ANALYSIS AND OPTIMISATION OF RAW WATER SYSTEMS IN A DISTRICT HEATING PLANT: CASE VANAJA POWER PLANT

Lappeenranta–Lahti University of Technology LUT

Energy technology Master's thesis

Master’s programme in Sustainable Energy Systems

2026

Tuike Linkoranta

Examiners: Docent Jussi Saari

Satu Lipiäinen, D.Sc. (Tech.)

ABSTRACT

Lappeenranta–Lahti University of Technology LUT

LUT School of Energy Systems

Energy Technology

Tuike Linkoranta

Analysis and optimisation of raw water systems in a district heating plant: Case Vanaja power plant

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2026

91 pages, 6 figures, 12 tables and 6 appendices

Examiners: Docent Jussi Saari and Satu Lipiäinen, D.Sc. (Tech.)

Keywords: Vanaja power plant, raw water, water treatment, water consumption, specific energy consumption, electrodeionisation, reverse osmosis, water balance

This master's thesis investigated the water use of Loimua Oy's Vanaja power plant. The purpose of the work was to analyse the use of raw water taken from Vanajavesi and the electricity consumption related to water transfer and treatment. The background to the study was the power plant's high raw water intake and the interest in identifying opportunities to reduce it. The study was carried out as a case study by combining the analysis of process data collected from the automation system and monthly personnel reports with a literature review. The data covers the years 2023–2025.

The total amount of water taken from Vanajavesi varied between approximately 776 000 and 925 000 m^3 per year. Cooling water constituted approximately 90 % of the total intake, and the most significant single cause of peaks was the once-through cooling of the gas turbine. The estimated annual electricity consumption of the process water treatment cycle was 73 465 kWh/a, of which the pumps accounted for 65 % and the continuous electrodeionisation modules for 35.3%. The total specific electricity consumption of the treatment chain was estimated to be 2.65 kWh/m^3 of product water.

The most significant improvement identified was the bypassing of the continuous electrodeionisation and mixed bed filtration stages in situations where complete demineralization is not required. These stages were installed in 2020 for the needs of the decommissioned steam turbine but are still in continuous use. In addition, opportunities were identified to decommission the auxiliary raw water circuit and to better match the raw water pumping to the actual process needs. The measures require further technical investigation before commissioning.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT

LUTin energiajärjestelmien tiedekunta

Energiatekniikka

Tuike Linkoranta

Raakavesijärjestelmien analyysi ja optimointi kaukolämpölaitoksessa: Case Vanajan voimalaitos

Energiatekniikan diplomityö

2026

91 sivua, 6 kuvaa, 12 taulukkoa ja 6 liitettä

Tarkastajat: Dos. Jussi Saari ja Satu Lipiäinen, D.Sc. (Tech.)

Avainsanat: Vanajan voimalaitos, raakavesi, vedenkäsittely, vedenkulutus, ominaisenergiankulutus, elektrodi-ionisaatio, käänteisosmoosi, vesitase

Tässä diplomityössä tutkittiin Loimua Oy:n Vanajan voimalaitoksen veden käyttöä. Työn tarkoitus oli analysoida Vanajavedestä otettavan raakaveden käyttöä sekä veden siirtoon ja käsittelyyn liittyvää sähkönkulutusta. Tutkimuksen taustalla oli voimalaitoksen korkea raakaveden ottomäärä ja kiinnostus tunnistaa mahdollisuuksia sen vähentämiseksi.

Tutkimus toteutettiin tapaustutkimuksena yhdistämällä automaatiojärjestelmästä sekä henkilöstön kuukausiraporteista kerätyn prosessidatan analyysi kirjallisuuskatsaukseen. Aineisto kattaa vuodet 2023–2025.

Vanajavedestä otettava kokonaisvesimäärä vaihteli noin 776 000–925 000 m³ vuodessa. Jäähdytysvesi muodosti noin 90 % kokonaisottomäärästä, ja merkittävin yksittäinen piikkien aiheuttaja oli kaasuturbiinin kertavirtausjäähdytys. Prosessiveden käsittelykierron arvioitu vuotuinen sähkönkulutus oli 73 465 kWh/a, josta pumppujen osuus oli 64,6 % ja jatkuvan elektrodi-ionisaatiomoduulien 35,3 %. Käsittelyketjun kokonaisominaissähkönkulutukseksi arvioitiin 2,65 kWh/m³ tuotevettä.

Merkittävimmäksi parannuskohteeksi tunnistettiin jatkuvan elektrodi-ionisaation ja sekakerrossuodatuksen vaiheiden ohittaminen tilanteissa, joissa täydellistä demineralisointia ei tarvita. Nämä vaiheet asennettiin vuonna 2020 käytöstä poistetun höyryturbiinin tarpeisiin, mutta ovat edelleen jatkuvassa käytössä. Lisäksi tunnistettiin mahdollisuus lisäraakavesipiirin käytöstä poistamiseen sekä raakaveden pumppauksen sovittamiseen paremmin nykyiseen prosessitarpeeseen. Toimenpiteet edellyttävät teknistä lisäselvitystä ennen käyttöönottoa.

ACKNOWLEDGEMENTS

I would like to thank the entire staff of Loimua Oy for their support during my master's thesis. First, I would like to thank Eki Muranen and Mika Riekkola for providing me with the topic for my master's thesis and for their guidance and trust during the process. A special thank you also goes to Matias Vilppola and Hannu Oksanen for introducing me to the plant's water processes and for sharing their technical knowledge with me. I would also like to thank Aapo Lehtonen, who provided me with technical information about the new electric boiler. From the Loimua Oy staff, I would especially like to thank Sirpa Bergholm, who has provided me with both information about the plant's processes and emotional support whenever I needed it.

I would also like to thank the friends I made during my studies, with whom we have shared both the difficult and enjoyable moments of student life. In addition, I would like to thank my entire support network, my family and friends, for their support and love during the five years of my studies. The distance has been long, but the support has been continuous and invaluable.

Finally, my greatest thanks go to my partner, Jesse. Without his constant support in helping me grow as a professional, and for always supporting the decisions I have made regarding my career and studies, I would not be here at this very moment. His encouragement and understanding throughout the years have meant more to me than words can express.

SYMBOLS AND ABBREVIATIONS

Roman characters

E	Electricity consumption	kWh
f	Frequency	Hz
I	Line current	A
P	Power	kW
SEC	Specific energy consumption	kWh/m^3
t	Operating time	h
U	Line-to-line voltage	V
V	Volume	m^3

Greek characters

η	Efficiency	-
$\cos \varphi$	Power factor	-

Subscripts

a	Annual
e	Electrical
f	Variable frequency
i	Component index
in	Electrical input
out	Mechanical output
th	Thermal

1	Operating point 1
2	Operating point 2

Abbreviations

BFB	Bubbling fluidized bed
CEDI	Continuous electrodeionisation
CFB	Circulating fluidized bed
CHP	Combined heat and power
DH	District heating
FNU	Formazin nephelometric unit
HVAC	Heating, ventilation and air conditioning
MB	Mixed-bed filtration
NaOH	Sodium hydroxide
PAX	Polyaluminium chloride
RO	Reverse osmosis
SEC	Specific energy consumption
VFD	Variable frequency drive

Plant equipment abbreviations

GT	Gas turbine unit
K5	Steam boiler unit
K6	Hot water boiler unit
SK3	Electric boiler unit

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DECLARATIONS

Turnitin

The originality of this thesis has been reviewed with the Turnitin similarity checking service.

AI usage

The author of the thesis, Tuike Linkoranta, used the following AI-tools during the preparation of the thesis:

1. AI tool: LUT Primo AI search
    a. Purpose of use: To find relevant academic sources from the university library collection efficiently.
    b. Explanation of the use of the tool: The tool was used to search for academic literature related to the thesis topic. The suggested sources were reviewed and used as background material for the literature review.
2. AI tool: Copilot
    a. Purpose of use: To support understanding of company-specific technical material and operational documentation.
    b. Explanation of the use of the tool: The tool was used to assist in interpreting technical and process-related material related to the case power plant.
3. AI tool: Claude AI
    a. Purpose of use: To support text refinement, structure development and intermediate feedback during the writing process.
    b. Explanation of the use of the tool: The tool was used to improve the clarity and structure of already written text and to provide feedback on readability and content.

Responsibility

The author, Tuike Linkoranta, takes full responsibility for the content of this thesis and has reviewed and edited the content generated by the use of AI tools.

1 Introduction

District heating plays an important role in the energy systems of Finland, especially in urban areas, where centralized heat production enables efficient and reliable heating of residential, commercial and public buildings. In Finland, district heating constitutes up to half of the heating sector and is generally produced in centralised heat and power plants using a variety of fuels and technologies. (Energiateollisuus 2026; Koskelainen, Saarela and Sipilä 2006)

Energy production systems are typically evaluated based on fuel consumption, energy efficiency and emissions. However, the operation of power plants also depends on several support systems that are essential to maintain stable and reliable production. Among these support systems, water-related processes form an essential part of plant operation. Water is needed for cooling, makeup water and various internal operational purposes, and its transport and treatment require electricity. The cost of water use is therefore influenced not only by the volume of water withdrawn, but also by the electricity consumption associated with pumping and treatment.

This thesis examines the water use and treatment associated electricity consumption at the Vanaja power plant operated by Loimua Oy in Hämeenlinna. The plant draws raw water from Lake Vanajavesi for cooling and process purposes, and the study analyses how this water circulates through the plant's systems and where the main sources of consumption are. Based on this analysis, the thesis evaluates measures to improve the efficiency of water use.

1.1 Background and significance

Water is an essential part of the operation of power plants and district heating plants. Several energy production processes require water for cooling and other operational functions. Raw water intake from natural water bodies is subject to environmental monitoring and reporting. Therefore, understanding the water cycle within the plant and identifying opportunities to reduce unnecessary water intake is important for both operations and the environment.

At the Vanaja power plant, raw water is collected from Lake Vanajavesi and cycled through different plant processes before being discharged back into the lake. During this cycle, some of the water is used for cooling, part is treated for boiler feedwater, and rest is for operational purposes at the plant. Although most of the water is ultimately returned to the lake, the total intake from Vanajavesi has been relatively high, which has sparked interest in understanding the reasons behind these intake levels.

Improving the efficiency of the water circulation could offer opportunities to reduce the required lake water intake without compromising the plant’s operations. Such improvements may include technical or operational changes to water use. At the same time, changes in the water cycle affect the electricity consumption associated with pumping and water treatment.

In Finland, water intake from natural water bodies and activities affecting aquatic environments are regulated primarily under the Water Act (587/2011) and the Environmental Protection Act (527/2014). These regulations define the conditions under which water intake, discharge and other activities affecting water bodies require a permit and establish obligations for monitoring and reporting environmental impacts. (Water Act 587/2011; Environmental Protection Act 527/2014).

For these reasons, analysing the current use and circulation of lake water at the Vanaja power plant, together with the associated electricity consumption and cost implications, is essential to support more efficient and economically justified use of resources in district heating production.

1.2 Objectives and research framework

The objective of this thesis is to identify the current water use of Vanajavesi and the related energy use, and to evaluate technically and operationally feasible measures for reducing raw water intake at the Vanaja power plant. The research focuses on understanding how lake water circulates in the plant's processes, in which processes or operating situations the highest water intake occurs, and how water volumes and energy consumption are interconnected within the plant’s water systems.

The research is guided by the following research questions:

- How is raw water currently used and circulated within the Vanaja power plant, and where are the main sources of water consumption?
- What is the current electricity consumption associated with boiler and district heating makeup water transfer and treatment?
- What technical and operational measures can be identified to reduce water intake?

The research is carried out as a case study, combining quantitative analysis of operational data with a review of existing literature on water use in district heating. The primary data consists of logged process measurements and water balance data from the Vanaja power plant. This data is analysed to identify patterns in water consumption, peak intake periods and electricity use associated with water handling. The data is used to calculate the specific energy consumption of water transfer and to estimate the cost of water circulation.

In addition to water use, the research examines electricity consumption of the water treatment chain 03UA related to water transfer and treatment as a supporting variable. Pumping and water treatment processes require electricity, and changes in the water circulation can therefore affect the plant's own electricity consumption. Analysing electricity consumption related to water treatment enables assessment of the operational impacts of potential improvement measures.

The scope of the thesis is limited to water use that is directly related to the raw water intake of Vanajavesi. Water supplied from the municipal water network has been excluded from the analysis so that the research can focus on the internal lake water circulation of the plant.

The research does not include in-depth chemical optimisation of water treatment processes. The thermal energy consumption related to water heating has been excluded from the analysis, and the total electricity consumption of the entire power plant is not examined. Furthermore, the thesis does not assess the overall energy efficiency or emission characteristics of the plant. The economic feasibility of the proposed improvement measures is not assessed through detailed investment calculations but at a technical and operational level.

1.3 Previous research and state of the art

The relationship between water use and thermal power generation has been extensively studied, although the research has focused primarily on large fossil fuel power plants, combined heat and power plants, and cooling system configurations.

Studies of global and national thermoelectric water use have shown that cooling systems account for majority of raw water withdrawals in power generation, and once-through cooling systems require significantly higher instantaneous water withdrawals per unit of energy produced compared to recirculating or closed-loop cooling configurations (Chi and McCracken 2024; Petrakopoulou 2021). The water costs associated with once-through cooling, defined as the combined effect of withdrawals and heat load on the receiving water body, have been shown to be significantly higher than those of alternative cooling arrangements, making once-through systems particularly sensitive to water availability constraints and environmental permit conditions (Petrakopoulou 2021). At the level of individual thermal power plants, Hlaváček and Vagenknechtová (2024) showed that cooling water can account for up to about 60% of the total industrial water consumption in a thermal power plant and that replacing once-through cooling with an indirect closed cooling system can significantly reduce raw water consumption without compromising operational reliability. Together, these studies indicate that cooling system configuration is a major determinant of plant-level raw water withdrawal and that technical improvements to the cooling arrangements are the most effective measure to reduce raw water withdrawal.

Water treatment systems for the production of boiler make-up water have also been studied in industrial and power plant applications. The treatment chain typically consists of several stages, including reverse osmosis and electrodeionisation, and each stage affects both water losses through reject streams and electricity consumption through pumping and electrochemical processes. Santos et al. (2024) reported a recovery rate of about 75% for reverse osmosis, which means that the reject stream is about 25% of the feed stream.

The role of flue gas scrubbers in the water balance of biomass-fired plants has received limited but relevant attention in the literature. Johansson, Li and Lin (2022) developed a module-based simulation model for heat and water recovery in a centrifugal wet scrubber and showed that condensation of moisture in biomass flue gases can produce significant amounts of condensate during heat recovery. This suggests that the water balance of the scrubber is strongly influenced by condensate formed from flue gas moisture and that the scrubber system can act as a net water source rather than a net consumer under certain operating conditions.

From an energy efficiency perspective, pumping and water treatment systems have been identified as important contributors to additional electricity consumption in industrial water treatment. Ononogbo et al. (2023) identified the elimination of unnecessary water circulation and the optimisation of pumping systems as key measures to improve energy and water efficiency in industry and concluded that the electricity consumption associated with pumping represents a significant and often underestimated share of auxiliary energy consumption. Santos et al. (2024) similarly showed that the electricity consumption of pumps constitutes a measurable part of the total energy consumption of water treatment systems and that the combined optimisation of treatment steps and associated pumping can significantly reduce the electricity cost of water production. Santos et al. (2024) also reported that pumping and electrodeionisation contributed significantly to the total energy consumption of demineralized water production.

Studies examining cooling water use mainly focus on large coal, gas and nuclear power plants, while research on the treatment of boiler plant make-up water and flue gas condensate recovery primarily addresses combined heat and power plants or specific treatment technologies separately. Furthermore, the published literature has not examined the effects of a significant change in plant configuration, such as the decommissioning of the steam turbine, on the existing water treatment configuration, the need for ultra-pure treatment steps, and the associated electricity consumption. This study addresses these shortcomings by providing a detailed case-study analysis of the raw water cycle and treatment associated electricity consumption at the Vanaja power plant, paying particular attention to the changed operating environment after the decommissioning of the steam turbine in 2020.

1.4 Structure of the thesis

This thesis progresses from a general background to a case-specific analysis and improvement proposals. Chapter 2 introduces the case company Loimua Oy and the Vanaja power plant, which provide the operational context for the study. Chapter 3 presents the basics of district heating systems and their role in the Finnish energy system. Chapters 4–6 form the theoretical framework for the study. These chapters describe the typical water cycle of district heating production, sources of water losses and the need for makeup water, water treatment processes, pumping systems, and energy efficiency principles related to the use of auxiliary water.

Chapter 7 presents the context and research methods of the case study, including the water cycle of the Vanaja power plant, the data used in the study, and the analysis methods. Chapter 8 examines the current status of raw water consumption and related electricity consumption at the plant. Based on this analysis, Chapter 9 assesses the potential for improving water use efficiency and presents technical and operational measures to improve efficiency. Finally, Chapter 10 summarizes the main conclusions of the study.

2 Case overview: Loimua Oy

Loimua Oy is a multi-service energy company with main areas of operation in energy services and energy production for real estate and industrial applications (Loimua Oy 2025).

2.1 Loimua Oy

The company previously operated as Elenia Lämpö Oy, a subsidiary of the Elenia Group. In summer 2019, Elenia sold its district heating business, and operations continued in January 2020 under the name Loimua Oy. (Loimua Oy 2019) Loimua Oy is owned by Abrdn plc, CVC DIF and LPPI Infrastructure Investments LP (Loimua Oy n.d.).

Loimua offers heating and cooling solutions, producing, distributing and selling district heat and natural gas, as well as providing maintenance and support services for real estate customers. Loimua also produces energy solutions for industry and offers outsourcing of energy production. (Loimua Oy 2025)

Loimua Oy's turnover was 112.6 million euros in 2024, and Table 1 represents Loimua’s energy sales and production values in 2024.

Table 1. Loimua’s energy sales and production volumes in 2024 (Loimua Oy 2025)

Energy Product / Service	Volume [GWh]
District heating sales	844.0
Electricity production	0.8
Natural gas transmission	74.2
Natural gas sales	49.2
Total sales of industrial energy services	347.3

Loimua operates in Kanta-Häme, Päijät-Häme, Pirkanmaa, Central Finland and North Ostrobothnia. Loimua Oy is also a shareholder in Oriveden Aluelämpö Oy and Kärkölän Lämpö Oy. (Loimua Oy 2025)

In 2024, Loimua announced that its key environmental goals are to achieve 100% carbon neutrality by 2030, ensure the sustainable use of wood-based fuels, and explore the utilization of waste heat. Carbon neutrality is achieved by replacing fossil fuels with biofuels, utilizing waste heat and thermal storage, and optimizing production. Loimua's share of renewable biofuels is approximately 91 % in 2024. (Loimua Oy 2025)

The utilization of waste heat from SSAB and HS-Vesi, as well as heat production with an electric boiler at the Vanaja power plant, are expected to begin in 2026. The objective is that the district heating demand of the city of Hämeenlinna can be met by using non-combustion technologies during summer months. (Loimua Oy 2025)

2.2 Vanaja power plant

The Vanaja power plant is located in Hämeenlinna, along the Lake Vanajavesi in the bay of Paikkala. The power plant was built between 1937 and 1939 by Imatran Voima and was the first commercial steam power plant in Finland. The plant was first built to operate as an electricity backup and peak power plant. The power plant started combined heat and power (CHP) production in 1983, and since then it has produced the majority of the district heat in Hämeenlinna. (Elenia 2019)

The Vanaja power plant produces primarily heat and small amounts of electricity. The plant consists of two base-load boiler units for heat production and one gas turbine capable of producing both electricity and heat. In 2026, the SK3 electric boiler is scheduled to be put into operation. The main object of said electric boiler is to produce heat using non-combustion technology on days when the price of electricity is below the limit agreed by Loimua Oy. The fluidized bed boilers K5 and K6 are fueled by solid biofuels, and the gas turbine uses natural gas as fuel. The combustion of milled peat was discontinued in April 2025. The used fuels and production values in 2025 can be seen in Table 2.

Table 2. Production values of the Vanaja power plant in 2025 (Loimua 2026b)

	Fuel used for production			**Produced heat**	**Produced electricity (gross)**
Year	Wood [t]	Peat [t]	Natural gas [nm3]	[GWh]	[GWh]
2025	148838	4375	118600	406.0	0.91

The heated water is supplied from the power plant to the district heating network at approximately 75–120 °C depending on the outdoor temperature, and it returns to the power plant at 40–60 °C depending on the time of year and day. (Loimua 2026a).

2.2.1 Energy production at Vanaja power plant

Boiler K5 is a steam boiler in which the water evaporates at high temperature and pressure. The produced steam is led through a pressure reduction station before the heat is transferred in a dedicated district heating heat exchanger to the district heating water. Boiler K5 has a fuel capacity of 58 MW and a nominal district heating output of 52 MWth. In addition, the flue gas scrubber connected to boiler K5 has a nominal heat output of 8 MWth. In 2025 boiler K5 was in operation for 5004.2 hours. (Loimua 2026b)

The steam boilers K5 and K4 were previously connected to a steam turbine for electricity production. However, the operation of the steam turbine was discontinued in 2020, and boiler K4 has since been replaced by the hot water boiler K6.

Boiler K6 is a hot water boiler. Heat from combustion is transferred to water circulating in an almost closed loop, and the heat is transferred through a separate district heating heat exchanger to the district heating network. Boiler K6 has a fuel capacity of 39 MW and a nominal district heating output of 45 MWth with a 10 MWth scrubber. In 2025 boiler K6 was in operation for 7079.3 hours. (Loimua 2026b)

The fuel capacity of the gas turbine is 130 MW and a nominal electrical output of 41 MWe, and it is fueled by natural gas. In addition, diesel oil and engine fuel oil are used as start-up fuels. The gas turbine is typically used for separate electricity production only when it is economically viable. The gas turbine can also be used for district heating production if K5 and/or K6 experience production disruptions. In the past few years, the use of the gas turbine has been limited to test runs only, but it has been kept in a ready-to-start state during winters. In 2025, the gas turbine was tested three times, and it was in operation for 10.4 hours. (Loimua 2026b)

Gasgrid Finland's 2026 tariff reform has particular implications for gas turbine units operating as peak or reserve capacity. A new capacity subscription charge of 1730.40 €/MW, determined by the highest single peak demand hour recorded during the year, means that a unit operating for only a limited number of hours annually is still charged based on its peak demand regardless of total gas consumed. (Gasgrid Finland 2026)

Additionally, short-term capacity products carry higher unit prices than annual products: the tariff multiplier for daily exit zone capacity is 2.00 and for within-day capacity 2.50 relative to the annual reference price. As a result, fixed transmission charges are spread over a small number of operating hours, raising the minimum electricity market price required to justify operation and reducing the economic competitiveness of peak load gas turbines under the revised tariff structure. (Gasgrid Finland 2026)

The production units of Vanaja power plant and their characteristics are presented in Table 3.

Table 3. Vanaja power plant production units and their characteristics.

Unit	Type	Fuel	Nominal output
K5	Steam boiler + flue gas scrubber	Solid biomass	52 MWth + 8 MWth
K6	Hot water boiler + flue gas scrubber	Solid biomass	35 MWth + 10 MWth
GT	Gas turbine + flue gas boiler	Natural gas	41 MWe + 60 MWth
SK3	Electric boiler	Electricity	30 MWth

The plant relies on water systems for cooling, boiler and district heat network makeup water and other auxiliary processes. The water systems of the Vanaja power plant, including raw water and cooling water intake and internal water circulation, are described in more detail in Chapter 7.

3 District heating production

District heating production forms the operational context of this thesis. Understanding the raw water consumption and associated improvement potential requires knowledge of how heat is produced and distributed. Different heat production technologies require different water systems for cooling, boiler makeup water production and other operational auxiliary uses. As a result, the configuration of the production plant directly affects both water consumption and the associated electricity consumption. This chapter introduces the fundamentals of district heating systems and presents the key production technologies relevant to the water systems analysed later in this thesis.

3.1 Fundamentals of district heating

District heating (DH) refers to a centralized production and distribution of heat. The heat is typically produced in heat-only boilers, combined heat and power plants, heat pumps, waste incineration plants or industrial waste heat recovery. The heat transfer medium in DH systems is typically hot water. Heat is distributed through a closed DH network to customers for space heating and domestic hot water production. (Koskelainen et al. 2006)

District heating enables centralized and flexible heat production using multiple fuels and heat sources within the same distribution network. In Finland, district heating production increasingly combines biomass combustion, waste heat utilization, heat pumps and electric boilers. The selected production technologies affect not only fuel use and energy efficiency but also the structure and operational requirements of systems, such as cooling, boiler makeup water production and flue gas treatment. The key challenges of district heating systems are related to high infrastructure investment costs, seasonal variations in heat demand and heat losses in long transmission networks, especially in sparsely populated areas. (Koskelainen et al. 2006)

3.1.1 District heating in Finland

District heating is the most common form of heating in Finland, and it accounts for approximately 50 % of the heating of residential and commercial buildings (Energiateollisuus 2026b). In 2024, the total amount of district heating supplied in Finland was approximately 36 000 GWh, of which 28 200 GWh was produced from fuel combustion and 7 800 GWh from heat pumps, heat recovery and electric boilers (Energiateollisuus 2026a).

The structure of Finnish district heating production has changed significantly in recent years due to the shift from fossil fuels to renewable and low-emission energy sources. The share of biomass-based fuels, such as wood chips, bark and industrial wood residue, has increased significantly, while the use of coal and peat has decreased. At the same time, the use of heat pumps, waste heat recovery and electric boilers has expanded. (Energiateollisuus 2026b)

In Finland, bioenergy plays a central role in both CHP and DH due to extensive forest resources and high domestic availability of solid biomass fuels. The majority of biomass fuels used in DH production originate from forest industry by-products such as chips, bark and sawdust. Biomass accounts for over 80 % of Finland’s renewable energy supply. (IEA Bioenergy 2024).

These changes have also affected the operational characteristics of district heating plants and their auxiliary systems. In biomass-fired plants, flue gas scrubbers are commonly used. The use of flue gas scrubbers increases the importance of auxiliary water treatment and internal water circulation management. In addition, the increasing use of heat pumps and electric boilers is changing the relative role of boiler makeup water production, cooling systems and electricity consumption in district heating production. As a result, auxiliary water systems have become an increasingly important part of the operational efficiency of modern district heating plants.

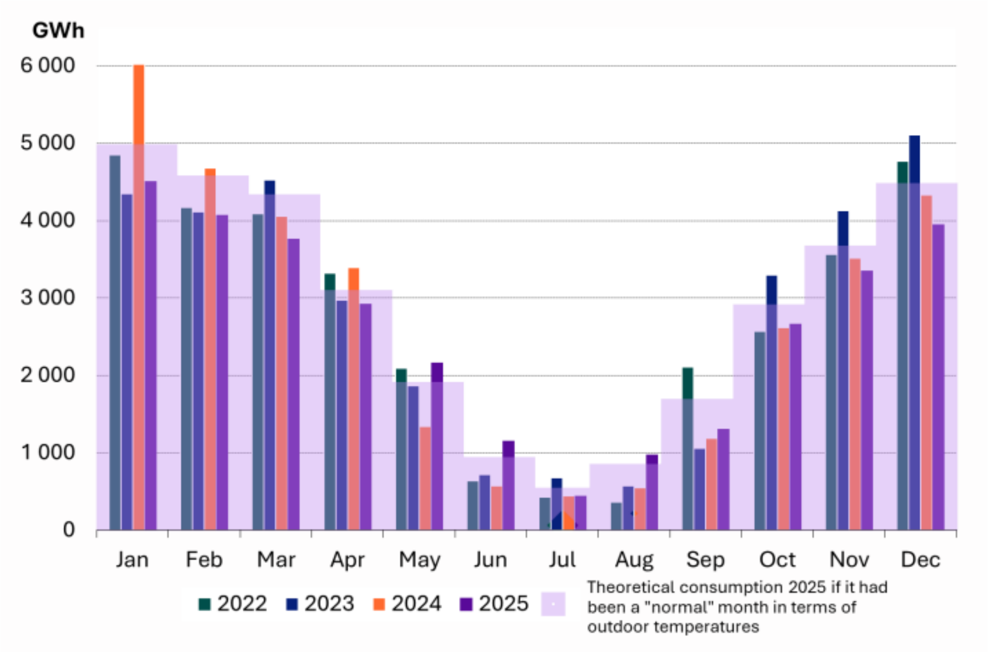

Figure 1. Monthly consumption of district heating in Finland (Energiateollisuus 2026a, p. 5)

District heating demand in Finland varies significantly between seasons due to climatic conditions. Heat consumption is highest in the winter months and lowest in the summer, leading to large annual variations in heat production, as illustrated in Figure 1. Seasonal demand variations can also affect the operating conditions of auxiliary systems, as higher production loads typically increase boiler usage, water treatment throughput and the need for flue gas cleaning. Consequently, auxiliary water consumption and the associated electricity consumption may also vary significantly between seasons.

3.2 District heating network

A district heating network transfers thermal energy from a production plant to customers through a closed piping system. The network typically consists of supply and return pipes, in which hot water is circulated from the production plant to customers and cooled return water is transferred back to the plant for reheating. Thermal energy is transferred to the customer's heating system through heat exchangers, which separate the district heating water from the building's internal heating circuit. (Koskelainen et al. 2006, pp. 43–44) The basic district heating network is illustrated in Figure 2.

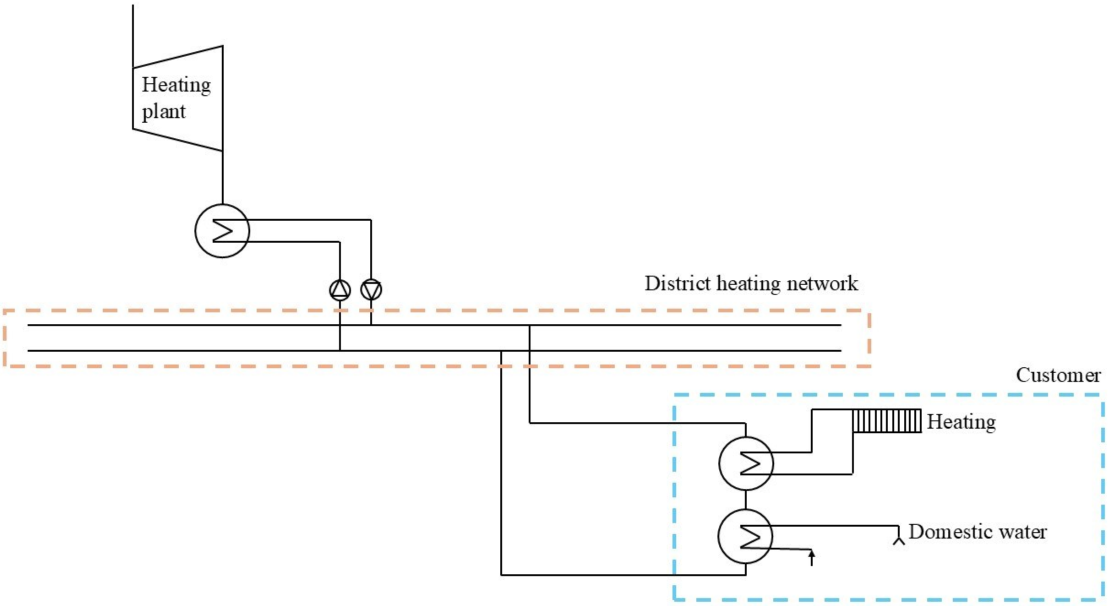

Figure 2. District heating system (modified from Koskelainen et al. 2006, p. 43)

Although district heating networks operate as closed systems, continuous water losses occur due to leaks, maintenance activities, pressure control and other operational factors. These losses create a continuous demand for makeup water that must be treated before it is supplied to the district heating network. Consequently, the condition and operation of the district heating network directly affect the auxiliary water demand of the production plant.

The operational characteristics of the district heating network also affect the operation of the auxiliary systems of the production plant. Seasonal variations in heat consumption affect network temperatures, circulation flow rates and heat production load, which in turn influence boiler operation, water treatment throughput and the overall demand for auxiliary water systems.

3.3 Gas turbine systems

Gas turbines are used in district heating and combined heat and power production, primarily for electricity generation and peak-load heat production, but the use varies by power plant. Gas turbines can use both gaseous and liquid fuels, although natural gas is the most commonly used fuel due to its relatively low emissions and operational flexibility. In gas turbine systems, combustion gases expand through a turbine, producing mechanical power for electricity generation. High-temperature exhaust gases can also be utilized for heat production through heat recovery systems. (Breeze 2019, Chapter 4; Darrow et al. 2017)

From an auxiliary water consumption perspective, gas turbines are particularly relevant because they require powerful and extensive cooling water circulations. In once-through cooling systems, raw water is drawn directly from a natural water body, circulated through cooling equipment and discharged back to the water body after use. Such systems can result in a high instantaneous cooling water demand even during relatively short operating periods. (Kehlhofer et al. 2009, Chapter 7.6)

At the Vanaja power plant, the gas turbine operates mainly during test runs and exceptional operating situations. Although its annual operating hours are limited, the gas turbine remains relevant from the perspective of short-term raw water consumption peaks due to the high cooling water flow rate required during operation. Therefore, the gas turbine operation is an important individual factor affecting the short-term variation of the plant’s raw water intake.

3.4 Fluidized bed boilers

Fluidized bed boilers are commonly used in biomass-fired district heating and combined heat and power plants due to their fuel flexibility and suitability for solid biofuels. In district heating production, fluidized bed boilers can operate as either steam boilers or hot water boilers, depending on the plant configuration and production requirements. The selected boiler type directly affects the structure and operational requirements of the auxiliary water systems. (Leckner 2024; Castilla et al. 2022)

In steam boilers, water is heated and evaporated under high pressure to produce steam. In heat-only district heating applications, the produced steam is led through a pressure reduction stage before the thermal energy is transferred to the district heating network through heat exchangers. Steam boiler systems require continuous makeup water to compensate for water losses caused by blowdown and other operational losses in the water-steam cycle. Therefore, steam-based production typically requires extensive water treatment systems to produce makeup water for boiler operation. (Vakkilainen 2017; Hinkelman et al. 2022)

In hot water boilers, heat is transferred directly to the pressurized circulating water without any phase change in the boiler water circuit. Compared to steam boiler systems, hot water boilers generally operate with a lower need for makeup water because the water circuit operates as a more closed loop with fewer continuous water losses. As a result, makeup water treatment requirements for hot water boiler systems are typically lower than for steam boiler systems. (Vakkilainen 2017; Rušeljuk et al. 2023)

Fluidized bed combustion is based on the suspension of solid fuel particles in an upward airflow, causing the fuel and bed material mixture to behave like a fluid. This allows for efficient heat transfer, stable combustion conditions and efficient mixing of fuel and combustion air. Fluidized bed boilers are generally divided into bubbling fluidized bed (BFB) and circulating fluidized bed (CFB) boilers. In BFB boilers, the fluidization velocity is lower, and the bed material remains mainly in the lower furnace, while in CFB boilers the bed particles are continuously circulated through the furnace and cyclone system. (Leckner 2024; Khan et al. 2008)

In biomass-fired district heating plants, fluidized bed boilers are commonly combined with flue gas cleaning and heat recovery systems, such as wet scrubbers, which further increases the importance of auxiliary water and internal water circulation management. Therefore, the operational characteristics of fluidized bed boiler systems are closely related to the plant’s auxiliary water consumption. (Castilla et al. 2022; Vakkilainen 2017)

4 Water cycles and losses in a district heating plant

District heating plants rely on several auxiliary water systems that serve different functions in heat and power production. Water is required for boiler makeup water production, cooling systems, flue gas cleaning and other auxiliary purposes. Depending on the plant configuration and production technology, water can circulate in closed loops or be used in once-through systems, where raw water is drawn directly from a natural water body and discharged after use.

In addition, water losses occur continuously due to blowdown, leakages and other operational factors. Together, these processes create a continuous demand for raw water, treated makeup water and associated auxiliary electricity consumption.

Steam boiler systems, hot water boiler systems, cooling systems and flue gas cleaning systems all have different water consumption characteristics and water treatment requirements. Therefore, understanding the plant water balance is essential for analysing raw water consumption and identifying improvement potential.

4.1 Raw water source, intake and distribution

Raw water forms the basis of auxiliary water systems in district heating and combined heat and power plants. Depending on the process requirements, raw water can be used directly in once-through systems or further treated for applications that require higher water quality, such as boiler makeup water production. Therefore, the source, intake and distribution of raw water directly affect the operation of auxiliary water systems and the overall water balance of the plant. (Kutum et al. 2023; Komorowska-Kaufman and Toczek 2022)

In district heating plants, raw water is drawn from a nearby natural water body, such as a lake or river, and distributed to different plant processes according to the operational requirements. High raw water flow rates are typically associated with cooling systems, where water is primarily used for heat transfer and is discharged after use. Studies have reported that cooling systems may account for up to approximately 60 % of total industrial water use in thermal power plants depending on the cooling configuration (Hlaváček and

Vagenknechtová 2024; Aili et al. 2021). In contrast, boiler makeup water production usually requires lower flow rates but significantly higher water quality. The required level of treatment depends on the process application and water quality requirements. Boiler systems typically require high-purity makeup water to prevent corrosion, scaling and operational problems. (Kutum et al. 2023; Komorowska-Kaufman and Toczek 2022). Water treatment is discussed in more detail in Chapter 5.

The operational characteristics of raw water intake and distribution systems are closely connected to the plant’s auxiliary water consumption and electricity demand. Variations in heat production load, cooling demand and boiler operation directly affect raw water intake rates, water treatment throughput and pumping demand. Therefore, understanding raw water flows and distribution within the plant is essential for analysing water consumption and identifying improvement potential. (Hlaváček and Vagenknechtová 2024; Kutum et al. 2023)

4.2 Role of pumping in district heating plant

In district heating plants, typical pumping duties include raw water intake, boiler makeup water production and transfer, treated water transfer, cooling water circulation for auxiliary equipment, and various intermittent service water functions such as backwashing and regeneration.

Pumping performance is often described using specific energy consumption (SEC) [kWh/m^3], which expresses the electrical energy required to transfer a unit volume of water through a defined part of the system. This indicator allows pumping-related electricity use to be directly linked to water volumes and enables comparison between different water streams and operating modes. SEC is widely used in pumping station analysis as a primary indicator for evaluating pump efficiency and optimisation potential under different operating conditions. (Kamalov et al. 2021; Abdullabekov and Sapaev 2023)

Pumping systems may operate continuously or intermittently. Continuous operation is common in cooling water systems and other applications, where stable flow is required for equipment reliability. Intermittent operation is typical for batch processes such as regeneration, flushing or tank transfer. While intermittent pumping may involve high instantaneous power demand, continuous systems usually dominate annual electricity consumption due to long operating hours (EPRI 2002).

4.3 Cooling water systems

Cooling systems are required to remove excess heat from the gas turbine, generator, blowdown tank and other auxiliary equipment. Depending on the plant configuration, cooling can be based on closed-loop circulation systems or once-through cooling systems that use raw water directly from a natural water body. The selected cooling method directly affects the raw water intake rates and the operating characteristics of the plant's water systems. (Hlaváček and Vagenknechtová 2024)

In once-through cooling systems, raw water is drawn from a natural water body, circulated through the cooling equipment and discharged after use. Such systems are typically characterized by high raw water flow rates but relatively low consumptive water losses because the cooling water is typically discharged back to the source without significant evaporation. High flow rate is required because the water is used primarily for heat transfer rather than for continuous circulation within the process. (Hlaváček and Vagenknechtová 2024; Ali et al. 2020)

Closed-loop cooling systems circulate cooling water through heat exchangers and cooling equipment, reducing the need for continuous raw water intake. In these systems, raw water is mainly needed to compensate for evaporation losses, leakages and other operating losses in the cooling circuit. Compared to once-through systems, closed-loop systems usually operate with lower raw water intake rates, but may require additional pumping and cooling equipment. (Hlaváček and Vagenknechtová 2024; Van Nguyen and Pirouzfar 2023)

Cooling water demand varies depending on operating conditions, production load and ambient temperature. High cooling demand is generally associated with gas turbine operation and auxiliary equipment cooling. As a result, cooling water systems can be a significant source of short-term variation in raw water intake and auxiliary electricity consumption. (Ali et al. 2020; Hlaváček and Vagenknechtová 2024)

The gas turbine system and its operational role at the Vanaja power plant were introduced in Section 3.3. The gas turbine utilizes a once-through cooling system, where raw water is drawn directly from Vanajavesi, circulated through auxiliary cooling equipment and discharged back to the lake after use. Consequently, even short operating periods create significant temporary peaks in raw water intake due to the high instantaneous cooling water flow.

4.4 Boiler makeup water

Boiler makeup water systems are required to compensate for water losses in boiler and steam systems during plant operation. In steam boiler systems, water losses occur due to blowdown, steam venting, leakages, and other operational losses in the cycle. These losses create a continuous demand for treated makeup water to maintain stable boiler operation and sufficient water volume within the system. Blowdown alone may represent approximately 1–20 % of boiler feedwater flow depending on feedwater quality and operating conditions. (Ion, Ene and Mocanu 2021; Shokri and Fard 2023)

Boiler systems require high-purity makeup water to prevent corrosion, scaling, and deposits on boiler surfaces, piping, and other process equipment. Poor water quality can reduce heat transfer efficiency, increase operational disturbances, and damage boiler equipment. Impurities such as hardness ions, silica, dissolved oxygen and dissolved gases are particularly associated with scaling and corrosion problems in boiler systems. Therefore, raw water used to produce makeup water typically requires extensive water treatment before use in boiler systems. (Shokri and Fard 2023; Phinney et al. 2022.) Water treatment processes and technologies are discussed in more detail in Chapter 5.

Compared to steam boiler systems, hot water boiler systems generally require less makeup water because the circulating water remains in a more closed loop, with fewer continuous water losses. As a result, the makeup water requirement and water treatment requirements of hot water boiler systems are typically lower than those of steam boiler systems. (Jonas and Machemer 2008; Song, Kim and Lee 2025)

Makeup water demand varies significantly with operating conditions. During steady-state operation at nominal load, makeup water primarily compensates for baseline losses. During steady-state operation, makeup water may represent 3–8 % of steam production (UNIDO, 2017).

However, during unsteady operation, such as start-ups, shutdowns, and load changes, water losses increase. Start-ups require boiler filling, system pressurization, and increased blowdown and steam venting to establish stable water chemistry. Initial steam production is often vented until stable conditions are achieved. Shutdowns may require controlled depressurization and system draining, depending on shutdown duration and maintenance requirements. Load ramps cause pressure and temperature transients, requiring increased steam venting and blowdown and steam venting from the system to maintain control. From an auxiliary water perspective, the water–steam cycle represents the primary and most predictable source of continuous auxiliary water demand. (NETL 2007)

Boiler makeup water production and associated water treatment processes also affect auxiliary electricity consumption. Pumping, reverse osmosis, continuous electrodeionisation and other water treatment processes require continuous electricity use during operation. Therefore, the operational characteristics of boiler makeup water systems directly affect both water consumption and the auxiliary electricity demand. Optimisation of condensate return and blowdown heat recovery has been identified as an important method for reducing both makeup water demand and auxiliary energy consumption in steam systems. (Ion, Ene and Mocanu 2021; Salimi et al. 2023)

4.5 Flue gas cleaning systems

Flue gas cleaning in solid biofuel-fired boilers typically involves multiple stages, which together influence the water balance of the plant. After combustion, flue gases contain particulates and other impurities that must be removed before the flue gas is released into the atmosphere. The composition of these impurities depends on the fuel used. Solid biofuels such as wood chips, bark and sawdust produce flue gases with relatively low sulphur content compared to fossil fuels or peat. The main impurities in wood-based biofuel combustion are particulates, nitrogen oxides and small amounts of chlorine compounds. In solid biofuel-fired boilers, dust removal is commonly performed using bag filters or electrostatic precipitators, which are dry processes that do not involve water. The subsequent wet scrubber stage, however, is directly linked to the plant's water systems. (Obernberger & Thek 2008; Singh and Shukla 2013)

In a wet scrubber, the flue gas is brought into contact with water sprays or circulating water, which absorbs remaining impurities and, when the gas is cooled below the dew point, also condenses moisture from the flue gas. This condensation releases latent heat that can be recovered to the district heating network, improving the overall efficiency of heat production. Studies have reported that wet scrubber systems can recover approximately 10–20% of the boiler energy input through flue gas heat recovery. The condensate produced in this process contains dissolved impurities from the flue gas and must be treated before it can be reused or discharged. (Johansson, Li and Lin 2022; Noor, Martin and Dahl 2020)

At district heating plants equipped with wet scrubbers, the condensate produced during heat recovery, after appropriate treatment, can be used as a source of process water or boiler makeup water, partially replacing the need to withdraw raw water from natural water bodies. Membrane-based condensate treatment systems have demonstrated water recovery rates of up to approximately 90 % in flue gas condensate reuse applications. (Iliev et al. 2020; Noor, Martin and Dahl 2020)

In addition to wet scrubber systems, water can also be used in fly ash handling and transport systems. Water can be used for dust suppression, ash cooling and fly ash transport, depending on the plant configuration and ash handling method. Although water consumption in fly ash handling systems is typically lower than in cooling or wet scrubber systems, these processes can still contribute to auxiliary water consumption in biomass-fired district heating plants. (Das et al. 2019)

4.6 Operational, service and washing waters

In addition to process cooling, boiler and district heating makeup water production, and flue gas cleaning, district heating plants require water for various operational and maintenance purposes. These uses include equipment washing, such as soot blowing, where water is used to clean heat transfer surfaces, cleaning of filters and other process equipment during maintenance, and floor and area washing, which generates wastewater that must be treated within the plant. (Ruffino 2020; Zakharychev, Pozynich and Telnova 2020)

These operational and maintenance water uses are typically intermittent and variable, making them more difficult to measure and control than continuous process water flows.

However, collectively they can represent a notable contribution to total raw water intake, especially during scheduled maintenance periods. Reducing unnecessary water use in these operations by improved operational practices and water recycling can contribute to improved overall water efficiency. (Ruffino 2020)

5 Water treatment processes in a district heating power plant

Water treatment processes are essential for reliable operation of district heating plants, as untreated water may lead to fouling, scaling and corrosion in boilers, heat exchangers, piping and other process equipment. Fouling and scaling increase heat transfer resistance, fuel consumption and maintenance requirements in boiler and heat exchanger systems. Boiler feedwater must therefore meet purity requirements determined by the processes, since dissolved salts, suspended solids and dissolved gases may significantly reduce heat transfer efficiency and lead to material degradation in boilers and associated components. (Zaidi et al. 2020; Zhao et al. 2024)

In addition to ensuring adequate water quality, water treatment systems directly affect makeup water demand. Water treatment represents a continuous and significant source of water consumption. The required treatment level is determined by boiler design, raw water quality and operating conditions (Bozzuto 2021, p. 231–232).

5.1 Water treatment and associated water losses

Water treatment directly affects makeup water consumption, because water treatment processes themselves are not fully closed systems. In order to maintain suitable water quality for boiler operation, part of the incoming water must be removed from the process together with dissolved and suspended impurities. In addition, treatment equipment requires periodic operations such as backwashing, cleaning or regeneration, during which treated water is discharged and replaced with fresh raw water. Especially filter backwashing, reject streams and ion exchange regeneration waste all contribute to continuous water losses within the treatment process. (UNIDO 2017; Carpenter 2017; Ullah et al. 2023).

Water treatment typically consists of a multi-stage “barrier system”, where each stage removes different impurities. Before more advanced treatment stages, raw water typically undergoes pretreatment processes such as clarification, filtration, aeration or chemical dosing to remove suspended solids and biological impurities. These steps improve the performance and lifetime of downstream treatment equipment but also introduce additional reject water streams, such as filter backwash water. (Basu & Debnath 2019)

5.2 Raw water treatment chain

Raw water treatment for district heating plants typically consists of a multi-stage treatment chain, where each treatment step removes different impurities and protects downstream equipment. The purpose of the treatment chain is to produce water that meets the water quality requirements of boiler and district heating systems while minimizing operational disturbances, fouling and scaling in process equipment. In addition to improving water quality, the treatment chain also affects water consumption through reject water streams, backwash and other operational losses. (Hell, Liebminger and Bharati 2024)

The first stages of raw water treatment typically consist of mechanical pretreatment processes, such as screens and strainers, which remove coarse solids and suspended particles from the incoming raw water. Mechanical pretreatment protects downstream equipment from clogging and improves the efficiency and reliability of subsequent treatment stages. (Abushawish et al. 2023; Alsawaftah et al. 2021)

After mechanical pretreatment, chemical coagulation and flocculation are used to remove smaller suspended particles and colloidal impurities from the water. At the Vanaja power plant, coagulation is performed using polyaluminium chloride (PAX), while sodium hydroxide (NaOH) is used for pH adjustment to maintain suitable coagulation conditions. During coagulation, suspended particles and colloids are destabilized and form larger flocs, which can be separated in subsequent filtration stages. Coagulation and flocculation improve the removal efficiency of suspended solids and reduce the amount of particles in downstream treatment processes. (Hell et al. 2024; Xavier et al. 2020; Qasim et al. 2019)

After coagulation and flocculation, the water is treated using sand filtration, where suspended solids and the formed flocs are mechanically removed through the filter media. Sand filtration reduces turbidity and residual particulate matter before further treatment stages. Effective pretreatment reduces membrane fouling potential and improves reverse osmosis recovery and membrane lifetime. Activated carbon filtration can also be used to remove dissolved organic compounds and micropollutants by adsorption onto the porous surface of the activated carbon. (Qasim et al. 2019; Nakazawa et al. 2021; Ullah et al. 2023)

Before reverse osmosis treatment, water typically passes through fine filtration using cartridge filters. The purpose of cartridge filtration is to remove remaining fine particles and protect reverse osmosis membranes from fouling and clogging. Effective pretreatment reduces membrane loading, improves reverse osmosis performance and reduces reject water generation in downstream membrane treatment processes. (Hell et al. 2024; Abushawish et al. 2023)

5.3 Ion exchange and electric deionisation

Reverse osmosis (RO) is a key demineralisation stage in the treatment of boiler makeup water. In reverse osmosis, pressurized raw water is forced through semi-permeable membranes that retain dissolved salts, ions, and other impurities while allowing purified water to pass through. The reverse osmosis process produces two outlet streams: permeate, which consists of purified water, and reject water, which contains concentrated impurities removed from the raw water. Multiple membrane stages can be used to improve separation efficiency and increase permeate recovery. (Hell et al. 2024; Qasim et al. 2019; Zaidi et al. 2020)

Continuous electrodeionisation (CEDI) is typically used as a polishing stage after reverse osmosis to further reduce the ionic content of the treated water. In CEDI, ions are removed from the water by ion exchange membranes and electrically regenerated ion exchange resins operating under an electric field. As a result, CEDI can produce high-purity water with lower chemical consumption than conventional ion exchange systems. However, the process also produces a continuous reject stream, which contributes to auxiliary water consumption. (Hell et al. 2024; Anis, Hashaikeh and Hilal 2019)

Mixed-bed filtration (MB) is used as the final polishing stage to produce high-purity boiler makeup water. MB filters contain both cation and anion exchange resins, which remove remaining dissolved ions from the treated water. The resulting product water has very low conductivity and is close to complete demineralisation. Unlike CEDI systems, MB filtration requires regular chemical regeneration with acids and alkalis, which generates additional wastewater streams and contributes to auxiliary water consumption. (Hell et al. 2024; Dong, Lin and SenGupta 2020)

5.4 Impact of water treatment processes on electricity consumption

Water treatment processes are also directly linked to electricity consumption. Pumps are needed to move water through treatment units, overcome pressure losses in filters and piping, and generate the pressure required for membrane separation. Studies have reported that pumping systems may account for approximately 60–80 % of the total electricity consumption of water treatment plants. (Skoczko 2025; Hamawand 2023) Treatment stages operating at higher pressures, such as reverse osmosis, therefore have higher electricity consumption, while backwashing and regeneration introduce additional intermittent pumping loads. Typical pumping energy consumption in water treatment systems has been reported to range approximately from 0.15 to 0.30 kWh/m^3 of treated water depending on pressure and hydraulic conditions (Skoczko 2025)

As water losses within the treatment chain increase, electricity consumption increases accordingly due to higher water throughput and longer pump operating times. For this reason, reducing treatment-related water losses can also reduce electricity consumption associated with water treatment and auxiliary water handling, even if the main production process remains unchanged. (Pan et al. 2020; Paraschiv, Paraschiv and Șerban 2023)

The electricity consumption of water treatment depends strongly on the treatment technology used and the volume of water processed. Membrane-based processes such as reverse osmosis generally require higher pressures and therefore consume more electricity per cubic metre than conventional filtration or ion exchange processes. Reported electricity consumption for membrane-based treatment processes is typically in the range of approximately 0.2–0.6 kWh/m^3, depending on operating pressure, salinity and recovery rate (Skoczko 2025). In addition, continuous electrodeionisation (CEDI) requires continuous electrical input for ion transport and resin regeneration, making it one of the more electricity-intensive polishing stages in boiler makeup water treatment. Electrodeionisation-type polishing processes have been reported to consume approximately 0.39–2.11 kWh/m^3 depending on water quality and process configuration (Choi et al. 2019). Monitoring and reducing the volume of water processed through high-energy treatment stages is therefore important for both improving water efficiency and minimizing associated electricity consumption.

6 Energy efficiency and optimisation of auxiliary water systems

The energy efficiency of auxiliary water systems is closely linked to the amount of water that must be transferred, treated and circulated within a district heating plant. Since water handling requires continuous electricity consumption for pumping and treatment processes, reducing unnecessary water use also decreases auxiliary electricity demand. Improving the efficiency of auxiliary water systems therefore requires both minimizing avoidable water losses and the optimisation of water treatment and transfer processes. Specific energy consumption can be used as a key indicator for evaluating and comparing the energy efficiency of different water systems and operating conditions. In water treatment facilities, electricity costs may represent approximately 30–50% of total operating costs, highlighting the significance of energy-efficient water handling systems (Skoczko 2025).

6.1 Fundamentals of energy efficiency in water systems

Energy efficiency in auxiliary water systems refers to the minimization of electricity consumption required to fulfil a given water handling function. In the context of heating plants, this means delivering the necessary volumes of cooling water, makeup water and treated water with minimal electricity consumption, while maintaining the quality and reliability required for plant operation.

The energy efficiency of water systems is influenced by both technical and operational factors. On the technical side, the design of pumps, pipes and treatment equipment determines the minimum achievable energy consumption for a given water handling task. On the operational side, how systems are controlled and maintained in practice determines whether they approach their design efficiency or deviate from it. Common sources of operational inefficiency include running pumps at fixed speed regardless of actual demand, maintaining unnecessarily high pressure setpoints, avoidable water losses that increase throughput, and operating treatment systems beyond their optimal range. (U.S. DOE 2012; UNIDO 2017.)

In district heating plants, the link between water efficiency and energy efficiency is direct. Reducing unnecessary water intake decreases the volume of water that must be pumped and treated, which in turn reduces the electricity consumed by pumps and treatment equipment. This relationship means that improvements in water management also yield electricity savings, making the combined optimisation of water and energy use a technically coherent and operationally practical approach. (U.S. DOE 2012.)

6.2 Energy efficiency of pumping systems

In auxiliary systems, part-load operation is common due to variable heat demand and varying makeup water demand. One of the most important operational factors affecting pumping electricity consumption is the method used to control flow. Traditional throttling control reduces flow by increasing hydraulic resistance, which dissipates energy without reducing pump speed. In contrast, variable frequency drives (VFDs) allow pump speed to be adjusted to match actual demand. For centrifugal pumps, reducing speed significantly lowers power consumption when flow demand is reduced, making speed control an effective measure in systems with variable operating conditions. Studies in district heating systems have reported pumping energy savings of approximately 20–50% when throttling control is replaced with variable-speed control. (Sârbu and Valea 2015; Sârbu, Mirza and Muntean 2022)

Oversized pumps, unnecessary circulation, parallel pump operation at low load and unnecessarily high pressure setpoints are common sources of avoidable energy consumption. Studies have reported that many pumping systems are oversized by more than 20%, and operating efficiencies may decrease by 10–25 percentage points below initial design values during operation. (Garcia et al. 2023) Efficiency can often be improved with operational changes, without changing the physical equipment. Optimized pump scheduling, pressure management and improved operating-point control have been reported to reduce pumping electricity consumption by approximately 8–30%, and in some cases up to 50%. (Hieninger, Schmidt-Vollus and Schlücker 2021; Oh, Inho and Chung 2023; Jones and Languri 2023)

Measuring water flow, pressure and electricity consumption is necessary for identifying inefficiencies. By monitoring specific energy consumption under different operating conditions, variations in pumping performance can be directly linked to water use patterns and operational practices (Lavrič, Drobnič and Fišer 2024; Garcia et al. 2023).

6.3 Specific energy consumption of water transfer and treatment

Specific energy consumption (SEC) is the primary indicator used to assess and compare the energy efficiency of water systems. SEC enables the energy performance of different water streams and operating conditions to be compared on a consistent basis and provides a quantitative link between water volumes and electricity consumption. SEC is widely used in both district heating and water treatment systems for benchmarking operating efficiency and comparing alternative operating strategies. (Morani et al. 2023; Skoczko 2025)

For raw water intake and transfer, SEC depends mainly on the pumping head, pipe friction losses and pump efficiency. For treatment processes, SEC reflects the energy intensity of each treatment step, with reverse osmosis and high-pressure membrane processes typically having higher SEC, particularly in seawater desalination applications. In district heating plants using freshwater as the raw water source, the SEC of RO is significantly lower, which is also reflected in the measurement results in Chapter 8. Typical SEC values for conventional freshwater treatment plants have been reported to range approximately from 0.2 to 0.4 kWh/m^3, while desalination systems may exceed 1 kWh/m^3 depending on salinity and process configuration (Skoczko 2025). For cooling water systems, SEC is determined by the flow rate, system pressure and operating hours.

Monitoring SEC over time and under different operating conditions allows deviations from expected performance to be identified. An increase in SEC without a corresponding increase in water demand may indicate pump deterioration, increased pipe friction due to fouling, or changes in operating conditions or control practices. Conversely, a reduction in SEC following an operational or technical change confirms the effectiveness of the implemented improvement. (Morani et al. 2023)

6.4 Optimisation of auxiliary water and electricity consumption

The optimisation of auxiliary water and electricity consumption in district heating plants involves identifying and eliminating sources of avoidable water losses and associated energy use. In practice, this requires a systematic assessment of all water streams within the plant, quantification of water volumes and associated electricity consumption, and identification of the processes or operating conditions responsible for the highest water and energy use.

System-level optimisation approaches have been widely applied in district heating systems to identify the most energy- and water-intensive operating conditions and prioritise improvement measures across interconnected process systems (Anbarasu et al. 2025; Vannahme, Ehrenwirth and Schrag 2024)

Key optimisation measures typically include recovery and reuse of condensate from steam systems and flue gas scrubbers, optimisation of water treatment reject ratios through adjustment of operating parameters, elimination of unnecessary cooling water circulation by matching flow to actual heat load, and replacement of throttling control with variable frequency drives (VFDs) on continuously operating pumps. (UNIDO 2017; U.S. DOE 2012; Bozzuto 2021.)

In the Finnish district heating context, flue gas condensate recovery has emerged as a particularly relevant measure for reducing raw water intake. At plants equipped with wet scrubbers, the condensate produced during heat recovery, after treatment, could partially or fully replace the need for raw water withdrawal from natural water bodies. This approach has been demonstrated at scale at Finnish bioenergy heating plants, where condensate recovery has been integrated into the plant's water balance as a routine operational practice. (Valmet 2020.)

Operating conditions change with heat load, season and plant configuration, and water consumption patterns change accordingly. Regular monitoring and benchmarking against defined targets allow deviations to be detected early and corrective action to be taken before they result in significant losses. Accurate monitoring of district heating water losses may require high-resolution operational data because temperature-driven volume changes can significantly affect apparent makeup water demand and leakage detection (Niemyjski and Zwierzchowski 2021).

6.5 Measurement and monitoring

Effective management of auxiliary water use requires adequate metering and monitoring infrastructure. At a minimum, total raw water intake should be metered continuously and logged at a suitable time resolution to allow temporal patterns to be identified. Ideally, individual water streams within the plant should also be metered separately, so that the contribution of each system to total intake can be quantified and tracked over time. In large district heating systems, continuous monitoring of makeup water flow is commonly used for leakage detection and system diagnostics, although temperature-driven volume changes may account for approximately 20–30 % of apparent makeup water flow, highlighting the importance of accurate and frequent measurements. (Niemyjski and Zwierzchowski 2021)

Electricity consumption associated with water handling should similarly be monitored at the level of individual pump systems or process areas, rather than only at the total plant level. This enables the specific energy consumption of individual water streams to be calculated and compared. Submetering of pumps and treatment equipment is therefore an important enabler of water and energy efficiency improvement. (Sushma et al. 2023; Cvetković et al. 2024)

In practice, many existing district heating plants have limited metering of auxiliary water systems, with flow measurement often available only at the raw water intake point. Where submetering is not available, water balances can be estimated using indirect methods, such as pump operating hours, flow calculations based on pump curves, and mass balances across process systems. These estimates are less accurate than direct measurement but can provide a useful starting point for identifying the main contributors to water consumption. (UNIDO 2017.)

Digital monitoring and data logging systems enable real-time tracking of water consumption and its relationship with operating conditions such as load level, outdoor temperature and production hours. Analysis of logged data can reveal correlations between water intake and operating variables, identify peak consumption periods, and support the prioritisation of improvement measures. This methodological approach is also applied in this thesis using operational data collected from the Vanaja power plant automation system, as described in Chapter 7.

7 Case Vanaja power plant: data and research methods

The operation of the Vanaja power plant requires uninterrupted access to cooling and process water. The amount of water required, especially during the operation of the gas turbine, has been large, so Vanajavesi has been the most suitable source for water supply.

This chapter presents the raw water system of the Vanaja power plant, and the data and methods used in the case study analysis. The chapter first describes the main components of the plant's water system, focusing on the raw water and cooling water intake from Lake Vanajavesi and the key water circuits within the plant. This description forms the basis for understanding how water flows through the plant's processes and where raw water intake occurs.

The data used in this study consists of logged process measurements collected from the plant's automation system and data collected manually by the operators every month. This dataset enables the identification of temporal patterns, seasonal variation and deviations in water and electricity consumption. The scope of the analysis is limited to water flows directly associated with raw water intake from Vanajavesi. The district heating water circuit is excluded from the analysis.

7.1 Current water permit for the use of Vanajavesi

The use of natural waters as raw water requires a water permit in accordance with the Water Act. In Finland, water permits are issued by the Finnish Licensing and Supervision Authority (Lupa- ja valvontavirasto), and compliance with the Water Act and permit conditions is supervised by the Licensing and Supervision Authority and municipal environmental protection authorities (Lupa- ja valvontavirasto n.d.).

The water use of the Vanaja power plant is regulated by a water intake permit issued under the Water Act and an environmental permit. The key permit requirements relate to the following topics:

- Intake of raw water from Vanajavesi
- Use of cooling and process waters
- Treatment of waters before discharge into the natural water
- Treatment of condensate from flue gas scrubbers
- Monitoring and reporting of environmental impacts

According to the current water permit, a maximum of 2 580 000 m^3 of cooling and process water may be extracted annually from Vanajavesi. In addition, the permit requires that the amount of extracted water is monitored in a manner approved by the Häme Environment Centre and that the impacts of water intake on the Vanajavesi water body are monitored in accordance with an approved monitoring program. Monitoring may be carried out jointly within the Vanajavesi and Pyhäjärvi water systems. According to the permit conditions, the permit holder is also responsible for any damage, inconvenience and other losses caused by the operation. In addition, the location of the water intake pipe in the bay of Paikkala must be marked with a sign placed on the shore.

The environmental permit specifies the treatment and discharge of water generated at the plant back into the natural water. The plant's cooling water, process water, reject water, flue gas scrubber condensate and storm water must be collected and treated in a controlled manner before discharge into the watershed so that the operation does not cause pollution of the watershed.

Flue gas scrubber condensate constitutes one of the most significant process waters requiring treatment at the plant. Depending on the fuel and operating conditions, the condensate contains different impurities, which is why it cannot be discharged directly into the watershed without treatment. Before discharge, the condensate is treated in a separate wastewater treatment process. A pH limit of 6–8 has been set for the condensate before discharge into the watershed. In addition, the treatment of condensate includes neutralization, chemical precipitation, clarification and filtration. Although, impurities are monitored regularly, no separate concentration limits have been set for them in the environmental permit.

The 2021 permit amendment also set a limit value for oil hydrocarbons for stormwater, according to which the hydrocarbon concentration of the water after the oil separator must be less than 5 mg/l. Stormwater treatment also requires the removal of solids and oil before discharge into the water system.

The permits also include monitoring and reporting obligations. The plant's water intake, water quality, temperature and emissions discharged into the water system are regularly monitored through continuous measurements and sampling. The results are reported annually to the authorities as part of the plant's environmental reporting. Environmental permits are largely based on treatment requirements, monitoring obligations and a general obligation to minimize emissions instead of numerical emission limits.

7.2 Overview of the use of Vanajavesi at Vanaja power plant

Raw water taken from Vanajavesi first passes through the intake screening station, where large solid impurities such as fish, branches and other debris are removed before the water enters the plant water systems. A total of approximately 780 000 m^3/a of water was taken from Vanajavesi in 2025. This total water volume can be divided into cooling water 725 000 m^3/a and process water 55 000 m^3/a. Most of the water withdrawn is used for cooling purposes and is returned to Vanajavesi via the plant's water discharge channel after use. A smaller portion is directed to the plant's water treatment system, where it is treated and used as process water, district heating makeup water production and other purposes.

Cooling water is also used for quenching grate slag, where water is added to the quenching trough to compensate for evaporation losses and the water removed together with the slag.

The water is distributed across four separate water cycles, each serving distinct functions within the plant. The four water cycles are the 03UA raw water treatment cycle, which produces mainly process water and district heating makeup water, the 05VG raw water cycle, which supplies untreated raw water to several auxiliary processes, such as flue gas scrubbers and fly ash wetting screw, the 08VG raw water cycle, which currently serves as cooling water for the sampling centre and electric boiler blowdown tank cooling, and the 03VC cooling water cycle, which supplies cooling water for gas turbine, when the gas turbine is in operation. These cycles are described in detail in Sections 8.2.1–8.2.4.

7.2.1 Raw water cycle 03UA for processes and district heating makeup water

Raw water cycle 03UA is the only raw water cycle with a treatment system. The detailed PI diagram of the 03UA treatment cycle is presented in Appendix 4. The raw water is used to produce feedwater for boilers K5 and K6, as well as for the electric boiler SK3 and makeup water for district heating network. The treatment chain consists of mechanical pretreatment, chemical conditioning, membrane separation, electrodeionisation and demineralisation. A schematic overview of the 03UA raw water treatment process is presented in Figure 3.

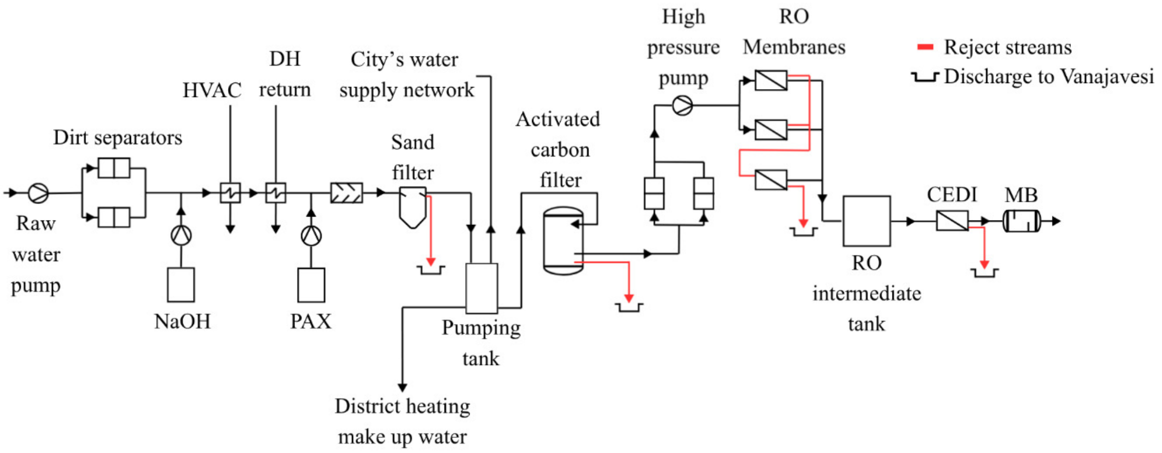

Figure 3. Raw water cycle 03UA treatment chain

Raw water is pumped from the cooling water channel connected to the Vanajavesi, using the raw water pump. From the raw water pump, water is conveyed to the raw water dirt separators. These dirt separators, referred to as "mud pockets" in plant terminology, remove coarse solids. The separators are installed in parallel, with typically one unit in operation at a time.

The raw water then undergoes chemical pretreatment, as it contains suspended solids and dissolved impurities that prevent direct treatment in membrane separation and polishing stages. The pH is adjusted to approximately 6 by dosing lye, i.e. sodium hydroxide (NaOH), from a chemical tank to the water. After pH adjustment, the water is preheated to around 20

°C to ensure effective coagulation, first with heat from the ventilation heating system in a heat exchanger, and then with the return water from the district heating network in a heat exchanger. After heating, the PAX coagulant is mixed into the water in pipe mixer. This causes the coagulant and suspended impurities to form flocs. The water is then directed to the Dynasand sand filter, where the flocs are separated from the raw water, and the treated water is collected in pumping tank.

There can be situations where raw water from Vanajavesi can't be used for process water and makeup water, for example due to malfunctions in the chemical treatment. Water quality is continuously monitored after the sand filter, and if the raw water does not reach the appropriate pH level or the turbidity is above 2 FNU (Formazin nephelometric units), the water is automatically diverted from the water circuit and led to the discharge channel to Vanajavesi. In these situations, the city's municipal water supply is directed into the process at the pumping tank, bypassing the chemical pretreatment stages described above.

There are two water outlets from the pumping tank. The water can be used as makeup water for district heating, or it can be led to further treatment prior to process use.

The stream that is directed for makeup for district heating network is separated from the circuit 03UA. This water is softened in cold water softeners. After softening, the water can be directed either to cool the K5 boiler economizer circulation pump, from where it will be discharged back to Vanajavesi, or to the district heating water expansion tanks and, if necessary, to the district heating accumulator.

The water directed for further treatment for process water passes through activated carbon filter and particle filters before reaching high-pressure pump. The high-pressure pump raises the water pressure to approximately 5 bars for the reverse osmosis stages.

Water is directed to the first and second RO membranes, the reject stream of which is directed to the third RO membrane. The reject stream of the third membrane is discharged to the discharge channel to Vanajavesi. The RO product water from all three membranes is directed to the RO intermediate tank and, from there it is pumped to continuous electrodeionisation (CEDI) modules. There are 5 parallel CEDI modules. The CEDI modules were originally installed to meet the water quality requirements of the steam turbine. Since the turbine is not in operation and the current water demand is lower, typically only three of the CEDI modules are in operation at the same time. The reject water from the CEDI modules is also led to the discharge channel to Vanajavesi. CEDI product water is further treated in mixed-bed (MB) filter.

The MB filter has four product water outlets. If the additional water tanks and the feedwater tanks are full, the water is led back to the pumping tank via line 03UA57 after the MB treatment. If the need for additional water in the district heating network and boilers is low, for example in the summer, the pumping tank is almost full. If the water returned from the MB filter exceeds the capacity of the pumping tank, the treated water is discharged back to the Vanajavesi through the overflow pipe. Demineralized water is also supplied from the MB filter for the electric boiler SK3 via line 03UA50.

The third outlet leads to the additional water tanks, from which the water is further directed towards the K6 boiler continuous blowdown tank 06RR10B001. The treated water is heated in a heat exchanger with the heat from the continuous blowdown tank, and the water is then transferred to the feedwater tank 04RL10B001. The fourth outlet is used as makeup water for the vacuum system tank of the K5 boiler cycle pressure reduction heat exchanger, 08SD50B001.

7.2.2 Raw water cycle 05VG

Unlike the 03UA cycle, the 05VG cycle does not include a water treatment process. Raw water is drawn from the cooling water channel connected to the Vanajavesi by the raw water pumps, and it is distributed directly to several end uses within the plant. A connection for a potential future raw water pump has also been installed with a manual shut-off valve 06VG01S001. The operation of the pumps is controlled by system pressure. At low water consumption, one pump operates at a time, and a second pump is started in parallel if the pressure drops below the set value. The pumps are operated alternately based on an operating hours counter.

The 05VG cycle supplies raw water to six end uses. The detailed PI diagram of the 05VG raw water cycle is presented in Appendix 6. First, raw water is used to cool the vacuum system tank of the K5 boiler cycle pressure reduction heat exchanger 08SD50B001, after which the cooling water is discharged to the water discharge channel leading to Vanajavesi. Second, raw water is added to the combined blowdown tank 06RR20B001 of boilers K5 and

K6 to reduce the temperature of the blowdown water to the set value of 45–50 °C, after which the cooled water is discharged to the water discharge channel.

Third and fourth, raw water is supplied to the flue gas scrubbers of boilers K5 and K6, 05NQ20N001 and 06NQ10N001. In a flue gas scrubber, flue gases are cooled and washed with water, causing the water vapour contained in the flue gases to condense into condensate. At the same time, impurities are removed from the flue gases and dissolved into the condensate. The clean condensate from both scrubbers is collected in condensate collection tank 06NQ65B001 and ultimately discharged to the water discharge channel. The contaminated condensate is discharged to the water discharge channel after the necessary treatment.

The contaminated condensate formed in flue gas scrubbers contains several impurities and therefore cannot be discharged directly into a watercourse without treatment. Depending on the fuel and operating conditions, the condensate may contain salts, nutrients, organic compounds, suspended solids and metals. The condensate also contains solids and sludge, which are removed during the treatment process.

Before discharge, the condensate from the flue gas scrubbers is treated in a separate wastewater treatment process. The treatment stages include neutralisation, chemical precipitation, clarification and filtration. The process uses, for example, sodium hydroxide for pH adjustment and flocculating chemicals such as polyaluminium chloride (PAX) and polymers for solids removal. After treatment, the pH of the water is typically adjusted to between 6 and 8 before discharge into the receiving water body.

The treatment process also produces scrubber sludge containing separated solids and metals. The sludge is dried and stored before being transported for further treatment as hazardous waste.

After treatment, the condensate from the flue gas scrubbers is discharged to the Vanajavesi through sewers and discharge channels. The condensate is classified as process wastewater, and its quality and quantity are monitored regularly. Continuous monitoring includes measurements of flow, temperature and pH. In addition, water samples are analysed for parameters such as suspended solids, nutrients, sulphate, chloride and metal concentrations.

Fifth, raw water is directed to the fly ash moistening screw 05NT40N002 in the fly ash silo to reduce the ash temperature during ash removal. This water leaves the plant together with the ash. Sixth, raw water is used to cool the circulating water pump of the K5 economizer 05NB10D001, after which the cooling water is discharged to the water discharge channel.

7.2.3 Auxiliary raw water cycle 08VG

The 08VG raw water cycle originally served as makeup water for the steam turbine cooling system (cycle 08VC) and for cooling the generator air of the steam turbine. Following the decommissioning of the steam turbine in 2020, neither of said functions is currently in use, and the cycle now serves two remaining end uses. The detailed PI diagram of the 08VG raw water cycle is presented in Appendix 6.

Raw water is drawn from Vanajavesi by raw water pumps, with typically one pump in operation at a time. The water is directed through the raw water tank to two end uses. First, water is supplied to the sampling centre for cooling process samples. Samples are taken from high-temperature processes, and raw water is circulated around the sample containers to reduce the sample temperature. Second, raw water is used to cool the continuous blowdown tank of the electric boiler SK3. In both cases, the water is subsequently discharged to the water discharge channel leading to Vanajavesi.

7.2.4 Gas turbine cooling water cycle 03VC

The 03VC cooling water cycle supplies raw water from Vanajavesi for gas turbine cooling. Raw water is drawn by cooling water pumps and distributed to three end uses, after which the water is discharged to the water discharge channel leading to Vanajavesi. The detailed PI diagram of the 03VC gas turbine cooling water cycle is presented in Appendix 5.

First, raw water is used to cool the circulating pumps of the heat recovery boiler, after which the cooling water is discharged directly to the water discharge channel. Second, raw water is circulated via circulation pumps to the generator air coolers of the gas turbine, where it is used to cool the generator cooling air. Third, raw water serves as the secondary cooling medium for the gas turbine lubrication oil water/water heat exchanger. This is a closed secondary circuit, meaning that the raw water from the 03VC raw water cycle cools the circuit through the heat exchanger without direct contact with the oil circuit.

As noted in Chapter 3.3, the gas turbine is currently used only for test runs and backup operation. The 03VC cooling water cycle is therefore not in continuous operation, but its instantaneous water demand during gas turbine operation is significant due to the once-through cooling configuration.

7.3 Data

The data used in this study consists of operational measurements collected from the automation system of the Vanaja power plant, as well as manually recorded data provided by Loimua personnel.

The automation system data includes process measurements related to water consumption, pumping systems, water treatment processes, and associated electricity use. Typical measurements include water flow rates, pump operating data, and electricity consumption measurements from selected water system components. The measurements are recorded and stored at hourly, daily, and monthly intervals.

In addition to the automation system data, manually recorded operational data has been used to complement the dataset. This data is collected by plant personnel and recorded on a monthly basis. The manually recorded data was primarily used to verify automation system measurements and to supplement missing or incomplete measurement data.

Before analysis, the data was checked for missing values and outliers. Periods related to maintenance outages, instrumentation failures and known operational disturbances were identified using the plant's operation logs and monthly operational data. Clearly erroneous measurements caused by instrumentation faults were corrected based on recorded data before and after error and typical values on similar power plant operation to avoid distortions in the calculated water balances and specific energy consumption values.

The combination of automated and manually recorded data provides a comprehensive basis for analysing water consumption, associated electricity use, and their temporal variation at the plant.

The analysed data covers the period from January 2023 to December 2025. Most of the process measurements were recorded with a time resolution of 1 h, 1 day and 1 month depending on the measurement point and the characteristics of the plant's automation system.

Monthly usage data was used to validate the annual water balances and identify maintenance periods, operational disturbances and exceptional operating situations.

Some limitations related to data availability and measurement accuracy are acknowledged. However, the available dataset is considered sufficient for identifying the major water consumption flows and evaluating their associated electricity use within the scope of this study. The data covers all major raw water intake points and the most energy-intensive treatment stages. This enables the identification of the most significant factors in terms of the plant's water consumption and auxiliary electricity use.

7.4 Research methods

The primary research method used in this study is quantitative operational data analysis focusing on raw water intake, internal water circulation and the associated auxiliary electricity consumption of the Vanaja power plant. The data was examined at different time resolutions, depending on availability, to capture both short-term variations and long-term trends.

In addition to quantitative analysis, the study includes qualitative assessment based on discussions with plant personnel. Discussions with plant personnel and process experts are used to support the interpretation of the data and to identify technically feasible improvement measures.

This study was conducted as a technical case study, combining operational data analysis with a process-based system assessment.

The analysis was conducted in three stages. First, the structure and operation of the plant’s water systems were mapped based on process documentation, operating principles, and automation system data. During this stage, a water balance framework was created that was used in the subsequent analysis. Second, operational process data were analysed. The distribution of raw water consumption between different water circuits, the temporal variation of water consumption, electricity consumption related to water treatment, and operating situations that cause peaks or deviations in water consumption were investigated. Specific energy consumption values were used as a key performance indicator to evaluate the relationship between treated water volumes and the associated electricity consumption of the water treatment systems. Third, technically feasible measures to reduce raw water withdrawal were identified and evaluated based on observed operational behaviour, process constraints, and the existing plant configuration.

7.5 Data analysis methods

The collected process data was analysed using mass balance calculations, flow comparisons, and electricity consumption estimation methods for the main water treatment and cooling water systems. The analysis focused on identifying the largest water flows, water losses and the relationship between water use and electricity consumption within the plant water systems.

Annual water balances were calculated based on measured process flows obtained from the plant automation system. Hourly flow measurements were converted into annual water volumes by integrating the measured flow rates over time. Additional monthly and yearly operational data obtained from plant personnel and environmental reports were used to validate the calculated results. Sankey diagrams were created to visualize the main water flows and water losses throughout the treatment process.

Electricity consumption related to water treatment was estimated for the main pumps and water treatment units. Due to the lack of direct electricity measurements for several devices, the electricity consumption was estimated using rated motor powers, operating hours and estimated operating loads derived from process measurements and VFD control signals. According to Chapman (2012), the electrical input power of a balanced three-phase electrical system can be calculated using Equation 1.

$$P_{\mathrm{in}} = \sqrt{3} \cdot U \cdot I \cdot \cos\phi \tag{1}$$

In the equation P_{in} is electrical input power [kW], U is the line-to-line voltage [V], I is the line current [A] and $\cos\varphi$ is the power factor. This equation is commonly used for calculating the electrical input power of three-phase motors and pumps operating under balanced load conditions.

In cases where voltage, current, or power factor data were unavailable, the electrical input power was estimated using the motor nominal output power and motor efficiency. The efficiency of an electric motor is defined as the ratio between the mechanical output power and the electrical input power, as illustrated in Equation 2 (Chapman, 2012).

$$P_{\mathrm{in}} = \frac{P_{\mathrm{out}}}{\eta} \tag{2}$$

In the equation, η is the motor efficiency [-], P_{out} is the mechanical output power [kW], and P_{in} is the electrical input power [kW]. Using Equations 1 and 2, the full-load and part-load electrical input power values were calculated for each pump based on the available motor nominal power, voltage, current, power factor, and motor efficiency data.

For centrifugal pumps equipped with variable-frequency drives (VFDs), the effect of rotational speed on pump power consumption can be estimated using the pump affinity laws. According to Marchi and Simpson (2013), pump power is proportional to the cube of the rotational speed, which is approximately proportional to the cube of the operating frequency, as presented in Equation 3.

$$\frac{P_{f1}}{P_{f2}} = \left(\frac{f_1}{f_2}\right)^3 \tag{3}$$

where P_{f1} and P_{f2} are the pump power consumptions at frequencies f_1 and f_2, respectively. Since all major pumps in the water treatment process were operated using VFD control, the electricity consumption estimates account for part-load operation and reduced rotational speeds observed during the operating conditions on 28 April 2026. The affinity laws were therefore used to estimate the reduction in electricity consumption under variable-speed operation.

Electricity consumption was then estimated using the calculated electrical input power and annual operating time, as shown in Equation 4.

$$E_{\mathrm{a}} = P_f \cdot t \tag{4}$$

In the equation, E_{a} is the estimated electricity consumption [kWh], P_f is the estimated electrical input power under variable-frequency operation [kW], and t is the annual operating time [h].

The specific energy consumption (SEC) values were calculated based on the operating conditions measured on 28 April 2026. The SEC for each component was calculated as shown in Equation 5.

$$SEC_{\mathrm{i}} = \frac{E_{\mathrm{i}}}{V_{\mathrm{MB}}} \tag{5}$$

In the equation SEC_i is the specific energy consumption of component i [kWh/m^3], E_i is the electricity consumption of component i during the selected operating period [kWh], and V_{MB} is the produced product water volume after the MB filter [m^3]. For the operating point on 28 April 2026, the product water flow rate after the MB filter was 3.2 m^3/h.

The calculated values represent engineering estimates based on available operational data and equipment specifications. Therefore, the results should be interpreted as indicative engineering estimates rather than exact electricity consumption values.

8 Current status of water cycles and uses and associated electricity consumption at the Vanaja power plant

The aim is to determine how water is consumed in the plant, how water use varies between different systems and how auxiliary electricity consumption is related to water transfer and treatment processes. Special attention is paid to the most important raw water cycles and their share of the total raw water intake of Vanajavesi.

The chapter first examines the total water consumption of individual water cycles and the role of different process areas in the overall water balance. After this, the electricity consumption related to the 03UA raw water treatment cycle is assessed in relation to the water flow and treatment demand. The results presented in this chapter form the basis for the efficiency assessment and improvements discussed in chapters 9 and 10.

8.1 Total water consumption

As illustrated in Table 4, the annual total raw water intake from Lake Vanajavesi during the study period varied between approximately 776 000 and 925 000 m³/a.

Table 4. Reported annual raw water and municipal water consumption 2023–2025

	2023	**2024**	**2025**
	[m^3]	**[m^3]**	**[m^3]**
Cooling water from Vanajavesi	704807	856943	724614
Process water from Vanajavesi	83131	68334	52081
HS-Vesi Oy municipal water	12614	6023	4453

Of this total water intake, cooling water from Vanajavesi ranged between 705 000-857 000 m^3/a and process water was between 52 000–83 000 m^3/a. Cooling water clearly dominates the total raw water intake, accounting for 90 % of the annual withdrawal from Lake Vanajavesi. In addition to raw water intake, approximately 4500–12 600 m^3/a of municipal water was supplied to the Vanaja power plant. This municipal water consumption includes domestic use of water and some fire hydrants. These water uses are not examined in this study.

The difference between the calculated known water flows illustrated in table 5, and the reported total water withdrawal is likely explained by several factors.

Table 5. Estimated annual raw water and cooling water consumption 2023–2025

	Raw water m3 08VG03, 08VG01, 05VG01, estimation	Gas turbine cooling water m3 03VC01, 03VC02, estimation	03UA rejections m3	Total m3
2023	380000	67000	53000	500000
2024	560000	35000	50000	645000
2025	400000	36000	50000	486000

First, the source data consisted of both manually recorded monthly values and measurements from the automation system, which introduces uncertainty into the comparison. As discussed in Section 9.1.3, measurement inaccuracies and equipment failures occurred during the study period, which may have affected the reported flow values. Second, the flow rates for 08VG01, 08VG03, 03VC01 and 03VC02 were not directly measured, but were estimated based on pump operating data and nominal pump information. In addition, historical monitoring of the plant has primarily focused on the total raw water withdrawal measured at the discharge screens, while individual process and auxiliary water flows have not previously been separately identified or monitored in detail. Therefore, the residual difference should not be interpreted as a single identifiable water flow, but rather as a combination of unmeasured auxiliary flows, reject and washing waters, overflow flows, measurement uncertainty and estimation uncertainty.

8.1.1 03UA

As illustrated in Table 6, the raw water intake of Vanajavesi remained relatively stable for three years, ranging between 67 400 m³ and 75 200 m³. Municipal water supplemented the raw water reserves in all three years. However, its volume decreased significantly from 1127 m³ in 2023 to 292 m³ in 2025. This reflects the reduced dependence on the municipal water network.

Table 6. Raw water utilization in 03UA cycle 2023 –2025

	2023	**2024**	**2025**
	[m3]	**[m3]**	**[m3]**
Raw water from Vanajavesi	75208	67427	68910
Municipal water to the pumping tank	1127	714	292
DH makeup water from pumping tank	7609	3129	5821
RO permeate	61871	64199	59937
Rejections from Dynasand, activated carbon filter and RO	6855	813	3444
Demineralised water from MB	43216	43569	41130
Rejections from CEDI and MB	18656	20630	18807
Water to makeup water tank	15644	15120	13219
Water not utilised for DH makeup or makeup tank	53082	49892	50162
Percentage of water not utilised for DH makeup or makeup tank [%]	30.5	26.8	27.5
Percentage of water intake to DH makeup water [%]	10.0	4.6	8.4
Percentage of water intake to makeup tank [%]	20.5	22.2	19.1

The identified water flows constitute approximately 60% of the raw water intake. Most of the incoming water passed through reverse osmosis stages, resulting in a reverse osmosis permeate of approximately 60 000–64 000 m³ per year. After further purification through CEDI and MB filters, the MB filter produced approximately 41 000–44 000 m³ of demineralized water per year. The CEDI and MB stages generated around 18 600–20 600 m³ of reject water per year and were the largest identified reject water stream. These reject streams account for around 25–30% of the incoming water and 30–32% of the reverse osmosis permeate.

The manufacturer of the CEDI modules used at the Vanaja power plant states that a typical reject stream share is around 26.5% of the incoming water flow. Assuming this reject water share, the CEDI reject water flow would be around 15 900–17 000 m³/a, while the MB filter reject would be around 2 700–2 900 m³/a.

Table 7. Share of inlet water directed to the main process uses in the 03UA cycle

Water intake to pumping tank	76335	68141	69202
Percentage of water intake to DH makeup water [%]	10.0	4.6	8.4
Percentage of water intake to makeup tank [%]	20.5	22.2	19.1

As illustrated in Table 7, the proportion of water fed to the makeup water tank was around 19–22% of the total feed, while the proportion of water used as makeup water for district heating was 5–10%. Thus, the proportion of water that was not discharged to district heating makeup water or the makeup water tank remained consistently high, at around 70–73% in all three years.

Figure 4 illustrates the stream distribution in cycle 03UA. This includes reject streams discharged to Vanajavesi, recycled water returned to the pumping tank, some of which is discharged to Vanajavesi, and unidentified losses in the treatment chain. This indicates that only a limited part of the treated raw water ultimately ends up in the final process applications, while a significant part is discharged with reject streams or recycled within the treatment process.

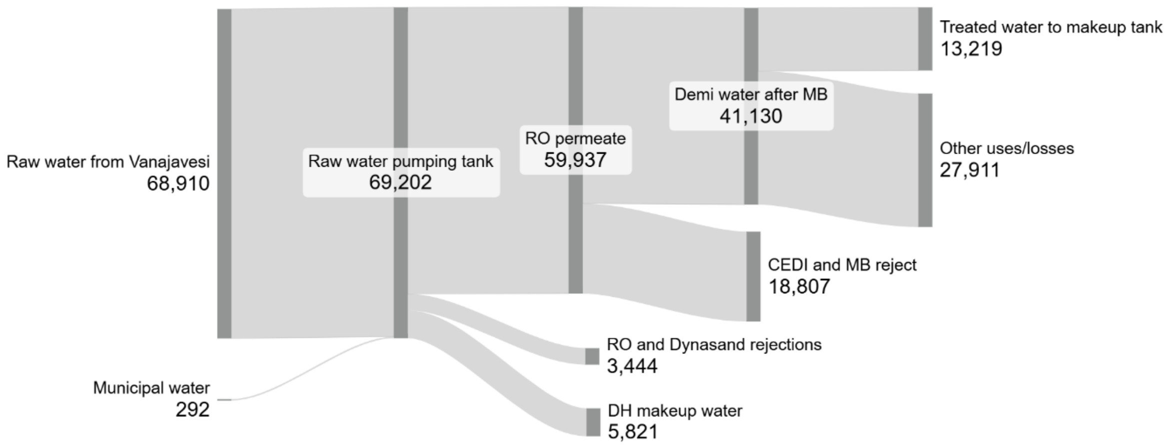

Figure 4. Water balance of the 03UA raw water treatment cycle in 2025 [m^3]

The Sankey diagram shows a consistent pattern across all three years. While raw water withdrawals varied annually, the amount of water classified as recycle, overflow and unidentified process losses remained largely stable at around 27 500–28 500 m³ per year. CEDI and MB discharge streams consistently represented the largest identifiable loss category, accounting for around 18 600–20 600 m³ per year.

8.1.2 Cooling waters 03VC, 08VG and 05VG

Figure 5 shows the combined raw water discharge flow for cycles 03VC, 05VG and 08VG with the monthly operating hours of the gas turbine cooling water pumps. The reported water volumes represent the measured discharge flows from these cycles and thus reflect the water returned to Vanajavesi. The water used for wetting the fly ash is not included in the figure, as this water is removed from the plant with the ash rather than being discharged back to the lake. In addition, the condensate generated in the flue gas scrubbers contains moisture condensed directly from the flue gas, which means that the amount of condensate to be removed may exceed the amount of raw water fed to the scrubbers.

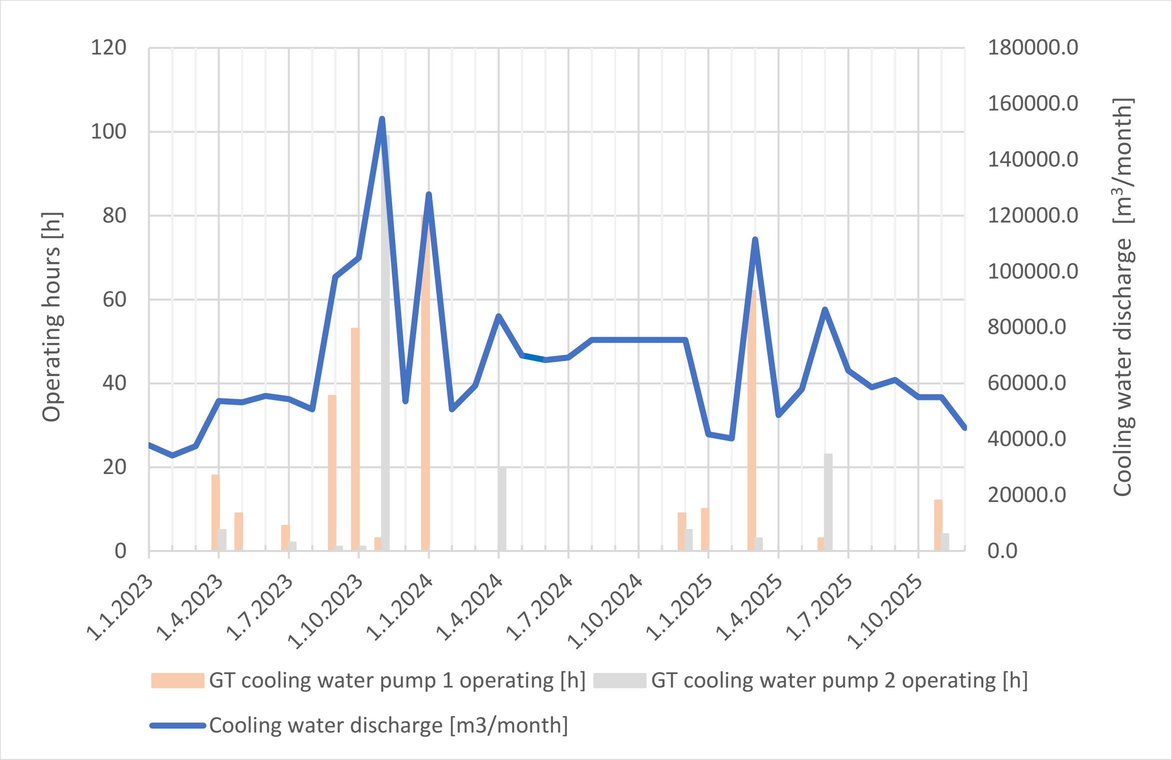

Figure 5. Monthly cooling and flushing water discharge volumes and gas turbine cooling water pump 1 and 2 operating hours during 2023 –2025

Figure 5 illustrates the monthly cooling and flushing water discharges and the operating hours of the gas turbine cooling water pumps 1 and 2 for the years 2023–2025. A clear relationship can be observed between the operation of the gas turbine cooling water pumps and the discharge flow from the cooling water systems. The periods of increasing operating hours of cooling water pump 1 correspond to clear peaks in the measured cooling water discharge values.

The highest discharges were measured in late 2023 and early 2024, when the operating hours of cooling water pump 1 also reached their peak. The largest single peak occurred in late 2023, when the pump operating hours exceeded 100 hours per month. These results show that even relatively short periods of gas turbine operation can produce very high cooling water flows due to the once-through cooling arrangement of the 03VC cooling water circuit.

However, the relationship between pump operating hours and cooling water discharge is not completely proportional. Cooling water flow remained at a relatively high level for several months, even though the operating hours of the gas turbine cooling water pumps were low or negligible. The base flow is associated with the 05VG and 08VG raw water circuits.

The operating hours of cooling water pump 2 remained significantly lower throughout the monitoring period compared to pump 1. This indicates that pump 1 acts as the primary cooling water pump, while pump 2 is mainly used as a backup or auxiliary pump for certain operating situations. In 2025, the operating hours of both cooling water pumps decreased significantly compared to 2023 and 2024. This is also reflected in lower and more stable cooling water flow rates.

Figure 6 shows the monthly cooling water discharge rates and average thermal output of boilers K5 and K6 for the years 2023–2025. The relationship between boiler thermal output and cooling water discharge is not completely proportional. Several clear short-term peaks can be identified in the cooling water discharge, which are primarily related to the operation of the gas turbine cooling water circuit 03VC.

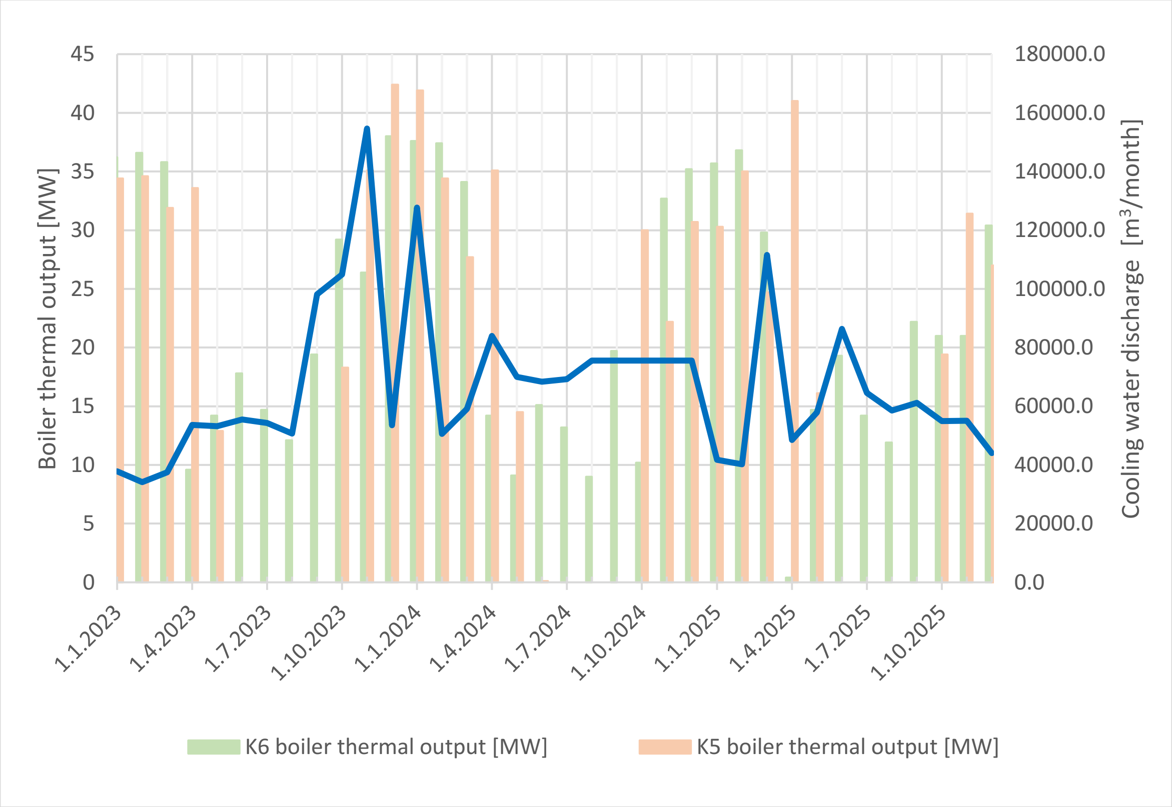

Figure 6. Monthly cooling water discharge volumes and K5 and K6 thermal output 2023 – 2025

The figure 6 also illustrates clear operational differences between boilers K5 and K6. Boiler K6 operates relatively continuously throughout the monitoring period and therefore appears to function as a primary baseload district heating unit. This is consistent with its operation as a hot water boiler with a largely closed water circuit and relatively low need for makeup water. In contrast, boiler K5 has a more variable thermal output. As a steam boiler, K5 requires more makeup water due to losses in the steam-water circuit, making its operation more closely related to process water consumption.

Despite this, the cooling water discharge does not seem to correlate with the operation of K5. This indicates that the majority of the measured cooling and flushing water discharge is not directly related to the boiler makeup water requirement.

Furthermore, the cooling water discharge can be observed to be relatively stable throughout the monitoring period. Even in months when the boiler thermal output is lower and the gas turbine operation is not significant, the discharge flow remains around 40,000–70,000 m^3/month. It is likely that certain cooling water circuits remain in operation even when the associated production units are not actively producing heat.

The results suggest that part of the raw water cycle is independent of the actual production requirement, suggesting opportunities to reduce unnecessary cooling water use by improving operational control or system-level optimisation.

As illustrated in Table 8, the water used for fly ash humidification in the 05VG cycle was 1636 m^3 in 2023, 907 m^3 in 2024 and 946 m^3 in 2025. The decrease from 2023 to 2024 is significant and reflects changes in ash handling volumes. In 2025, the consumption of wetting water remained almost unchanged compared to 2024. A total of 3600 tons of fly ash were produced in 2023, compared to 2500 tons in 2024 and 2900 tons in 2025.

Table 8. Monthly raw water to fly ash wetting 2023 –2025 [m^3]

	Raw water to fly ash wetting		
	m^3	m^3	m^3
	2023	2024	2025
January	177	125	133
February	107	119	126
March	166	91	103
April	96	72	54
May	68	19	51
June	92	35	36
July	55	21	28
August	176	25	48
September	197	97	43
October	129	85	101
November	147	91	103
December	226	127	119
Total	**1636**	**907**	**946**

The specific consumption of water used for wetting fly ash also decreased during the study period. Specific water consumption decreased from approximately 0.45 m^3/t in 2023 to 0.36 m^3/t in 2024 and 0.33 m^3/t in 2025. The amount of wetting water used is affected by operating methods, as the operator unloading the fly ash can adjust the desired moisture level of the ash to be loaded onto trucks. The monthly distribution of wetting water for fly ash generally follows a seasonal pattern, which is comparable to heat production. However, in 2023, consumption was relatively evenly distributed throughout the year.

The flue gas scrubbers of boilers K5 and K6 receive raw water from the 05VG circuit. Condensate is formed in the scrubbers during heat recovery. Clean condensate is collected and led back to the drainage channel leading to Vanajavesi. Contaminated condensate is treated as necessary, after which it is led back to Vanajavesi. As illustrated in Table 9, the total annual amount of scrubber condensate was 90 147 m^3 in 2023, 89 102 m^3 in 2024 and 85 842 m^3 in 2025. The total amount of raw water supplied to the 05VG cycle, including scrubber water, was 66 279 m^3 in 2023, 59 921 m^3 in 2024 and 56 094 m^3 in 2025. The annual scrubber condensate discharges consistently exceeded the total amount of raw water used in the 05VG cycle. This indicates that a significant part of the discharged scrubber condensate originates from moisture condensed from the flue gases and not from the raw water supplied. The scrubbers therefore act not only as a heat recovery and flue gas cleaning system but also as a net source of water in the 05VG cycle balance.

Table 9. Monthly flue gas scrubber condensate discharged to Vanajavesi 2023 –2025 [m^3]

	Flue gas scrubber condensate		
	m^3	m^3	m^3
	2023	2024	2025
January	11307	11057	12817
February	10336	11145	12110
March	11073	10835	10620
April	7206	9227	6688
May	12624	6447	6664
June	4107	4781	2823
July	1845	1797	1928
August	1606	1591	1981
September	2596	3252	3898
October	6666	7702	7902
November	9484	9275	8841
December	11296	11995	9569
	90147	**89102**	**85842**

The monthly distribution of scrubber condensate closely follows the seasonality of district heating production, with the highest volumes measured in the winter months and a clear decrease in the summer. January, February and March consistently produced the highest condensate volumes in all three years, while July and August recorded the lowest, typically less than 2 000 m^3 per month. This seasonality reflects the direct dependence of scrubber condensate production on boiler operating hours and heat load.

8.1.3 Operational factors causing peaks and deviations in water consumption

Several operational factors affecting raw water consumption and related electricity consumption could be identified from the operational data and annual environmental reports. The most significant short-term raw water intake peaks were related to the use of the gas turbine. The relationship between the operating hours of the gas turbine and the cooling water consumption is presented in Chapter 8.1.2. Although the gas turbine was only used during test runs and exceptional situations, its once-through cooling system requires a large instantaneous flow of cooling water directly from Vanajavesi.

Annual maintenance shutdowns and inspection periods also affected water consumption and production conditions. During the annual inspections carried out in August of 2023–2025, the plant’s heat production was completely suspended for several days. These shutdown periods affected both the demand for process water and the use of cooling water, as boiler operation, steam production and related auxiliary systems were temporarily out of service. Maintenance activities may also increase short-term water consumption due to equipment washes, system drains, refills and testing procedures associated with restarts. This is reflected in the monthly consumption data as a consistently lower water consumption in August, especially in 2023 and 2025.

In addition to planned operational changes, several incidents and exceptional situations were reported during the study period. These events have potentially affected water consumption and include changes in fuel quality, temporary disruptions in ash handling and flue gas cleaning systems, and leakages in the district heating accumulator. Such events may indirectly affect water consumption through increased cleaning needs, the need for additional water or changed operating conditions of auxiliary systems. In addition, the cooling water discharge flow meter located at the suction strainer malfunctioned in August

2024. The fault was detected in January 2025, after which the measuring device was replaced. As a result, the reliability of the cooling water discharge data recorded between August 2024 and January 2025 is impaired.

8.2 Total electricity consumption related to raw water treatment cycle 03UA

The electricity consumption related to water treatment was estimated based on the rated motor power of the main pumps and treatment equipment, operating hours and estimated load factors. Due to the lack of direct electricity consumption measurements of individual equipment, the values presented represent engineering estimates based on available operating data and equipment specifications. The analysis covers the energy consumption of the water treatment process chain from raw water intake to mixed-bed water production. The district heating makeup water pump has been excluded as it represents a separate process branch.

The electricity consumption analysis presented in this study is mainly based on a single measured operating point and estimated operating times. As a result, the calculated annual electricity consumption values should be interpreted as indicative estimates and not as exact annual consumption values.

The analysis does not include a detailed sensitivity analysis for seasonal operating variations, part-load operation, variable pump frequencies or variations in the number of CEDI modules in use. Therefore, the actual annual electricity consumption may differ from the presented estimates depending on the operating conditions of the plant. Despite these limitations, the analysis provides a sufficiently reliable order of magnitude estimate of the distribution of electricity consumption between pumping, CEDI treatment and chemical dosing.

Due to the lack of continuous electricity consumption measurements of individual treatment equipment, the energy consumption analysis is based on a representative operating point measured on 28 April 2026. During the measurement period, boiler K6 operated with an average steam output of 17.8 MW, while boiler K5 and the gas turbine were not in operation. The selected operating mode therefore represented a stable base load operation of one boiler with three active CEDI modules and normal water treatment conditions. The values presented should be interpreted as technical estimates and not as exact annual electricity consumption values. The 03UA water treatment circuit operates essentially continuously throughout the year, with flow rates consistently exceeding 7 m³/h during normal operation. The only significant interruption occurs during the annual maintenance shutdown in August, during which the circuit is taken out of service for a limited period. The annual operating time of 8650 hours used in the calculations represents the average of the actual recorded operating hours over the three-year study period from 2023 to 2025, providing a realistic basis for annual electricity consumption estimates.

Since the 03UA circuit operates as a stable base load system with relatively constant flow conditions, a single well-chosen operating point is considered sufficient to describe the typical electricity consumption of the treatment chain. Significant variations in operating conditions in the treatment circuit itself are not expected during normal plant operation. However, it should be noted that the simultaneous operation of boilers K5 and K6 may potentially affect water consumption and thus the load on the treatment circuit. Although this effect is expected to be small given the relatively stable flow conditions observed in the data, it is an uncertainty in the electricity consumption estimates that must be taken into account when interpreting the results.

Table 10. Estimated energy consumption and distribution based on the operating conditions of 28 April 2026 and theoretical maximum electricity consumptions

		Water pumps	**CEDI modules**	**Chemical pumps**	**Total**
Daily energy consumption	[kWh/day]	132	72	0.29	204
Annual energy consumption	[kWh/a]	47 424	25 936	104	73 465
Share of total consumption		64.6 %	35.3 %	0.1 %	100 %
Theoretical maximum energy consumption	[kWh/a]	258 063	43 250	424	301 737

As shown in Table 10, the estimated annual energy consumption of the water treatment process is 73 465 kWh/a. Water pumps account for the largest share of consumption at 64.6%, followed by CEDI modules at 35.3%. Chemical dosing pumps account for a negligible 0.1% of the total consumption. At the measured operating point, the daily energy consumption was 204 kWh/day.

Table 11. Specific energy consumption based on the operating conditions of 28 April 2026

Product water [m^3/h]	**Specific energy consumption [kWh/m^3]**					
	Raw water pump	Pressure boosting pump	RO high pressure pump	CEDI pump	CEDI modules	
	03UA10 D001	03UA10 D002	03UA10 D003	03UA62 D001	03UA63 N001, N004-N005	**Total SEC [kWh/m^3 product water]**
3.2	0.5	1.0	0.1	0.1	0.9	2.6

As illustrated in Table 11, the total specific energy consumption (SEC) of the raw water treatment process based on the operating conditions on 28 April 2026 was 2.65 kWh/m^3 of produced product water. The CEDI modules represented the most energy-intensive single component with a specific energy consumption of 0.94 kWh/m^3, reflecting the electrochemical nature of the ion exchange process. Among the pumps, the pressure boosting pump exhibited the highest SEC value at 1.01 kWh/m^3, while the RO high-pressure pump showed a relatively low specific energy consumption of 0.10 kWh/m^3. This relatively low energy demand is likely related to the low salinity and osmotic pressure of freshwater compared to seawater desalination applications. All pumps were operated using variable-frequency drives (VFDs), and the energy consumption estimates account for the part-load operating conditions observed on 28 April 2026.

Appendices 1, 2 and 3 present the energy consumption calculation Excel for each component of the 03UA raw water treatment chain with different operation values.

9 Efficiency improvement and recommended measures

The assessment of water and energy saving potential was based on the operational data analysis presented in Chapters 7 and 8 and the identified operational characteristics of the raw water, cooling water and water treatment systems of the Vanaja power plant. The objective was to identify technically and operationally feasible measures for reducing raw water intake, auxiliary electricity consumption and unnecessary internal water recirculation within the plant systems.

The assessment focused particularly on measures affecting the largest identified water flows, continuous reject streams and the most energy-intensive pumping and water treatment processes. The proposed improvement measures were evaluated based on their estimated water saving potential, impact on electricity consumption, technical feasibility, operational reliability and implementation complexity.

The evaluation was carried out using operational process data, plant operational experience and discussions with plant personnel. Particular attention was given to maintaining reliable plant operation and sufficient water quality for district heating production and auxiliary process requirements.

9.1 Principles for assessing savings potential

The improvement potential was assessed based on three main principles:

- Minimizing unnecessary raw water intake
- Reducing avoidable water losses and reject streams
- Reducing the electricity consumption related to water transfer and treatment

The assessment focused primarily on water flows and process systems that have the greatest impact on the overall raw water intake and auxiliary electricity consumption. Special attention was paid to continuous high-volume flows, reject flows and systems with high specific energy consumption.

Special attention was paid to the 03UA raw water treatment cycle, as it is one of the largest continuous consumers of raw water and includes several pumping, filtration and water treatment stages with significant associated electricity consumption. Therefore, measures affecting the operation of the 03UA system were considered to have the highest overall saving potential.

In addition to the average annual consumption values, the assessment also considered short-term peaks and process disturbances caused by maintenance shutdowns, start-up situations and exceptional operating conditions. Measures affecting continuous baseline water consumption were considered particularly important, as even relatively small reductions in continuous flows may result in significant annual water and electricity savings.

Based on the water consumption analysis presented in Chapter 8 and the operational characteristics of the water treatment and cooling systems at the Vanaja power plant, three key areas for improvement were identified.

9.2 1st saving potential: CEDI and MB bypass

The first key area concerns the necessity of the CEDI and MB filtration stages under the current operating conditions. The CEDI and MB filters were originally installed to meet the water quality requirements of the steam turbine, which was decommissioned in 2020. According to the present operating practice of the Vanaja power plant, the boiler feedwater applications, namely boilers K5, K6 and the electric boiler SK3, do not require the full demineralisation level provided by the CEDI and MB stages. Nevertheless, the entire treatment chain, including CEDI and MB, remains in continuous operation.

As stated in Section 8.2, the CEDI modules represent the single most energy-intensive component in the treatment chain, with a specific energy consumption of 0.94 kWh/m^3, corresponding to 35.3% of the estimated annual electricity consumption of the 03UA cycle. In addition, the CEDI and MB reject streams consistently represent the largest identifiable source of water loss in the treatment chain, accounting for approximately 18 600–20 600 m^3 per year. Based on the operational data analysis, optimisation of the 03UA treatment chain was identified as the single most significant improvement opportunity in terms of combined water and electricity savings. Additional flow measurements for the CEDI and MB reject streams would further improve the accuracy of the water balance analysis and enable more precise identification of avoidable reject water losses and optimisation potential within the treatment process.

Although bypassing the CEDI and MB treatment stages was identified as a technically interesting opportunity for reducing electricity consumption, the feasibility of such a modification depends critically on the required feed water quality of the remaining boiler systems and district heating network.

The present study does not include a detailed analysis of water quality requirements, conductivity limits, silica concentration, dissolved oxygen limits or equipment-specific water quality criteria. Therefore, the operational feasibility and long-term risks of reduced demineralisation remain open questions. Additional technical investigations would be required to verify that bypass operation would not increase the risk of corrosion, scaling or operational disturbances in the boiler and district heating systems.

9.3 2nd saving potential: 08VG raw water circuit shutdown

The second key area concerns the necessity and configuration of the 08VG raw water circuit. Following the decommissioning of the steam turbine, the 08VG circuit lost its two primary functions and currently has only two remaining end uses: cooling of the sampling centre and cooling of the SK3 blowdown tank of the electric boiler. The cooling of the sampling centre could be supplied from an alternative water source. Similarly, the cooling water for the SK3 blowdown tank could be supplied from the same water system as the SK3 makeup water, which is already taken from the 03UA cycle. If these alternative supply arrangements were implemented, the 08VG cycle could be taken out of service during periods when only the electric boiler is operating, thereby reducing unnecessary raw water circulation. Additional direct flow measurements for the 08VG raw water pumps would also improve understanding of the actual operating demand and water consumption of the circuit during different plant operating situations.

The annual raw water consumption of the SK3 electric boiler is estimated to remain very low compared to the plant's current raw water systems. Based on preliminary operational estimates, the annual cooling water consumption of the blowdown tank is approximately 8.2

m^3/a, assuming one weekly blowdown at a flow rate of 4.2 m^3/h and a duration of approximately 2.26 minutes per week. The estimated annual boiler filling volume is approximately 6.1 m^3/a. In addition, the estimated annual additional water consumption is approximately 7.3 m^3/a, assuming one weekly additional blowdown at a flow rate of 1 m^3/h and a duration of approximately 8.36 minutes.

Based on these estimates, the total annual lake water consumption of the electric boiler would be approximately 21.5 m^3/a. However, the estimate is very indicative, and the actual water consumption depends on several operating factors, such as boiler operating hours, start-up frequency, blow-down requirements, water quality monitoring and operating methods.

In addition, a separate feedwater treatment system based on municipal water is currently under construction for the electric boiler, which is planned to be commissioned in the summer of 2026. After commissioning, lake water would only be needed for blow-down cooling, while the rest of the water consumption would be supplied from the municipal water network. This will significantly reduce the future impact of the electric boiler on the plant's raw water balance.

9.4 3rd saving potential: 03UA excessive water circulation

The third key area concerns unnecessary water treatment and internal recirculation within the 03UA cycle. As noted in Section 9.1.1, approximately 70–73% of the total raw water entering the 03UA cycle does not end up in final process applications such as the makeup water tank or district heating makeup water. Some of this difference is caused by unmeasured flows, but a significant share consists of recycled water, overflows and unidentified losses. This indicates that a considerable share of the treated water circulation is not directly linked to productive end use. Inefficiencies occur particularly when the pumping tank reaches full capacity and treated water is returned to Vanajavesi via the pumping tank overflow pipe. In this situation, raw water is continuously pumped, processed through energy-intensive treatment stages and subsequently discharged, resulting in both avoidable raw water withdrawal and unnecessary electricity consumption.

Direct measurement of the pumping tank overflow flow would significantly improve the identification and quantification of avoidable overflow losses and unnecessary internal recirculation within the 03UA treatment chain. In addition, direct flow measurements for the 03VC gas turbine cooling water pumps would improve understanding of short-term cooling water peaks associated with gas turbine operation. Further measurements of the raw water supplied to the flue gas scrubbers would also improve understanding of the relationship between scrubber operation, condensate generation and actual net raw water demand.

9.5 Evaluation and prioritization of proposed measures

The identified improvement measures were evaluated based on their estimated impact on raw water intake, auxiliary electricity consumption, operational reliability and technical feasibility. Particular emphasis was placed on measures affecting continuous high-volume flows and the most energy-intensive treatment stages.

The most significant single improvement opportunity was identified as the optimisation of the 03UA treatment chain. Bypassing the CEDI and MB filtration stages under operating conditions where full demineralisation is not required would provide the largest combined reduction in both water consumption and auxiliary electricity use. The CEDI modules represent the most energy-intensive component of the treatment chain and simultaneously produce the largest identifiable reject stream. Based on the operational analysis, the current treatment configuration appears partly oversized relative to the present boiler feedwater quality requirements following the decommissioning of the steam turbine in 2020.

Implementing a partial bypass arrangement would require verification that reverse osmosis treated water is sufficient for existing boiler applications and that the current piping configuration allows bypass operation without significant system modifications. Expected benefits include direct reductions in CEDI operating hours, lower auxiliary electricity consumption and reduced reject water generation.

The second most significant improvement opportunity concerns the reduction of unnecessary internal recirculation and overflow losses within the 03UA cycle. The analysis showed that a significant share of the treated water circulation is not directly connected to linked end use, particularly during low-demand operating conditions when overflow discharge occurs from the pumping tank. Adjusting raw water intake to better match actual process demand would reduce unnecessary pumping, treatment and overflow discharge.

Two approaches were identified. The first approach is to stop or reduce raw water pumping when the pumping tank reaches full or near-full capacity. The second approach is demand-based raw water intake control, where raw water intake is adjusted according to actual process demand. However, demand-based operation may increase the risk of sedimentation and fouling during prolonged low-flow periods and would therefore require careful operational evaluation before implementation.

Simplification of the 08VG raw water circuit was identified as a technically feasible measure with moderate water and electricity saving potential and relatively low implementation complexity. Following the decommissioning of the steam turbine, the circuit currently serves only limited remaining cooling applications. If alternative cooling water arrangements are implemented for the sampling centre and SK3 blowdown tank, the 08VG pumps could be taken out of service. This would eliminate unnecessary seasonal raw water circulation and reduce the auxiliary electricity consumption associated with the 08VG pumps.

Overall, the analysis indicates that the greatest optimisation potential lies in reducing unnecessary water treatment, reject generation and internal recirculation during low-demand operating conditions. In particular, optimisation of the 03UA treatment chain offers the most significant combined reduction potential for both raw water intake and auxiliary electricity consumption without requiring major process modifications.

9.6 Risks and impacts

The identified improvement measures involve technical and operational risks that should be evaluated before implementation. The risks are primarily related to feedwater quality, operational reliability, process stability and potential impacts on plant equipment. In addition to the technical risks, the identified measures differ in their estimated impact on raw water intake and auxiliary electricity consumption.

The estimated impacts, risks and implementation complexity of the identified improvement measures are summarized in Table 12.

Table 12. Estimated saving potential, implementation complexity and main risks of the identified improvement measures.

Measure	Estimated water saving	Estimated electricity saving	Implementation complexity	Priority
CEDI/MB bypass	High 19 500 m³/a reject reduction	High 30 MWh/a CEDI + CEDI pump shutdown	Medium	High
03UA overflow reduction	Medium–high 10 600 m³/a		High	Medium
08VG seasonal shutdown	High 38 600 m³/a		Medium	Medium

As shown in Table 12, the single most significant improvement opportunity was the optimisation of the 03UA treatment chain by bypassing the CEDI and MB stages. The water savings achieved by bypassing the CEDI and MB stages can be estimated directly from the measured reject flow. The CEDI and MB reject flow measured in the automation system is the only directly measured reject flow in the 03UA cycle and represents water that leaves the process as processing loss without recovery. If the CEDI and MB stages are bypassed, these reject flows are eliminated completely. This measure offers the largest combined reduction potential for both raw water intake and auxiliary electricity consumption. However, the most significant risk associated with the bypass arrangement is insufficient feedwater quality. Although current boiler applications are not expected to require complete demineralisation, this study does not verify whether the quality of the reverse osmosis treated water meets the actual feedwater quality requirements of the K5, K6 and SK3 boilers. If the reverse osmosis water quality is insufficient, bypassing may lead to scale build-up, corrosion or accelerated wear of the boiler internals and heat transfer surfaces. Therefore, prior to commissioning, the water quality achieved after reverse osmosis treatment should be checked against the feedwater requirements specified by the boiler manufacturers or applicable industry standards.

Another identified improvement measure concerns the reduction of unnecessary internal recirculation and overflow losses in the 03UA cycle. The main operational risk associated with demand-based raw water intake control is sedimentation and fouling of the untreated raw water pipeline during prolonged periods of low flow. If untreated raw water is left in the system for long periods, suspended solids and biological material can accumulate in the pipes, valves and other components. This can lead to blockages, flow restrictions and increased maintenance requirements. The lower-risk operational approach is to divert untreated raw water from the pumping tank to Vanajavesi when the makeup water tanks and feedwater tank reach full capacity. This approach avoids unnecessary treatment of water that would otherwise be discharged as overflow and does not require prolonged stagnation of untreated raw water within the piping system. However, a fully demand-based intake control strategy would require careful operational evaluation and possibly additional flushing before implementation.

The third identified measure concerns the seasonal or complete shutdown of the 08VG raw water circuit. The primary risk associated with this measure is that the proposed alternative cooling water arrangements may not be technically feasible within the existing piping configuration. If the cooling water for the SK3 blowdown tank and the SK3 make-up water tank cannot be supplied from the same 03UA-based system without modification, additional piping or equipment may be required. However, the measure was considered technically feasible and the implementation complexity relatively moderate, as the operational role of the 08VG circuit is currently limited after the decommissioning of the steam turbine. The estimated water savings of 38 600 m^3/year from the decommissioning of the 08VG raw water circuit were derived from the automation system data. The calculation was based on hourly pump status signals stored in the automation system, where a value of 1 means that the pump is running and 0 means that it is stopped. These binary hourly operating signals were multiplied by the pump's nominal flow rate of 87 m^3/h to obtain an estimate of the total amount of water circulating through the 08VG circuit per year. The resulting figure therefore represents the total amount of raw water that would no longer need to be taken from Vanajavesi if the 08VG circuit were completely decommissioned.

It should be noted that the nominal flow rate of 87 m^3/h represents the nominal capacity of the pump and not the directly measured average flow rate. If the actual operating flow rate deviates from the nominal value, the savings estimate would change accordingly. The estimate should therefore be interpreted as an indicative order of magnitude and not as a precise value based on measurements. However, the calculation method is considered appropriate based on the available data and the result provides a reasonable basis for comparing the relative savings potential of the identified improvement measures.

Overall, the analysis shows that the greatest optimisation potential lies in reducing unnecessary water treatment, reject water generation and internal recirculation during low-demand operating conditions. In particular, optimisation of the 03UA treatment chain appears to offer the most significant combined reduction potential for both raw water intake and auxiliary electricity consumption.

10 Conclusions

This thesis examined the use of raw water from Vanajavesi at the Vanaja power plant in Hämeenlinna, operated by Loimua Oy, and the electricity consumption associated with water transfer and treatment. The results indicate that a significant share of the current raw water treatment and circulation at the plant is related to historical operating conditions that no longer exist following the decommissioning of the steam turbine in 2020. The motivation for the study was the relatively high raw water withdrawal from Vanajavesi and the interest in understanding the reasons behind these withdrawal levels and identifying opportunities to reduce them.

The first research question concerned how raw water is currently used and recycled at the Vanaja power plant and where the main sources of water consumption are. The analysis showed that the total raw water withdrawal from Vanajavesi varied between approximately 776 000 and 925 000 m³ during the study period 2023–2025. Cooling water dominated the total withdrawal and accounted for approximately 90 % of the annual withdrawal. The single largest contributor to cooling water peaks was the use of the gas turbine, which, although limited to test runs and emergency situations, resulted in significant short-term raw water flows due to the once-through cooling configuration of the 03VC cycle.

In the 03UA raw water treatment cycle, only approximately 27–29 % of the total raw water consumption ultimately ended up in the major final applications of the makeup water tank and district heating makeup water. The remainder consisted of reject streams from the treatment process, recycled water, overflow discharges and unidentified losses. This uncertainty is mainly related to limitations in measurement coverage, overlapping process flows and the lack of separate flow measurements for certain auxiliary water systems. As a result, the presented water balance should be interpreted as an approximate operational analysis and not as an accurate mass balance for the entire plant.

The second research question concerned the electricity consumption associated with water transfer and treatment. The estimated annual electricity consumption of the 03UA raw water treatment cycle under measured operating conditions was 73 465 kWh/a. The water pumps accounted for 64.6 % of this consumption and the continuous electrodeionisation (CEDI) modules for 35.3 %. The specific energy consumption of the treatment chain was estimated to be 2.65 kWh/m^3. The CEDI modules represented the most energy-intensive single component with a specific energy consumption of 0.94 kWh/m^3, while the specific energy consumption of the reverse osmosis (RO) high-pressure pump was notably low at 0.10 kWh/m^3, which is consistent with the relatively low osmotic pressure of freshwater compared to seawater desalination applications.

The third research question concerned technically and operationally feasible measures to reduce raw water withdrawal and associated electricity consumption. Three key improvement measures were identified. The most significant measure is bypassing the CEDI and mixed bed (MB) filtration stages, which were originally installed to serve the steam turbine that was decommissioned in 2020 and are no longer required for the current boiler applications. This measure would reduce both the largest identifiable reject flow, currently 18 600–20 600 m^3 per year, and the largest single source of electricity consumption within the treatment chain. The second measure is the optimisation and potential decommissioning or seasonal shutdown of the 08VG raw water circuit. If the remaining end uses of the 08VG cycle can be supplied through alternative water systems within the existing plant configuration, the circuit could potentially be fully decommissioned. The third measure is optimisation of raw water intake management within the 03UA cycle to prevent unnecessary treatment and overflow discharge when the pumping tank, makeup water tanks and feedwater pumping systems are at full capacity.

All three measures require further technical assessment before implementation. The water quality achieved by the RO stages must be verified against the boiler feedwater specifications before the CEDI and MB bypass can be implemented. The feasibility of alternative cooling water arrangements must be confirmed before the 08VG cycle can be simplified or decommissioned. In addition, the sedimentation and fouling risks associated with demand-based raw water intake control must be carefully evaluated before implementation. The annual maintenance shutdown planned for August 2026 provides a natural opportunity to implement potential modifications identified based on these assessments.

The study shows that there is significant optimisation potential in the auxiliary water systems of the Vanaja power plant, particularly within the 03UA treatment chain. The greatest benefits are associated with adapting the water treatment configuration to match the plant's current operating environment, which has changed significantly following the decommissioning of the steam turbine in 2020. The identified measures could reduce unnecessary raw water withdrawal from Vanajavesi while simultaneously lowering the auxiliary electricity consumption of the plant water systems without requiring major process modifications.

The study also included several limitations that should be considered when interpreting the results. The analysis was based primarily on operational process data, existing plant measurements and engineering assessments rather than direct experimental validation or dedicated measurement campaigns. As a result, uncertainty remains regarding the exact distribution of water flows, electricity consumption and individual system losses within the auxiliary water systems.

One of the most significant limitations was the lack of direct electricity consumption measurements for individual treatment equipment and pumping systems. The electricity consumption values presented in the study were therefore estimated using nominal capacities, operating hours and estimated load factors based on operating conditions. While the estimates provide a reasonable indication of the relative significance of the different treatment stages, the actual electricity consumption may vary depending on operating conditions, pump loading, equipment efficiency and process control strategies.

The availability and accuracy of water flow measurements also introduced uncertainty into the analysis. Several auxiliary water flows and reject flows could only be estimated indirectly due to limited measurement coverage within the plant water systems. In addition, some measurement devices malfunctioned during the study period. For example, the cooling water discharge flow meter located at the suction strainer malfunctioned in August 2024, and the fault was not identified until January 2025 when the device was replaced. As a result, the reliability of some cooling water discharge data during this period may be reduced. Since the water systems include several interconnected recycle flows, overflow flows and parallel process branches, it was not always possible to establish a completely closed and fully measured water balance for every operating situation.

Another limitation is related to the changing operating conditions of the power plant during the study period. The annual operating hours of the boilers, gas turbine and auxiliary systems varied significantly from year to year due to maintenance shutdowns, seasonal operating conditions and changes in heat production demand. Furthermore, the increasing role of non-combustion heat production technologies, such as electric boilers, means that the current operating environment may continue to evolve in the future. Consequently, the presented water consumption models and optimisation opportunities represent the operating conditions observed during the study period rather than a permanent long-term steady-state operating configuration.

The study focused primarily on technical and operational analysis and did not include detailed economic calculations or investment feasibility assessments for the proposed optimisation measures. Although several potentially significant improvement opportunities were identified, practical implementation would require further technical validation, process risk assessment and economic evaluation before changes could be introduced into actual plant operation. For example, the long-term effects on boiler water chemistry, corrosion risk and operational reliability were outside the scope of this thesis.

Furthermore, some of the proposed optimisation opportunities were identified based on current operating practices and discussions with plant personnel rather than direct experimental testing. For example, the feasibility of reducing raw water circulation under low-demand operating conditions remains uncertain due to potential risks associated with stagnant untreated water, sediment accumulation and biological fouling within the piping system. These operational risks were identified in the study, but their quantitative impacts could not be assessed within the scope of this thesis.

Despite these limitations, the study provides a comprehensive practical overview of the raw water systems and auxiliary water-related electricity consumption at the Vanaja power plant. The analysis identifies several technically plausible improvement opportunities and provides a foundation for future detailed optimisation studies and implementation planning.

Future research should focus particularly on improving the measurement accuracy and monitoring coverage of the plant water systems. One of the main areas for improvement identified in this study was the lack of detailed flow measurements in individual cooling water circuits and branches. Although the total cooling water flow is monitored, the distribution of water consumption between individual users and process branches cannot currently be determined with sufficient accuracy. More detailed sub-metering of individual cooling water branches would significantly improve understanding of actual water consumption patterns and enable more accurate identification of systems responsible for continuous baseline cooling water consumption and short-term consumption peaks.

In addition to the main water flows, the plant contains several smaller side streams that are not currently measured. Individually, these flows may appear insignificant, but together they may represent a considerable share of the total water balance and unidentified water losses. Future studies should therefore focus on developing a more comprehensive plant-wide water balance with improved measurement coverage for side streams, overflow flows and reject water branches. This would reduce uncertainty in the water balance analysis and improve the reliability of future optimisation studies.

Further studies are also needed regarding the electricity consumption of the water systems. In this study, electricity consumption was estimated based on motor ratings, operating hours and estimated load. In particular, historical operating data from frequency converters could provide valuable information on actual pump loading, operating conditions and process variation over time. This would allow more accurate determination of electricity consumption under different operating conditions and water consumption levels.

Further monitoring of reject water flows and treatment process operating parameters would also support future optimisation work. Continuous historical data on reverse osmosis recovery rates, CEDI reject flows and particularly pumping tank overflow flows could be used to identify inefficient operating periods and evaluate how operating conditions affect water losses and electricity consumption.

Additional long-term optimisation potential may also exist in the utilisation of flue gas scrubber condensate as an alternative internal water source. Currently, the condensate generated in the flue gas scrubbers is discharged directly to Vanajavesi without further utilisation. Recovery and reuse of this condensate could potentially reduce raw water withdrawal and decrease the demand for treated makeup water. However, further water quality analyses and operational assessments would be required before large-scale utilisation could be implemented.

Overall, the study demonstrates that significant reductions in raw water withdrawal and auxiliary electricity consumption may potentially be achieved through relatively moderate modifications to the existing water treatment and cooling water systems when the current operating requirements of the plant are critically reassessed.

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Appendix 1. Electricity consumption calculation of raw water pumps 03UA

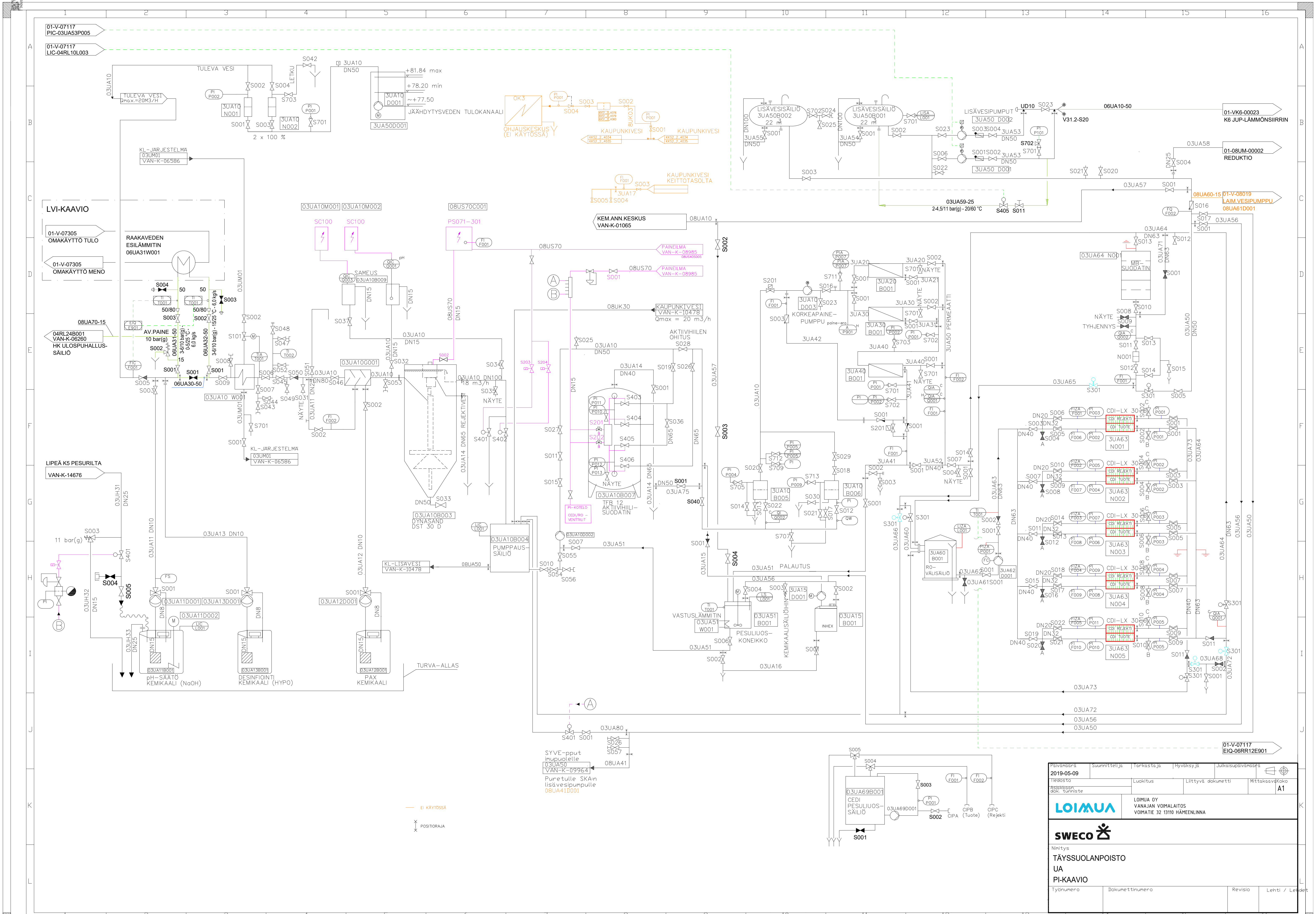
Pump type	**Function**	**Position**	**Motor nominal power P2 [kW]**	**Voltage [V]** Nominal	**Current [A]** Nominal	**cos phi**	**Motor efficiency [%]** Full load	**P1 [kW]** calculated full load	**Frequency factor** f [-]	**Nominal flow [m3/h]**	**Operating hours [h]** Estimation	**Energy consumption [kWh/a]** Estimation (f control)	**Energy consumption [kWh/a]** measured operating point of f on 28.4.2026	**Operating hours on 28.4.2026**	**Energy consumption [kWh/day]** measured operating point of f on 28.4.2026
Submersible borehole pump	Raw water pump	03UA10D0	4	400	9,6	0,8		5,32	0,1	17	8650	46	13843	24	38
									0,25		8650	719			
									0,5		8650	5753			
									0,75		8650	19417			
									1		8650	46025			
Centrifugal pump	Pressure boosting pu	03UA10D0	5,5	400	11	0,9	87,5	6,29	0,1	16	8650	54	27838	24	77
									0,25		8650	850			
									0,5		8650	6796			
									0,75		8650	22938			
									1		8650	54371			
Centrifugal pump	RO high pressure pu	03UA10D0	11				91,2	12,06	0,1	30	8650	104	2817	24	8
									0,25		8650	1630			
									0,5		8650	13041			
									0,75		8650	44015			
									1		8650	104331			
Centrifugal pump	CEDI pump	03UA62D0	5,5				89,2	6,17	0,1	17	8650	53	2927	24	8
									0,25		8650	833			
									0,5		8650	6667			
									0,75		8650	22501			
									1		8650	53335			
											Total minimum	258	kWh/a		
											Total maximum	258063	kWh/a		
											Total 28.4.2026	132	kWh/day		
											Total based on 28.4	0	kWh/a (8650 h)		

Appendix 2. Electricity consumption calculation of CEDI-modules 03UA

	P [kW]	Modules in use	P modules total [kW]	Nominal flow [m3/h]	Nominal flow total[m3/h]	Operating hours [h]	Energy consumption [kWh/a]	Operating hours on 28.4.2026	Energy consumption [kWh/day]
CEDI modules 03UA63N001-N005	1	1	1	3,3	3,3	8650	8650	24	72
		2	2		6,6	8650	17300		
		3	3		9,9	8650	25950		
		4	4		13,2	8650	34600		
		5	5		16,5	8650	43250		
						Total minimum (1 module)	8650	kWh/a	
						Total maximum (5 modules)	43250	kWh/a	
						Total 28.4.2026	72	kWh/day (three modules)	
						Total based on 28.4. f	0	kWh/a (8650 h, three modules)	

Appendix 3. Electricity consumption calculation of chemical dosing pumps 03UA

Pump type	**Function**	**Position**	**P1 [W]**	**Frequency [HZ]**	**Frequency factor** f [-]	**Operating hours [h] (estimation)**	**Energy consumption [kWh/a]**	**Operating hours on 28.4.2026 [h]**	**Energy consumption [kWh/day]** measured operating point of f on 28.4.2026
Chemical dosing pump	NaOH dosing pump	03UA11D001	25	50	0,1	8650	22	24	0,048
					0,25		54		
					0,5		108		
					0,75		162		
					1		216		
Chemical dosing pump	PAX dosing pump	03UA12D001	24	50/60	0,1	8650	21	24	0,242
					0,25		52		
					0,5		104		
					0,75		156		
					1		208		
						Total minimum	42	kWh/a	
						Total maximum	424	kWh/a	
						Total 28.4.2026	0,29	kWh/day	
						Total based on 28.4. f	0	kWh/a (8650 h)	



Päivämäärä	Suunnittelija	Tarkastaja	Hyväksyjä	Julkaisupäivämäärä
2019-05-09				

Tiedosto
Luokitus
Liittyvä dokumentti
Mittakaava
Koko
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Asiakkaan dok. tunniste

LOIMUA

LOIMUA OY
VANAJAN VOIMALAITOS
VOIMATIE 32 13110 HÄMEENLINNA

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Työnumero
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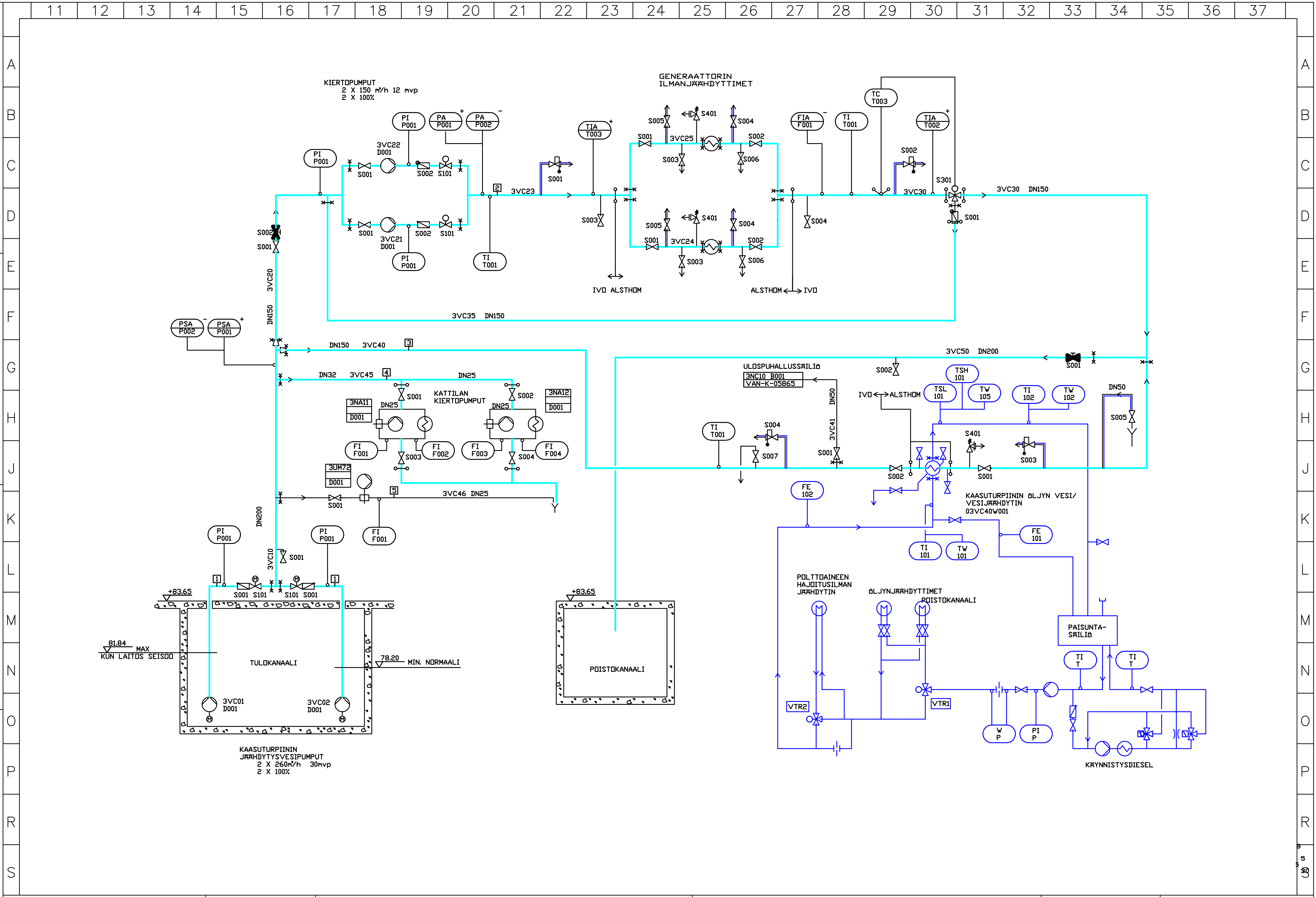

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VATTENFALL LÄMPÖ OY
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PI-KAAVIO

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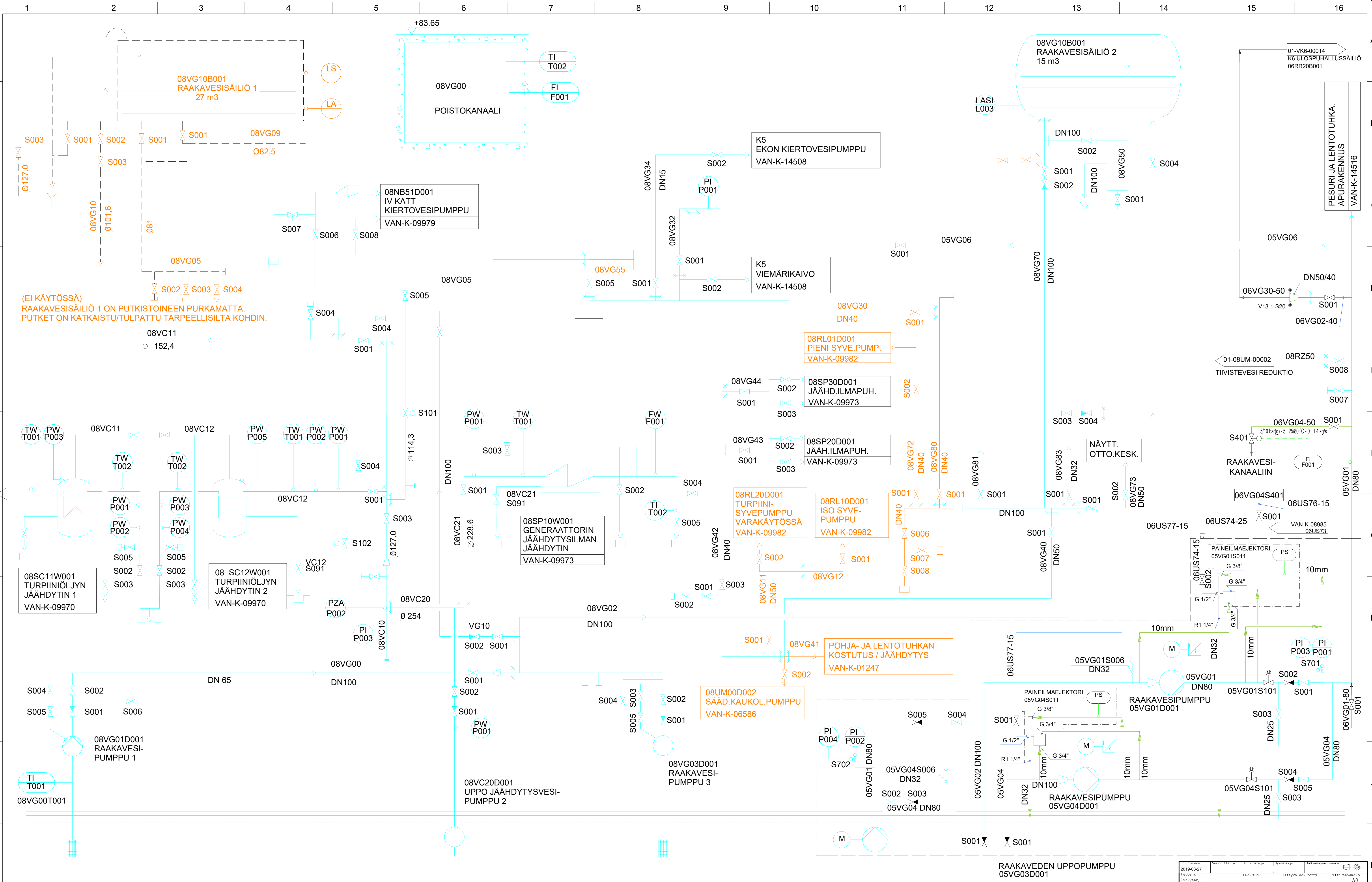

∅ SISÄHALKAISIJA

— EI KÄYTÖSSÄ

10.03.2025

Päivämäärä
2019-03-27
Suunnittelija
Tarkastaja
Hyväksyjä
Julkaisupäivämäärä
Tiedosto
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