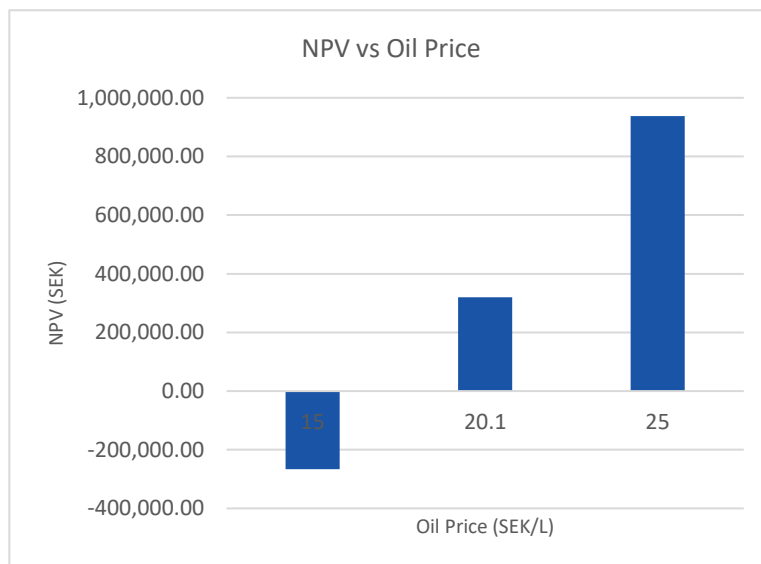


Figure 17: NPV vs Oil Price

5.7.2 Electricity Price Variations

While the electrified heating system eliminates the consumption of fossil fuels, it creates a strong dependence on electricity prices. Electricity costs vary by region, season and contract type, and the electric boiler in the proposed design consumes more energy than the heat pump. To account for this uncertainty, the analysis evaluates three price points: 1.0 SEK/kWh (a low-price scenario representative of surplus renewable generation), 1.35 SEK/kWh (the base case) and 1.6 SEK/kWh (a high-price or peak-period scenario). Because the P2H system’s operating cost is proportional to the sum of the heat-pump and boiler electricity demand, changes in the power price have a direct effect on annual savings. At 1.0 SEK/kWh the P2H OPEX drops to 72,652 SEK per year. The oil-based system still costs 372 461 SEK, so the

project saves 299,809 SEK annually, recouping the capital investment in about 5.952 years and producing a healthy 10-year NPV of 530,533 SEK. The base-case price of 1.35 SEK/kWh yields savings of 272,473 SEK with a 6.55-year payback and a modest positive NPV. When electricity rises to 1.6 SEK/kWh, however, the P2H OPEX climbs to 113,243 SEK and annual savings shrink to 259,218 SEK. The payback period extends to 6.88 years and the NPV drops to 217,100 SEK, still positive but noticeably lower than the base case. These findings suggest that while the project remains viable across the tested electricity price range, securing affordable electricity through long-term contracts, demand response, or on-site renewables would further strengthen the financial case. **Table 23** shows the effect of electricity price variation on NPV and Payback and **Figures 18 & 19** visualizes it graphically.

Table 23: Effect of Electricity Price Variations on NPV and Payback

Electricity price (SEK/kWh)	P2H OPEX (SEK/yr)	Annual savings (SEK/yr)	Payback (yr)	NPV (SEK)
1.0	72,652	299,809	5.952	530,533
1.35	96,330	272,473	6.553	319,464
1.6	113,243	259,218	6.884	217,100

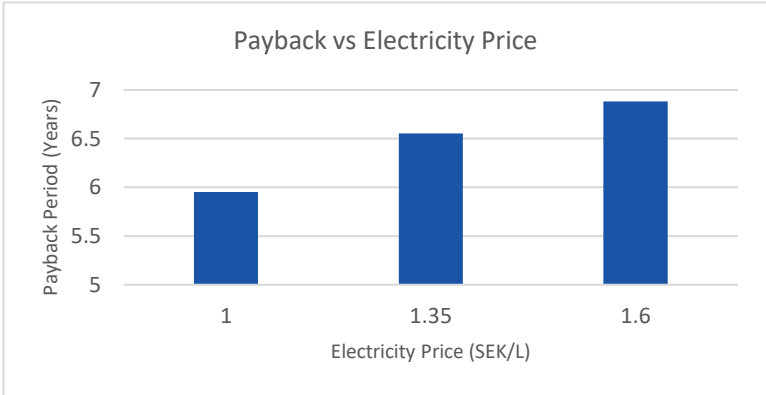


Figure 18: Payback vs Electricity Price

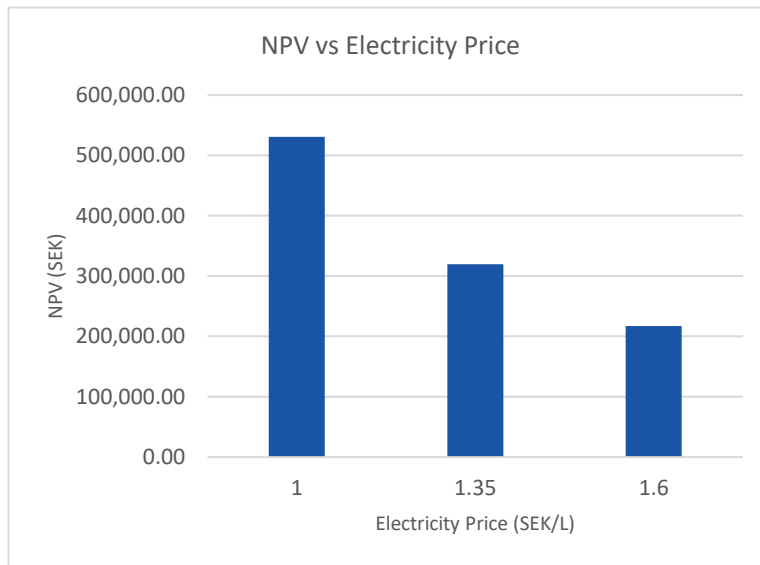


Figure 19: NPV vs Electricity Price

5.7.3 Carbon Tax Evolution

Sweden’s carbon tax is one of the highest in the world and is a major driver of the financial benefits of electrification. The carbon tax applies to fossil fuels but not to electricity because the national grid is largely decarbonised. The base case uses a tax rate of 1.33 SEK/kg CO₂. To assess the effect of future policy shifts, the tax is varied to 2.00 SEK/kg CO₂ and 3.00 SEK/kg CO₂. The oil-based system’s operating cost increases linearly with the tax because emissions are proportional to the volume of oil burned. At 1.33 SEK/kg CO₂ the oil-based OPEX is 372 461 SEK per year, yielding savings of 272,473 SEK when compared to the P2H system. This delivers the familiar payback and NPV. Raising the tax to 2.00 SEK/kg CO₂ increases the oil-based OPEX to 402 287.168 SEK. Annual savings rise to 305,957 SEK, the payback shortens to 5.83 years and the 10-year NPV jumps to 578,009 SEK. An aggressive carbon tax of 3.00 SEK/kg CO₂ drives the oil-based OPEX up to 446 804.168 SEK. The project then saves 350,474 SEK per year, pays back the capital cost in 5.092 years and has a very favourable NPV of 921,756 SEK. These figures illustrate how carbon-pricing policy can dramatically improve the business case for electrification, effectively penalising fossil-fuel use and rewarding low-carbon technologies. **Table 24** shows the effect of carbon price increment on NPV and Payback and **Figures 20 & 21** visualizes it graphically.

Table 24: Carbon Tax Increment Effect on NPV and Payback

Carbon tax (SEK/kg CO ₂)	Oil-based OPEX (SEK/yr)	Annual savings (SEK/yr)	Payback (yr)	NPV (SEK)
1.33	368,803	272,473	6.553	319,464
2.00	402,287	305,957	5.833	578,009
3.00	446,804	350,474	5.092	921,756

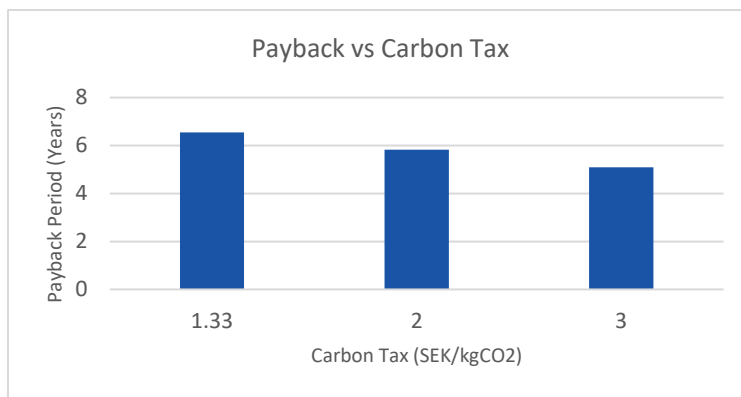


Figure 20: Payback vs Carbon Tax

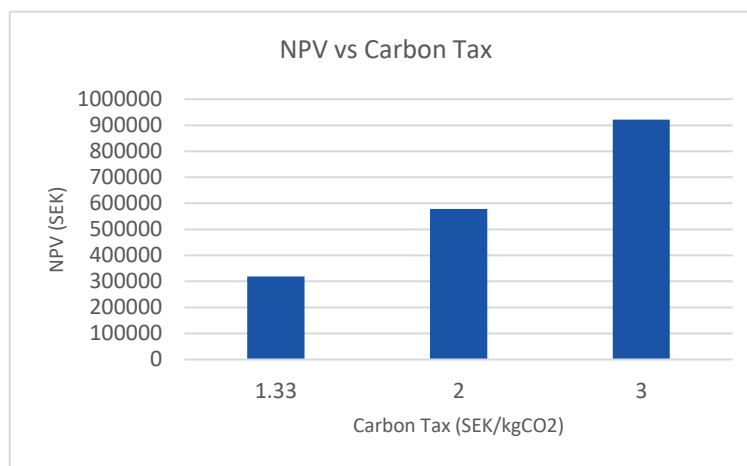


Figure 21: NPV vs Carbon Tax

5.7.4 Discount Rate Changes

The discount rate reflects the cost of capital or the opportunity cost of investing money in a project. Publicly financed infrastructure projects often apply low discount rates (around 3 %) to account for societal benefits and lower borrowing costs, whereas private investors may use higher rates (7 % or more) to reflect risk and return expectations. The sensitivity analysis examines discount rates of 3 %, 5 % and 7 % while keeping all other parameters at their base values. Because the discount rate only affects the time-value of money, the annual savings remain constant at 272,473 SEK.

At a 3 % rate the present value of these savings is high; the 10-year NPV of the project reaches 570,953 SEK. At the base rate of 5 % the NPV drops to 319,464 SEK, which is positive. When the discount rate increases to 7 %, future savings are valued less and the NPV drops to 154,934 SEK , still positive but substantially lower than at 3%. These results show that the project remains viable across all tested discount rates, though public-sector financing (at lower rates) significantly enhances the value generated. For private investors requiring higher returns, the smaller but still positive NPV at 7% suggests the project meets basic viability thresholds, though additional incentives or a longer evaluation horizon could strengthen the case. **Table 25** shows discount rate fluctuations and its effect on NPV and Payback and **Figure 22** visualizes it graphically.

Table 25: Discount Rate Fluctuations and its Effect on NPV

Discount rate	NPV (SEK)
3 %	570,953
5 %	319,464
7 %	154,934

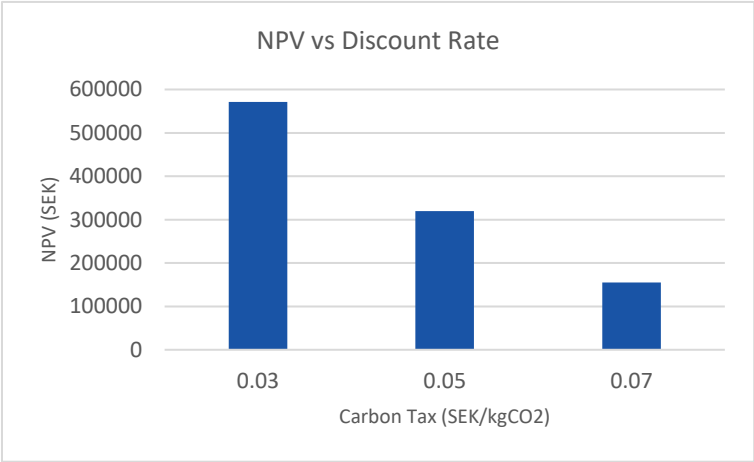


Figure 22: NPV vs Discount Rate

5.8 Multi-Variable Sensitivity Analysis

The single-variable sensitivity analyses in Sections 5.7.1-5.7.4 isolate the effect of one parameter at a time. However, real-world conditions change multiple variables simultaneously. This section introduces three multi-variable analyses that provide a more realistic assessment of the project resilience.

5.8.1 Electricity Price x COP Payback Matrix

Elec ↓ / COP →	COP=2.5	COP=2.92	COP=3.5	COP=4.0	COP=5.0
0.8 SEK/kWh	5.9	5.8	5.6	5.6	5.5
1.0 SEK/kWh	6.2	6.0	5.9	5.8	5.7
1.2 SEK/kWh	6.5	6.3	6.1	6.0	5.8
1.35 SEK/kWh	6.8	6.6	6.3	6.2	6.0
1.5 SEK/kWh	7.1	6.8	6.5	6.3	6.1
1.8 SEK/kWh	7.8	7.4	7.0	6.7	6.4
2.0 SEK/kWh	8.4	7.8	7.3	7.0	6.7

Figure 23: Payback Period Heatmap: Electricity Price x COP

The two parameters most directly affecting the P2H system operating cost are the electricity price and the heat pump COP. Their combined effect on payback period is captured in the following matrix. The base case (1.35 SEK/kWh, COP = 2.92) yields a payback of 6.5 years. The matrix reveals that even at lower COP values (2.5), the project remains viable if electricity stays below 1.0 SEK/kWh. Conversely, electricity above 1.8 SEK/kWh requires COP of at least 3.5 for reasonable payback.

5.8.2 Carbon Tax Trajectory Projection

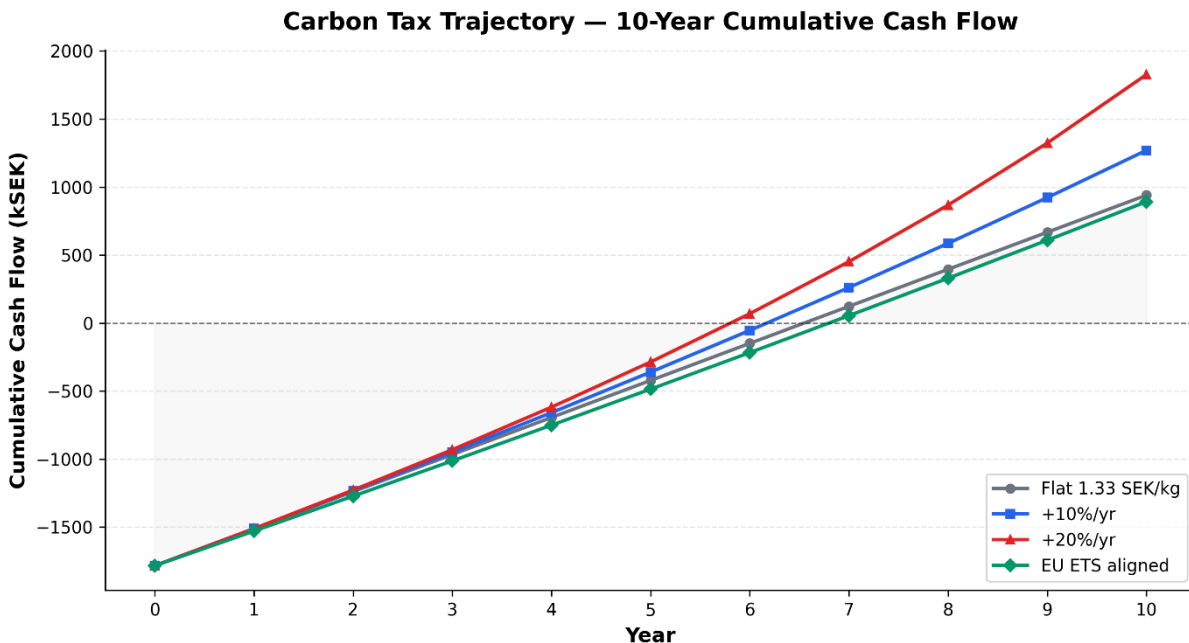


Figure 24: Carbon Tax Trajectory: 10 Yr Cumulative Cashflow

Carbon tax policy is the single strongest lever affecting the project long-term profitability. Four plausible scenarios were modelled over a 10-year horizon: Flat (1.33 SEK/kg CO₂, no change), +10%/year (moderate escalation), +20%/year (aggressive

decarbonisation, Year 10: 8.19 SEK/kg), and EU ETS aligned (starting 0.9 SEK/kg with 6.5%/year growth). Even the flat scenario breaks even by year 7; under +20%/year escalation, cumulative cash flow reaches over 3 million SEK by year 10. This insight has important implications: even if current economics appear marginal, anticipated policy tightening strongly favours early investment in electrification.

Table 26: Carbon Tax Trajectory Projection

Scenario	Year 10 CT (SEK/kg)	Year 10 Cum. Cash Flow (SEK)	Breakeven Year
Flat 1.33	1.33	939,849	Year 7
+10%/yr	3.45	1,385,206	Year 6
+20%/yr	8.24	2,114,757	Year 5
EU ETS aligned	1.69	924,579	Year 7

5.8.3 Technology Mix Optimisation

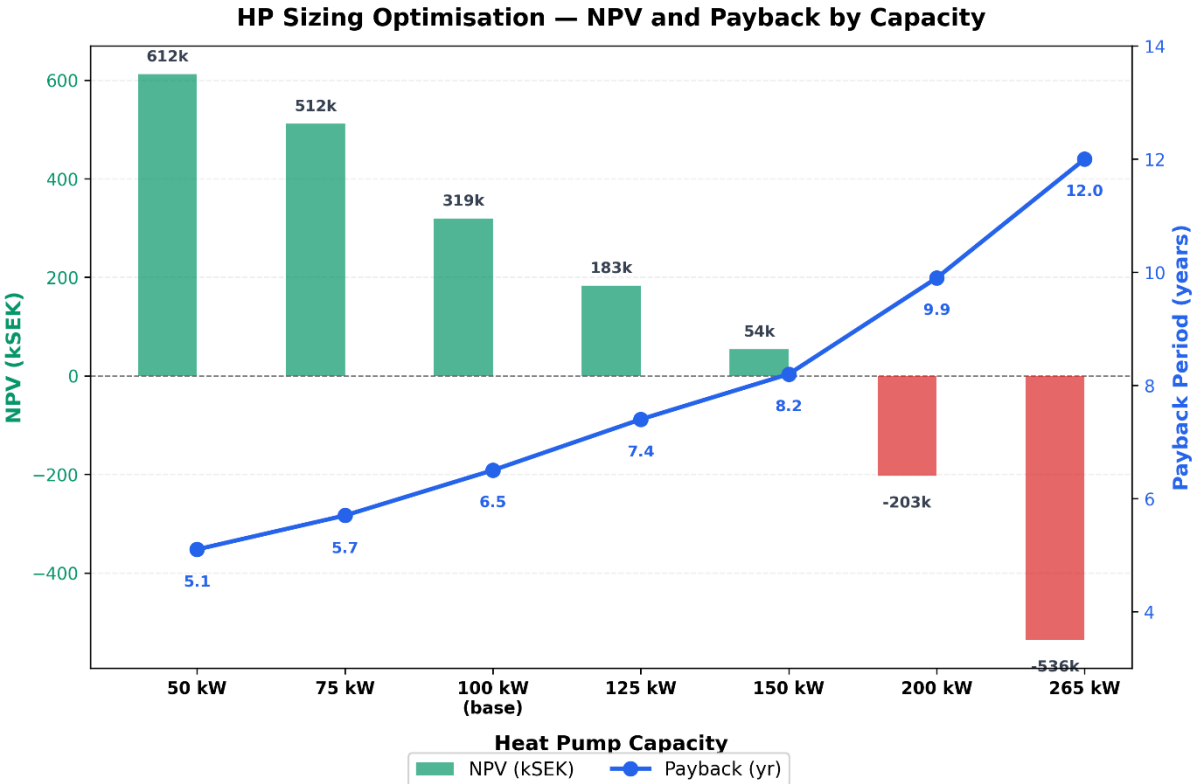


Figure 25: HP Sizing Optimisation - NPV and Payback by Capacity

The initial sizing analysis used a 100 kW heat pump. The hourly model enables a more comprehensive analysis across seven capacity options (50-265 kW), with the electric boiler sized to cover the remainder. The 100 kW heat pump delivers the best balance between investment cost and savings. Smaller HPs (50-75 kW) show shorter payback due to lower CAPEX, but leave more load to the less efficient electric boiler. Sizes above 150 kW suffer diminishing returns as incremental thermal coverage is minimal while CAPEX rises steeply.

Table 27: Technology Mix Optimisation (Hourly COP Model)

HP (kW)	EB (kW)	HP Share	CAPEX (SEK)	OPEX (SEK)	Payback (yr)	NPV (SEK)
50	215	60%	1,167,250	134,586	5	641,307
75	190	76%	1,485,250	111,210	5.8	503,815
100 (base)	165	87%	1,803,250	96,331	6.6	300,707
125	140	93%	2,121,250	87,189	7.5	53,297
150	115	97%	2,439,250	82,163	8.5	-225,898
200	65	99%	3,075,250	78,260	10.6	-831,756
265	0	100%	3,902,050	77,714	13.4	-1,654,338

5.9 HEX Data Analysis and Operator Tool

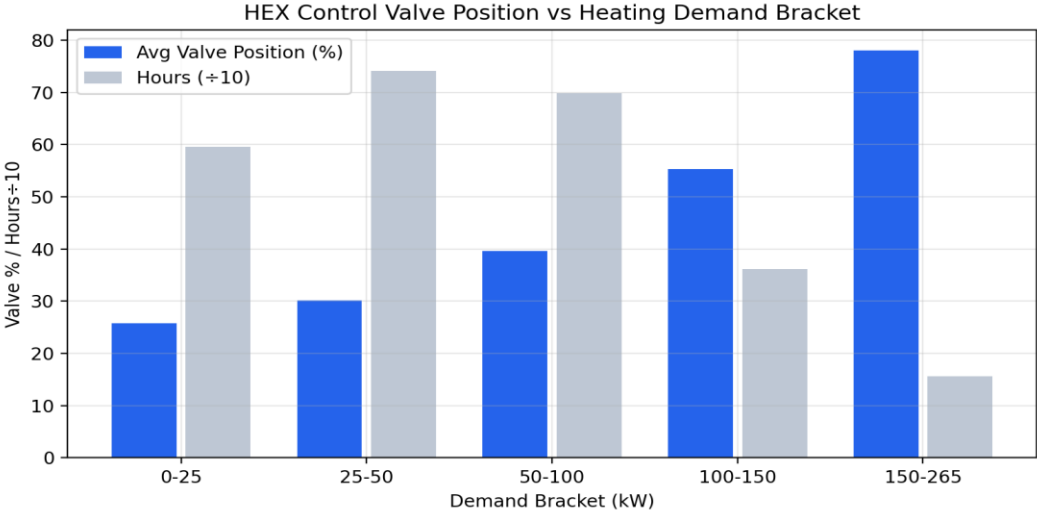


Figure 26: HEX Control Valve Position vs Heating Demand Bracket

The analysis of 10,224 hourly SCADA records from the heat exchanger (HEX) control system, aggregated into 427 daily data points, reveals a moderate but operationally useful correlation ($r = 0.398$) between valve position and heating demand. Higher demand brackets correspond to higher valve positions (from 25.8% at 0-25 kW to 78.1% at 150-265 kW), confirming the valve as a reliable real-time demand proxy.

Table 28: HEX Valve Analysis by Demand Bracket

Demand Bracket	Hours	Avg Valve (%)	Avg HEX Temp (C)	Total Energy (kWh)
0-25 kW	596	25.8	87.2	8,284
25-50 kW	741	30.2	86.1	26,391
50-100 kW	698	39.6	85.4	50,300
100-150 kW	362	55.3	84.8	43,998
150-265 kW	156	78.1	83.2	28,433

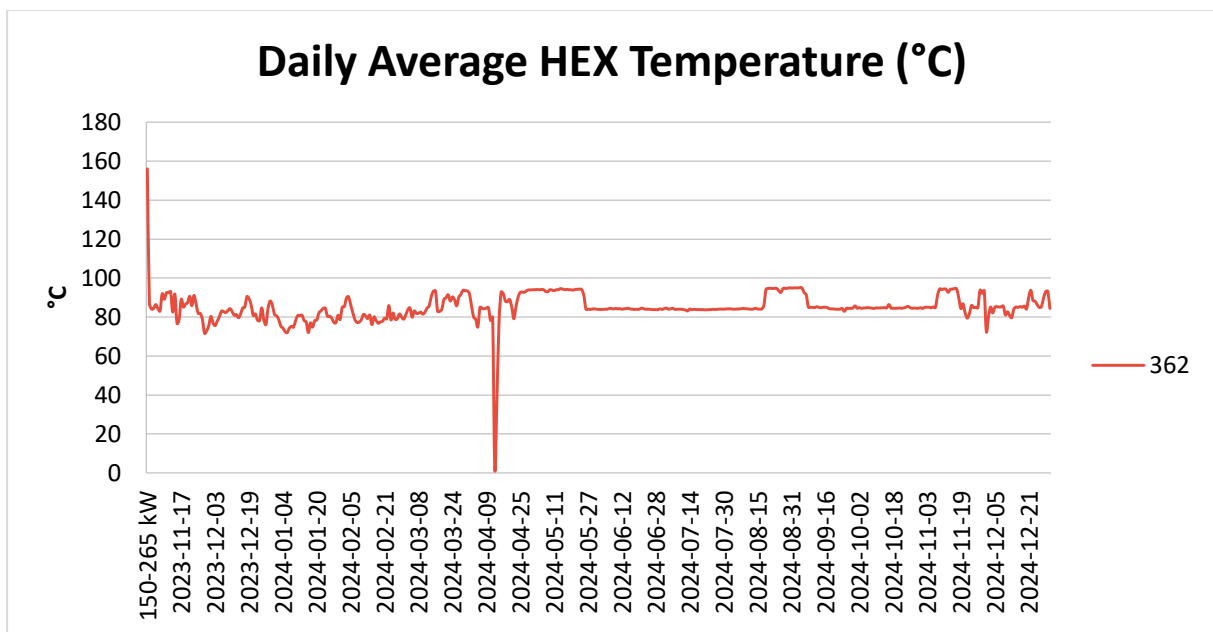


Figure 27: Daily Average HEX Temperature

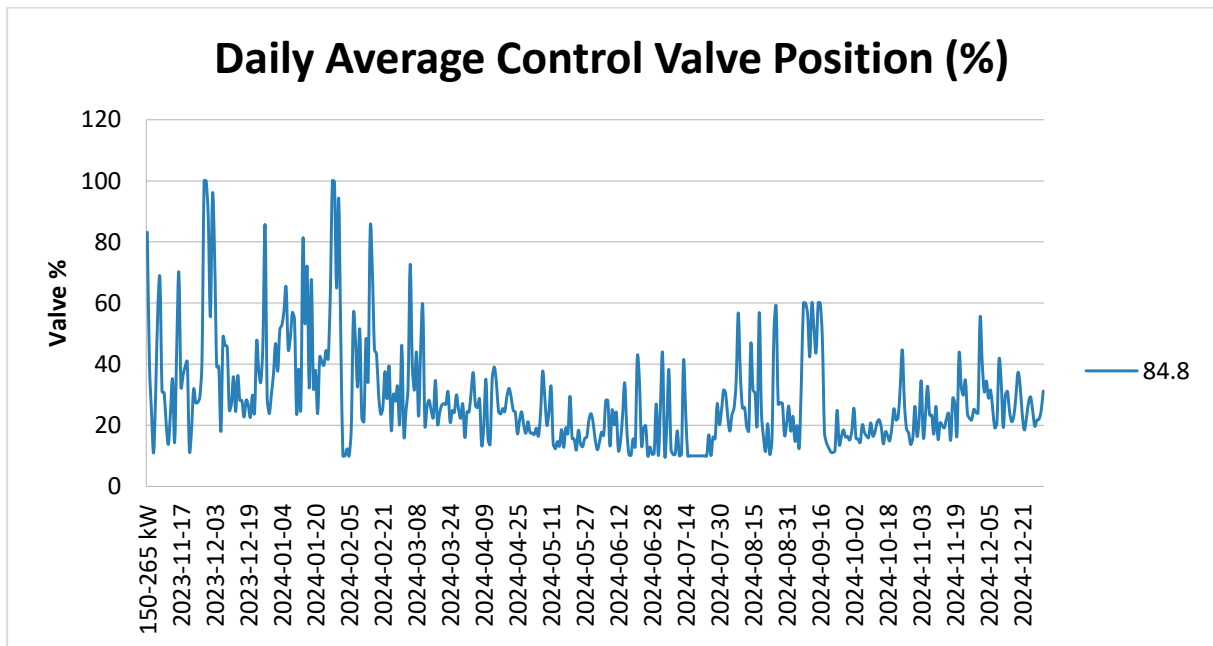


Figure 28: Daily Average Control Valve Position (%)

From **table 28 and figures 27 and 28**, two patterns emerge. First, the average valve position increases monotonically with demand, confirming the valve as a useful operational indicator. Second, the HEX temperature decreases as demand rises (from 87.2 C to 83.2 C), reflecting thermal stress on the biogas system near capacity.

Table 29: HEX Valve Operator Decision Thresholds

Valve Position	Interpretation	Recommended Action
Below 40%	Biogas sufficient for current demand	HP standby; monitor only
40 - 80%	Biogas nearing capacity; supplemental heat needed	Activate HP at base load; buffer absorbs peaks
Above 80%	Biogas maxed out; deficit imminent	HP at full capacity + EB for peak loads

5.9.1 Excel Model as Primary Operator Tool

The Excel workbook is the central analytical and operational tool delivered by this thesis. It contains 13 sheets with over 43,000 formulas and 25 embedded charts, serving as both the complete auditable record of all calculations and a practical scenario-evaluation tool. Key sheets include: Energy Balance (2,553 hourly data points), Hourly COP Model (per-hour calculations producing the weighted 2.922), Cost Considerations (editable input cells for electricity price, oil price, carbon tax, discount rate), Sensitivity Analysis (single and multi-variable), HEX Analysis (427 daily

aggregated records), and a Dashboard summary. The workbook requires no macros, add-ins, or external connections and runs in any standard Microsoft Excel installation.

5.9.2 HTML Dashboard for Visualisation

A standalone HTML dashboard was developed as a visual companion tool. This single-file application opens in any web browser without installation and provides six interactive tabs: Overview, Hourly COP, HEX Data, Economics, Sensitivity, and Inputs. All economic parameters can be adjusted via input fields, and all charts and metrics recalculate in real time. The HTML tool complements the Excel model by enabling rapid visual exploration of scenarios during meetings and operational planning sessions.

Chapter 6: Discussion, Conclusions, and Future Work

6.1 Discussion

The results of this study clearly demonstrate that the proposed Power-to-Heat (P2H) system—consisting of a 100 kW heat pump and a 150 kW electric boiler—can effectively eliminate the use of fossil oil at the Ernemar WWTP while ensuring reliable winter heating. The techno-economic model confirmed that this hybrid configuration achieves a 98.1% reduction in CO₂ emissions and reduces operational costs by 74%. These outcomes validate the hypothesis that electrification of heating through P2H technologies is both technically and economically feasible for small-scale wastewater treatment plants. Furthermore, the robustness of the system under different sensitivity scenarios indicates that the solution remains stable across a range of market and operational conditions, reinforcing its potential for wider adoption in similar facilities.

A key methodological contribution of this work is the hourly COP model, which revealed that a static COP assumption of 4.0 underestimates heat pump electricity consumption by 120% while simultaneously overestimating electric boiler usage. When the static model was replaced with hourly matching to actual effluent temperatures, the heat pump share of thermal output rose from 54% to 87%, total system electricity fell by 28%, and the NPV improved from the static estimate to 319,464 SEK. This finding underscores the importance of temporally resolved performance data in climate-sensitive heat pump applications.

The integration of HEX control valve data as a real-time demand proxy represents a practical innovation bridging the analytical model and daily plant operations. By correlating the existing SCADA-monitored valve position with heating demand, the

study provides operators with actionable thresholds (green/amber/red zones) requiring no additional instrumentation.

When compared with previous studies and best practices in the wastewater sector, the findings are consistent with the growing recognition of electrification as a key enabler of decarbonization. Literature has highlighted that small and medium-sized WWTPs often face similar challenges—seasonal variations in biogas production, limited storage capacity, and reliance on fossil backup systems. This research builds on those insights by providing a quantifiable pathway toward full fossil-free operation without major infrastructure changes. The hybrid approach also aligns with Sweden’s national climate objectives and the EU’s broader renewable energy directives, demonstrating that municipal infrastructure can be rapidly decarbonized using commercially available technologies.

The technical and economic implications of the proposed system are equally significant. The hybrid configuration enables flexible load management, where the heat pump efficiently covers base and intermediate loads while the electric boiler handles peak demand periods. This division of operation improves both energy efficiency and system reliability. However, the model also revealed potential challenges—namely, the high initial investment required for the heat pump installation and the system’s dependence on fluctuating electricity tariffs. While these constraints could influence financial attractiveness, the long-term cost stability, reduced maintenance requirements, and avoidance of carbon taxation provide strong counterbalancing advantages. The results emphasize that system design optimization, accurate energy profiling, and tariff-based operational strategies are essential to maximize the benefits of P2H integration.

Despite the overall success of the proposed solution, the study highlights areas requiring further investigation. The lack of high-resolution operational data introduced minor uncertainties into energy balance calculations, while simplified assumptions on electricity pricing and load variability limited the model’s temporal precision. Moreover, although biogas storage and waste heat recovery were not considered within this scope, their potential future integration could further enhance energy resilience and sustainability. Overall, the discussion underscores that while electrification offers an immediately deployable and impactful solution, continued exploration of complementary technologies—such as dynamic control systems, renewable electricity integration, and advanced storage—will be vital to achieving fully optimized, carbon-neutral wastewater treatment operations

6.2 Conclusions

The main objective of this thesis was to identify a technically and economically viable solution to eliminate fossil oil use at the Ernemar Wastewater Treatment Plant during the winter months. This goal was successfully addressed through the

development of a techno-economic model that evaluated the feasibility of electrifying the heating system using P2H technologies—specifically, heat pumps and electric boilers.

The study demonstrated that a hybrid heating system, composed of a 100 kW heat pump for base and intermediate loads and a 150 kW electric boiler for peak loads, could fully replace oil usage, reduce CO₂ emissions by 98.1%, and cut operational costs by 74%, with a payback period of 6.5 years and a 10-year NPV of 319,464 SEK. Sensitivity analyses confirmed that the proposed solution remains robust under variations in oil price, electricity cost, technology performance, and carbon taxation. Thus, the model met its intended purpose and offers strong support for decision-making at small-scale WWTPs.

Among the positive effects of the proposed solution are significant emission reductions, improved cost predictability, and alignment with Sweden's climate goals. The project also showed that such transformations can be achieved with commercially available technology and without major changes to existing infrastructure.

However, some drawbacks include the relatively high upfront investment for the heat pump system and the increased dependence on electricity pricing. There are also operational complexities associated with integrating variable-load equipment and ensuring seamless interaction between the two heating systems.

Insights gained through this process include the importance of accurate energy demand profiling, the value of hybrid design in managing load variability, and the need for site-specific solutions that balance efficiency, cost, and scalability.

For others working in this area, it is recommended to prioritize data collection early, consider modular system configurations, and actively involve plant operators in scenario evaluation.

If this project were to be repeated, earlier collaboration with technology suppliers and energy utilities could have improved component cost accuracy and offered better insights into long-term electricity contract strategies. Additionally, more effort could have been made to explore grid reinforcement requirements or possible synergies with on-site solar PV.

6.3 Future Work

Building on the outcomes of this study, several promising directions for future research and development could enhance both the accuracy of the model and the practical implementation of the proposed system. One clear avenue for continued work lies in the design of a detailed control system that ensures smooth integration of the heat pump, electric boiler, buffer tank, and VFD. Fine-tuning their coordination would

help optimize energy use and improve operational responsiveness, especially during fluctuating load conditions.

Moreover, the model could be extended into a dynamic simulation framework that reflects hourly and even minute-by-minute demand fluctuations. This would allow the integration of time-of-use electricity pricing, seasonal trends, and temperature variations, ultimately leading to more precise performance forecasts and cost savings.

A particularly impactful improvement would be to combine the P2H system with on-site renewable generation, such as solar PV or small-scale wind turbines. Doing so could lower reliance on grid electricity and push the plant closer to full energy autonomy, thereby enhancing sustainability and reducing exposure to future energy price volatility.

Another area worth exploring is the potential revival of waste heat recovery at Ernemar. Although previously deemed unfeasible, emerging technologies—such as those proposed by Alfa Laval—might now offer viable solutions to overcome earlier technical hurdles. Future research could assess whether these innovations can be tailored to the site and integrated cost-effectively.

One other area that hasn't been fully explored in this study is flaring, which tends to happen in summer when the plant generates more biogas than it can use or store. Looking into the scale of this issue, and how it could be minimized—through options like thermal storage, load shifting, or better integration of biogas into heating—would strengthen the plant's overall energy strategy.

Lastly, the model developed here could be applied to other small or medium-sized wastewater treatment plants in Sweden or elsewhere in Europe. Such a replicability assessment would test the generalizability of the conclusions and potentially inform regional or national strategies for WWTP decarbonization. These extensions could greatly enhance the policy relevance and practical value of the current work.

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Appendices

Energy Balance

Monthly Oil Consumption		
Monthly	Oil Consumption (Litres)	Energy Covered by Oil (kWh)
Nov-23	1516.5712	15317.36884
Dec-23	3504.3915	35394.35409
Jan-24	5520.2118	55754.13896
Feb-24	3608.6734	36447.60153
Mar-24	1149.3406	11608.3396
Apr-24	285.5463	2884.017495
	15584.7347	157405.8205
Highest Daily (Litres)	436.6238	4409.900378 kWh 4.409900378 MWh
We can size the technologies based on the highest heat demand which is almost 4.5 MWh's per day.		
Highest Hourly (Litres)	26.2408	265.0325077 kWh 0.265032508 MWh

	Emission factor	2.68 kg CO2/L	IPCC default for light fuel
	LHV	10.1 kWh/l	
	Oil consumed	15469.5164 L	
		15.46951635 m3	
	Energy Covered	156242.1152 kWh	
		156.2421152 MWh	

In a year Ernemar WWTP consumes approximately 11.6 m3 Litres of oil which translates to 117.06 MWh of energy covered (heat demand).

	Yearly CO2 emissions (Nov & Dec Months from 2023)	41458.30382 kg CO2	
		41.45830382 tonnes CO2	
	Plant provided data emissions	44517.42496 kg CO2	
		44.51742496 tonnes CO2	

The November and December months are taken from 2023 for accurate reading due to the winters being less cold during 2024 and 2025

Technology Sizing

Estimated ΔT	15	°C
Effluent Water Temperature	7	°C
Heat Demand	265.0325077	kWh
Boiler Efficiency	99%	
Kelvin	273.15	K
Real COP from Carnot	0.4	
	Setpoint Temp	
Digester	37	°C
Facility	10	°C
Office Building	20	°C

Power-to-Heat Technologies							
E-boiler	Electrical Power (kW)						
	267.7096037						
Heat pump	Supply Temp (°C)			COP (Carnot)	Real COP	Required Temperature Lift (°C)	Electrical Power (kW)
	Digester	Facility	Office Bldng				
	52	25	35	10.3383333	4.135333	45	64.08975681

Techno-Economic Analysis

Assumptions

Parameter	Value	
Elec Price	1.35	SEK/kWh
Oil Price	20.1	SEK/L
CO2 Emission Factor	2.68	kgCO ₂ /L
Carbon Tax	1.33	SEK
Grid Emissions	12	gCO ₂ /kWh
COP (Heat Pump)	2.922	Weighted hourly COP from 2,553 data points (static 4.0 used for initial sizing only)
COP (E-boiler)	100%	Boiler efficiencies are usually between 99-100%

Known Values

Parameter	Values
Energy Covered by Oil (Winter Months)	157,405.82 kWh
Real COP (Heat Pump)	2.922
Total Energy Covered (Heat Pump)	136,775.00 kWh
Total Energy Covered (E-boiler)	20,631.00 kWh
Thermal Capacity (Heat Pump)	100 kW
Thermal Capacity (E-boiler)	150.00 kW
Electrical Power Input (Heat Pump)	34 kW
Electrical Power Input (E-Boiler)	150.00 kW
Hours Covered (Heat Pump)	2553 Hours
Hours Covered (E-boiler)	519.00 Hours
Buffer Tank Size	200 kWh
Lower Bound	4.04 kW
Upper Bound	100 kW
Oil Consumption	15584.7347 Litres

Cost Breakdown

CAPEX			
Component	Unit Cost (SEK)	Total (SEK)	
Heat Pump	13,970 (SEK/kW)	1,397,000	
Electric Boiler	1,250 (SEK/kW)	187,500	
Buffer Tank	1000 (SEK/kWh)	200000	
Total		1,784,500	
OPEX			
Component	Value (kWh)	Cost Rate	Cost (SEK)
HP Elec	46,813.00	1.35 SEK/kWh	63198
EB Elec	20,839.00	1.35 SEK/kWh	28133
Buffer Tank Ops	-	Estimated Annual	5,000
Total			96,330

Emission Analysis

Source	Elec Used	Grid Emissions Factor	CO2 Emissions (kg)
Heat Pump	46,813.00	0.012 kgCO ₂ /kWh	562
E-boiler	20,839.00	0.012 kgCO ₂ /kWh	250
Total	-	-	812

Financial Evaluation

Oil-Based System			
Oil Fuel Cost	15584.73 L × 20.1 SEK/L		313253
Oil CO₂ Emissions	15584.73 L × 2.68 kgCO₂/L		41767 kg CO ₂
Carbon Tax	41767 kg × 1.33 SEK/kg		55550
Total Oil OPEX	15584.7347		368803
Oil Cost (SEK/L)	20.1		
Comparison	313,243		
Oil OPEX	44,517		368803
P2H OPEX	1.33		96330
Annual Savings	59207.61		272473
Cost Reduction	372,451		73.9%
Payback Period			6.55 years
NPV (10yr, 5%)			319464 SEK
Item	Value		
Annual OPEX	96,330		
Annual Savings	276,121		
Total CAPEX	1,784,500		
Payback Period (Years)	6.462755533		
NPV (SEK)	347630.1589		

Cost Component	Oil System (SEK)	P2H System (SEK)	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
Annual OPEX	372451	131461										
Annual CO ₂ Tax	59208	0		-1,508,379	-1,232,259	-956,138	-680,018	-403,897	-127,776	148,344	424,465	700,585
												976,706
Year	Cumulative (SEK)											
0	-1784500											
1	-1543510											
2	-1302520											
3	-1061530											
4	-820540											
5	-579550											
6	-338560											
7	-97570											
8	143420											
9	384410											
10	625400											

Sensitivity Analysis

Electricity Price Variations			
Base			
Component	Value (kWh)	Cost Rate (SEK/kWh)	Cost (SEK)
HP Elec	46,813.00	1.35	63198
EB Elec	20,839.00	1.35	28133
Buffer Tank Ops	-	Estimated Annual	5,000
Total			96,330
Low			
Component	Value (kWh)	Cost Rate (SEK/kWh)	Cost (SEK)
HP Elec	46,813.00	1	46813
EB Elec	20,839.00	1	20839
Buffer Tank Ops	-	Estimated Annual	5,000
Total			72,652
High			
Component	Value (kWh)	Cost Rate (SEK/kWh)	Cost (SEK)
HP Elec	46,813.00	1.6	74901
EB Elec	20,839.00	1.6	33342
Buffer Tank Ops	-	Estimated Annual	5,000
Total			113,243

Oil Price (SEK/L)	Oil OPEX (SEK/yr)	P2H OPEX (SEK/yr)	Annual Savings	CAPEX (SEK)	Payback (yr)	NPV (SEK)
15	289321	96330	192991	1784500	9.247	-294275
20.1	368803	96330	272473	1784500	6.549	319464
25	445168	96330	348838	1784500	5.116	909135
Electricity Price	Oil OPEX (SEK/yr)	P2H OPEX (SEK/yr)	Annual Savings	CAPEX (SEK)	Payback (yr)	NPV (SEK)
1	368803	72652	296151	1784500	6.026	502300
1.35	368803	96330	272473	1784500	6.549	319464
1.6	368803	113243	255560	1784500	6.983	188867
Heat Pump Capacity	Oil OPEX (SEK/yr)	P2H OPEX (SEK/yr)	Annual Savings	CAPEX (SEK)	Payback (yr)	NPV (SEK)
100	368803	96330	272473	1784500	6.549	319464
120	372460.778	113164.454	259296.324	2063900	7.959619204	-61682.51796
150	372460.778	87716.414	284744.364	2483000	8.720102358	-284279.4986
COP	Oil OPEX (SEK/yr)	P2H OPEX (SEK/yr)	Annual Savings	CAPEX (SEK)	Payback (yr)	NPV (SEK)
3.5	372460.778	135557.946	236902.832	1784500	7.532624177	44800.87268
4	368803	96330	272473	1784500	6.549	319464
4.5	372460.778	128274.398	244186.38	1784500	7.3079424	101042.4997
Carbon Tax (SEK/kg)	Oil OPEX (SEK/yr)	P2H OPEX (SEK/yr)	Annual Savings	CAPEX (SEK)	Payback (yr)	NPV (SEK)
1.33	368803	96330	272473	1784500	6.549	319464
2	396787	96330	300457	1784500	5.939	535549
3	438554	96330	342224	1784500	5.214	858063
Discount Rate	NPV (SEK)					
0.03	539750					
0.05	319464					
0.07	129236					

ENHANCED SENSITIVITY ANALYSIS

Scenario Comparison

Parameter	Pessimistic	Base Case	Optimistic	Best Case
Oil Price (SEK/L)	15	20.1	25	30
Elec Price (SEK/kWh)	1.6	1.35	1	0.8
Carbon Tax (SEK/kg)	1.33	1.33	2	3
COP	2.5	2.922	3.5	4
HP Capacity (kW)	100	100	100	100
Annual Savings (SEK)	163,443	272,479	408,235	543,817
Payback (years)	10.9	6.5	4.4	3.3
NPV (SEK)	-522,439	319,510	1,367,781	2,414,709

Combined Sensitivity: Oil Price × Carbon Tax → NPV (SEK)

Oil Price ↓ / Carbon	0.5 SEK/kg	1.33 SEK/kg	2.0 SEK/kg	3.0 SEK/kg	5.0 SEK/kg
12 SEK/L	-922,984	-655,297	-439,213	-116,699	528,328
15 SEK/L	-561,960	-294,274	-78,189	244,324	889,352
18 SEK/L	-200,936	66,750	282,834	605,348	1,250,375
20.1 SEK/L	51,780	319,466	535,551	858,064	1,503,092
25 SEK/L	641,452	909,138	1,125,222	1,447,736	2,092,764
30 SEK/L	1,243,158	1,510,844	1,726,928	2,049,442	2,694,469

Breakeven Frontier: Max Electricity Price for NPV ≥ 0

Oil Price (SEK/L)	Carbon Tax 1.33	Carbon Tax 2.0	Carbon Tax 3.0	Carbon Tax 5.0
12	0.10	0.51	1.13	2.36
15	0.79	1.20	1.82	3.05
18	1.48	1.89	2.51	3.74
20.1	1.96	2.38	2.99	4.23
25	3.09	3.50	4.12	5.36
30	4.24	4.66	5.27	6.51

Scenario	NPV (SEK)
Pessimistic	-522443
Base Case	319170
Optimistic	1367774
Best Case	2414701

Electricity Price × COP → Payback (years)

Elec ↓ / COP →	COP=2.5	COP=2.92	COP=3.5	COP=4.0	COP=5.0
0.8 SEK/kWh	5.9	5.8	5.6	5.6	5.5
1.0 SEK/kWh	6.2	6.0	5.9	5.8	5.7
1.2 SEK/kWh	6.5	6.3	6.1	6.0	5.8
1.35 SEK/kWh	6.8	6.6	6.3	6.2	6.0
1.5 SEK/kWh	7.1	6.8	6.5	6.3	6.1
1.8 SEK/kWh	7.8	7.4	7.0	6.7	6.4
2.0 SEK/kWh	8.4	7.8	7.3	7.0	6.7

Carbon Tax Trajectory: Cumulative Cash Flow Over 10 Years

Year	CT Flat 1.33 SEK	CT +10%/yr	CT +20%/yr	CT EU ETS aligned	Cum. Flat	Cum. +10%	Cum. +20%	Cum. EU ETS
1	1.33	1.46	1.60	0.96	-1,512,065	-1,506,510	-1,500,955	-1,527,582
2	1.33	1.61	1.92	1.02	-1,239,630	-1,222,410	-1,204,078	-1,268,061
3	1.33	1.77	2.30	1.09	-967,195	-931,588	-891,203	-1,005,769
4	1.33	1.95	2.76	1.16	-694,760	-633,372	-559,129	-740,525
5	1.33	2.14	3.31	1.23	-422,325	-327,023	-204,018	-472,139
6	1.33	2.36	3.97	1.31	-149,891	-11,728	178,739	-200,404
7	1.33	2.59	4.77	1.40	122,544	313,408	594,669	74,895
8	1.33	2.85	5.72	1.49	394,979	649,370	1,050,409	353,992
9	1.33	3.14	6.86	1.59	667,414	997,239	1,553,921	637,132
10	1.33	3.45	8.24	1.69	939,849	1,358,206	2,114,757	924,579

HP Sizing Optimization (Hourly-Matched)

HP kW	HP Share%	EB Share%	HP Elec kWh	EB Elec kWh	OPEX SEK	CAPEX SEK	Payback yr	NPV SEK
50	59.9	40.1	32,269	63,721	134,586	1,167,250	5	641,307
75	76.4	23.6	41,157	37,516	111,210	1,485,250	5.8	503,815
100	86.9	13.1	46,813	20,839	96,331	1,803,250	6.6	300,707
125	93.3	6.7	50,282	10,598	87,189	2,121,250	7.5	53,297
150	96.9	3.1	52,182	4,976	82,163	2,439,250	8.5	-225,898
200	99.6	0.4	53,655	611	78,260	3,075,250	10.6	-831,756
265	100	0	53,862	0	77,714	3,902,050	13.4	-1,654,338

Oil Price × Carbon Tax → NPV (SEK)

Oil ↓ / CT →	0.5 SEK/kg	1.33 SEK/kg	2.0 SEK/kg	3.0 SEK/kg	5.0 SEK/kg
12 SEK/L	-923,278	-655,591	-439,507	-116,993	528,034
15 SEK/L	-562,255	-294,569	-78,484	244,029	889,057
18 SEK/L	-201,232	66,454	282,538	605,052	1,250,079
20.1 SEK/L	51,484	319,170	535,254	857,768	1,502,795
25 SEK/L	641,154	908,841	1,124,925	1,447,438	2,092,466
30 SEK/L	1,242,859	1,510,545	1,726,629	2,049,143	2,694,170

Breakeven Frontier: Max Electricity Price for NPV ≥ 0

Oil Price SEK/L	CT=1.33	CT=2.0	CT=3.0	CT=5.0
12	0.10	0.51	1.13	2.36
15	0.79	1.20	1.82	3.05
18	1.48	1.89	2.51	3.74
20.1	1.96	2.37	2.99	4.23
25	3.09	3.50	4.12	5.35
30	4.24	4.65	5.27	6.51

Hourly COP Summary

HOURLY MODEL SUMMARY						
Total Hours Modeled	2553					
Total Energy Demand	157406	kWh				
HP Thermal Covered	136775	kWh				
EB Thermal Covered	20631	kWh				
HP Share	86.9	%				
EB Share	13.1	%				
HP Elec Consumption	46813	kWh				
EB Elec Consumption	20839	kWh				
Total Elec	67652	kWh				
Weighted Average COP	2.922					
COMPARISON vs STATIC MODEL						
Static COP Used	4					
Static HP Elec	21244	kWh				
Hourly HP Elec	46813	kWh				
Difference	+120%					
MONTHLY BREAKDOWN						
Month	Avg COP	Avg Eff T°C	HP Elec	EB Elec	Hours	
Nov	3.079	9.81	3,916	3,294	239	
Dec	3.006	8.71	10,643	3,438	617	
Jan	2.870	6.63	15,571	11,182	691	
Feb	2.849	6.41	11,864	2,670	597	
Mar	2.934	7.67	3,872	252	336	
Apr	3.043	9.26	947	2	73	

Operator's Tool (HTML Version)

P2H ANALYSIS ENGINE
 Emerald WWTP, Oskarslamn - Hourly COP-Matched - 2,553 Data Points

OVERVIEW HOURLY COP HEX DATA ECONOMICS SENSITIVITY INPUTS

COPI COP COP
 2.922 319k -98.1%

WINTER HEAT DEMAND: 157.4 MWh

ANNUAL SERVICE: 272,472 SEK

FEEDBACK PERIOD: 6.5 years

TOTAL CAPEX: 1,784,500 SEK

STATIC COP=4 VS HOURLY COP=2.92

EMISSIONS: OIL VS P2H (TONNES CO₂/YR)

LOAD ALLOCATION

MONTHLY DEMAND & COP PROFILE

P2H ANALYSIS ENGINE
 Emerald WWTP, Oskarslamn - Hourly COP-Matched - 2,553 Data Points

OVERVIEW HOURLY COP HEX DATA ECONOMICS SENSITIVITY INPUTS

COPI COP COP
 2.922 319k -98.1%

MONTHLY COP FROM HOURLY MATCHING (2,553 DATA POINTS)

MONTH	HOURS	EFF T°C	COP	HP ELEC	EB ELEC	DEMAND
Nov	184	9.81	3.079	3,996	3,294	15,317
Dec	515	8.71	3.006	10,643	3,438	35,394
Jan	905	6.63	2.870	15,571	11,822	55,754
Feb	634	6.41	2.849	11,864	2,670	36,448
Mar	254	7.67	2.934	3,872	252	11,608
Apr	61	9.26	3.043	947	2	2,884
TOTAL	2,553	7.73	2.922	46,813	20,839	157,406

COP & EFFLUENT TEMPERATURE BY MONTH

STACKED ELECTRICITY CONSUMPTION

ANNUAL EFFLUENT TEMPERATURE PROFILE

P2H ANALYSIS ENGINE
 Emerald WWTP, Oskarslamn - Hourly COP-Matched - 2,553 Data Points

OVERVIEW HOURLY COP HEX DATA ECONOMICS SENSITIVITY INPUTS

COPI COP COP
 2.922 319k -98.1%

VALVE POSITION VS DEMAND

CORRELATION: $r = 0.998$

VALVE @ 100kW: 63.9%

VALVE @ 150kW: 32.7%

HEX TEMPERATURE & ENERGY BY BRACKET

OPERATOR DECISION THRESHOLDS

- Valve < 40%**
 Biogas sufficient, HP in standby. No supplemental heating needed.
 - MONITOR ONLY
- Valve 40-80%**
 Biogas nearing capacity. HP should activate at base load. Buffer absorbs peaks.
 - START HP
- Valve > 80%**
 Biogas missed out. HP at full capacity plus E-boiler for peak demand.
 - HP + EB ACTIVE

